EMERGING RISKS AND SYNERGIES FOR WATER NEEDS IN THE GLOBAL ENERGY SYSTEM

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Abstract

Human societies show increasing social, technological and environmental interdependencies. This growing complexity of socio-ecological systems has led to the question of how stable or sustainable these systems are now or will be in the future. One example of such a complex system is the global energy system. Over the last decades it received major attention with respect to its contribution to climate change and the necessary technological and structural transformations to decarbonize the energy system in the future as a potential solution. But besides the concern that greenhouse gas (GHG) emissions could actually further rise over the coming decades, there is also a scientific and political debate on the local and regional water demand that is associated with energy production. Water is required for the extraction of fossil resources, the growing of energy crops, the processing and conversion of primary energy sources, but also the for cooling purposes, mainly at thermal power plants. Today, freshwater sources are often exploited to meet the water requirements of the modern energy sector. Being identified as one planetary boundary (Steffen et al. 2015), regional freshwater use can lead to socio-ecological interactions on a global level, and hence make the energy system's water demand besides GHG emissions another major global environmental issue.

With potentially growing water use in the energy system due to increasing global energy demand, an aggravation of water stress and scarcity in already water-stressed regions, such as the Middle East and North Africa, and even emerging water stress in currently water-rich areas might occur over the coming decades. Along with the actual energy demand, the choice of energy source and technology drives water use for the sector itself, its availability for other sectors, and vice versa. Future energy supply might not only depend on water management within the energy sector, but also resource management outside. This circumstance resulted in a recent discussion on the specific interconnections with other sectors, especially agriculture as the global main water withdrawer and consumer. Water shortages can affect both sectors, furthering resource competition and even potential conflict, particularly on a local level.

Depending on local environment and energy technology choice, water use can show large variabilities. For this dissertation, three research contributions investigated potential water resource issues on different spatial and temporal scales when planning future energy systems. Exploring possible future water demand for energy in the form of regional and global energy scenarios allowed for answering a set of practical resource questions. The first contribution took a specific technological perspective and examined the significance of concentrating solar power deployment in North Africa for local and regional freshwater demand. It also illustrated the effect rising air temperatures could have on power production and consequently water use efficiency. The second contribution took a sectoral approach to water use for energy production in the Middle East and North Africa. It determined the importance of different production stages in the energy sector with
respect to water, and put them into relation with overall and agricultural water needs. This is a
critical point, as particularly highly water-stressed regions like the Middle East and North Africa
have a greater need for integrated efficient resource management. For the third contribution,
preceding findings were extended to a global level. It presents potential risks and synergies
regarding water needs in the agricultural and energy sectors for all parts of the world, revealing key
differences and regionally specific saving potentials. All contributions followed a comparable
scenario approach. Despite differing in background assumptions and spatial and temporal scales,
they all conclude that a rapid expansion of renewable energy, either in the form of photovoltaic and
wind capacities or thermal power plant capacities using alternative cooling systems, has not only
the potential to reduce global GHG emissions drastically but also to save water resources when
compared to current technology mixes as well as potential future water needs for fossil resource
use. An exception to this overall finding was investigated in the final, cross-sectoral analysis,
considering a large expansion of first-generation biofuels as one potential future development in the
global energy system. In this case water requirements for energy supply could increase to a level
where it could potentially exceed water needs for food supply.

By showing that the sustainability of future energy systems does not only depend on its GHG
emission rates but also on water needs for certain energy technology mixes, the overall results of
this dissertation underline the need for more integrated cross-sectoral water-energy policies.
Planning the future energy system calls for a technology-sensitive approach with respect to water,
as well as the integration of developments and resource management in other sectors that are
using large amounts of water and which may allow for water resource trade-offs between those
sectors. A better understanding of the complex interactions and feedback loops between sectors
and regions - as here demonstrated for energy and water resource interconnections - appears
crucial for a successful transition to global sustainable development that simultaneously targets a
wide range of ecological, economic and social goals.
Zusammenfassung


In Abhängigkeit von lokalen Bedingungen sowie Technologiewahl ist der Wasserverbrauch im Energiesektor durch große Variabilität gekennzeichnet. Diese Dissertation setzt sich aus drei Forschungsbeiträgen zusammen. Deren Grundlage bilden jeweils regionale und globale

einen erfolgreichen Übergang zu globaler nachhaltiger Entwicklung, welche gleichzeitig eine große Anzahl verschiedener ökologischer, ökonomischer und sozialer Ziele verfolgt.
Acknowledgments

This dissertation would not exist without the great support and encouragement I received from many people over the course of my PhD studies. It has been quite a journey, academically but even more so personally, facing a number of obstacles and setbacks that let me doubt if I can make it to this point. But I did. I surprised myself, and I am extremely happy and grateful to have people in my life without whom this might not have been possible. They gave me the opportunity to grow and helped me find my own way in and outside the academic world.

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I would like to thank Joanne Linnerooth-Bayer and Pavel Kabat as well as Helga Kromp-Kolb and Herbert Formayer for offering their support, particularly regarding the progress and success of my academic career. Dagmar Schröter and Carmenza Robledo Abad, thank you for your time and open ears, for keeping up the spirit, and, for simply being there.

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Remarks

This dissertation follows a cumulative research approach, consisting of three consecutive scientific research contributions. PART I consists of a synopsys presenting the conceptual framework, motivation and background, research design and main findings of all three contributions. PART II comprises the contributions itself in the form of stand-alone, individual research articles as they appear in peer-reviewed scientific journals.
# PART II – INDIVIDUAL ARTICLES

## 7 CONTRIBUTION 1 - Costs of reducing water use of concentrating solar power to sustainable levels: Scenarios for North Africa

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PART I – SYNOPSIS

1 CONCEPTUAL FRAMEWORK

1.1 Emerging global systemic risks

The Earth system with its current meteorological, hydrological and geological conditions forms the basis for the development and evolution of life. Especially over the last 10,000 years remarkably stable conditions allowed for the emergence of modern human societies and their ongoing socio-economic progress. Complex sub-systems ranging from climate and biosphere to agriculture, infrastructure and economy reached a state where those sub-systems co-evolve, adapting constantly to changes within and across each other, leading to a large number of positive, negative or non-linear feedbacks that determine its own and other system’s future development. Humans are part of the natural ecosystems they evolve in and yet at the same time their actions change their appearance and further evolution by increasing or decreasing those ecosystems’ stability (resilience). Global humanity depends on the resources and resource flows of natural ecosystems but still shows enough independence and self-organization to fundamentally transform these supply systems and consequently re-adapt to ensure its own system’s stability. These dynamics raise the question to which extent human societies can push the adaptability of the current ecosystems they depend on, and at which point living conditions in the current Earth system might not further support today’s ecosystems and therefore the survival of humans. In this context, global systemic and emerging risks are defined as the systemic risk being that unlikely and unexpected interactions can lead to a unpredicted threatening of the system’s survival; and emerging risk as that danger that stems from new interdependencies and technologies and which is caused by the nature of the system itself (Centeno et al. 2015).

Global resource assessments such as for forests and land use (FAO 2010), water (UNEP 2006) or energy (GEA 2012) and the relatively new scientific field of sustainability science (Clark and Dickson 2003, Komiyama and Takeuchi 2006) were able to demonstrate the importance and interdependencies between different natural and social sub-systems of the Earth system. Dynamic, non-linear feedbacks between oceans, atmosphere and landmass create conditions in which human societies can evolve and thrive. But there is reason to suspect that there are global boundaries within this Earth system that guarantee the survival of the ecosystems we depend on. For example, climate change research identifies and forecasts the potential consequences of changing air temperature and precipitation patterns.
on regional and global hydrological cycles and biosphere and vice versa (IPCC 2014). Conditions within the Earth system are changing at an increasing speed. The identification and integration of a set of different natural variables that have to be kept within so-called planetary boundaries (PB) to ensure ‘safe operating space’ for human societies was the goal of a team of researchers publishing their latest findings on PBs in 2015 (Steffen et al. 2015). They identified nine planetary boundaries, climate change, novel entities, stratospheric ozone depletion, atmospheric aerosol loading, ocean acidification, biochemical flows, freshwater use, land system change, and biosphere integrity (see Figure 1). Based on their fundamental importance for the Earth system, climate change and biosphere integrity were recognized as core PBs through which the other PBs operate. Transgressing any of the identified PBs might result in substantial risks for the Earth system in its current state and hence human societies. Global and regional scales are linked through sub-regional boundaries. Freshwater use is one example for a sub-regional boundary showing strong regional operating scales, but which can also generate feedbacks to processes that show global thresholds. Sub-global dynamics hence can play a crucial role for the entire Earth system’s stability.

Figure 1: Currently identified planetary boundaries and the state of control variables for seven out of nine boundaries. The boundary itself lies at the intersection of the green and yellow zones (Steffen et al. 2015).

Human societies and their activities, especially over the last 60 years, show increasing social, technological and environmental interdependencies. Globalization led to rapid transformations of natural and artificial systems (climate, land use or the global energy and food system are just examples). This growing speed and scale of interactions has led to an increase in
complexity and hence endogenous risks for both the Earth system and global humanity as a sub-system. Feedback loops, new dynamics and non-linear responses of systems to changes inherently increase the fragility of complex socio-economic systems as well as the Earth system to which they are linked. Global social and environmental risks can emerge in systems that might appear stable/ resilient even if fragility/ vulnerability increases to a (tipping) point where small perturbations might lead to catastrophic results (Centeno et al. 2015).

1.2 Resulting policy challenges

The increasing complexity and interdependencies of environmental and socio-economic systems led to the question of how stable or sustainable these systems are now and will be in the future. Sustainability from a human society perspective integrates the environmental, economic and social capacity of a system to maintain conditions that guarantee our long-term survival within this system. With ongoing human development new global risks to the sustainability of the entire Earth system might emerge. The detection and research on potential boundaries and tipping points is therefore of high relevance for environmental policy. Environmental problems can be considered as complex and require a long-term perspective, while available knowledge is often only fragmentary and not systemized (Sigel, Klauer and Pahl-Wostl 2010). Still, environmental policy integration (EPI) appears to be of fundamental importance regarding sustainable development (Adelle and Russel 2013). In 1987 the Brundlandt report already underlined the significance of an integration of environmental policy into policies concerning the economic and social development of human societies: “The ability to choose policy paths that are sustainable requires that the ecological dimensions of policy be considered at the same time as the economic, trade, energy, agricultural, industrial, and other dimensions on the same agendas and in the same national and international institutions. That is the chief institutional challenge of the 1990s.” (WCED 1987).

Almost 30 years later this integration still presents itself as a challenge to policy makers and national and international political structures. Jordan and Lenschow (2010) noted that EPI is a multi-sectoral and multi-level coordination challenge. For a successful EPI Lafferty and Hovden (2003) identified three levels of necessary policy integration: coordination (removal of contradictions), harmonization (realize synergies), and prioritization (favoring environmental objectives). In practice, however, we observe two main obstacles for EPI. One, poor coordination and communication leads to research outputs not known or used by policy makers (Quevauviller et al. 2005). And two, there often also seems to be a lack of political will to give priority to environmental concerns. This leads to the current situation where EPI is still not fully utilized (Runhaar, Driessen and Uittenbroek, 2014). Understanding EPI as an
integration of environmental aspects and policy objectives into sector policies, such as energy or agriculture, synergies might arise for achieving environmental and sector policy goals together. But there is also the possibility of having to weigh trade-offs and risks between different environmental and other policy objectives when aiming at sustainable development (Persson 2004).

As suggested by research on systemic changes in the complex ecological and socio-economic systems, global risks are increasing and might threaten the survival of these very systems. EPI or in particular climate policy integration offers a political tool to find answers and solutions for global environmental and socio-economic challenges. Consistent with results from current EPI research, Centeno et al. (2015) suggest three main policy dilemmas when dealing with such global risks: First, the difficulty of using the appropriate future discount rate on the consequences of current actions (or lack thereof). Second, current management tools price productive efficiency over sustainability and fail to adequately price resulting fragility. And third, global systemic risks suffer from all the general problems of collective goods that require coordination among and compromise between individual preferences.

One example for these dilemmas would be the risk of climate change and the full decarbonization of the global energy system as a viable solution. The cost of fossil energy today do not include the cost of resulting climate change and its negative consequences for future human development. National governments, guaranteeing its economic efficiency without regard for environmental consequences (climate, water, soil, biosphere) often even subsidize the ongoing use of fossil energy sources. Natural ecosystems, freshwater sources and the atmosphere are all examples of common goods that are affected by the global energy system. Hence, current energy policies often appear detrimental to sustainability goals, increasing global risk on many environmental and socio-economic levels by leading to diverse (unpredictable) feedback loops between different complex ecological and social systems. An environmental issue stemming from global energy production other than greenhouse gas (GHG) emissions is local and regional freshwater use. On a local to regional level freshwater use was identified as one potential planetary boundary feeding back directly to both core PBs, climate change and biosphere integrity. Hence, changes in the water use of regional energy sectors can lead to a wide range of socio-ecological interactions on a global level, and make the energy sectors’ water demand besides GHG emissions another major environmental concern.

It is necessary to integrate multiple PB simultaneously when considering a single environmental policy challenge and technological pathways as sustainable solution. Addressing only one out of many interconnected environmental issues could potentially
mitigate one socio-ecological problem (for example GHG emissions from the energy system) while leading to an aggravation for another (for example freshwater use for energy). An awareness of existing interlinkages and potential trade-offs and their consideration in the form of integrated environmental policy strategies support a sustainable development in many social and ecological dimensions while reducing possible risks and conflicts from one-sided approaches and contradictory policy goals. Sustainable development policies should hence include as many known interconnected socio-ecological issues as possible to avoid unintended adverse feedbacks that might even exacerbate currently perceived environmental problems.
2 MOTIVATION

2.1 The need for integrated energy and water policy

2.1.1 The complexity of the global energy system

Energy has always been crucial for the development of human societies (Smil, 1994). Up to the 1950s energy systems were primarily local, although in some case they crossed national borders. Some international energy trade took place, but general energy economics remained on a national scale. Since then, however, the energy system evolved to a global system, a circumstance that has been fully understood since the oil crisis 1973-74 (Haefele and Sassin 1977). Today’s global energy system can be characterized as complex (adaptive) system as it is comprised of a multitude of interconnected entities, which interact with natural, social and technological systems, is strongly path dependent and capable of undergoing fast and largely unpredictable changes (Cherp, Jewel and Goldthau 2011). World population growth, economic development and urbanization are the key drivers that shape the environment in which the global energy system evolves and adapts. Recognizing the essential role of energy for achieving global sustainable development goals (UNDP et al. 2004), it appears important to determine the major elements of the energy system and detect interactions within the energy sector itself but also with other sectors such as agriculture, water management or urbanization and many others in order to assess their effect on future energy transitions and vice versa.

The present energy system is confronted with multiple social and environmental challenges on a global scale. Those include a fast growing energy demand with a concentration in urban centers, the lack of access to modern energy technologies for billions of people as well as the need to reduce GHG emissions to lower the energy system’s impact on the global climate (UNDP 2004, IEA 2012, IPCC 2014). About three-quarters of our current energy supply stem from fossil energy resources, accounting for 70% of global GHG emissions (IPCC, 2014). All of these challenges are large, urgent, global and systemic (Cherp, Jewell and Goldthau 2011) and call for a fundamental transformation of the energy system. Such a transformation will feed back to how energy is produced, transmitted and consumed and will consequently affect all societal levels from private households to global economy. All of the challenges for the global energy system need to be addressed simultaneously when aiming at achieving global development goals (GEA 2012). Potential transformations of the energy system have to integrate increasing interdependencies with social and environmental externalities. While the energy system faces the challenge of reliably and sustainably meeting a steadily growing...
Motivation

demand in the future, it is also becoming increasingly sensitive to the socio-ecological conditions that it is embedded in, but is at the same time also (re-)shaping.

2.1.2 Arising water issues in regional energy sectors

Besides the interaction of the current, fossil fuel based energy system with climate in the form of rise in global greenhouse gas emissions and a consequential rise of global mean temperatures (IPCC 2014), there are also important, and potentially large, feedbacks between the energy system and the water cycle. Freshwater (blue water) use has been identified as one underlying sub-global planetary boundary, interacting with the climate and biosphere system on a global level. Thus, not only fossil fuel use affects the core PB climate change and biosphere integrity as well as other (sub-)global systems, but also local to regional water use for energy supply can feed back to those two linked global complex systems. Rising global population numbers and strong economic development have led to a steep rise in energy demand over the last 150 years (Smil 2010, BP 2013). Associated with this trend has also been an increasing demand for freshwater resources. Water is required for the extraction of fossil resources, the growing of energy crops, the processing and conversion of primary energy sources, but also for cooling purposes at thermal power plants. Often freshwater sources are exploited to meet the water requirements of the modern energy sector. But the growing water demands are not only due to a higher energy demand and hence energy supply per se. The contentious exploitation of oil and gas reservoirs as well as the growth of unconventional fossil energy resource extraction, such as hydraulic fracturing, increases water demand for fossil resources per energy unit extracted. Regarding electricity generation, rising average air temperatures and an increase in the frequency of heat waves as a result of climate change increase cooling water needs of thermal power plant capacities and can lower or limit their output during these times (van Vliet et al. 2012), making them less efficient and hence increasing the need for regional energy capacities or energy imports. At the same time, those increasing air temperatures additionally drive electricity demand during the summer time, especially as the demand for air-conditioning rises, creating a positive feedback loop for energy and the associated water requirements. In the transport fuel sector, the growing development of first-generation biofuels, such as bioethanol in Brazil or biodiesel in Europe, which require the planting and irrigation of energy crops, drives the water demand for transport fuels significantly. Also large-scale hydropower is sometimes considered as a significant water user within the energy sector. Reservoirs show very high evaporation rates, especially in arid and semi-arid regions such as the southwest of the United States or North Africa. Accounting for the water losses associated with hydropower generation itself, however, remains problematic, as these reservoirs often serve multiple purposes. The water requirements for energy hence not only grow due to higher per capita and absolute energy
demands globally, but are also driven by the increasing demand of current energy sources and technologies themselves, lowering the water efficiency per energy unit output.

The comprehensive assessment of water use in the energy sector began in the 1970s in the United States, a region with high and at this time fast growing energy demand, a large fossil fuel extraction industry, and sub-regional water scarcity combined with early attention to local environmental concerns (Harte and El-Gasseir 1978, Davis and Velikanov 1979, Holdren 1980, Gleick 1994). A main concern was the temporal and geographic variability of freshwater resources and as a consequence a potential limitation of future energy supply. Since then, these early evaluations have been continuously updated and expanded (US DOE 2006 and 2009, Mielke et al. 2010, Macknick et al. 2011 and 2012, MacMahon and Price 2011, Meldrum et. al. 2013, Spang et al. 2014). Especially in the US quantitative data collection became more and more comprehensive, in particular for the electricity sector, where the choice of technology and cooling system can have enormous effects on water demand and thus local water availability, making water consumption and withdrawal data for electricity generation increasingly reliable and representative over the last few years. Water demand or water consumption is defined as the amount of water that evaporates or gets polluted during the energy production stages and there cannot (directly) return to the original water source. Water withdrawals comprise the entire amount of water a water user, like a power plant, draws from a water source, including both the water share that actually gets consumed and the share that is returned to the source. Water withdrawal rates therefore always lie above water consumption rates.

More recently, one also finds discussion and quantitative evaluations on this topic in other parts of the world (FAO 2008, Kahrl and Roland-Holst 2008, Malik 2010) as well as on a global level (SEI 2011, Kyle et al. 2013, Vassolo and Döll 2005, IEA 2012). Special attention is often payed to particularly water-stressed regions such as Spain (Carillo and Frei 2009), California (Larson et al. 2007), Australia (Marsh 2008) or the Middle East and North Africa (Siddiqi and Anadon 2011). But also regions like Europe that are characterized by large water resources can face electricity supply limitations due to water restrictions (van Vliet et al. 2012). These recent studies now allow data comparison between the US and other parts of the world with respect to the average water demand of different energy technologies. Current scientific literature appears conclusive that the water demand of a region’s energy sector can have increasingly negative impacts on local and regional water availability, limiting energy generation and also aggravating competition with other water users, especially agriculture (Feeley et al. 2008, Sovacool and Sovacool 2009, Haddadin 2001).

In parallel, we find discussion of rising energy requirements for water supply (Wang et al. 2012). Water treatment, as a result of not only increasing water demand but also water
pollution, drives the associated energy demand, which then again drives the water demand for the energy supply itself. This is another positive feedback loop, where water and energy demand growth reinforce each other. In very water-stressed regions, the large-scale development of desalination technologies began. These technologies currently require enormous amounts of energy (WSTB 2008, Dubreuil et al. 2012). Depending on the energy source chosen, this trend might in turn increase both GHG emissions and water demand for energy, but also lower source water quality, aggravating future water resource restrictions (Lattemann and Höpner 2008).

The rising attention to the water intensity of the energy sector also contributed to a discussion on its interconnection with other sectors, especially agriculture as the global main water withdrawer and consumer (70% and 90%, respectively (AQUASTAT 2014)). Water shortages can affect both sectors, furthering resource competition and even potential conflict, particularly on a local level (Allouche 2011, Kuzdas and Wiek 2014, Apipalakul, Wirojangud and Ngang 2015). Often summarized under the term Water-Energy-(Land)-Food (WE(L)F) nexus, one finds studies that not only look at the interrelationships between energy and water, but also between water and food, energy and food, and land and food, sometimes trying to integrate more then two resources in one assessment. Similar to water-energy assessments, from those studies’ perspectives a growing demand for natural resources in order to meet a growing request for food, energy, and water seems inevitable. Hence, a rising demand for water in the energy sector in combination with a rising food demand and the associated water requirements, might limit future production capacities in both sectors and calls for efficient integrated resource management.

The arising water issues in the energy sector might have far-reaching, and cross-sectoral negative environmental and social consequences. Along with the energy demand, the choice of energy source and technology drives water availability for the sector itself but also for other sectors and vice versa. Future energy supply might not only depend on water management within the energy sector but also resource management outside. Considering current trends and patterns in water resource use, an aggravation of water stress and scarcity in already water-stressed regions, such as the Middle East and North Africa, and even emerging water-stress in currently water-rich areas might occur over the coming decades. In this regard, planning the future energy sector calls not only for a technology-sensitive approach with respect to water, but also the integration of developments and resource management in other sectors that are using large amounts of water and which may allow for water resource trade-offs between those sectors in the future.
2.2 The case of the Middle East and North Africa

The Middle East and North Africa (MENA) is a world region that shows a number of unique and important characteristics with regard to its energy and water resources. The region has the world’s largest amounts of oil and gas reservoirs and the export of fossil energy forms the basis of the entire region’s economy. MENA plays the most important role for global energy extraction and contributes currently about 40% to global oil exports (BP 2013). At the same time, internal per capita energy demand is still relatively low (The World Bank 2015), but is expected to be steadily growing over the coming decades (OECD 2012). Current demographic projections indicate that a rapidly growing population will further increase MENA’s own energy demand. Today, water in the energy sector is primarily used for crude oil extraction. Per capita electricity demand is low (The World Bank 2015) and due to a population distribution that shows highest concentrations of people along coastlines, electricity from today’s thermal power plants require only small amounts of fresh water, as predominantly seawater cooling systems are installed (Davies et al. 2013). Concerning transport fuels, currently crude oil is often exported and final oil products reimported, shifting the associated water demand to other parts of the world. The current overall water demand of the energy sector appears minor with less than 2% of overall freshwater withdrawals (Siddiqi and Anadon 2011), especially compared to the agricultural sector, which is responsible for 97% of the region’s freshwater withdrawals (AQUASTAT 2014), in many cases non-renewable water from fossil aquifers.

MENA is also the world region that shows the highest water stress in relation to its population numbers (Shiklomanov 2000). Current per capita water availability averages at 1,100 m$^3$ per year. In comparison, global average water availability amounts to 8,900 m$^3$/yr (AQUASTAT 2014). Given that the region’s population is expected to almost double by mid-century (UN DESA 2009), per capita water availability might further decrease. At the same time, driven by population growth, urbanization and economic development, water demand for food and energy supply, per capita and in total, is likely to increase and might intensify import dependencies at least for the former. The region also shows high variability and low rainfall, making it largely dependent on fossil water bodies and trans-boundary water. Moreover, climate change affects the region by increased air temperatures and rising sea levels, reducing freshwater availability and quality even further (Sowers et al. 2011, CEDARE 2006). Changing precipitation patterns at the stream sources of the region’s main river systems, Nile and Tigris-Euphrates, might additionally limit MENA’s renewable freshwater resources in the future (Arnell 1999, IPCC 2014).

The already scarce water resources are often used inefficiently, water pollution rates are high, and water allocation is strongly driven by food (and energy) trade policies, subsidies, and
economic drivers such as tourism, leading to excess irrigation and groundwater depletion. Water scarcity therefore not only exists on a physical level, but also through a scarcity of organizational capacity and accountability for sustainable outcomes (The World Bank 2007). A number of MENA countries have begun to increasingly invest in dam construction and energy-intensive desalination technologies for a continuous freshwater supply (WSTB 2008), while institutional water policies and management nevertheless remain weak (Sowers et al. 2010). Today we find the world’s largest desalination capacities in the MENA region, usually using considerable amounts of fossil energy to operate (Miller 2003). A further growth of the need for desalination capacities in this particular world region seems likely, making the choice of energy source providing the necessary energy for different desalination technologies also an important one regarding feedback loops for water use associated with this very energy source (Al-Karaghouli and Kazmerksi 2013).

An electricity technology that has the potential to meet not only the region’s own growing energy demand (including that for desalination) but also substitute current fossil energy exports with renewable energy, and hence lowering MENA’s greenhouse gas emissions drastically, is concentrating solar power (CSP). CSP is a solar energy technology that allows for a continuous generation of electricity also during cloudy conditions and nighttime. Preferred locations for this technology are semi-arid and arid regions that are characterized by high solar irradiation. Over the last ten years MENA gained increasing attention for its enormous solar resources, available flat land and proximity to potential export partners in the north and south, making it an ideal site for large-scale CSP development. Since 2003 the DESERTEC concept supported, besides photovoltaic and wind, concentrating solar power as one of the three renewable energy sources this region could produce and eventually also export to the European Union. DESERTEC advocates a large-scale renewables project for sustainable solutions regarding future energy, water and climate security for Europe and the MENA region until 2050 (Desertec Foundation 2009). The idea was supported by three main studies that tried to show that a transition to renewable energy, efficiency gains and fossil fuels as backup capacities, are capable of providing secure and compatible energy until the mid-century. MED-CSP (Trieb 2005) focused on electricity and water supply and underlined the importance of renewables for sustainability and socio-economic development. TRANS-CSP (Trieb 2006) discussed the requirements for an interconnection of the electricity grids of Europe, the Middle East and North Africa as a means to trans-continental electricity trade and provided ideas for an underlying political framework. AQUA-CSP quantified future water deficits and discusses potential technological solutions in the form of desalination capacities (Trieb 2007). From 2009 until 2014 a large number of shareholders supported the foundation as partners in the Desertec industrial initiative (Dii) consortium. Despite the recent withdrawal of most European shareholders, a number of CSP projects in North Africa are still in the planning and development stages: eight (hybrid) CSP plants, two in Morocco, one in Algeria.
and one in Egypt, as well as one in Israel and three on the Arab peninsula are currently operating (CSP Today 2015). CSP has the technological and economic potential to become a major energy source for MENA and Europe. Being able to personally contribute to a recent study by Pfenninger et al. (2014), new scientific findings show that CSP deployment in the Mediterranean, among other regions, could provide baseload and dispatchable power without major cost penalties and consequently could become a viable substitute for current fossil energy sources in both regions. This advantage over current wind and photovoltaic technologies might make CSP a very important energy technology in the future energy mix of MENA and neighboring regions.

Given MENA’s current economic significance but also dependence on the global energy system as well as its abundance of both fossil and renewable energy resources, this world region will probably continue to play a major role for the world’s future energy supply. In the case of a continuation of large-scale fossil resource extraction over the coming decades, water requirements for the energy sector will keep being concentrated on oil exploitation and might further grow with the region’s and the world’s rising energy demand. However, in case of a large-scale deployment of renewable energies, water use for fossil energy extraction would decline, while new water demands may arise in the electricity sector, for example with the installment of large-scale CSP in remote desert areas. Like other thermal power technologies CSP requires cooling for which some technologies use large amounts of water. The next chapter describes this potential ecological and economic issue in more detail. Thus, when targeting an alleviation of the generally increasing water stress in the MENA region, the specific choice of energy source and technology might have a considerable effect on future regional water availability.

2.3 Guiding research question

As summarized in the previous sections, the choice of energy source and technology, fuel type, or cooling system has a large impact on the water demand of the energy sectors in different world regions. The extraction of fossil and nuclear energy resources always require water, while renewable energy apart from bioenergy crops don’t require the additional input of water resources for making the energy source itself accessible. Regarding fuel production, the water demand for each type of fuel, fossil or renewable, also varies, while for electricity large amounts of water are often consumed at thermal power plants when using water as a cooling source. So far, there are no comprehensive quantitative studies on a whole energy sector’s total water demand outside the US, and global energy models such as MESSAGE (Messner and Strubegger 1995) currently do not take in to account the water requirements of energy technology mixes. An expected increase in global energy demand, together with the
implementation of climate policies, will likely lead to a profound transformation of the global energy system. Depending on the specific energy technologies that will be employed over the coming decades, future regional water demand might either substantially increase or can be limited to sustainable levels.

By quantifying water demands (and to some extent water withdrawals) for different fossil and renewable energy technologies and developing local, regional and global scenario approaches, this dissertation aims to answer the question to what extent the choice of future energy technologies could affect global and regional water availability. This demand influences not only regional water availability but also global resource and socio-economic interactions and hence ecosystem stability. A special geographical focus is set on the Middle East and North Africa, being a world region that stands out for both energy resource abundance as well as water scarcity. Technological focus is set on CSP as a possible dispatchable renewable electricity source, showing large potential for future energy generation in semi-arid and arid world regions (Pfenninger et al. 2014), while possibly large water requirements might be one reason for a delay of its rapid deployment. Being able to estimate and compare future water demands for different technology shares in the energy sector, including resource extraction, fuel production, and electricity generation, and relating those results to water demands in other sectors, especially agriculture, help to detect potential risks and synergies and supports a more integrated natural resource management approach and resource policy when taking more than climate policy goals into consideration.
3 HISTORICAL AND TECHNOLOGICAL BACKGROUND

3.1 Water use in the energy sector

Water is used for various purposes when providing energy. This section presents an overview of requirements in three production stages within the energy sector. One, water is required when extracting and processing fossil resources, especially crude oil, but also natural gas, coal and uranium. Two, converting primary energy sources, such as crude oil or biomass, into transport fuels like gasoline or bioethanol, requires water mainly for separation processes and cooling. And three, in the electricity sector primarily thermal power plants require large amounts of water for cooling purposes. Table 1 presents an overview of average water consumption ranges for different energy technologies.

<table>
<thead>
<tr>
<th>A. Extraction technology</th>
<th>Average water consumption [m³/TJ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>COAL</td>
<td></td>
</tr>
<tr>
<td>Mining + washing + transport</td>
<td>41³</td>
</tr>
<tr>
<td>CRUDE OIL</td>
<td></td>
</tr>
<tr>
<td>Primary recovery</td>
<td>6¹</td>
</tr>
<tr>
<td>Secondary recovery</td>
<td>248¹</td>
</tr>
<tr>
<td>Enhanced recovery (EOR)</td>
<td>56 - 10,240¹</td>
</tr>
<tr>
<td>Unconventional sources</td>
<td>6 - 139¹</td>
</tr>
<tr>
<td>NATURAL GAS</td>
<td></td>
</tr>
<tr>
<td>Conventional gas + transport</td>
<td>4¹</td>
</tr>
<tr>
<td>Shale gas</td>
<td>7¹</td>
</tr>
<tr>
<td>URANIUM</td>
<td></td>
</tr>
<tr>
<td>Mining</td>
<td>13¹</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>B. Fuel technology</th>
<th>Water consumption (range) [m³/TJ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BIOFUELS (excl. crop production)</td>
<td>0 - 238²,³,⁵</td>
</tr>
<tr>
<td>COAL</td>
<td>37 - 93²,³,⁵,⁶,⁷</td>
</tr>
<tr>
<td>HYDROGEN</td>
<td>37 - 64⁵,⁶,⁸,⁹</td>
</tr>
<tr>
<td>NATURAL GAS</td>
<td>4 - 34¹⁰,⁵</td>
</tr>
<tr>
<td>OIL PRODUCTS</td>
<td>2 - 3¹¹</td>
</tr>
</tbody>
</table>
### C. Electricity generation technology (non-renewable)

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Cooling System</th>
<th>Average Water Consumption [m³/GWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>COAL</strong></td>
<td><em>once-through</em></td>
<td>250 - 1,116&lt;sup&gt;²&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td><em>closed-loop</em></td>
<td>1,225 - 3,840&lt;sup&gt;²&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td><em>dry</em></td>
<td>0 - 120&lt;sup&gt;¹&lt;/sup&gt;</td>
</tr>
<tr>
<td><strong>NATURAL GAS</strong></td>
<td><em>once-through</em></td>
<td>75 - 1,165&lt;sup&gt;²&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td><em>closed-loop</em></td>
<td>505 - 4,530&lt;sup&gt;²&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td><em>dry</em></td>
<td>0 - 120&lt;sup&gt;¹&lt;/sup&gt;</td>
</tr>
<tr>
<td><strong>NUCLEAR</strong></td>
<td><em>once-through</em></td>
<td>385 - 1,550&lt;sup&gt;²&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td><em>closed-loop</em></td>
<td>2,250 - 3,275&lt;sup&gt;²&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td><em>dry</em></td>
<td>0 - 120&lt;sup&gt;¹&lt;/sup&gt;</td>
</tr>
<tr>
<td><strong>OIL</strong></td>
<td><em>once-through</em></td>
<td>250 - 1,550&lt;sup&gt;⁺&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td><em>closed-loop</em></td>
<td>2,225 - 4,025&lt;sup&gt;⁺&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td><em>dry</em></td>
<td>0 - 120&lt;sup&gt;¹&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

### D. Electricity generation technology (renewable)

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Cooling System</th>
<th>Average Water Consumption [m³/GWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BIO MASS</strong> (excl. crop plantation)</td>
<td><em>once-through</em></td>
<td>1,165&lt;sup&gt;²&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td><em>closed-loop</em></td>
<td>1,815 - 3,655&lt;sup&gt;²&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td><em>dry</em></td>
<td>0 - 120&lt;sup&gt;¹&lt;/sup&gt;</td>
</tr>
<tr>
<td><strong>GEOTHERMAL</strong></td>
<td><em>closed-loop</em></td>
<td>18 - 19,950&lt;sup&gt;²&lt;/sup&gt;</td>
</tr>
<tr>
<td><strong>HYDROPOWER</strong> (water consumption = evaporative loss)</td>
<td><em>not required</em></td>
<td>5,525 - 69,390&lt;sup&gt;²&lt;/sup&gt;</td>
</tr>
<tr>
<td><strong>SOLAR</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concentrating solar power</td>
<td><em>power tower</em> +</td>
<td>not required</td>
</tr>
<tr>
<td></td>
<td><em>closed-loop</em></td>
<td>2,100 - 4,295&lt;sup&gt;²,³&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td><em>parabolic trough</em></td>
<td><em>dry</em></td>
</tr>
<tr>
<td>Photovoltaic</td>
<td><em>not required</em></td>
<td>negligible</td>
</tr>
<tr>
<td><strong>WIND</strong></td>
<td><em>not required</em></td>
<td>negligible</td>
</tr>
</tbody>
</table>

**Sources:**

Table 1: Water consumption associated with energy. (A) Water consumption in energy resource extraction, presenting ranges and average water consumption for various technologies. (B) Water consumption in fuel production, presenting ranges and average water consumption for various fossil and renewable fuels. (C) Water consumption in non-renewable electricity generation. For seawater cooling same values apply as for dry cooling. (D) Water consumption in renewable electricity generation. For seawater cooling same values apply as for dry cooling.
**Primary energy resource extraction**

For all fossil and nuclear energy reservoirs the specific location, geology and recovery technique determines the water demand. For coal and uranium the water demand at the mine depends on its location underground or on the surface. Water is used for dust control and in case of coal for cutting. Coal additionally requires water for washing and if transported in the form of slurry. Water requirements are very low between 0.02 and 0.06 m$^3$/GJ. Also conventional natural gas extraction requires little water resources for drilling and transport (0-0.01 m$^3$/GJ). Larger amounts of water are used for conventional oil extraction in later recovery stages. Starting with primary recovery, conventional oil extraction requires very little water, as natural mechanisms are sufficient to push the oil to the surface and into the pipeline. When natural pressure declines due to lower resource volume inside the reservoir, water can be used to keep pressure and hence extraction rates stable. In this secondary recovery stage, water demand increases on average from 0.06 m$^3$/GJ in the primary stage to up to 0.25 m$^3$/GJ in the secondary stage. If the extraction factor drops further but a continuation of oil extraction appears economically profitable, the reservoir can transition into a tertiary recovery stage, using enhanced recovery methods (EOR). Often steam or CO$_2$ injection methods, and currently rarely other techniques like caustic injection, forward combustion, or micellar polymer injection can be used to increase extraction rates; water consumption here varies between 0.1 and 10 m$^3$/GJ. On large extraction sites one finds all three recovery stages simultaneously depending on the part and age of the oil field.

Over the last ten years also unconventional fossil resource reservoirs were commercially developed, including the extraction of oil and gas from shale formations, tar sands (in situ or surface mining) or heavy oil recovery. They show average water demands ranging from 0.01 to 0.14 m$^3$/GJ (Gleick 1994, US DOE 2006, Mielke et al. 2010). Depending on the geographical location, fresh, salt or brackish water can be used for conventional and unconventional oil extraction. Often, (salt) water makes part of the reservoir itself and can be reused for pumping purposes. For both conventional and unconventional fossil resource extraction the use of chemicals can affect local water quality (Veil et al. 2004).

The first commercial on-shore oil extraction began 1858 in Oil Springs, Ontario, Canada. The first off-shore oil drilling started 1896 at the Summerland Oil Field, California, USA. The first commercial oil fields in the Middle East and North Africa (MENA) region started operating in the 1930s with the Kirkuk field in Iraq and the Gachsaran field in Iran (Black 2012). Today the largest developed oil field is the Ghawar field in Saudi Arabia producing five million barrels per day and accounting for 6% of the world’s total crude oil production (Sorkhabi 2010). In the US, today about 80% of commercial conventional oil recovery is in the secondary recovery stage, with the reminder in tertiary recovery (Mielke et al. 2010). In the MENA region, large-scale
commercial oil recovery started on average 21 years later than in North America (Finnegan 2003).

**Transport fuels**

Fossil fuels comprise among others gasoline, diesel and kerosene, which are extracted from crude oil via fractional distillation. About 0.003 m³/GJ are needed when vaporizing the crude oil and separating and processing the single oil products. Oil refineries mainly require water for processing and cooling purposes (Alves and Nascimento 2010). Natural gas or coal (gas-to-liquid (GTL), coal-to-liquid (CTL)) can also be used to produce transport fuels in the form of methanol or synthetic fuel, e.g. via the Fischer-Tropsch process. Here water demands for gasification and liquefaction processes range from about 0.004 to 0.93 m³/GJ.

Biomass can also be used as a source for transport fuels such as methanol, ethanol or biodiesel, with bioethanol and biodiesel being the most common biofuels at this point. For producing methanol and ethanol also Fischer-Tropsch or fermentation processes are used. Water demand ranges from 0 to 0.2 m³/GJ and is therefore on average lower then for fossil CTL or GTL (van Vliet et al. 2009). However, these water consumption rates only comprise water requirements for fuel production processes itself, not for the possibly necessary planting of required biomass. In case of first-generation biofuels, where crops are grown for the specific use of fuel production, such as sugarcane for bioethanol in Brazil or rapeseed for biodiesel in Europe, water demand increases tremendously, depending on specific crop and region to an average of between 10 and 140 m³/GJ (Gerbens-Leenes et al. 2008).

Another transport fuel source is hydrogen. It is produced most commonly via steam-methane reforming (SMR), but also through thermochemical water splitting, electrolysis or in the form of biological hydrogen production. Conventional SMR requires the least water resources with 0.04 m³/GJ but shows high carbon dioxide emissions when coal is used as methane source. Highest water requirements appear for electrolysis with 0.06 m³/GJ (Naterer et al. 2010, van Vliet et al. 2009).

**Electricity generation**

The electricity sector constitutes the part of the energy sector where most water-related research and data collection took place over the last 40 years. High water use for electricity generation appears as an environmental issue with respect to reduced power output during times of water scarcity in specific locations (Bartos and Chester 2015) and increasing competition with other sectors, especially agriculture (FAO 2014), but also reduced water quality as a consequence of temperature increase of natural water bodies (EU 2006). Thermal
power plants can withdraw and consume large amounts of water when using once-through or closed-loop cooling systems. Once-through cooling systems withdraw water from an open water body such as a river, and then release the amount of water that is not consumed for cooling purposes (evaporated) back to the original water source. As this technology also affects the water temperature of the water body as water returns at higher temperatures, environmental protection measures lead to an increased deployment of closed-loop cooling systems over the last decades, especially in Europe (EU 2006). Closed-loop cooling systems show somewhat higher water consumption rates than once-through technologies, though water withdrawal rates remain much lower. Mean water consumption rates for thermal power plants vary between 0.02 and 1 m$^3$/GJ (Macknick et al. 2012). Alternative cooling systems in the form of dry cooling (air-cooled condenser or natural draft cooling towers) use relatively low air temperatures for cooling purposes. Today, air-cooling systems lead to higher investment cost and lower overall efficiency when compared to wet-cooled power plants. High ambient temperatures can further decrease the plant’s thermal efficiency. A technological option to reduce the water demand of a power plant but also lowering the thermal efficiency loss are hybrid cooling systems, where small amounts of water, for example in the form of spray, are used to increase cooling efficiency. Along coastlines, thermal power plants can also be cooled using seawater. The installment of additional carbon capture and storage (CCS) systems would currently further increase water demand (Zhai et al. 2011).

Other potentially large water users in the electricity sector are hydropower and bioenergy. Depending on local climate conditions, large water reservoirs used for hydropower generation can show high evaporation rates. These water losses are, however, difficult to attribute solely on the power generation itself as these water bodies are also often used for other purposes. Thermal power generation using biomass shows similar water demand rates as other thermal power plants. If biomass is purposely grown to generate electricity, an additional amount of water is required for growing energy crops. Apart from fossil and renewable thermal power technologies as well as hydropower, renewables such as wind turbines, photovoltaic or certain CSP technologies require very little amounts of water for processing and cleaning.

Depending on the specific mix of electricity technologies and their associated cooling systems the water demand of the electricity sector varies from world region to world region. Mainly using thermal power plants for electricity generation, currently the most common cooling systems are once-through and closed-loop technologies. This condition together with a rapidly growing energy demand led to the energy sector being one of the most significant industrial water users today. Data on varying cooling system shares in different world regions can be found in Davies et al. (2013).
3.2 Special focus on concentrating solar power

Technological characteristics

Concentrating solar power is an energy technology that uses mirrors or lenses to focus large amounts of solar radiation onto a small area. By converting sunlight into thermal energy sufficient heat is generated for thermal electricity production. At this time, there are four main CSP technologies that are established well enough for commercial use. Parabolic trough and linear Fresnel systems concentrate solar radiation on a linear receiver, a tube most commonly filled with heat oil that absorbs the thermal energy and is used for generating steam that drives a standard turbine generator. The mirror shape of parabolic trough is concave, while Fresnel technologies use multiple flat mirrors. Power tower technologies use a circular field of mirrors to focus sunlight onto a tower, where a working fluid such as molten salt is heated up for generating steam. They can reach significantly higher temperatures (500-1,000 deg C) than linear CSP technologies (up to 550 deg C), hence showing higher efficiencies when producing electricity. Dish/engine systems produce relatively small amounts of electricity – with up to 1.5 MW - when compared to other CSP technologies, which show installed capacities up to 300 MW (CSP Today 2015). Mirrors shaped as a parabolic dish collect and focus the sunlight onto a central Stirling engine that directly produces electricity. In order to reach highest possible solar irradiation, all CSP technologies have their mirrors track the sun over the course of the day. Sometimes additional photovoltaic units supply the energy required for those mirror adjustments. In contrast to photovoltaic systems, CSP technologies also offer the possibility for large-scale storage of energy in form of heat storage. Tanks filled with for example molten salt make it possible to collect enough heat to produce electricity during the night or at times when it is cloudy, allowing for a much more continuous electricity supply. Current maximum storage capacities can be found at the Gemasolar CSP plant in Spain with up to 15 hours of heat storage (NREL 2011).

Using steam turbines to generate electricity, CSP like any other thermal power plant requires adequate cooling systems that ensure a certain range of temperature difference within the thermodynamic cycle and therefore specific thermal efficiency of the power plant. Being preferably located in dry, sunny areas including deserts like the Mojave or Sahara, evaporation rates from wet-cooling systems, closed-loop or once-through, are high and could potentially lead to water resource competition on a local and regional scale. Thus, the choice of the cooling system plays an important role for local water availability. Increasing air temperatures with climate change would further increase water demand while reducing plant efficiency. Dry or hybrid cooling systems are able to reduce the water demand of CSP drastically, but lower plant efficiency even further (Szabo 2010). The additional construction of
cooling ponds (if possible) or seawater cooling systems are other measures to reduce potential local freshwater stress and avoid competition with other water users.

Worldwide CSP development

After extensive research in the 1970s, in 1982 the first large-scale CSP power tower plant, Solar One, started operating in the Mojave Desert in Southern California. In 1995 it was converted into Solar Two, showing increased the mirror field size and an enhanced storage medium. Luz Industries started operating the first commercial parabolic trough plant, SEGS 1 (Solar Energy Generating Systems) in 1984, also located in the Mojave Desert. Until 1990 it was followed by the deployment of eight more parabolic trough plants, SEGS II to SEGS IX, improving collectors, transfer fluid qualities and storage facilities to increase overall plant efficiency and demonstrate economic feasibility. All plants are still operational. In the early 1980s smaller scale projects were also developed in Spain. Additionally encouraged by the continuous improvements demonstrated by the SEGS plants in the US, Andasol-1 started operating in 2008 in Granada, Spain, as the first commercial parabolic through CSP plant in Europe. Planta Solar 10 was the first commercial power tower plant, built in 2005 close to Sevilla, Spain. In 2009 the first commercial linear Fresnel plant started operating in Queensland, Australia. There is only one dish/engine plant that is currently being built for commercial operation in Utah, US. At this point, parabolic trough is the main commercially successful CSP technology with a global share of 74%, followed by power tower projects with a share of 23%. About 73% of operational CSP plants today are located in Europe, 18% are located in the North America. However, 45% of all CSP projects that are currently under constructions can be found in the US (Baharoon 2015). The currently high share of CSP in Europe is the result of a solar power boom in Spain since 2004 when the Spanish government decided to support large-scale solar power through feed-in tariffs that would lower economic barriers for solar energy development. Concurrently Spain also became a world leader in the solar energy industry. However, with the financial crisis in 2008, Spain scaled back subsidies and hence led to a worldwide slowdown for solar power development (Gonzales and Johnson 2009). This example shows how much national energy policies can foster or limit the growth of new technologies on an international level. Simultaneously it raises the question of ecological barriers for such new energy technologies. In the case of CSP, from a climate perspective sustainability could be increased through potential GHG emissions reduction in the energy sector, while from a water resource perspective it could lead to a decrease in sustainable water use. Besides its theoretical economic potential, knowing the ecological boundaries for an integrated sustainable growth of new technologies is therefore of high importance for future energy policy.
3.3 Global and regional interconnections with other sectors

The by far largest water user, regarding both global withdrawals and consumption, is the agricultural sector. Especially required for irrigation purposes, total water withdrawals in this sector amount to 70%. 20% are allocated to industry of which the energy sector constitutes an important part with respect to water demand (AQUASTAT 2014). On a global level, it appears, sectors other than agriculture play only a minor role, but in regions where water resources are limited, water users may face competition, when the demand for water in one sector might restrict availability in another and vice versa. Water shortages such as during extended drought periods affects all water users and the fair allocation of scarce water resources remains a challenge for resource management and water policies (Hellegers et al. 2008). Observing fast growing water demands for not only energy but also food, a number of scientific studies have analyzed the interactions between water, energy, (land) and food resources over the last decade (Bazilian et al. 2011). Recognized under the term WE(L)F nexus, they try to describe the resource interactions with regard to water that is required for food and energy, energy that is required for water and food, and land that is required for food and energy supply. One finds qualitative studies, presenting the interrelationships of different natural resources from a local to global level, but also quantitative studies on this topic. All existing quantitative studies focus on a specific part of the WE(L)F nexus, with most of them concentrating on the water-food and water-energy nexus.

All recent qualitative WE(L)F studies, such as presented by Ringler, Bhaduri and Lawford (2013), Halstead et al. (2014), Bogardi et al. (2012), de Fraiture et al. (2010) or Rosegrant, Ringler and Zhu (2009) envision a drastic increase in food, energy and water demand based on an extrapolation of current resource needs and population and development trends. Hence, they call for an integrated policy and management framework for those diminishing resources. The same findings are underlined by a number of quantitative global and regional WE(L)F studies. Global approaches such as by Chartres and Sood (2013), Sulser et al. (2010), or regional studies such as by Hardy, Garrido and Juana (2012) and Lawford et al. (2013), all show increasingly limited water resources due to a rising food and energy demand. Special attention in the scientific literature is paid to the production of biofuels, for example bioethanol or biodiesel. As a potential substitute for liquid fossil transport fuels, a number of studies have looked at their associated water demand when specific crops are planted for the use as energy source; examples are de Fraiture, Giordano and Liao (2008) or Yang, Zhou and Liu (2009). Depending on the world region, water requirements vary but always show a large additional increase in water demand in case first-generation biofuel production were extended in the future.
Those studies’ findings show that on a local to regional level, developments in the energy and agriculture sector to meet the expected future demand can have large effects on water availability. On a global level, however, the trends in the energy sector still appear minor in comparison to the agricultural sector. One exception to this finding though could be biofuels, whose water requirements could compete with those for food production on a global level in case of a drastic expansion in the future. Direct interconnections between the agricultural and energy sector remain therefore most noticeable on a smaller scale in areas where water resources are scarce, while global interlinkages are most prominently displayed only indirectly in the form of virtual water trade associated with food and energy exports (Hoekstra and Hung 2004, Galan-del-Castillo and Velazquez 2010).

Nonetheless, the water demand in the energy sector is not trivial, and when facing water stress saving potentials in the energy sector can have a noticeably positive effect on water availability for other sectors and the other way around. Water is one of the most important natural resources, and feedback loops within each sector but also across sectors require an integrated analysis approach, which facilitate resource management and supports integrated environmental policy goals regarding overall sustainability. Thus, quantifying each sector's resource needs is a necessary step in order to evaluate its significance as water user, absolute and in relation to other users.
4 RESEARCH DESIGN

4.1 Structural overview and individual research questions

This dissertation consists of three complementary research steps (contributions), each consecutive step building upon each other by using common collected datasets and advancing modeling approaches:

(1) The first one is building the basis for further research in the form of a detailed regional technology analysis and scenario development for future large-scale concentrating solar power deployment in North Africa. The goal is to estimate and compare the costs of reducing water demand of CSP to sustainable levels in this particularly water-stressed region, and hence test this technology’s ecological and economic feasibility.

(2) The first contribution is followed by a more integrated approach assessing the entire water demand of the Middle East and North Africa’s energy sector, including fossil resource extraction, electricity generation and transport fuel production. After an initial accounting of current water needs in the region’s energy sector, a new set of regional energy scenarios explores the direct impacts of alternative energy futures on the water demand in MENA, setting special focus on CSP.

(3) In a last step, data and modeling approaches from contribution 1 and 2 are extended and adapted for a global analysis, estimating the water demand for electricity and transport fuels in five world regions. Comparing these potential future water requirements with those for food supply from the agricultural sector, the aim is to detect and relate water-saving potentials and trade-offs for scarce water resources in the energy and agricultural sector. This final analysis allows for an integration of the results from the local to global energy-water analyses with the most important water user, agriculture, contributing currently about 70% to global water withdrawals. Besides absolute global and regional results, it hence provides also a relative perspective on this complex resource issue.

Figure 2 displays a structural outline of the research approach, summarizing its goal, methods, single research steps in the form of independent but consecutive and complementary research contributions, and their general results providing significant information for integrated natural resource policy and management. The remainder of this chapter provides an overview on applied scenario and modeling approaches, as well as datasets that form the basis for model runs in each research step.
4.2 Scenario approaches

Scenarios are stories on how the future might unfold. They are based on the present reality and conditions as perceived. As a way to develop and compare a range of plausible futures, scenarios are used in a wide range of scientific disciplines and across various spatial and temporal scales. Scenario approaches constitute a common method for example climate predictions, population developments or changes in the energy system. Over the last decade, a number of global scenario frameworks have tried to cover a wide range of potential socio-economic and ecological futures. These can also be used as a underlying conditions for regional and local scenarios, aligning spatially specific assumptions on the future with global developments, increasing comparability to other scenarios within the same global framework. When developing a set of scenarios, baseline assumptions have to be inherently consistent and drivers for observed changes over time should be clearly identifiable.

Older global scenarios, like for example presented in the Special Report on Emissions Series (SRES) (Nakicenovic and Swart 2000) and depicted in Figure 3, mostly follow a sequential approach, where a set of scenarios on GHG emissions and socio-economic development results in a set of climate and Earth system projections that then can be used for analyses regarding impact, adaptation and mitigation measures. Driving forces are population, economy, technology, energy, land use and agriculture. The resulting climate scenarios reflect a range between more global and regional development approaches as well as between more economically or environmentally oriented societal changes. Depending on
those development assumptions, future regional climate projections vary widely, while some pathways in the accompanying literature are considered more plausible than others. Resulting climate scenarios like those computed with the ECHAM5 general circulation model (Roeckner et al. 2003) provide climate data over the next couple of hundred years. For the first contribution, climate data from the A1B run, describing a balanced more global, more economic future, are used for developing regional energy scenarios for North Africa by analyzing air temperature and radiation data from four case study sites.

More recent global scenarios prefer to follow a parallel approach, where interactions between GHG emissions and socio-economic developments and climate projections are used to develop a set of pathways that can be used to develop a range of diverse but plausible scenarios that could all lead to similar ecological outcomes. Figure 3 presents this approach for the so-called representative concentration pathways (RCPs), which were used as a framework for the latest IPCC report (IPCC 2014). Van Vuuren et al. (2011) present the RCP approach that covers a wide range of global future GHG concentrations between 2.6 and 8.5 W/m². To be able to make consistent assumptions when using the RCPs for scenario development, they are underlain by the so-called shared socio-economic pathways (SSPs), a framework that represents plausible alternative developments in society and economy without integrating climate change or new climate policies. They focus on demographic development, economic growth and urbanization (IIASA 2015). For the second contribution, a set of regional energy scenarios that were developed for the Middle East and North Africa were embedded into the two most extreme out of four global RCP projections. For the third contribution, SSP projections were applied for drawing a set of resource consumption scenarios on a global scale.

Figure 3: Sequential versus parallel approach for global development scenarios as used for IPCC reports (IPCC 2007 and 2014) and applied as framework for regional and global scenario approaches for all three contributions.
All three research contributions base their analysis on a scenario approach. For the first and second one, regional energy scenarios for North Africa and the Middle East and North Africa, respectively, were developed. Assumptions on future energy demand are aligned with global energy pathways as outlined above. The third contribution goes one step further by expanding the analysis to a global level. Using global socio-economic projections from the SSPs as a framework, it presents regional scenarios on food and energy consumption.

4.3 Modeling approaches

4.3.1 Models and tools

Computer simulations reproduce the behavior of a system as perceived. Hence, the calculated simulations are an abstract model of the world, containing only a part of the agents and known feedbacks within any modeled system. Different types of models can be used for a wide range of resource assessments and scenario calculations. Accounting models combine a basic set of assumptions and principles to record and measure different quantities of resources and stock flow between different parts of the system. System dynamics models are an approach to simulate non-linear behavior of systems over time, including stocks, flows and feed-back loops. (Linear) optimization models can be used to detect the potential minimization or maximization of a certain function (e.g. cost, natural resource use) within a system. On a smaller scale, they allow for an integration of very detailed spatially specific and technological information, while on a larger, regional to global scale, often averages and broader assumptions are used to describe the overall situation.

Energy models are one example of resource models. Aiming at supporting decision making of energy policy makers from a regional to global level, one finds large-sale energy models like MARKAL (IEA) or MESSAGE (IIASA), models and tools that can be used and adapted to every spatial scale like RETScreen (Canada) or LEAP (SEI), but also technology- and spatially specific models like HOMER (NREL) or MARGE (IIASA). Each research contribution in this thesis used distinctive energy modeling approaches (accounting and linear optimization) and associated tools, including geographical assessments and supplementary accounting models, for their scenario calculations.

**MARGE CCL**

The Mediterranean Area Renewable Generation Estimator (MARGE), developed by Williges et al. (2010) is a cost-optimization model, which allows the development of site-specific CSP scenarios. It calculates annual costs based on a component-by-component breakdown of
each power plant. In relation to the annual electricity delivered, MARGE determines the levelized electricity cost (LEC). The model also includes the associated intercontinental transmission costs via high-voltage direct current (HVDC) lines. The goal is to identify factors that drive overall investment cost as well as the resulting subsidies required to make CSP deployment economically profitable. After identifying four case study sites for CSP development through a meteorological, topological and economic assessment for the first research contribution, MARGE was extended to the MARGE CCL (Cost of Cooling Load) model. For this particular study, integrating the water requirements and cooling system costs in greater detail into the model made it possible to calculate and compare the cost penalties of different cooling systems for CSP at distinctive sites. High internal rates of return from 15 to over time 10% were applied to reflect the investors' ongoing and slowly declining perception of CSP as relatively high-risk investments, also leading to higher required subsidies to make CSP cost-competitive in the future. To be able to also include the resulting net present value of such hypothetically necessary subsidies in this study, a low social discount rate of 5% was applied.

**MESSAGE**

The Model for Energy Supply Strategy Alternatives and their General Environmental impact (MESSAGE) is a global energy assessment model, used for accounting and projecting future energy requirements when using a cost-optimization approach. The model provides a mid- to long-term framework for representing an energy system on a regional or global scale (Messner and Strubegger 1995) and is applied for the development of energy scenarios and identification of socio-economic drivers and technological response strategies to those developments. MESSAGE is used for a number of major global resource assessments and energy scenario studies, such as the Global Energy Assessment (GEA 2012) or the Special Report on Emissions Series (SRES) (Nakicenovic and Swart 2000). The second contribution uses results from MESSAGE runs for 2.6 and 8.5 RCP scenarios regarding the future energy technology mix. MESSAGE itself does not account for the associated water demand of those technology mixes yet, and also does not include potential inter-regional electricity trade. Hence, water use factors were added in a second modeling step, accounting for the water requirements of all represented technology capacities as well as traded electricity.

**Global water demand for food and energy supply**

For the third contribution, a two-part global accounting and linear optimization model was developed, using the programming language R (Venables et al. 2015). In contrast to the previous models, in this modeling approach not minimum cost but minimum water requirements for energy and food supply were goal of the optimization part of the model that
could be applied to five world regions as defined for the SSPs. Specific model constraints regarding regional water availability and inter-regional trade, food consumption patterns and possible changes, and electricity and transport fuel technology shares were defined on a regional level in order to ensure plausible model outputs for all food and energy scenarios.

4.3.2 Data

To be able to use the resource models described above for scenario runs, initial input data had to be collected. Table 2 gives an overview of the main datasets that had to be compiled and to some extent adapted for each research contribution.

<table>
<thead>
<tr>
<th>Contribution 1</th>
<th>Contribution 2</th>
<th>Contribution 3</th>
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<tr>
<td>Water demand factors for specific energy technologies</td>
<td>Water demand factors for specific energy technologies</td>
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<td>Technology efficiency data</td>
<td>Regional cooling system shares</td>
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<td>Water resource data</td>
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<td>Climate data</td>
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<td>Food supply and trade data</td>
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<td>Water Footprint Network data</td>
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Table 2: Overview of data collection required as initial model input for regional and global energy (and food) scenarios.

Water demand factors, primarily in the form of water consumption, but also water withdrawal, build the core of each scenario approach. Mielke et al. (2010) provide basic data on water demand for fossil resource extraction. Macknick et al. (2012) provide a summary of water consumption and withdrawal factors for the most common fossil and renewable electricity technologies. Studies from Spain (Carillo and Frei 2009) and Australia (Smart and Aspinall 2009) allowed for an international comparison of those data. Data on water demand for transport fuel production is mainly based on findings from Anze et al. (2010) and van Vliet et al. (2009) and was complemented by studies from Yang and Jackson (2011), Younos et al. (2009), Naterer et al. (2010) and Spath and Mann (2001). If necessary, data on regional cooling systems shares of thermal power plants were adapted from Davies et al. (2013). Case-study specific CSP efficiency data was provided by Szabo (2010).
Large global databases were used for information on future climate, regional water resource availability and sectoral withdrawals, regional energy supply, and food supply and trade. ECHAM5 was used for local climate projections. AQUASTAT is FAO’s public global water information system, providing data on water resources and use on a national level (AQUASTAT 2014). The World Bank’s database lists, among others, open data on annual national energy and transport fuel production by main technology (The World Bank 2015). FAOSTAT offers a wide range of annual data on agriculture and forestry, trade, development and GHG emissions on a national level (FAOSTAT 2014). Additionally, the International Trade Center (ITC) provides annual data on import and export trade statistics by country, product, and service from 2001 to 2013 (ITC 2014).

Regarding water requirements for food and first-generation biofuels, data from the Water Footprint Network database was collected (Mekonnen and Hoekstra 2011 and 2012). For food products, the database includes average blue, gray and green water consumption by product on a (sub-)national level, calculated using the global CROPWAT model (Hoekstra et al. 2011). For bioenergy production, Gerbens-Leenes et al. (2008) present blue and green water consumption factors. Blue water is defined as the fresh surface and groundwater. Gray water is water that is required to dilute pollutants to such an extent that the quality of the water remains above agreed water quality standards. Green water is the precipitation on land that does not run off or re-charge the groundwater but is stored in the soil or temporarily stays on top of the soil or vegetation. Eventually, this part of precipitation evaporates or transpires through plants. The assessment for contribution 3 focused primarily on the blue water demand of different food products (Ridoutt and Pfister 2012, Sulser et al. 2010).

In many cases, regional averages could be calculated from national data, while for energy technology data only broad averages from the current scientific literature had to be applied to entire world regions. Water demands of specific energy technologies are highly site-dependent, but the large amount of collected data in the US, a country showing high geographical variability, over the last thirty years suggests that the currently given ranges are able to reflect actual water use ranges adequately when used on a larger spatial scales. For specific power plant sites, however, data were adapted to local climate conditions.
5 CONCLUSIONS

5.1 Contribution 1 - Costs of reducing water use of concentrating solar power to sustainable levels: Scenarios for North Africa

Concentrating solar power has the potential of playing a major role for North Africa’s own electricity supply but also potential energy exports in the future. With the Sahara Desert stretching over the entire region from Morocco to Egypt, North Africa shows enormous amounts of solar energy resources. At the same time, high water stress led to the exploitation of fossil aquifers, large-scale dam and pipeline construction as well as the development of desalination plants along the coastlines to meet the region’s growing freshwater demand. This water scarcity might hinder a large-scale deployment of CSP technologies in this region if large amounts of water were required for the cooling systems of those capacities. Dry (or hybrid) cooling system could be a potential solution for CSP projects in arid regions such as North Africa, though they also would increase investment cost (CEC 2002) and reduce thermal efficiency and thus power output of the power plant when compared to wet-cooled systems (Balogh and Szabo 2009).

Investigating the ecological and economical drawbacks from conventional and alternative cooling systems at four different case study sites and including an outlook with climate change, revealed the climate-specific differences between different potential CSP locations in North Africa, resulting in wet cooling water needs between 2,100 and 3,490 m³/GWh (0.58-0.97 m³/GJ) depending on site and year. Approached in the form of three scale-up scenarios to 15, 30 or 50% of CSP meeting North Africa’s and the EU’s electricity demand by 2050, show that CSP would use up to 33% of current renewable freshwater resources in case those capacities were wet-cooled. Alternative cooling systems such as dry and seawater cooling would reduce this water demand by about 90%, and hence constitute a more sustainable option. Figure 4 compares the different water use scenarios for North Africa. Levelized electricity cost (LEC) for those alternative cooling systems would increase up to seven percent on average, with mean air temperature and consequently plant efficiency as the largest driver for this cost increase. Compared to the variance in CSP costs due to the variability of average solar irradiance values, such a cost penalty appears to be minor. This regional study for large-scale CSP deployment shows that its sustainability neither depends on technical limitations nor major economic drawbacks, but rather on political regulations and integrated resource management to ensure its ecological and economic feasibility.
5.2 Contribution 2 - Direct impacts of alternative energy scenarios on water demand in the Middle East and North Africa

Following the first, the second contribution analyzed the water demand of the entire Middle East and North Africa region for all production stages in the energy sector. Fossil resource extraction is currently the by far largest water consumer within the sector, though its overall demand requires only about 2% of today’s renewable freshwater resources. However, with the further exploration of fossil energy reservoirs and/or the increase in renewable energy technologies such as CSP to meet the significantly increasing energy demand of the region itself, but also keeping or even expanding energy exports as major source of income in the future, this water demand could increase significantly and compete with other water users, especially agriculture, a sector that is responsible for 97% of the region’s freshwater withdrawals.

Based on the global Representative Concentration Pathways, three regional energy scenarios until 2100 explored different energy pathways for MENA with respect to water and its perpetual importance for global energy supply. For the pathway characterized by improved efficiency, a transition to renewable energy sources, and declining energy exports (2.6), the water demand of the energy sector doubles until the end of the century. By contrast, in the pathway characterized by a continued commitment to fossil resource extraction, use and export (8.5), water demand for energy might rise up by a factor of five. This trend is mainly
driven by the increased exploitation of fossil resources using enhanced recovery methods as well as a growing regional electricity demand. In a third, hybrid scenario, MENA maintains high levels of energy exports like in the 8.5 scenario but substitutes the export of fossil fuels with the export of electricity derived from the sunlight. In this case, a freshwater volume equivalent to the current household needs of up to 195 million people could be saved, as (dry-cooled) solar technologies show lower water demand factors than fossil resources from enhanced recovery extraction. This study shows that a shift away from fossil towards renewable energy resources has the potential to limit the increase in water demand for energy in and from the MENA region. Despite a rapidly growing population and rising domestic energy demands, it appears that the region could also sustain high energy exports in the future, but with much less pressure on its freshwater reserves if solar electricity from low water-consuming technologies instead of fossil fuels constitute the energy source. Figure 5 gives an overview for overall water consumption for MENA’s energy supply through 2100.

![Figure 5](image_url)

**Figure 5**: Overall water consumption for MENA’s energy supply through 2100. Bars present each stage of the energy sector and their respective export shares in lighter shades, while conventional and unconventional fossil resources are highlighted separately. Values for the RCP2.6 and hybrid scenario are identical except for water demand for solar electricity exports in the latter scenario. In comparison to RCP8.5, water savings achieved in the hybrid scenario amount to a maximum of 14.1 billion m$^3$ in 2080 and decline thereafter to 7.6 billion m$^3$ in 2100.
5.3 Contribution 3 - Water saving potentials and possible trade-offs for future food and energy supply

The third contribution used the results and information from the previous two contributions for an extended assessment of the water demand in the energy sectors of five world regions, leading to a global quantitative analysis of current and potential future water requirements. This approach is complemented by an assessment of water needs for current and future food supply, which allows for a comparison of the energy and agriculture sectors when looking for opportunities to save water resources and detect possible trade-offs across both sectors. In contrast to previous water-energy-food nexus studies, this research tries to deter from simple resource use extrapolation approaches for future resource demand by investigating and comparing the relative and combined effects of potentially changing food and energy consumption patterns on regional and global water demand.

Also in the future, agriculture remains the sector showing highest water consumption rates. However, the water demand for the energy sector presumably increases with rising per capita and absolute demand due to growing population numbers. Using three food and two energy scenarios for drawing potential consumption trends until 2050 on a global level, shows that dietary shifts and technological changes are able to improve water efficiency in both sectors. Despite an increasing food demand, trends towards more nutritious diets, lower in sugars and grains but higher in protein and fat, reveal large water saving possibilities with a global potential of 10% lower overall water demand for food supply despite a rising population. Water demand increases in the energy sector can be limited through the deployment of renewables that show low water consumption rates. Overall, water saving potentials in the agricultural sector are able to outweigh potential increases in the energy sector. One caveat, however, is shown in an additional scenario, assuming the expansion of first-generation biofuels to a share of transport fuel supply of globally seven percent. The water requirements for such a development would exceed those for current food supply. This scenario approach shows that a total increase in water demand for both future food and energy supply is not inevitable. There is an overall potential to save water across the two sectors, a finding especially relevant for water-stressed world regions. It also highlights the importance of integrated energy policies with regard to biofuels, as a strong development of first-generation biofuels has the potential to increase water requirements drastically, and hence lead to a global competition for water resources required for food and energy production. Figure 6 compares the total current with potential future water demand for food, electricity, and liquid fuel supply by world region.
Emerging risks and synergies for water needs in the global energy system

Figure 6: Total current and potential future water demand for food, electricity, and liquid fuel supply by region. Extrapolating the water demand of both sectors in Asia (ASIA), Latin America (LAM), Middle East and Africa (MAF), OECD countries (OECD) and the countries from reforming economies of Eastern Europe and the former Soviet Union (REF) to meet the goal of today’s OECD consumption patterns for the entire future population results in a substantial increase in water demand. Dietary shifts and technological changes can lead to improvements in water efficiency for both food and energy supply. However, an increase in biofuel supply to meet 7% of the future population’s transport fuel needs would lead to a drastic rise in water demand, potentially exceeding water requirements for food supply.

5.4 Overall research findings and their policy implications

Water resource challenges for future energy systems

Water is a critical resource for today’s global energy system. Through sub-global interactions with regional ecosystems and societies, it interacts with other (global) resource flows and hence affects their structure and availability. Using the concepts of planetary boundaries and global emerging systemic risks as framework for this research on integrated water and energy resource management, makes it possible to embed and link water issues in the energy system to other sectors from a regional to a global level. It underlines the importance of
sustainable local and regional water management and policy with regard to other, possibly competing water users as well as potential global implications as a result of interactions with other complex natural and socio-economic systems.

With rapidly growing energy demands in all world regions over the past 150 years and an expected continuation of demand growth over the coming decades, using current technologies would result in an increasing amount of water that is required to supply the demanded energy. Limitations to energy production as a consequence of water restriction were firstly discussed in the US in the 1970’s. Today, with still growing resource demands in all sectors and adverse ecological changes like rising mean air temperature due to climate change, increasing water demand even further, one finds discussion on the water-energy nexus in all continents. The ongoing scientific and public debate shows that when designing the future energy system, several ecological challenges need to be integrated. So far, global energy scenarios only include associated GHG emissions and thus their global warming potential into their assumptions. But as water-energy nexus studies demonstrate, water is another environmental concern when it comes to secure future energy supply.

The three contributions in this dissertation answer practical questions on different spatial and temporal scales. The first one takes a specific technological perspective and investigated CSP’s significance for local and regional freshwater demand. It also illustrates the effect rising air temperatures can have on power production and hence water use efficiency. The second contribution takes a sectoral approach to water use in the energy sector of the Middle East and North Africa. It shows the significance of different production stages in the energy sector with respect to water, and puts them into relation with overall and agricultural water needs. This is an important point, as particularly highly water-stressed regions like the Middle East and North Africa have a greater need for integrated efficient resource management. An application of the preceding findings to a global level, like done for contribution 3, shows the relation between water needs in the agricultural and energy sector for all parts of the world, revealing key differences, and regionally specific saving potentials. Besides large-scale hydropower, thermal electricity generation along with first-generation biofuel production are the largest water users within the energy sector today. Being of lesser significance than the agricultural sector, the three consecutive analyses from a local to global level still show that water requirements in the energy sector are not trivial and do have regionally-specific importance for overall water use. Above, a further rising demand for energy over the next decades would coincide with lower overall water availability due to climate change; a development that could also limit future energy supply.

As water needs for energy production are highly technology dependent, actual resource requirements can show large variability when planning future energy systems. To explore the
Emerging risks and synergies for water needs in the global energy system

effects different energy demand rates as well as technology mixes would have on the water demand for energy, scenario approaches were applied to compare different energy mix options from a water use perspective. Despite differing in background assumptions and spatial and temporal scales, all developed scenarios show that a rapid expansion of renewable energy, either in the form of photovoltaic and wind capacities or thermal power plant capacities using alternative cooling systems, have not only the potential to reduce GHG emissions drastically but also to save water when compared to current technology mixes as well as future water needs for fossil resource use. An exception to this overall finding was investigated in the final contribution, considering a large expansion of first-generation biofuels as one potential future development. In this case, water requirements for energy supply would increase to a level where it could potentially exceed the water needs for food supply. The overall results of this dissertation demonstrate that the sustainability of future energy systems does not only depend on its greenhouse gas emission rates but also on water demands for certain technology mixes. Renewable energy technologies can be used to reach two sustainability goals simultaneously, one, reducing GHG emissions, and two, saving water resources by planning technology mixes that require less water than current ones. A rise in overall water demand for energy until the mid- or end of the century is still a common important result of all presented energy scenarios. This increase is primarily driven by an increased energy demand; its extent though varies greatly between different energy futures.

The energy-water-nexus has been discussed but only partially quantified in previous scientific papers and reports. Each contribution in this dissertation made a valuable step towards a more profound quantitative understanding of this complex resource issue. Motivated by the perceived need for more precise energy policy recommendations with respect to water, the first contribution demonstrates the significant difference water management for CSP development would make in a particularly vulnerable world region. The second contribution shows that also when planning an entire energy sector’s development, the technology choice plays a major role for both overall GHG emissions as well as water use. The third contribution puts the energy-specific findings in a global perspective and relates them to the agricultural sector. Even when today’s water demand for food supply exceeds the needs for energy in most world regions by far, a likely increase in water requirements in the energy system would add up to a considerable share in global water use. All three studies show on different technological and spatial scales the importance of an integration of sustainable water use goals in contemporary energy policies (and vice versa), either through specific technology support mechanisms or targeted transformations of the whole energy sector. They demonstrate that there are possibly large potential synergies but also conflicts between the two goals of reducing GHG emissions and achieving more sustainability with respect to water use in the energy system. Integrating this knowledge into current energy policies could make a substantial difference for the overall sustainability of future global energy production and
underlines the significance of environmental policy integration. As the example of Spain shows, the political will and support of renewable energy sources can have an enormous effect on the growth and success of new energy technologies, not only on the national but also international level. Promoting a rapid technological transformation of the energy system today appears to be rather a political than a technological challenge. Along with fostering the growth of renewable energies, e.g. through direct subsidies such as feed-in tariffs or tax incentives, the simultaneous support of water-saving energy technologies, especially in water-stressed regions, appears to be crucial for a successful transformation of the energy system.

In a next step, these findings also have to be interlinked with developments in other sectors, in this case especially agriculture, in order to integrate and relate synergistic or opposing trends and identify potentially emerging risks and weigh trade-offs. Studies on the nexus between water and energy, or water or energy and food, underline the growing importance of integrated resource management and sustainability policies and their cross-sectoral integration. For the energy system, a better understanding of the various interactions and feedback loops between sectors and regions within this complex global socio-ecological system appears to be critical for a successful transition to global sustainable development that simultaneously targets a wide range of ecological, economic and social goals.

Uncertainty and needed further research

Despite the consistent overall findings when evaluating all three contributions, there are a number of uncertainties and research gaps that were not specifically addressed in the presented regional and global energy scenario themselves. Each scenario presents only one out of a vast number of possible energy futures. Together, the here drawn scenarios are aiming at opening up a thinkable range of different energy futures, helping to identify potential positive and negative implications from such hypothetical developments.

Above, within this possible range lies another source of uncertainty with respect to the choice of considered energy technologies meeting future energy demand. With the exception of carbon capture and storage (CCS), all generated energy scenarios consider only today’s commercially operating energy technologies and their present water-use efficiencies. However, technological progress in the energy system is to be expected. One example are higher power plant efficiencies, leading also to lower water use factors (Gadhamsgetty et al. 2006). Also, a combination of different renewable energy technologies, such as CSP and photovoltaic (Carter and Campbell, 2009), or the backup of solar thermal power plants through biogas turbines could lead to higher sustainability in regard to both GHG emissions and water use. There is a wide range of energy technologies, both for electricity and fuel production (e.g. second- and third-generation biofuels) that are currently being researched.
and developed. As some of those technologies would show lower water efficiency compared to today’s technologies, others would lead to a higher water demand. Overall water demand in the energy systems would depend on their specific shares in the future energy mix, a development impossible to foresee at this point. The in this work presented scenarios illustrate the importance of future energy technology choice with regard to water based on the example of today’s wide-spread energy technologies, some of them playing a major role for overall water demand in the energy system. In the same way, currently developing, new energy technologies should be evaluated when taken into consideration for future research.

Examples of other knowledge gaps are listed below.

(1) The specific share of technologies and, if necessary, cooling systems determines the overall water use efficiency of the energy sector. More detailed reporting on today's shares in different world regions as well as more refined assumptions on future shares could improve results. This would be of special importance for analyses on a national and sub-national level.

(2) Carbon capture and storage (CCS) options were only included in the analyses for contribution 2. This could increase future water demand significantly if current CCS technologies were commercially applied, potentially making them a critical driver for water use for energy (Zhai et al. 2011).

(3) As outlined in Chapter 2, there are several positive feedback loops associated with future energy and water needs. The increase in demand for one resource drives the demand for the other and vice versa. So far, there is only little scientific evaluation to which extent this effect alone could drive additional resource use over the coming decades (Dubruil et al. 2012).

(4) All three studies’ results offer important information for energy and environmental policy makers on a regional and global level. As also underlined by a number of other water-energy and water-energy-food nexus studies, political regulations and governance are key for sustainable, integrated resource management (Hussey and Pittock 2012). More precise information on specific strategies and their successful implementation are needed to meet this complex environmental and socio-economic challenge.

Further scientific research could provide this lacking information and help to refine future resource assessments as well as widen the span on plausible societal and technological assumptions when comparing potential future energy systems.
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Emerging risks and synergies for water needs in the global energy system


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Emerging risks and synergies for water needs in the global energy system


PART II – INDIVIDUAL ARTICLES

7 CONTRIBUTION 1 - Costs of reducing water use of concentrating solar power to sustainable levels: Scenarios for North Africa

Kerstin Damerau, Keith Williges, Anthony G. Patt, Paul Gauché


Abstract

Concentrating solar power (CSP) has the potential to become a leading sustainable energy technology for the European electricity system. In order to reach a substantial share in the energy mix, European investment in CSP appears most profitable in North Africa, where solar potential is significantly higher than in southern Europe. As well as sufficient solar irradiance, however, the majority of today’s CSP plants also require a considerable amount of water, primarily for cooling purposes. In this paper we examine water usage associated with CSP in North Africa, and the cost penalties associated with technologies that could reduce those needs. We inspect four representative sites to compare the ecological and economical drawbacks from conventional and alternative cooling systems, depending on the local environment, and including an outlook with climate change to the mid-century. Scaling our results up to a regional level indicates that the use of wet cooling technologies would likely be unsustainable. Dry cooling systems, as well as sourcing of alternative water supplies, would allow for sustainable operation. Their cost penalty would be minor compared to the variance in CSP costs due to different average solar irradiance values.
7.1 Introduction

About eight tons of CO$_2$ are emitted each year on average by every citizen of the European Union (U.S. Energy Information Administration (EIA), 2009). This is the result of an energy-intensive lifestyle, mainly relying on burning fossil fuels for energy generation. The consequences are experienced by the whole planet as global climate change (Solomon et al. 2007). An increase in average air temperatures and hence the frequency and intensity of extreme weather events, such as floods or droughts, will threaten human life more and more during the upcoming decades (Parry et al., 2007). One way to counteract this development efficiently is to restructure the energy sector by replacing fossil energy resources with renewable ones, making energy generation sustainable and reducing CO$_2$ emissions substantially (Metz et al. 2007).

There are many visions of how Europe could obtain its energy sustainably. While their time horizon, emission goal and technology preferences can differ widely, there is relative consensus that if we want to achieve a sustainable energy market by the mid-century, transformation must begin over the next few years (Knopf et al., 2010; Van Vuuren et al., 2010). One energy technology that could play a major role in a fast and efficient transformation to renewables is concentrating solar power (CSP). Already in commercial operation today and equipped with affordable energy storage capacities for either peak or baseload power generation, CSP has the economic and technological potential to become a leading energy technology in future (Khosla 2008, Lorenz et al. 2008, Pitz-Paal 2005). But to make the most efficient use of solar energy, deserts are the preferred location for CSP plants. Several researchers have suggested that for CSP to supply sufficiently large amounts of power to the energy mix, the European electricity grid would need to expand southwards to the Sahara, allowing new cooperation and transition possibilities for both North Africa and Europe (Battaglini et al. 2009, MacKay 2009, Patt 2010). Two recent political and private sector initiatives in this direction are the Mediterranean Solar Plan (2008) and the Desertec Industrial Initiative (2009), respectively. This increasing interest of European energy policy leads to the need of proactive investigation of potential adverse environmental consequences of such large-scale projects, making local resource studies from North Africa of interest for Europe.

While CSP has great potential, one issue that has arisen in its development, especially in the United States, is its sustainability in the very desert environments to which it is most suited (Pitz-Paal 2005). In contrast to other renewable technologies like photovoltaic (PV) or wind, CSP requires a considerable amount of water, mainly for cooling purposes, when using recirculating wet cooling, a characteristic this technology shares with other thermal power technologies. While coal or nuclear power plants show a similar water demand, natural gas
plants require only up to a fourth of that (cf. US DOE 2006 and 2009). Some renewable energy experts argue that this water demand constrains the large-scale development of wet-cooled CSP in desert regions; either they would consume too much water in an area with by definition very low water resources, or, when using more expensive alternative cooling systems, like dry cooling, CSP could not become cost-competitive with other energy technologies (Carter and Campbell 2009, Hogan 2009, Woody 2009, Patel 2010).

We investigate the validity of this argument for the case of large-scale investment in CSP in the Sahara, starting with four case studies from Morocco to Egypt, and then scaling up to a regional level where CSP could meet a substantial part of the future electricity demand of both regions, North Africa and Europe. We focus on growth scenarios that include power production for the European market because here the potential social and political ramifications of unsustainable water use are the most acute.

7.2 Background

Concentrating solar power technologies use an assembly of mirrors that reflect and concentrate solar thermal energy to heat up a fluid that then impels a conventional steam power cycle for electricity generation. Heat storage capacities, mostly involving the use of molten salt, allow running the steam turbine after the sun goes down, and during periods of cloudiness. Parabolic trough (PT) and central tower (CT) are the most mature technologies at present, with CT showing highest thermodynamic efficiencies. Both will be compared in this paper. Other technologies are Fresnel collectors or dish/engine systems (which use Stirling engines). Interested readers can find a detailed overview of the four main CSP technologies in the IEA Technology Roadmap (2010).

7.2.1. Cooling technologies

Most of today’s CSP plants have recirculating wet cooling systems that require a constant supply of freshwater. But water is also needed for mirror cleaning, as make-up water for the steam cycle, and for personnel needs. A representative wet-cooled parabolic trough plant located in the Mojave Desert, California, consumes about 3000 m$^3$/GWh, while a representative wet cooled central tower plant consumes somewhat less, about 2100 m$^3$/GWh (US DOE 2009). This is due to the higher concentration ratio and improved thermal efficiency possible in the CT plant type and represents a similar level of condensing water as used in a coal fired power plant. With dry cooling systems, this amount can be reduced to about 300–340 m$^3$/GWh (US DOE 2009), of which about 75 m$^3$/GWh is used for mirror cleaning (Turchi and Kutscher 2009). Depending on local ground and wind conditions this latter amount may vary widely, and industry experts suggest that the application of new techniques currently being experimented with may substantially reduce the water consumption for mirror...
cleaning (Burgaleta 2010).

There are several alternative technologies for dry cooling. The oldest is direct dry cooling using air-cooled condensers (ACCs). With this technology, the steam from the closed-loop turbine cycle passes through a device similar in design to a car radiator, with large fans blowing air across a lattice of pipes. A second technology, known as the Heller system, uses indirect dry cooling. In this case, the heat of the turbine cycle steam is transferred to a much larger body of water. That water, in turn, is circulated through an air-cooled heat exchanger at the bottom of a large cooling tower. Either a fan system or temperature differentials from the tower’s height generates convective air currents that draw cool air through a radiator. Finally, there are hybrid technologies, utilizing some water. To hybridize a principally air-cooled system, it is common to combine its use with a separate, wet cooling system. Another option is to evaporate water spray on the hot surfaces of the condenser or into the hot ambient inlet air, also increasing their cooling rate (Micheletti and Burns 2002). This proves to be effective at high ambient air temperatures and low humidity conditions.

Dry cooling systems have a few disadvantages. First, the projected costs of installing dry instead of wet cooling systems for large CSP plants, with capacities from 500 to 1000 MW, are higher; the overall investment costs would likely increase by about 2%, and for hybrid cooling systems by 3%. It is important to note the speculative nature of these estimates; they are based on literature data (California Energy Commission (CEC) (2002)), personal information (Burgaleta 2010) and calculations with the Mediterranean Area Renewable Generation Estimator (MARGE) model (Williges et al. 2010). Second, the power output of dry-cooled plants of comparable size located in similar environmental conditions remains somewhat below that of wet-cooled plants due to the difference between the wet and dry bulb temperatures. In addition, the higher the average ambient temperature of a plant location, the higher the efficiency loss, primarily due to thermodynamic losses in the power cycle but also to the cooling system’s energy demand. Based on annual mean temperatures, the difference from wet to dry cooling amounts to about 3% annual output loss in southern Spain (Burgaleta 2010, Szabo 2010) and on average 4.5% in the Mojave Desert (US DOE 2009, Szabo 2010). In North Africa, with annual mean temperatures between 23 and 30 deg C in the Sahara and 20 deg C at coastal sites, the annual output loss would be 5–10% (see Fig. 1). The value of hybrid cooling systems, which are more expensive to install and which increase water usage about that of pure dry systems, is to reduce these efficiency losses at high ambient temperatures (Kutscher and Costenaro 2002, CEC 2003).

Based on Szabo (2010), wet cooling systems show an almost linear increase in water consumption with increasing ambient temperatures, while the auxiliary energy need for the cooling system levels off for increasing air temperatures from 0 deg C. Direct and Heller dry cooling systems do not require water for evaporation. The auxiliary power required stays
constant for natural-draft Heller systems for temperatures above 2 deg C. Direct air-cooled condensers have an increasing power demand until 10 deg C, from this point it decreases again slightly. For hybrid cooling systems the added wet cells show a steeply increasing water demand if continuously used with rising air temperatures, while their power demand stays constant from temperatures above 15 deg C. A threshold temperature can be set from which wet cooling will enhance the dry cooling system. Hybrid Heller systems show a constant water and energy demand.

![Relative output loss due to thermodynamic losses and auxiliary power needed for the cooling system. Approximation based on Szabo (2010).](image)

**Fig. 1.** Relative output loss due to thermodynamic losses and auxiliary power needed for the cooling system. Approximation based on Szabo (2010).

### 7.2.2 Available water resources

As we have shown, all CSP technologies require a certain amount of water. In arid regions like the Sahara, water is an extremely rare resource, and those requirements may compete with the region’s other water uses, mainly for agricultural purposes. Today, the annual freshwater withdrawal in North Africa — 94 billion m$^3$ — is already twice the internal renewable freshwater resources (FAO 2010). With growing populations, economic development, as well as increasing temperatures and coastal inundation due to climate change, the future availability of water will further decrease (Abou-Hadid 2006, Elsharkawy et al. 2009, Bakir 2001). De Wit and Stankiewicz (2006) project in their scenario a decrease in rainfall of 10–20% by the end of the century, while a drying of 20% along the African Mediterranean coast under an A1B scenario can be found in the regional climate projections of the fourth IPCC report (Christensen et al. 2007). Arnell (1999) assumes a decrease in
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surface runoff up to 25 mm/yr for major parts of the region until the 2050s. Changing hydrological patterns are to be especially expected in the drainage area of the Atlas Mountains (Boulet et al. 2008, Born et al. 2008). Recent climate models do not provide conclusive results regarding the catchment area of the Nile River, which provides 90% to Egypt’s current water demand.

This means that sustainable water use by CSP plants in North Africa likely demands alternative sources to surface water. Most of the regional groundwater resources are fossil aquifers that are already over-pumped, so they would not be a sustainable option either. Seawater cooling would be an option, though such cooling towers and water transport systems require special alloy and more intensive cleaning. Since all plants need a certain amount of freshwater, e.g. for mirror cleaning and periodic replacement of steam within the power cycle, we considered meeting the entire supply of water with freshwater sources as the most efficient solution for plants that are not located directly at the coast. Thus, treating wastewater or desalinating seawater and transporting it, if necessary, to the plant’s location can be a possible solution for meeting the water demand of CSP. Zhou and Tol (2004) present a survey of cost development for water treatment over the last 40 yr. As most of today’s desalination plants are located in the Middle East and North Africa (MENA), the study’s results seem suitable for our approach. At the time unit costs are about 1.1 EUR/m³ for desalination, 0.9 EUR/m³ for wastewater treatment and 0.7 EUR/m³ for brackish water (EUR 2000). Further, Zhou and Tol (2004) discuss water transport costs based on estimations from Egypt. Transporting a water volume of 100 million m³/yr in a canal costs 6.5 cent/100 km horizontal transport and 5.5 cent/100 m vertical transport with a capacity elasticity of 0.92, as pipeline costs increase by 271%. We considered those figures to be adequate as well.

7.3 Methods

As the water demand of a plant depends on its precise location, its access to water resources as well as its climate, we examine four representative locations for CSP plants in North Africa. For each location, we identify appropriate cooling technologies for both central tower and parabolic trough plants. We compare wet cooling systems with dry cooling (integrating direct and indirect technologies) as well as with hybrid (two wet cells added to the dry cooled condenser) and spray cooling systems. We then use the results of those case studies to estimate and compare the amount of water that would be required on a regional level by sketching scenarios of a high share of CSP in the future European and North African energy mix. We choose a background storyline presented in a roadmap to 2050 for Europe and North Africa (PricewaterhouseCoopers (PwC) 2010) with the target of a 100% renewable electricity market. This is reached through an inter-regional smart energy grid that connects and
distributes various renewable energy resources while making use of CSP as a peak and baseload technology, and implies a large scale-up of this technology during the next four decades.

7.3.1. Case studies

Despite the sheer vastness of the Sahara, not every site appears suitable for the installation of a CSP plant. In order to achieve highest potential efficiencies throughout the year, Ummel (2010) suggested that a minimum solar radiation of 4.7 kWh/m²/day is required. This condition is met in parts of the central and southern Sahara. Other criteria are stable and flat ground conditions (slope <3%), and access to infrastructure as well as to planned electricity grid corridors towards Europe. We chose four representative sites that would likely be attractive locations for CSP plant construction, shown in Fig. 2. Showing differing climatic and water profiles, Aswan, Egypt, is the most southern and also hottest site but has respectable water resources. Ghadames, Libya, lies further north but still shows very good annual insolation records. Tataouine, Tunisia, slightly fails the 4.7 kWh/m²/day threshold, but is located close to the Mediterranean coast with unlimited salt water availability. Tan Tan, Morocco, lies southwards of the last two locations, but shows a lower and unique annual irradiance curve due to its proximity to the Atlantic Ocean. Combining the characteristics of all four locations, they represent a good overview of potential future CSP sites, including coastal site characteristics only to a small extent due to land-use and climatic constraints, and focusing on the inland of North Africa, the Sahara desert, with excellent solar radiation conditions and smooth climate variations.

![Fig. 2. Annual direct normal irradiance (DNI) in North Africa (National Renewable Energy Laboratory (NREL) 2006) and case study locations.](image)
All sites show higher average temperatures than plant environments examined for a United States Department of Energy (US DOE 2009) report on CSP plants primarily located in the Mojave Desert. In order to meet these differing climatic conditions, we apply US DOE data only as basic water demand of 2100 to 3000 m$^3$/GWh, respectively, to our wet cooled CT and PT plants. For each hour in the range from 35 to 50 deg C an auxiliary water and parasitic power demand is added. This approach may underestimate the real water demand of a CSP plant in North Africa as not only average temperatures but also seasonal climatic variance differs in both regions. We set a 35 deg C threshold temperature, above which hybrid cooling options are applied. So, by extrapolating data linearly up to 50 deg C, wet and hybrid (from 35 deg C) cooling systems cause an output loss of 0.8%/deg C. Dry cooling, by contrast, shows a loss of 0.95%/deg C (see Fig. 1). The higher the number of hot hours above 35 deg C, the higher the additional efficiency loss of the CSP plant, irrespective of the cooling system installed. Of course, absolute losses diverge for all systems. The loss of net turbine output that we present is due to both decreasing thermodynamic efficiency and the auxiliary energy need of the cooling system. However, we further assumed that a typical condenser temperature is held constant for each plant type, leading to the same theoretical losses for all power cycles. In reality though most plants show condenser temperatures inline with the ambient temperature, viz. depending on the specific thermodynamic efficiency of a power cycle, the efficiency loss can differ, leading to somewhat higher efficiency losses for parabolic trough plants than for central tower when ambient temperatures rise.

With climate change, mean temperatures in North Africa will further increase (Meehl et al., 2007). For calculating the impact this rise would have on prevalent cooling technologies and thus plant performance, we take (uncorrected) temperature data of the ECHAM5 climate model for the A1B scenario path. Three climate periods were set. First, 1976–2005 is our base period, and observational data were used. Because observation data cover only a part of the basic climate period, results remain to some extent questionable. We then examine two subsequent periods, from 2006 to 2035, and from 2036 to 2065. For these, we add the calculated change signal, from the model, to our observation data. As Fig. 3 shows, we project mean temperatures to increase, especially during the third period, in all locations. The projected rise is the greatest in the Aswan and Ghadames locations.

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\(^{1}\) The Mojave Desert shows average temperatures of about 16–18.51C (61–65 deg F).
Based on these characteristics, we calculated the annually required amount of water as well as the output loss for each CSP plant when equipped with wet, dry or hybrid cooling systems, and the corresponding costs. To do so, we used the MARGE model presented in Williges et al. (2010), which permits the development of site-specific CSP scenarios, and projects annual costs based on a component-by-component breakdown of each plant and the associated intercontinental transmission costs via high-voltage direct current (HVDC) lines. For the current analysis, we expanded MARGE to the MARGE CCL (Cost of Cooling Load) model by elaborating the cooling component in greater detail. We estimated the site-specific costs of

Table 1: Key characteristics of CSP prototypes.

<table>
<thead>
<tr>
<th>Location</th>
<th>Aswan</th>
<th>Ghadames</th>
<th>Tan Tan</th>
<th>Tataouine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generation capacity (MW)</td>
<td>1000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Storage capacity (h)</td>
<td>&gt;14</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operation (h/yr)</td>
<td>7000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capacity factor</td>
<td>80%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Theoretical maximum output (GWh)</td>
<td>7000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar-to-electricity efficiency CT</td>
<td>20% (IEA, 2010)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar-to-electricity efficiency PT</td>
<td>15% (IEA, 2010)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean annual insolation (kWh/m²/yr)</td>
<td>2430</td>
<td>2250</td>
<td>1230</td>
<td>1790</td>
</tr>
<tr>
<td>Mirror field size CT (ha)</td>
<td>1440</td>
<td>1560</td>
<td>2850</td>
<td>1960</td>
</tr>
<tr>
<td>Mirror field size PT (ha)</td>
<td>1920</td>
<td>2080</td>
<td>3800</td>
<td>2610</td>
</tr>
<tr>
<td>Yearly sum of hours above 35°C (2000)</td>
<td>1710</td>
<td>1220</td>
<td>20</td>
<td>1260</td>
</tr>
<tr>
<td>Yearly sum of hours above 35°C (2050)</td>
<td>2450</td>
<td>1740</td>
<td>25</td>
<td>1310</td>
</tr>
</tbody>
</table>
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water treatment and transport for assuring a sustainable water supply at the least costs. Concerning treatment costs, we expect a further drop of unit costs over the next decades as North Africa is already today strongly investing in the capacity extension of desalination plants. We assumed a half of unit costs until 2050. Sites in Ghadames and Tataouine are supplied with desalinated water from the coast, while for Ghadames a pipeline (as part of the Great Man-made River Project) already exists and could be used inversely (Alghariani 2003). Plants around Aswan and Tan Tan use treated wastewater from the cities.

7.3.2. Scenarios

For the year 2050, energy scenarios project a doubling of the European electricity demand, while the North African demand rises eight-fold (World Energy Council 2007, European Commission 2006). This means that the electricity demand rises to annually 7800 TWh in Europe and 1500 TWh in North Africa. For CSP to meet 15–50% of this demand, consistent with the PricewaterhouseCoopers (PwC) (2010) renewable energy vision for Europe, would require installation of 200–700 GW of current CSP technologies. Starting in 2010 with almost no capacity installed in North Africa, CSP would entail an annual growth rate of 21–25% until 2050, depending on the capacity goal.

For our scenario calculations with MARGE CCL we assume a strong development of CSP technologies only in the Mediterranean region. We set a hypothetical learning rate of 15%, 5% discount rate, and project internal rates of return starting at 15% and declining to 10% as the technology matures and risk diminishes. With these parameters we calculate the effects of different cooling systems on the levelized electricity cost (LEC), the year of price parity with the fossil resources coal and gas, and finally the total amount of discounted subsidies that would be required to reach this price parity. For the latter two calculations we assume European gas and coal prices consistent with the World Energy Outlook 2008 (IEA, 2008); all costs are given in EUR (2000). As several of our base data and scenario assumptions differ substantially from the cost scenarios presented by Williges et al. (2010), our study also leads to considerably distinct results.

7.4 Results

7.4.1 Case study results

Water demand at all four sites averages 2240 (CT) or 3180 m³/GWh (PT) with the hottest sites showing highest water demands. Hybrid systems require about 360–380 m³/GWh on average and naturally dry-cooled system stay stable at 300/ 340 m³/GWh. Until 2050 these

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2 Europe includes EU27, Belarus, Bosnia-Herzegovina, Croatia, Macedonia, Montenegro, Norway, Serbia, Switzerland, Turkey and Ukraine.
requirements increase with climate change under an A1B scenario on average by about 2% (45 [CT] - 60 [PT] m$^3$/GWh) for wet-cooled systems and 1.5-3% (5-15 m$^3$/GWh) for hybrid-cooled CT systems or 2-3% (7-15 m$^3$/GWh) for PT.

Integrating the three factors, water use, efficiency loss and water costs, now and in 2050, together with differing investment costs, we then calculated the hypothetical, technology-specific levelized electricity cost at each site for a conventional local wet-cooled plant and in comparison with sustainable cooling options. It turned out that the relatively low costs for importing treated water to wet-cooled plants does not significantly affect the final LEC. Further we could not find a difference between hybrid and spray-cooled plants (see Table 2). Our results show that mainly the efficiency loss from alternative cooling systems, due to high temperatures, affects the levelized electricity costs. Higher costs for cooling technologies as well as for water treatment and transport play only a marginal role.

### Table 2: Case study results representing the local water demand of different CSP technologies in 2010 and 2050 as well as the associated LEC 50% in the energy mix in 2050.

<table>
<thead>
<tr>
<th>Location</th>
<th>Central tower</th>
<th></th>
<th>Parabolic trough</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wet cooling</td>
<td>Dry cooling</td>
<td>Spray/hybrid</td>
<td>Wet cooling</td>
</tr>
<tr>
<td>Aswan</td>
<td>m$^3$/GWh 2010</td>
<td>2330</td>
<td>340</td>
<td>380-410</td>
</tr>
<tr>
<td></td>
<td>m$^3$/GWh 2050</td>
<td>2430</td>
<td>340</td>
<td>390-440</td>
</tr>
<tr>
<td></td>
<td>LEC $/$kWh 2010</td>
<td>14.58</td>
<td>16.11</td>
<td>15.84</td>
</tr>
<tr>
<td></td>
<td>LEC $/$kWh 2050 (15% share)</td>
<td>3.95</td>
<td>4.33</td>
<td>4.25</td>
</tr>
<tr>
<td></td>
<td>LEC $/$kWh 2050 (30% share)</td>
<td>3.49</td>
<td>3.81</td>
<td>3.74</td>
</tr>
<tr>
<td></td>
<td>LEC $/$kWh 2050 (50% share)</td>
<td>3.10</td>
<td>3.38</td>
<td>3.32</td>
</tr>
<tr>
<td>Ghadames</td>
<td>m$^3$/GWh 2010</td>
<td>2270</td>
<td>340</td>
<td>370-390</td>
</tr>
<tr>
<td></td>
<td>m$^3$/GWh 2050</td>
<td>2340</td>
<td>340</td>
<td>380-410</td>
</tr>
<tr>
<td></td>
<td>LEC $/$kWh 2010</td>
<td>16.32</td>
<td>17.76</td>
<td>17.33</td>
</tr>
<tr>
<td></td>
<td>LEC $/$kWh 2050 (15% share)</td>
<td>4.37</td>
<td>4.77</td>
<td>4.68</td>
</tr>
<tr>
<td></td>
<td>LEC $/$kWh 2050 (30% share)</td>
<td>3.84</td>
<td>4.19</td>
<td>4.11</td>
</tr>
<tr>
<td></td>
<td>LEC $/$kWh 2050 (50% share)</td>
<td>3.41</td>
<td>3.70</td>
<td>3.63</td>
</tr>
<tr>
<td>Tan Tan</td>
<td>m$^3$/GWh 2010</td>
<td>2100</td>
<td>340</td>
<td>340</td>
</tr>
<tr>
<td></td>
<td>m$^3$/GWh 2050</td>
<td>2100</td>
<td>340</td>
<td>340</td>
</tr>
<tr>
<td></td>
<td>LEC $/$kWh 2010</td>
<td>17.49</td>
<td>18.53</td>
<td>18.70</td>
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<tr>
<td></td>
<td>LEC $/$kWh 2050 (15% share)</td>
<td>4.74</td>
<td>4.90</td>
<td>4.94</td>
</tr>
<tr>
<td></td>
<td>LEC $/$kWh 2050 (30% share)</td>
<td>4.07</td>
<td>4.19</td>
<td>4.43</td>
</tr>
<tr>
<td></td>
<td>LEC $/$kWh 2050 (50% share)</td>
<td>3.60</td>
<td>3.79</td>
<td>3.82</td>
</tr>
<tr>
<td>Tataouine</td>
<td>m$^3$/GWh 2010</td>
<td>2270</td>
<td>340</td>
<td>370-390</td>
</tr>
<tr>
<td></td>
<td>m$^3$/GWh 2050</td>
<td>2280</td>
<td>340</td>
<td>370-390</td>
</tr>
<tr>
<td></td>
<td>LEC $/$kWh 2010</td>
<td>18.44</td>
<td>19.52</td>
<td>19.34</td>
</tr>
<tr>
<td></td>
<td>LEC $/$kWh 2050 (15% share)</td>
<td>4.85</td>
<td>5.11</td>
<td>5.08</td>
</tr>
<tr>
<td></td>
<td>LEC $/$kWh 2050 (30% share)</td>
<td>4.26</td>
<td>4.47</td>
<td>4.45</td>
</tr>
<tr>
<td></td>
<td>LEC $/$kWh 2050 (50% share)</td>
<td>3.76</td>
<td>3.94</td>
<td>3.92</td>
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</table>

7.4.2 Scenario results

Scaling our case study results up to a level where CSP could provide between 15% and 50% of Europe’s and North Africa’s electricity demand; a system based exclusively on wet-cooled CT plants would require about 11 billion m$^3$ of water each year, while one with wet-cooled PT plants would require 15.5 billion m$^3$. Fig. 4 presents the total annual water demand for each wet-cooled technology and compares those results with current renewable water resources as well as the region’s average freshwater withdrawal.
behind one to two years that of wet cooled ones. Fig. 5 presents an exemplary LEC trend in the 30% capacity scenario, including parabolic trough systems. Across alternative scenarios differing according to capacity goal and cooling technology, CT could reach price parity with gas between 2025 and 2028, PT between 2027 and 2032, and with coal between 2030 and 2035 (CT) or between 2033 and 2039 (PT). It is important to note that there is a considerable uncertainty concerning many of the costs associated with both PT and CT technologies, independent of the cooling system. For example, the ECOSTAR (Pitz-Paal et al. 2005) data on mirror field costs on which these results are partly based suggest lower costs for CT systems than for PT. For each scenario goal, price parity with gas or coal of electricity from alternatively cooled CSP plants lags behind one to two years that of wet cooled ones. Fig. 5 presents an exemplary LEC trend in

Future renewable water resources are likely to decline, but no explicit projections can be made yet. Hence, with prevalent wet cooling systems CSP would require up to 23% as CT or even 33% as PT technology of today’s renewable water resources—of which 61% are held in Morocco and another 11% in Algeria (FAO AQUASTAT 2010). However, such wet-cooled CSP would take a substantial share of water resources that are already today exposed to strongly competing uses. Compared to that, dry cooling systems would require 1–3% of the renewable water resources, depending on the share of CSP. Hybrid cooled systems would consume between one and four percent.

An overview of the average LECs derived from the case study results is given in Table 3. Comparing these numbers, we found that alternative cooling systems lead to an average increase in the LEC of about 6% for central tower plants and about 7% for parabolic trough systems. Across alternative scenarios differing according to capacity goal and cooling technology, CT could reach price parity with gas between 2025 and 2028, PT between 2027 and 2032, and with coal between 2030 and 2035 (CT) or between 2033 and 2039 (PT). It is important to note that there is a considerable uncertainty concerning many of the costs associated with both PT and CT technologies, independent of the cooling system. For example, the ECOSTAR (Pitz-Paal et al. 2005) data on mirror field costs on which these results are partly based suggest lower costs for CT systems than for PT. For each scenario goal, price parity with gas or coal of electricity from alternatively cooled CSP plants lags behind one to two years that of wet cooled ones. Fig. 5 presents an exemplary LEC trend in
the 30% capacity scenario, comparing wet and dry cooling. While costs for parabolic trough remain to some extent above those for central tower, gaps between all LECs decrease with extending capacities. The total amount of discounted subsidies that would be required to reach price parity with coal amounts to about EUR 6.7 (wet-cooled plants) to 8.8 (dry cooling) billion for central tower technologies. Parabolic trough would require EUR 13.2-17.2 billion. To reach price parity with gas with central tower plants, EUR 1.7-2.4 billion of subsidies were necessary; with parabolic trough this amount would increase to EUR 4.1-5.5 billion. Comparing local with imported wet cooling, required subsidies differ up to EUR 2-24 million, depending on site characteristics, CSP technology and capacity goal.

![LEC curves wet vs. dry (30% capacity goal)](image)

Fig. 5: LEC trend for wet and dry cooled CSP in the 30% capacity scenario, including transmission costs.
Cost penalties can be estimated by considering three sets of considerable output losses, in comparison to wet cooling up to 6% (hybrid) or dry cooling systems reducing this demand significantly. It leads to considerable output losses, in comparison to wet cooling up to 6% (hybrid) or 9% (dry cooling) annual efficiency loss at our hottest site in Aswan. In estimating cost penalties, three sets of

<table>
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<tr>
<th>Technology</th>
<th>Capacity goal (%)</th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
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<tr>
<td>Dry cooled Central tower</td>
<td>15</td>
<td>17.98</td>
<td>17.83</td>
<td>11.48</td>
<td>6.51</td>
<td>4.19</td>
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<td>30</td>
<td>17.61</td>
<td>17.51</td>
<td>10.64</td>
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<tr>
<td></td>
<td>50</td>
<td>17.09</td>
<td>17.09</td>
<td>9.87</td>
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<td>15</td>
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<td>7.93</td>
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<td>4.55</td>
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<tr>
<td></td>
<td>50</td>
<td>18.87</td>
<td>18.87</td>
<td>10.83</td>
<td>6.39</td>
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<tr>
<td>Hybrid cooled Parabolic trough</td>
<td>15</td>
<td>22.69</td>
<td>21.13</td>
<td>13.48</td>
<td>8.49</td>
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<td>20.18</td>
<td>20.18</td>
<td>11.59</td>
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<tr>
<td>Dry cooled Parabolic trough</td>
<td>15</td>
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<td>12.64</td>
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<td>50</td>
<td>20.38</td>
<td>20.38</td>
<td>11.70</td>
<td>6.90</td>
<td>4.30</td>
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</table>

Table 3: Development of average LECs depending on technology and capacity goal for 2050.

7.5 Discussion

Concentrating solar power has the potential to become an important source for the future energy mix of Europe and North Africa. All types of CSP plants require a certain amount of water, while PT plants still require about 40% more water than CT technologies. Our study investigated regional environmental and economical drawbacks of CSP technologies that could hinder a large-scale development in North Africa. For CSP in desert regions, the energy-water nexus is a key issue when targeting a sustainable electricity generation. Eventually, the improvement of resource management together with enhanced efficiency of power generation will be needed for meeting future challenges in North Africa (Bakir 2001, The World Bank 2007). Otherwise serious (water) conflicts may become inevitable (Tropp and Jaegerskog 2006, Maas and Taenzler 2009).

But there are already technical solutions for reducing a high water demand and supplying plants with sustainable water sources. Wet cooling does require large amounts of water, especially in hot regions like the central Sahara, on average about 2240 (CT)/ 3180 (PT) m³/GWh. Applying hybrid or dry cooling systems reduces this demand significantly. It leads to considerable output losses, in comparison to wet cooling up to 6% (hybrid) or 9% (dry cooling) annual efficiency loss at our hottest site in Aswan. In estimating cost penalties, three sets of
factors currently appear important.

First, the hotter the climate in which CSP is located, the lower its output and the higher the cooling water demand for wet and hybrid cooling systems. There are noticeable differences in water demand contingent on location. Time will also play a role. Climate change will likely lead to increase in mean temperatures and thus declining water availability in North Africa as soon as during the next four decades. However, other uncertainties like variance in solar irradiation might disguise this effect to some extent. Despite this uncertainty, our study shows that climate change in North Africa would increase the cooling demand of CSP plants additionally, while their efficiencies would drop further. In our A1B scenario this means an increase in the cooling water demand of 2% for wet-cooled systems by 2050, for hybrid cooling systems between 1.5% and 3%, depending on technology.

Second, options for supplying the plant with sustainable water resources are highly site-dependent. In few parts of North Africa renewable freshwater resources may supply a plant’s demand without competing with other water uses, but for most areas alternative water resources are required. For population centers Aswan and Tan Tan, wastewater treatment for plant cooling appears as the most sustainable option. For sites like Ghadames or Tataouine desalinated seawater seems more suitable, assuming the responsible brine disposal suggested by Trieb (2007).

Third, a review of cooling systems revealed that technological progress is to be expected. At the moment, a large water demand or significant output loss makes certain technologies appear environmentally or economically less attractive, but this is likely to change during the coming years. One set of potentially important technological research, of consequence for cooling, are improvements which allow higher working temperatures of the power cycle. The performance of dry-cooled plants may be enhanced by pre-cooling the inflow air to the air-cooled condenser (Gadhamsghetty et al. 2006). PV systems could be used to run cooling fans (Carter and Campbell 2009), and in northern areas with lower DNI rates but sufficient organic material, a combination of CSP plants with biogas turbines is another possibility to reach better efficiencies in a sustainable way. Advanced CSP plants may also employ pressurized gas receivers that heat the air up to 1000 deg C and do not require condenser cooling.

With technological progress, these alternatives can become more efficient, and economically as attractive as conventionally cooled plants. Even without such developments, however, the cost penalties associated with reducing water consumption appear to be relatively minor. Examining future scenarios, we have shown that the penalty costs of alternative cooling systems have little effect on the total subsidies required to establish CSP technology, or the time it will take for it to become cost-competitive. Thus, the sustainability of CSP does not
depend on technical limitations or major economic penalties. Instead, it will likely depend on political regulation and governance to ensure an ecologically sound development that matches the appropriate technologies with different locations’ precise needs.

7.6 Acknowledgments

Funding for this work was received from the European Climate Foundation. We would like to thank Michael Hogan, Herbert Formayer, Zoltan Szabo and Juan Ignacio Burgaleta for providing data and valuable assistance, as well as stakeholder participants at two workshops, held in Potsdam, Germany, in March 2010 and Hammamet, Tunisia, in June 2010, for presenting useful insights. Any remaining errors are those of the authors.
7.7 References


Emerging risks and synergies for water needs in the global energy system


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Emerging risks and synergies for water needs in the global energy system

<http://www.eia.doe.gov/ieaS>


Abstract

The Middle East and North Africa (MENA) region stands out globally both for the immensity of its energy resources, and the paucity of its freshwater resources. Most energy extraction and conversion technologies have associated freshwater demand, and in the MENA region these account for 2% of the available sustainable supply. We examine how this demand could change over the 21st century, assuming growth in population and economic output, and considering three alternative pathways for energy efficiency, carbon intensity, and energy exports from the region. We find that in the pathway marked by improved efficiency, a transition to renewable energy sources, and declining energy exports, water consumption for energy is twice as high as today’s values by the end of the century. By contrast, in the pathway marked by continued commitment to fossil resource extraction, use, and export, water demand for energy might rise by a factor of five. If the region were to maintain high levels of energy exports, but would substitute the export of fossil fuels by an equivalent amount of electricity derived from sunlight, a freshwater volume comparable to the household needs of up to 195 million people could be saved.
8.1 Introduction

Growing population and economic development have led to a steep rise in energy demand over the last 150 years (Smil 2010, BP 2013). Associated with this trend has been an increasing demand for water resources, as water is required for the extraction, processing and conversion of fossil and renewable energy sources. Technology choices can have a significant impact on the energy sector’s water demand, sometimes leading to local and regional water availability being a limiting factor for energy generation (Feeley et al. 2007, Sovacool and Sovacool 2009). When presenting data on this resource interconnection, recent scientific literature focuses mainly on the US (Mielke et al. 2010, Macknick et al. 2012, MacMahon and Price 2011, US DOE 2006), but one finds discussion on this topic also in other parts of the world (FAO 2008, NRAA NN) as well as on a global level (SEI 2011, Kyle et al. 2013, Vassolo and Döll 2005). An ongoing increase in energy demand, declining overall water availability and climate change might further increase water requirements for energy in certain world regions (Sowers et al. 2011, CEDARE 2006, Haddadin 2001), and hence aggravate resource competition with other sectors such as agriculture.

A region that stands out with regard to both energy and water is the Middle East and North Africa (MENA). While having the world’s largest reservoirs of fossil energy along with enormous renewable energy resources, MENA is also the region that shows highest water scarcity. Climate policy choices, and the energy technologies they favor, may have a large effect on MENA’s fossil energy exports, electricity system and fuel production. Following an increasing energy demand, within the region and globally, the deployment of new fossil and renewable energy technologies might lead to positive or negative feedbacks concerning the water dependency of the energy sector and hence potentially important trade-offs with other water users. In this paper we examine the effect of changing energy technology mixes, a crucial prerequisite to meet global climate and regional development goals, on MENA’s water demand. By using the Representative Concentration Pathways (RCPs) (van Vuuren et al. 2011) as a framework, we develop three energy scenarios for the MENA region as a whole, in order to answer the question of whether a transition from fossil fuels to renewable energy sources, both for domestic energy consumption and for energy exports, can also have a beneficial effect on the region’s sustainability with respect to water.

8.2 Background

8.2.1 Water in the energy system

Water consumption can be defined as the water volume that gets evaporated, and/ or polluted per unit of time. The terms water demand and water requirements are used synonymously
with the term water consumption in this study. There is a range of water qualities that can serve for extraction and conversion of resources in the energy system. Today mostly fresh water is used, water showing a salinity of less than 500 ppm. Brackish (500–30,000 ppm) or saline water, such as seawater, with a salinity of 30,000 to 50,000 ppm can also be utilized for many energy technologies, though more intense treatment might be necessary compared to fresh water (Griffiths and Woynillowicz 2003). Water withdrawals, the water amount that is removed from a source, are larger than the actual water consumption, as part of the withdrawn water is returned to the source, often at higher temperatures. For this paper, we chose to focus only on water consumption, as to date data availability and quality for water withdrawal in the extraction and fuel production parts of the energy sector remain insufficient.

Water is required to extract fossil energy from its on- and off-shore reservoirs. Regarding oil extraction, water is primarily used to maintain the underground pressure that forces the oil to the surface. Only small amounts are needed for maintenance, operation and transport. Over time water needs increase in conventional oil reservoirs as they shift from primary to secondary and finally tertiary (enhanced oil recovery [EOR], mainly steam and CO₂ injection) extraction. Average water needs for shale oil, oil sand and heavy oil reservoirs are considerably lower than for enhanced oil recovery from conventional oil fields, but often use similar extraction techniques. Coal mining, washing and transport shows lower water consumption factors than conventional oil, while conventional and unconventional gas (in MENA mainly shale gas and gas hydrates (Rogner 1997)) extraction requires the least water amounts.

The part of the energy system that has received most attention so far with regard to water use is the electricity sector. Here, water is mainly required for the cooling systems of thermal power plants. Main driving factors for differentiating water demands of power plants appear to be operational as well as thermodynamic efficiency, to a lesser degree ambient temperature, fuel type, water source and age of the cooling system (Yang and Dziegliewski 2007). Once-through and closed-loop are the most common but also most water-intensive cooling systems today, with once-through systems showing highest water withdrawal rates and closed-loop systems highest water consumption. In more arid regions the shares of dry cooling systems, seawater cooling or a mix of wet and dry, hybrid cooling systems are higher. Regarding fuel processing, fossils and most renewables such as bioethanol require water both for extracting the fuel from the energy source and for cooling. When emission capturing (such as CO₂ or SO₂) is not already part of the extraction and processing of fuels and electricity generation, additional water demand occurs — especially for Carbon Capture and Storage (CCS) technologies that rely solely on wet cooling systems at this time, which in turn require considerable amounts of water (Zhai et al. 2011).
8.2.2 Water use analyses

Analyses of the water requirements, both withdrawal and consumption, of energy extraction and conversion so far have mostly focused on the United States (US) (Harte and El-Gasseir 1978, Gleick 1994, DOE 2006, Mielke et al. 2010, Macknick et al. 2011, 2012), where locally water shortages can limit potential energy production. Information on fossil fuel extraction are limited and mostly stem from case studies in the US or Canada (Argonne 2008, Griffiths and Woynilowicz 2003, NRTEE 2010, CAPP 2012). Data on fuel production can be found in various smaller studies like Van Vliet et al. (2009), Spath and Mann (2001) or Naterer et al. (2010). Regarding electricity generation, there is a series of reports analyzing and comparing different power plant technologies. The most complete to date is Macknick et al. (2012), which presents the comprehensive ranges of water demand from various US reports and studies over the last decades, and constitutes also the main basis for our analysis of MENA’s electricity sector. As a result of the high amount of surveyed literature in Macknick et al. (2012), data ranges are relatively wide. Comparing these comprehensive results to more geographically confined studies from Australia (Smart and Aspinall 2009), Europe (Carillo and Frei 2009) or North Africa (Damerau et al. 2011), data usually fall within the ranges presented for the US. The share of different types of cooling systems has a fundamental impact on the overall water demand of the electricity sector. As reported in Davies et al. (2013), data on a global level are hard to obtain. We adopted cooling system shares from this study for the MENA region, where currently seawater cooling stands out as the preferred cooling technology. The water demand for hydropower appears to be exceptionally high as it refers to the evaporative loss of water from reservoirs that usually serve multiple purposes. Therefore we mostly disclose this water demand separately within our overall calculations, especially as hydropower capacities increase in our energy scenarios. A stage of energy production where additional water demand occurs is plant construction. Current reports and studies used as basis for our analysis do not include full life-cycle water usage, focusing only on operational and maintenance water demand. A full life-cycle analysis for the US electricity sector can be found in Fthenakis and Kim (2010). A comprehensive overview of the current ranges and average water use requirements for different energy technologies can be found in Table S1 in the Appendix.

So far, relatively little analysis has focused on the Middle East and North Africa region or its constituent countries, and most regional studies on water demand for energy focus solely on the electricity sector. Regional findings are presented in Davies et al. (2013) as part of a global study. Basis for their analysis of the Middle East is a study by Vassolo and Döll (2005), also a global analysis of water demands in the electricity sector, where assumptions on water consumption of thermal power plants appear to be somewhat lower when compared to our analysis. A more comprehensive study on the whole energy sector in MENA can be found in
Siddiqi and Anadon (2011). Making use of similar data sources to ours, quantitative results are presented only for parts of the energy sector, and hence only allow a limited comparison with our study.

Despite being of minor importance with regard to the total water use in the entire region today (Siddiqi and Anadon 2011, FAO 2014), expected declining water resources and a rising energy demand might lead to a considerable increase in the water demand and therefore increased competition with other water users. Depending on energy sources and technologies chosen, we investigate the current and future reliance of the whole energy sector on water in this particularly water-scarce region.

8.3 Methods

8.3.1 Framework for regional energy scenarios

The frame for our outlook in MENA’s energy future until 2100 is set by the regional emission trajectories embedded into a set of global pathways on radiative forcing. These Representative Concentration Pathways were developed for a new scenario approach to anthropogenic climate change for the IPCC Fifth Assessment Report (IPCC 2013) and give a wide range of potential greenhouse gas (GHG) emission developments from 2.6 to 8.5 W/m² of global radiative forcing. Fitting our scenarios into this framework facilitates potential comparison with other scenarios in the scientific literature. We take the lower and upper boundary to explore how MENA’s energy sector could develop in face of strong population growth (UN DESA 2009, UN 2010) and therefore rising energy demand, both for electricity and fuels, while possibly opposed by climate change mitigation measures (Riahi et al. 2007, IEA 2009, Nakicenovic and Swart 2000). In the lower boundary pathway GHG concentrations peak globally at about 490 ppm CO₂-equivalent before 2100 and decline thereafter, while the upper boundary pathway shows concentrations rising beyond 1,370 ppm CO₂-equivalent. We selected these two pathways to present the most optimistic (RCP2.6) as well as most pessimistic (RCP8.5) outlook regarding the global CO₂ concentration until 2100. As the other two pathways, 6.0 and 4.5, lead to a stabilization of CO₂ concentrations between the IPCC’s 2.6 and 8.5 pathways, they would likely show a stronger mix of both fossil and renewable energy over the next decades. Because our scenarios mainly favor either one or the other, we are able to see stronger effects on the overall water demand when comparing different technologies as a part of energy scenarios.
8.3.2 Calculating current water demand for energy

We derived detailed data on MENA’s current energy sector from the online database of the International Energy Agency (IEA) referring to the year 2008 (IEA 2008). The IEA database offers, inter alia, data on fossil resource extraction and domestic processing and (sectoral) consumption as well on trade and stock changes of fossil and renewable energy sources. Multiplying these data with our collected water consumption data, if possible regionally specific, allowed us to calculate the current water demand of the entire sector. For estimating the shares of extraction technologies for conventional and unconventional oil extraction, we used shifting rates from the US and applied them to MENA, where commercial oil recovery began on average about two decades later. We assumed that unconventional resources like shale oil, oil sand and heavy oil play only a minor role, with a share of 10% within all unconventional recovery methods, leaving 90% to EOR methods with similar shares in technologies like found in the US today (Mielke et al. 2010). Cooling system shares for electricity generation in the region were adopted from estimates in Davies et al. (2013). To be able to relate our results to MENA’s total water resources and use, we collected data from the AQUASTAT online database of the Food and Agriculture Organization (FAO 2014), which offers recent data (2003-2007, partially estimated or modeled, published in 2014) on a country level including renewable freshwater resources. Though this database does not include actual data on water consumption in MENA, total water withdrawal can give us an approximation: 96% of all water is withdrawn for agricultural purposes, where due to high evaporation losses water consumption is assumed to follow withdrawal rates very closely (compare Water Footprint database (Hoekstra and Mekonnen 2012)).

8.3.3 Scenario development

We used the MESSAGE integrated assessment model to draw the two regional energy futures that present a detailed potential mix of energy technologies. MESSAGE provides a mid- to long-term framework for representing an energy system on a regional or global scale (consequently, we looked at the MENA region as one entity), and included interdependencies from resource extraction and conversion to sectoral consumption and international trade (Messner and Strubegger 1995, RCP Database 2009) The two base scenarios all satisfy the GHG emissions constraints associated with RCP 2.6 and 8.5, as well as assumptions about regional resource potentials and energy technology developments available to meet the regional energy demand of growing populations and economies (UN DESA 2009, Riahi et al. 2007). Starting our scenarios in 2010, and extracting results in 10-year steps until the end of this century, we multiplied MESSAGE’s technology-specific energy supply data for each scenario with the average water consumption factors presented in Table S1 (see Appendix). In neither scenario, RCP2.6 and RCP8.5, do electricity exports play a role. This is an artifact of the scenario modeling environment, which does not explicitly take weather-driven variability
from renewables into account, but rather deals with it indirectly by placing constraints on the
direct impacts of alternative energy scenarios on water demand in the Middle East and North Africa.

There are reasons to believe mixing renewably generated power from widely dispersed locations and transmitting them via high-voltage direct current (HVDC) lines, as well as relying on concentrating solar power with the possibility of thermal storage (in contrast to photovoltaics, and therefore the preferred solar energy technology by the energy model), could help to alleviate load management issues that grid operators face, and would make solar power from MENA an attractive import commodity in neighboring regions (Battaglini et al. 2009, Pfenninger et al. 2014). As a result we developed a third scenario, representing a hybrid of the other two and of particular relevance to the MENA region, which relies on energy exports for its economic base and might continue to do so in future. The hybrid scenario maintains total domestic energy use and greenhouse gas emissions, as well as fossil fuel (oil and gas) exports, at the level of the RCP 2.6 consistent scenario, while maintaining total net energy exports at the level of the RCP 8.5 consistent scenario. In this hybrid scenario, MENA intensifies the use of its solar potential and closes the gap between total fossil fuel exports in RCP2.6 and RCP8.5 through exports of electricity generated by concentrating solar power (CSP), resulting in a mix of fossil and renewable energy exports.

As more and more conventional oil reservoirs get depleted and unconventional resources have to be explored in order to meet a growing energy demand, extraction technologies shift to more water-intensive technologies. Note that the MESSAGE model lists fossil fuels from tertiary extraction techniques (EOR) as unconventional resources. The shares of secondary and tertiary oil recovery are expected to increase over time. To be able to incorporate these shifts, we assumed the same average shift rates observed in the US, resulting in levels of 30% primary, 60% secondary and 10% EOR today (Mielke et al. 2010) and assuming a share of 30% saline water consumption. Extrapolating this trend, we arrive at a share of 60% secondary and 40% EOR in MENA in 2100, holding the share of saline water consumption stable at 30%. We also held shares of EOR technologies stable at current US levels, as any changes in future technology trends are hard to predict. As for the other unconventional resources, shale oil, oil sand and heavy oil, that are not part of the fossil fuel mix in MENA today but might be to a small degree in future according to our scenarios, we adopted current resource shares (IEA ETSAP 2010) with the majority being heavy oil, and technology shares for oil sand from Canada (NRTEE 2010). Over time, we then steadily adjusted today’s shares to presumably available resource shares, which show quite equally distributed reserves globally, and specifically for oil sands a higher potential for in situ than surface mining (IEA ETSAP 2010, Griffiths and Woynilowicz 2003). Water requirements therefore increase slightly over time, but including an assumed constant share of 20% for saline water consumption and making an overall contribution of only 10% to unconventional oil resources, this effect remains minor. Water consumption factors for coal and gas extraction (conventional and
unconventional) were held stable; no uranium mining takes place in the MENA region.

Regarding shares of cooling systems in the electricity sector, we do not assume changes for specific technologies. Today the majority of MENA’s thermal power plants is seawater cooled and is expected to continue to use these cooling systems in future, as those plants are primarily located along the more densely populated coast lines. In our study main drivers for a changing water demand on a technological level is therefore the deployment of new, renewable capacities, especially CSP where the choice if cooling systems has a large impact of the electricity sector’s water demand in future. Depending on their location, seawater cooling like for existing fossil power plants appears to be less efficient with regard to potential power output of CSP plants. Hence, we assume new CSP capacities placed more inland (compare Pfenninger et al. 2014) with an equal share of the two currently most common technologies, parabolic trough and tower, where we find higher solar potentials but seawater cooling is not a viable option. In our scenarios we present results for both wet and dry cooled CSP.

Today, main resources exported from MENA to other world regions are crude oil and gas, while refinery fuels only play a minor role. The amount of assumed future energy exports in MESSAGE depends on global and domestic fossil fuel demand in the energy scenario, regional resource availability and estimated energy cost. Therefore fossil fuel export plays a larger role in RCP8.5 than in RCP2.6. MESSAGE does not include potential electricity trade, but was added in our hybrid scenario as a feasible option in form of solar electricity export to neighboring world regions.

8.4 Results

Applying the average water consumption factors, presented in Table S1, to the mix of plant capacities that are currently represented in MENA’s energy sector allowed us to estimate the actual water consumption for energy in the region. For 2008 we calculated a total freshwater consumption of 9.4 billion m³. 7.1 (76 %) of these 9.4 billion m³ are attributed to fossil resource extraction, and another 0.04 billion m³ to the refining of oil products (higher amount than estimated by Siddiqi and Anadon (2011)). Together, fossil fuels require 1.7 % of MENA’s available renewable freshwater supply of 425 billion m³ (FAO AQUASTAT 2014). Figure 1 shows these results, disaggregating the fossil fuel water demand according to shares for domestic supply (30 %) and international exports (70 %). Much less fresh water, 2.2 billion m³, is required for electricity generation. 44 % of that constitutes evaporative loss from hydropower plants, half of this from Egypt’s Lake Nasser (IEA 2008). Comparing to Davies et al. (2013), we calculate a water consumption of 0.9 bn m³, 0.15 bn m³ more, for the electricity sector in the Middle East (both excluding hydropower) — this difference can be explained by
larger water consumption factors used in our study. There are no total comparable water consumption data available from FAO AQUASTAT for MENA. However, according to this database, total current water withdrawal reaches 300 billion m$^3$/year, of which 96% are used in the agricultural sector, leaving to assume that total water consumption reaches only slightly lower levels.

![Fig. 1: Current water consumption of MENA's energy sector. The countries included are Algeria, Bahrain, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Morocco, Oman, Palestine, Qatar, Saudi Arabia, South Sudan, Sudan, Syria, United Arab Emirates and Yemen. Data are presented on a logarithmic scale. For each fossil resource, the bars indicate the water use requirements associated with extraction to supply energy use within the MENA region, and associated with extraction bound for exports from the region. Separate bars for electricity identify water needs at the point of energy conversion, in the case of fossil fuels primary for the cooling of thermal power stations. Renewable water resources refer to actual total renewable water resources (FAO AQUASTAT, 2014)](image)

As a next step, we analyzed MENA’s future water consumption for energy. The three scenarios, RCP2.6, hybrid, and RCP8.5, describe the same levels of population and economic growth in MENA (MESSAGE assumes the economy continues to grow steadily around current levels), but differ according to the energy intensity of the economy and the carbon intensity of energy use. Regarding the former, primary energy demand in the MENA region rises from 33 EJ/year to 46 EJ/year in the RCP2.6, and 200 EJ/year in the RCP8.5 scenario. Regarding the latter, MENA’s fossil fuel extraction in the RCP2.6 scenario peaks in 2030 at 120 EJ/year and then steeply declines to 33 EJ/year by 2100. The emissions these fossil fuels generate are compensated through the use of carbon capture and storage (CCS). Conventional oil and gas continue to be the major fossil resources extracted. Unconventional oil extraction is not necessary to meet the demand, and unconventional gas extraction is...
phased out by 2030.

In the RCP8.5 scenario, by contrast, there is strong increase in fossil resource extraction, to a maximum of 225 EJ/year in 2100, making unconventional oil the major energy resource from 2040 onward. Perhaps surprisingly, crude oil and gas exports decline not only in the RCP2.6 but also in the RCP8.5 scenario, although the decline is steeper in the former, 88% compared to 55%. However, the export of oil products such as fuel oil increases in both scenarios. Overall export of fossil fuels declines by 68% in the RCP2.6 scenarios but increases by 16% in RCP8.5 until the end of the century. The driving factor for the decrease in exports in the RCP2.6 scenario is the global shift away from fossil fuel combustion, whereas in the RCP8.5 scenario no such export limitations occur and make fuel instead of crude resource exports an economically more attractive option in future. Figure 2 presents an overview of these regional energy scenarios, conforming in their GHG emissions to the lower and upper global RCPs. Table 1 gives additional information on total energy and renewable energy demand changes between the start year 2010 and 2100 for all three scenarios.

![Fig. 2: Total fossil resource extraction and energy exports in MENA through 2100. Comparing three regional energy scenarios, the blue area in each graph represents extraction for domestic consumption, while green areas represent energy resources destined for export markets. The light green shaded area in the hybrid scenario represents the amount of solar energy that is required to increase total energy export from RCP2.6 to RCP 8.5 levels](image)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>2010 (Starting year)</th>
<th>RCP2.6</th>
<th>Hybrid</th>
<th>RCP8.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total energy demand [EJ]</td>
<td>86</td>
<td>78</td>
<td>122</td>
<td>276</td>
</tr>
<tr>
<td>Energy export [EJ]</td>
<td>53</td>
<td>18</td>
<td>62</td>
<td>62</td>
</tr>
<tr>
<td>Total share renewable energy [%]</td>
<td>0.6</td>
<td>57.2</td>
<td>72.7</td>
<td>18.3</td>
</tr>
<tr>
<td>Total share renewable energy export [%]</td>
<td>0.0</td>
<td>0.0</td>
<td>71.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Table 1: Total energy demand (extracted fossil resources plus produced non-fossil fuels and electricity) and export in all scenarios as depicted in Fig. 2. The domestic electricity demand in RCP2.6 and the hybrid scenario is met to 95 % by renewables until 2100 in RCP8.5 65% renewables finally meet the regional electricity demand.
Applying the technology specific water consumption factors to these three energy scenarios, we draw a potential picture of water consumption in the energy sector over the coming decades. Figure 3 displays aggregate water consumption by the MENA energy sector associated with each scenario; additional results, further decomposing that water demand by technology, appear in the Appendix. For the RCP2.6 scenario, water consumption peaks in the first half of the century at almost three times the current level, and then declines thereafter, as fossil fuel extraction for both domestic use and exports falls off. By 2100, annual water demand is still about twice as high as today, at 18 billion m$^3$, but the relative shares for fossil fuel extraction and electricity generation have roughly reversed. In the RCP8.5 scenario, by contrast, water consumption peaks higher and later. In 2080, total water demand lies at 52 billion m$^3$, about six times today’s level, and then declines to 47 billion m$^3$ by the end of the century. Shrinking population numbers are the main driver for this decrease. The hybrid scenario tracks the RCP2.6 scenario in all respects, except for the additional water demand associated with renewable electricity generation for exports from CSP. Under baseline assumptions concerning generation technologies, the water demand for renewables-based exports is consistently lower than that for crude and refined oil and gas exports. In 2080, when the difference has the greatest absolute magnitude, fossil fuel exports in the RCP8.5 scenario account for 14.1 billion m$^3$ more water consumption than the corresponding electricity exports in the hybrid scenario.

Fig. 3: Overall water consumption for MENA’s energy supply through 2100. Bars present each stage of the energy sector and their respective export shares in lighter shades, while conventional and unconventional fossil resources are highlighted separately. Values for the RCP2.6 and hybrid scenario are identical except for water demand for solar electricity exports in the latter scenario. In comparison to RCP8.5, water savings achieved in the hybrid scenario amount to a maximum of 14.1 billion m$^3$ in 2080 and decline thereafter to 7.6 billion m$^3$ in 2100. Detailed analyses for all three scenarios can be found in the Appendix.
The largest factor driving this growth is the rising water demand for unconventional fossil resource extraction (especially EOR), followed by the generation of electricity; in both cases we have made critical assumptions based on the best available evidence: In the case of unconventional fossil resource extraction, the critical assumption is that primarily fresh water will be used to enhance recovery; the use of saline water above our assumed 30%, could reduce this water demand at some sites in MENA. In the case of electricity production, our scenarios assume that all new CSP plants are constructed away from the coast and utilize dry cooling, a technology currently available and prevalent in dry climates, but carrying a slight cost penalty compared to wet cooling (Damerau et al. 2011). Were wet cooling to be installed, total water demand for electricity generation would be substantially higher by 2100: by 26 billion m$^3$ in the RCP2.6 scenario, 33 billion m$^3$ in the RCP8.5 scenario, and 56 billion m$^3$ in the hybrid scenario. Indeed, water consumption for energy exports would be 2.6 times higher in the hybrid scenario than in the RCP8.5 scenario, were wet-cooled CSP the technology delivering the electricity for export. Additional information can be found in the Appendix.

### 8.5 Discussion

Our study provides a new, more detailed approach to analyzing the implications on water resources of different potential energy pathways in the MENA region. Continued development along a fossil-fuel intensive pathway, consistent with the RCP8.5 scenario, would mean that the energy sector would have to find sources for roughly five times the amount of water than it requires today. The share of the region’s renewable water resources that the energy sector currently demands, slightly more than 2%, is small, and yet this could easily change. In the RCP8.5 scenario, it rises to 11% of current renewable water resources, resources that are likely to decline over the next decades. The main driver for this trend is the water demand associated with rising levels of unconventional fossil resource extraction. By contrast, a strong commitment to energy conservation and a transition from fossil fuels to renewable energy sources, consistent with the RCP2.6 scenario, could result in a much smaller change in water demand by the energy sector, despite a rapidly growing population. Indeed, it appears that MENA could sustain high levels of energy exports, with much less demand on freshwater reserves, were those exports to shift from its fossil resources to its solar resources, when assuming that solar thermal power plants use dry instead of wet cooling systems, and hence accepting an only marginal economic disadvantage in order to save water resources (Damerau et al. 2011). If we consider, for example, the maximum net water savings of 14.1 billion m$^3$/year around 2080 that would result from shifting exports from oil and gas to solar power, this amount is comparable to MENA’s current domestic water needs of roughly 195 million people, 30% of the total population for the MENA region projected for 2050 (Chapagain and Hoekstra 2004, UN DESA 2009).
While they do deliver valuable insight, our results have important limitations, due to many of the assumptions that we were forced to make. First, our scenarios include only slight use of CCS added to conventional electric power plants within the MENA region, though for reaching certain emission goals this technology could play a significant role in the future. If large capacities would be installed in water-stressed regions like MENA, the need for dry-cooled facilities would emerge, as current CCS technologies entirely rely on wet cooling (Zhai et al. 2011). Second, regarding unconventional oil extraction (primarily EOR in MENA) the share of technologies chosen in future can be an important driver for water demand. Third, our results do not include additional water demand that would be required for crop production if first-generation bioenergy would be produced in the region. As MENA’s potential for bioenergy is considered very low, this energy source is not part of our scenarios, but it may lead to significantly increased water demands for renewable energy in other world regions. There are also only minor regional fissile resources in the MENA region (BGR 2009) and a shift towards nuclear power plants would therefore largely depend on uranium imports. Fourth, we do not assume any changes in water use efficiency for the fuel and electricity technologies themselves, as any assumptions at this point seem highly speculative. Fifth, our scenarios are just three potential paths for MENA’s energy sector development until the end of the century, and all of them rely on a single scenario for population and economic growth. Sixth, MENA countries differ substantially from one another, and our results provide only a regional view. Scaling down from the regional level would require the use of much more detailed national data. Our results suggest that this may well be a worthy exercise.

Despite the differences between countries, the MENA region as a whole is characterized by extreme water scarcity, where every drop of consumption faces competition from some other user. With a growing population, there is every reason to believe that this competition will grow even more intense in the future. Given the importance of energy exports for the economies of MENA countries, there is also reason to suspect that the water needs of that sector would be met, even if it meant cutting back on water use elsewhere. Currently the agriculture sector is the dominant freshwater user, and yet the implications of failing to conserve water in the energy sector are nevertheless large. The potential feedbacks, which we do not address in this paper, are also large. If 195 million people—the number we highlighted in the previous paragraph—were to rely on desalinated water for their household needs, this would require 75–355 EJ/year, depending on desalination method chosen (WSTB 2008). Comparing that to the region’s current energy demand of roughly 53 EJ/year, it becomes obvious that the future linkages between energy and water are important and complex, and a more integrated approach to water resource management is required when facing future challenges of food and energy security.
8.6 Acknowledgments

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8.7 References


Emerging risks and synergies for water needs in the global energy system


Emerging risks and synergies for water needs in the global energy system


9 CONTRIBUTION 3 - Water saving potentials and possible trade-offs for future food and energy supply

Kerstin Damerau, Anthony G. Patt, Oscar P.R. van Vliet
In review at *Global Environmental Change*

Abstract

The sufficient supply of food and energy requires large amounts of fresh water. Mainly required for irrigation, but also processing and cooling purposes, water is one of the essential resources in both sectors. Rising global population numbers and economic development could likely cause an increase in natural resource demand over the coming decades, while at the same time climate change might lead to lower overall water availability. The result could be an increased competition for water resources mainly in water-stressed regions of the world in the future. In this study we explore a set of possible changes in consumption patterns in the agricultural and energy sector that could be primarily motivated by other goals than water conservation measures - for example personal health and climate change mitigation targets, and estimate the indirect effect such trends would have on global water requirements until 2050. Looking at five world regions, we investigated three possible changes regarding future food preferences, and two possible changes in future resource preferences for electricity and transport fuels. We find that while an increase in food supply in form of protein demand would lead to an increase in water demand as well, this trend could be counteracted by other potential dietary shifts such as a reduction in grains and sugars. In the energy sector we find that an increasing water demand can be limited through specific resource and technology choices, while a significant growth of first-generation biofuels would lead to a drastic rise in water demand, potentially exceeding the water requirements for food supply. Looking at the two sectors together, we conclude that an overall increase in water demand for both food and energy is not inevitable and that changes in food and energy preferences could indeed lead to an alleviation of water resource use despite rising population numbers.
9.1 Introduction

The types of foods and energy we consume have considerable direct and indirect effects on global freshwater use. By far most water resources get used for irrigation purposes in the agricultural sector, mainly for food production. In another sector, energy, electricity and fuel production requires increasing amounts of water, mainly for resource extraction and cooling (Macknick et al. 2012, Mielke et al. 2010). In some regions this trend has already led to a competition between different water users (The World Bank 2014). Rising global population numbers and socio-economic development could lead to a further increase in water demand in both sectors over the coming three to four decades. At the same time environmental changes like climate change might decrease the water availability and quality in many parts of the world (Jimenez Cisneros et al. 2014). Hence, the source and type of food, electricity, and transport fuel we choose in the future can either accelerate a rising water demand or offset increasing resource needs, depending on the effects of consumer preferences and policy initiatives on consumption patterns in both sectors. Water is one of the most important natural resources and the interactions between water use, energy demand and food production are complex, as changes in the demand of one resource in one sector can change its availability and that of another resource in another sector and vice versa. Water is used and re-used for food, electricity, and fuel production, while energy is required for agriculture and water supply, creating positive feedback loops that can aggravate already existing water shortages or generate new ones.

Over the last decade a number of scientific papers and policy reports have examined the interactions between the agriculture and energy sector from a natural resource perspective. Resources that received highest attention with regard to their regionally interrelated availability are water, energy, and to some extent land. The term often used to describe this interconnection is the so-called water-energy-(land)-food (WE(L)F) nexus, i.e. the interaction regarding water that is required for food and energy, energy required for water and food, and land required for food and energy supply. There are qualitative and quantitative approaches, as well as global and regional studies covering either specific parts of the WE(L)F nexus or trying to integrate several resource interdependencies at the same time, searching for trade-offs and potential conflicts. The existing studies on this topic discuss a growing scarcity of natural resources due to rising population numbers and economic development, and their potential social implications, while most of them focus on the water-food or water-energy nexus.

Within this context, an important issue that has not yet been examined in the scientific literature are the effects that potential changes in consumer preferences could have on
natural resource use. The amounts of water that get consumed for supplying food, electricity, and transport fuel can vary vastly depending on type of food and energy source chosen. In this study, we address this very question: how an increasing global per capita and overall demand for food and energy would potentially be influenced through a set of different consumption trends regarding changes in dietary and energy source preferences. In the form of a global high-level quantification for water consumption in the agricultural and energy sector, we model the water use for irrigation, cooling and processing purposes in five world regions as defined for the shared socio-economic pathways (SSPs) used for the latest IPCC assessment report (Field et al. 2014). Our aim is to compare and evaluate the water consumption shares for food, electricity, and transport fuels until 2050 and detect global and regional patterns in water demand across these two sectors. Through this integrated analysis we will be able to identify a set of relative and combined effects of resource preference changes on the presumably steadily rising water demand in both sectors.

9.2 Background

A number of recent qualitative and qualitative papers have discussed the WE(L)F nexus in general and particular resource interactions, often focusing on specific parts of the world which are characterized by significant natural resource scarcity and competition. A first set of studies has looked at (aspects of) the WE(L)F nexus on a qualitative basis. Ringler, Bhaduri and Lawford (2013) discussed the linkages of water and food, energy and water, energy-food, land-energy, and energy-land, and underlined the importance of an integrated management approach. Halstead et al. (2014) reviewed the current literature on the WEF nexus, though did not relate water use shares of both sectors to each other. FAO (2014) examined the WEF nexus as a new approach to support food security and sustainable agriculture. Bogardi et al. (2012) analyzed the interconnected challenges for water security for a planet facing increasing regional water stress due to rising population, climate change, urbanization and development, calling for an integrated management framework in order to address all of those challenges simultaneously. De Fraiture et al. (2010) discussed comprehensive assessment methods for water management in agriculture. Also Rosegrant, Ringler and Zhu (2009) focused on the water use intensity of the agricultural sector and how to maintain food security while water stress increases with an emphasis on improving efficiencies. Hellengers at al. (2008) presented a debate on the interactions between water, energy, food and environment with a focus on water-related policy issues. Allouche (2011) looked at water and food security predominantly from a social and political perspective, doing so on a global, regional and national scale. Harvey and Pilgrim (2011) explored the “new competition for land”, integrating food, energy and climate change into their discussion. All of these studies have envisioned a drastic rise in natural resource demand based on an extrapolation of current requirements to
future population numbers and ongoing socio-economic development trends, and hence have called for an integrated policy and management framework.

Another set of studies has tried to quantify natural resource interconnections on a global level. Hanjra and Qureshi (2010) analyzed expected reduced global water availability and future food security, reviewing quantitative results from previous studies to underline the severity of limited water resources for agriculture over the coming decades. Chartres and Sood (2012) undertook a global quantitative analysis for the water demand for food production until 2050. Using the WATERSIM model they developed three scenarios with differing assumptions on population and GDP growth rates where they extrapolated current dietary patterns, but did not integrate a discussion on potential changes in future consumer preferences. All scenarios show an increase in global water demand for agriculture from 2,400 km$^3$/yr in 2010 to between 3,820 and 7,230 km$^3$/yr in 2050. Sulser et al. (2010) used IFPRI’s IMPACT model for their analysis of the Nile and Ganges river basins, including a set of global scenarios that illustrate the potential growth rates of consumptive water use in the agricultural sector until the mid-century depending on global per capita income growth. In their baseline scenario they projected an increase from 1,425 km$^3$/yr irrigation (blue) water demand for crop production in 2000 to 1,785 km$^3$/yr in 2050.

A third set of studies followed a regional approach to the WE(L)F nexus. Lele, Klousia-Marquis and Goswani (2013) debated governance issues when integrating food, water and energy security, including a case study for water management in China and India. Gulati et al. (2013) presented a national WEF study for South Africa, exploring the interdependencies of these three resources, including an economic analysis. Hardy, Garrido and Juana (2012) undertook a quantitative analysis of the water-energy nexus for Spain, calculating a potentially increasing water demand for energy supply. Scott et al. (2011) looked at the policy and institutional dimension of the water-energy nexus including cases studies from the United States, highlighting the role of integrated local water management. Larson (2012) presented a water analysis for alternative food security policies in the Middle East and North Africa, focusing on wheat production and trade, while Mushtaq et al. (2009) presented an energy and water trade-off assessment for rice production in Asia. Rasul (2014) did a study on food, water and energy security in South Asia. Lawford et al. (2013) gave a basin perspective on the WEF security nexus, using results from case studies from different large river basins. Perrone, Murphy and Hornberger (2011) presented an integrated qualitative analysis framework for the water-energy nexus on the community level. In all of these regional analyses natural resource availability is expected to decline due to rising demands and simultaneous adverse ecological changes.
There have also been several regional and global studies looking particularly at the water (and land) demand of energy in the form of biofuels, and their potentially negative impacts on food security and water availability when scaling up biofuel production in the future (Farrell et al. 2006, Sims et al. 2006). Dominguez-Faus et al. (2009) analyzed the water requirements for maize as energy crop in the US, concluding that a major shift to such an energy source would have large detrimental effect regarding water availability and environmental health. Fingerman et al. (2010) examined the water impacts of producing bioethanol in a comprehensive environmental assessment with a case study for California, finding that the production of ethanol from maize or sugar beets would require enormous amounts of water with up to 5,100 l/l ethanol. Yang, Zhou and Liu (2009) calculated the land and water requirements for biofuel production in China and its potentially adverse consequences for food supply and the environment. Using the WATERSIM model, de Fraiture, Giordano and Liao (2008) looked at international biofuel policies and their implications for water demand in the agricultural sector on a global level. They put emphasis on the countries China and India, where a fast growing energy demand and limited water resources could lead to strong resource competition in the future were biofuels utilized as one of the main transport fuels. Globally they estimated irrigation water withdrawals for bioethanol of 30.6 km$^3$/yr in 2005, an amount that could rise to 128.4 km$^3$/yr in 2030.

Given current consumption patterns, a high per capita supply of food and energy, rising global population numbers, and socio-economic development, all calling for high natural resource inputs, and their resulting ecological consequences like climate change aggravating regional resource scarcity, every one of the WE(L)F studies undertaken so far picture an increasing resource demand for the coming decades, and consequently underline the necessity for better, integrated management measures to avoid or alleviate resource competition. Their results show that current practices and development trends would lead to an increased demand for food, water, energy, and land, and that targeting multiple resource use goals at once can lead to higher management efficiency with regard to sustainability. What none of them has done, however, is to examine the effects that sectoral specific changes – both technological and behavioral – could have on such future resource demands. This is important, both because sectoral specific changes may represent the best leverage points for policy, and because it may be that the opportunities for resource conservation in one sector may dominate those in all other sectors. It is the issue we now address.
9.3 Methods

9.3.1 Modeling framework

For our own quantitative approach we focus on water consumption (here synonymous with water demand) for food and energy at the supply stage. We choose not to include water withdrawals of these two sectors, as this might lead to a multiple accounting of the same water resources used and re-used for various purposes in both sectors. Rather then extrapolating current trends and consumption patterns as done in previous studies, which necessarily lead to an increase in resource use in absence of policy interventions that directly target water use efficiency as well as technological improvements, we explore the variability within those patterns. As this variability might potentially influence water demand within and trade-offs between the two sectors, we test the extent to which preferences for certain food sources as well as electricity and transport fuel sources could indirectly drive overall future regional and global water demand.

To test this, we develop a scenario approach for which we use population projections until the mid-century and built a two-part accounting and linear optimization model calculating water consumption associated with food and energy demand. To be able to detect potential drivers, water saving opportunities and possible trade-offs between the agriculture and energy sector with regard to future water use, we test three potential dietary and two energy demand trends in the form of changed global consumption patterns in 2050 compared to today’s food and energy source preferences. Figure 1 displays an overview of our methodological approach.

Figure 1: Methodological approach for testing a set of potential dietary and energy source demand trends with regard to water consumption, starting in 2011.
9.3.2 Underlying scenarios and data

The Shared Socio-economic Pathways (SSPs) constitute a framework for climate change research that describes plausible alternative developments in society and economy without integrating climate change or new climate policies. For our study they serve as reference point mainly regarding population growth as well as for assumptions on general socio-economic development. We take the average population projections from the framework’s five global world regions, Asia (ASIA), Latin America (LAM), the Middle East and Africa (MAF), the OECD countries (OECD), and countries from reforming economies of Eastern Europe and the former Soviet Union (REF). In all SSP projections overall growth of population numbers as well as GDP is projected in ten-year steps until 2100 (O’Neill et al. 2014, IIASA 2013), we select the year 2050 as projection point for our own analysis for which we estimate a total global population rise to roughly nine billion people.

We choose 2011 as reference year as this year marks the most recent consistent point in time for data collection on global food and energy supply. FAO’s online database (FAOSTAT 2014) offers data on annual food supply (food sold on markets and in stores) on a country level for major foods and food groups. This information reflects actual food consumption only to some extent, as post-supply food waste rates and shares vary from food group to food group and region to region (Gustavson et al. 2011) and does not include supplies from subsistence farming. Of course, food waste occurs already between production stages and final supply and this also varies between regions, as shown in the database as well, but shares do not distinguish waste associated to the edible part of the product and non-edible but otherwise used parts. For each of the five SSP regions we calculate the average food supply (weight and energy content) based on population shares within the region for the following main food groups and their individually listed foods: cereals, starchy roots, sweeteners, pulses, nuts, vegetable oils, vegetables, fruit, meat, animal fats, eggs, dairy, and fish – 43 products in total. The World Bank energy database offers annual data on electricity and transport fuel supply, giving main energy sources technology shares on a country level (The World Bank 2015). We aggregate these data for each world region and adapted global assumptions on the shares of energy plant cooling technologies from Davies et al. (2013) for the electricity sector of each region.

For calculating the water consumption of the global food supply as well as for first-generation biofuel production we collect data from the global Water Footprint (WFP) Network. It forms an often-applied approach to assess the water consumption that occurs when producing a certain good (Mekonnen and Hoekstra 2011 and 2012, Gerbens-Leenes et al. 2008). The Water Footprint is defined as the volume of fresh water appropriated to produce a product, taking into account the volumes of water consumed and polluted in the different steps of the
supply chain (direct and indirect water consumption). It is mostly used when assessing the virtual water trade that accompanies international product trade. Regarding agricultural products, the database lists the average blue, gray and green water consumption by product on a sub-national level, calculated using the global CROPWAT model (Hoekstra et al. 2011). For bioenergy production Gerbens-Leenes et al. (2008) list blue and green water consumption. Blue water is defined as the fresh surface and groundwater. Gray water is water that is required to dilute pollutants to such an extent that the quality of the water remains above agreed water quality standards. Green water is the precipitation on land that does not run off or re-charge the groundwater but is stored in the soil or temporarily stays on top of the soil or vegetation. Eventually, this part of precipitation evaporates or transpires through plants. For this analysis we choose to focus primarily on to the blue water demand of different agricultural products (Ridoutt and Pfister 2012, Sulser et al. 2010). As the WFP Network offers data on the national and sub-national level, we calculate the average water consumption (blue water) of a product for each region when produced within this region. For biofuels we select the three most prominent energy plants in each region. Regarding global food trade, we combine trade data from the FAO and ITC databases, providing trade shares and information on trading partners (FAO 2014, ITC 2014). We determine the two to three main trading partners (world regions) for each imported product and hence are able to estimate the amount of water that is imported through a certain food product (virtual water trade). The WFP Network database provides water use for unprocessed agricultural products as well as processed food products. For estimating the amount of water that gets attributed to the final food product, we choose averages for final uncooked foods that align with the food supply data from FAO. Regarding the water demand of specific energy technologies, we apply a set of data collected by Damerau et al. (2015).

9.3.3 Model and constraints

In order to integrate all collected resource demand data, we develop a two-part accounting model that allows us to calculate the water demand (blue, green and gray water separately) for each selected food per kcal within each region, including the regional water amount from imported products. Listing the associated food group and specific macro-nutrient content of each food creates the basis for a rough qualitative comparison between single foods and food groups. In a next step, we build a linear optimization model using the programming language R (Venables et al. 2015), which makes it possible to limit the amount of energy, macro-nutrients, food groups, and single foods as listed in the caption to Table 1, as well as green and gray water use, when optimizing the water demand (blue water) of a given or assumed daily nutritional intake within a region. We follow the same methodology for the energy sector, where instead of food supply in kcal we list the water demand per GJ for electricity and transport fuel supply, including virtual water imports from imported fossil fuels for the latter.
To be able to run the optimization model for food supply and potential future dietary patterns without compromising variety and health or excluding staple foods typically consumed in a certain world region, as well as limiting virtual water trade, we compile a list of assumptions and restrictions as presented in Table 1.

<table>
<thead>
<tr>
<th>Objective</th>
<th>Limitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>No increase of current water stress through food imports (Hoekstra and Mekonnen 2011)</td>
<td>No increase in blue water trade</td>
</tr>
<tr>
<td></td>
<td>Increase in green water trade limited to a maximum of 10%</td>
</tr>
<tr>
<td></td>
<td>(New) foods added to the current diet only consume water resources stemming from within the region</td>
</tr>
<tr>
<td>No fundamental changes in dietary patterns assumed (compare Last et al. 2015)</td>
<td>Must keep at least 50% of a region’s staple food (e.g. rice and wheat in ASIA)</td>
</tr>
<tr>
<td></td>
<td>No increase in uncommon foods within a region, e.g. sorghum in OECD</td>
</tr>
<tr>
<td>Mitigate potential health risks from sugar overconsumption (Fried and Rao 2003, Shapiro et al. 2010)</td>
<td>No increase in sugar and sweeteners</td>
</tr>
<tr>
<td>Mitigate potential health risks from dairy consumption: only about 30% of the global population are able to digest lactose (Lomer et al. 2007)</td>
<td>No increase in dairy</td>
</tr>
<tr>
<td>Mitigate potential health risks from soy overconsumption (Gilani et al. 2011, Cederroth et al. 2012)</td>
<td>Soy and soy products are limited to a maximum of 100 kcal/cap/d</td>
</tr>
<tr>
<td>Limit biodiversity loss (Koh and Wilcove 2008, Burgess et al. 2013)</td>
<td>No increase in palm(kernel) oil consumption</td>
</tr>
<tr>
<td>Limit potential water demand changes for meat, as soybean oil cake is widely used as animal fodder</td>
<td>No increase in seafood consumption</td>
</tr>
<tr>
<td>Limit potential increase of soybean oil to 10%</td>
<td>Limit potential increase of soybean oil to 10%</td>
</tr>
<tr>
<td>Ensure variety in nutrient supply (Foote et al. 2004)</td>
<td>Keep all main foods within each region’s typical diet</td>
</tr>
<tr>
<td>Keep current vegetable and fruit consumption stable</td>
<td>Keep current vegetable and fruit consumption stable</td>
</tr>
<tr>
<td>Include quality assumptions when comparing plant and animal protein sources (Friedman 1996, Sarwar 1996)</td>
<td>Combine grains and legumes to provide sufficient protein source, including lower quality assumptions of about a third compared to average animal protein</td>
</tr>
</tbody>
</table>

Table 1: Model constraints for regional food supply and trade. This table lists and explains the model’s restrictions and boundaries with regard to water consumption (blue and green water), regional diet patterns and nutritional assumptions concerning regional food supply. Single foods included in the analysis are wheat and wheat products, rice, barley, maize and maize products, rye, oats, sorghum, other cereals (cereals); cassava, potatoes and potato products, sweet potatoes, yams, other roots (tubers); sugar and sweeteners; beans, peas, soybeans, other pulses (pulses); nuts; soybean oil, groundnut oil, sunflower seed oil, rapeseed oil, cottonseed oil, palm(kernel) oil, coconut oil, sesame seed oil, olive oil (plant oils); vegetables; fruit; beef, goat, pig, poultry, offal, other meats (meat); animal fats incl. butter; eggs; dairy; fish.

For our energy model we also define a set of constraints. After calculating the specific electricity technology shares for coal, gas, nuclear, oil, combined cycle, biomass, concentrating solar power (CSP), photovoltaic, wind, geothermal, and hydropower, and if applicable their associated cooling technologies for each of the five world regions, we make the baseline assumption that the specific energy technology shares do not change over time within each region. This first step represents a simple extrapolation from current energy supply conditions that later allows a comparison to possibly changing technology mixes and
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their associated water demand in the energy sector in the future. Such shifts in technology shares are reflected in possible changing demands for certain energy technologies that do not directly target water saving goals. We account for water consumption from hydropower separately as this water use stems mainly from evaporation losses at hydropower reservoirs, which are often used for multiple purposes and thus make assumptions on attributable water losses due to power production problematic. Electricity generation from biomass is here assumed to be provided by waste matter and does not require the additional planting, and therefore irrigation of energy crops.

Regarding transport fuels, we include virtual water imports from fossil fuels extracted and exported from the Middle East and North Africa, a region contributing about 40% to global oil exports today (BP 2013). For biofuels, we use assumptions on conventional first generation biofuels such as bioethanol from sugar cane or biodiesel from rapeseed oil. From the WFP Network data on bioenergy we determine the (weighted) average water consumption for three main biofuel crops planted within each world region. To these numbers we add the water demand for processing and converting these crops into liquid transport fuels (van Vliet et al. 2009).

9.3.4 Alternative scenarios incorporating shifts in food and energy consumption patterns

Global development goals include food and energy security for a large number of people for which both food and energy demand (absolute and per capita) are likely to increase over the coming decades. FAO’s food security definition states that food security exists when all people at all times have access to sufficient, safe, nutritious food to maintain a healthy and active life (FAO 1996). From there, one can make very different assumptions about potential changes in future consumer preferences and their motivation. We assume an overall desired trend towards more balanced diets (sufficient and proportionally adequate supply of all essential macro- and micro-nutrients) that target health, longevity, and optimal physical and cognitive performance. We do not assume extreme changes in global dietary patterns, but rather examine the effect of how more moderate shifts towards more nutritious and safe foods can have on the water demand for future food supply. For this purpose we specify three concurrent dietary shifts.

The first is an increase in protein supply in all regions except the OECD region to levels comparable to those in OECD, which we assume to be nutritionally sufficient for supporting basic metabolic processes and physical performance. In OECD countries we calculate an average supply (not consumption) of protein of approximately 110g/cap/d with a share of about 40% plant and 60% animal protein. For closing this ‘protein gap’ globally we compare potential animal and plant protein sources for each selected region, using linear optimization
to identify the least water-intensive protein sources. Given the lower overall nutritional quality of plant protein in comparison to animal protein, and the necessity to combine different plant foods in most cases for a sufficient amino acid supply, we take average digestibility data from various studies, assuming a 50/50 protein share from grains and legumes and an average digestibility factor of 1.5 compared to animal protein sources; i.e. one needs to consume 50% more plant protein to reach similar bioavailability as average animal protein (Friedman 1996).

In the second shift, without changing the macro-nutrient shares typical for today’s diets - on a global level roughly 60% carbohydrates, 10% protein, and 30% fat (FAOSTAT 2014) - we look for possibilities to swap to some extent certain foods with each other. Staying within the main food groups and overall macro-nutrient shares of an average regional diet, an example for such an exchange would be the replacement of one plant oil in the diet with another, potentially more nutritious one when directly compared (USDA 2014, Siri-Tarino et al. 2010, Deol et al. 2015).

In the third shift, we examine the potential effects a decrease in absolute and relative total carbohydrate share from roughly 60% today to 40% and hence an increase in the fat share of a diet. This is driven by current empirical and clinical evidence on the potential negative health effects of long-term high-carbohydrate diets (Sondike et al. 2003, Bazzano et al. 2014, Westman et al. 2007). We assume this shift to be moderate as it reflects the average diet of a large number of people; 40% carbohydrates still represents a high macro-nutrient share within such an average diet. In this step we also include increased protein levels in ASIA, LAM, MAF and REF as calculated for trend one and kept overall energy supply stable in each region, as the average energetic supply of each world region’s diet appears to be sufficient if not excessive in some regions, though certain macro- and micro-nutrient needs might not be met by modern (Western) diets (Gosby et al. 2014, Hunt 2003). In all of these three potential basic trends, water savings are not assumed to be the primary goal, but can be supported by smart choices regarding the resource intensity of different foods.

For the energy sector, we envision two concurrent developments reflecting potential consumer preference changes until 2050. The first is an increased awareness of climate change and engagement to meet climate mitigation goals, leading to a higher demand for renewable energy sources such as solar and wind power. The second is growing health concerns associated with noise and air pollution from traffic relying mainly on fossil fuels (Anderson et al. 2012, Curran et al. 2013), leading to higher shares of electric transport and/or biofuels, such as bioethanol and biodiesel. Over the last decade a number of countries have defined various goals for future biofuel shares in their transport fuel mix, often ranging from 10 to 20% (Lane 2014). Producing their own biofuels would increase those countries’ energy independence, though a competition of bioenergy with food production could be one of
the potential downsides. Above, first-generation biofuels can have large negative ecological impacts, not only with regard to water (Creutzig et al. 2014). The European Union therefore revised their biofuels targets until 2020, limiting first-generation biofuels to a share of 7% (The Economist, 2015). We adopted this goal for our global estimates. We test both possible trends, estimating the effect they would have on regional and global water resources without directly targeting future water availability. Additional factors that might influence or counteract the trends we detect will be evaluated in the discussion section of this study.

9.4 Results

Figure 2 displays our first set of results regarding combined and relative water demands on a global level, comparing water consumption for food and energy supply by region for 2011, 2050 in a baseline scenario as well as 2050 in an improved scenario with and without a major expansion of first-generation biofuels. As our baseline scenario shows, extrapolating current food and energy consumption to a global population in 2050 would inevitably lead to a large increase in water demand, much more so in the agricultural sector than in the energy sector. An increase in food supply in the form of a higher global average protein demand comparable to OECD levels in 2050 would result in a higher calorie demand of 40-60% depending on the protein source chosen. If at the same time energy demand were to increase to per capita levels we currently see in OECD countries, assuming no changes in the energy technology shares, we would see a total rise in energy demand by 180%. Both rising resource demands would lead to an increase of overall freshwater consumption by 50% compared to current global water requirements, 15% of which would be required in the energy sector. In our improved scenario, where we consider three shifts regarding food consumption patterns, and one shift in the energy sector towards more renewables (and/or dry-cooled thermal power production in general) and electric transport until 2050, we see a slight decrease for the combined water demand of both sectors by 4% despite a global population growth to nine billion people. The water savings for food supply outweigh growing water requirements for electricity and transport fuels. Compared to the baseline scenario, this projection shows an in total 35% lower water consumption in 2050. One caveat, however, is presented in the last scenario with an expansion of first-generation biofuels to globally 7% of total transport fuels. This would result in a water demand for energy supply higher than for the current food supply, total global water demand in this scenario would more than double.
Contribution 3 - Water saving potentials and possible trade-offs for future food and energy supply

Figure 2: Total current and potential future water demand for food, electricity, and liquid fuel supply by region. Extrapolating the water demand of both sectors in Asia (ASIA), Latin America (LAM), Middle East and Africa (MAF), OECD countries (OECD) and the countries from reforming economies of Eastern Europe and the former Soviet Union (REF) to meet the goal of today's OECD consumption patterns for the entire future population results in a substantial increase in water demand. Dietary shifts and technological changes can lead to improvements in water efficiency for both food and energy supply. However, an increase in biofuel supply to meet 7% of the future population’s transport fuel needs would lead to a drastic rise in water demand, potentially exceeding water requirements for food supply.

In Figure 3 we present a second set of results illustrating the specific effects single trends would have on the water demand for food supply in each world region. Daily per capita water intensity of food supply is currently highest in the REF region, and lowest in MAF. This present water consumption is put into relation with (1) a potential driver of water consumption in the form of increased protein demand in four out of five world regions, and two water-saving trends: (2) more nutritious food sources could to some extent replace current food items, and (3) a combination of food replacements and a macro-nutrient shift from 60 to 40% carbohydrates in the average diet by 2050. Overall results show that in all five regions a considerable reduction in water demand could be achieved indirectly through dietary changes.
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Fig. 3: Current regional water demand for food supply and effects of potential dietary shifts. Water demand in liters per capita and day increases when animal (orange) or plant (yellow) protein sources are added to the average diet. In three regions, ASIA, OECD, and REF, substituting half of the amount of certain foods with less water-intensive ones reduced overall water demand significantly. An even greater effect can be reached in all regions through a shift from carbohydrate sources towards more fat sources.

(1) Increasing protein supply. Reaching the level of protein supply as observed in OECD countries today, including a high animal protein share, would lead to an increase in dietary protein and calories associated with these protein sources in all other world regions, ASIA, LAM, MAF, and REF. In ASIA and LAM animal protein sources would lead to slightly stronger water demand increase than plant protein sources, while in REF plant protein requires slightly more water. The biggest difference between the water requirements for different protein sources was found in MAF, where animal protein (goat) would require considerably less water than a maize/pea mix. In all regions an increase of protein supply through plant protein sources would also lead to a considerably higher increase in energy supply than that for animal protein, exceeding current OECD levels of roughly 3,500 kcal/cap/d.

(2) Replacing foods. In LAM and MAF we did not find single significant foods where an exchange would lead to substantially lower water requirements. In ASIA however, a hypothetical replacement of half its wheat and rice consumption with more nutritious tubers such as sweet potatoes and yams would lead to an 18% reduction of overall water intensity of the average Asian diet. In OECD and REF we find similar saving potentials. Given the relatively high dairy consumption, a 50% replacement of dairy products with either eggs in
OECD countries or goat/sheep meat in REF countries would lower water demand by 6 to 10%; also, replacing 50% of these regions’ current soybean and safflower oil supply with rapeseed or coconut oil would lead to a reduced water demand of another 5%. Such shifts could potentially offset water demand increases from rising population demands as discussed above, while increasing the micro-nutrient content of the average diet.

(3) **Shifting macro-nutrient composition.** This trend includes a slight increase in protein to OECD levels (as calculated for trend one) as well as potential water savings described for trend two. We assumed additional protein sources to be supplied by animal sources, which show lower carbohydrate loads. In all five regions a trend away from very high carbohydrate supplies towards diets higher in fat, in four regions animal protein, and also micro-nutrient content, would lead to a per capita water demand of the average global diet lower than seen today (from 560 to 400 l/cap/d). Depending on the region, we detect a number of drivers for this trend including a shift away from grains (and sugar) towards tubers (though the other way around in LAM), more plant oils such as coconut oil, less dairy but more meat sources such as goat, sheep and in MAF also poultry, and more eggs and animal fats in OECD countries. We find a decrease in per capita water consumption between 12% in LAM and 45% in REF. Adding up these potential saving over the whole global population, we see a decrease in total water demand for global food supply in 2050 by 10% despite the demographic growth.

Figure 4 illustrates a third set of results by comparing current water demand for electricity and transport fuel supply to (1) a global increase to per capita energy intensity as currently observed in OECD countries, (2) a scenario in which 50% of the this energy supply goal could be met by renewables and/or dry-cooled energy technologies, including a 50% share of electric transport, and (3) an increase of first-generation biofuel share to globally 7%.

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Figure 4: Current regional water demand for electricity and liquid fuels and effects of changing demand patterns. Increasing the per capita energy demand in all regions to current OECD levels also leads to an increase in water demand of the energy sector. Water savings can be achieved through shifts towards wind or photovoltaic but also dry-cooled thermal power capacities. A significant increase in first-generation biofuels, however, would increase the overall water demand for energy dramatically. Water demand for hydropower is not included in this graph.

(1) Extrapolating current technology shares. Meeting the potential future electricity and transport fuel demand in ASIA, LAM, MAF, and REF would result in an increased water demand by a factor of 2.5 in REF to factor of 8 in ASIA. When compared to today’s consumption levels, a considerable share would be required for increased fossil fuel production, also leading to a significant rise in associated virtual water trade with MAF. Not included in these estimates is water contributing to hydropower production. Without hydropower we would see a global increase in water consumption for electricity and transport fuel production by a factor of four, from 74 km³/yr to 298 km³/yr. This is a significant increase that might indeed lead to increased competition for water resource in water-stressed areas. Compared to the potential increase in water use for food supply, i.e. increased protein supply, from 1,449 to 1,942 km³/yr this trend in the energy sector still appears minor, though not trivial. If hydropower needs were included this scenario, this would add another 1,580 km³/yr of water consumption.

(2) New energy technologies in the electricity mix. New power plant capacities are required either to replace outdated plants or increase overall electricity supply. Some technologies
require negligible amounts of water to operate such as photovoltaic and wind turbines. In the case of thermal power plants dry or seawater cooling technologies can be employed to reduce the water demand by about 90%. Hence, if 50% of the electricity plants in 2050 were to either use wind or photovoltaic, or dry/seawater-cooled technologies such as CSP, geothermal or biomass/waste plants, the water demand of the electricity sector could be almost cut in half. The same holds true for the transport sector, if fossil fuels were to be replaced with electricity from those water-saving technologies.

(3) Increase in first-generation biofuels. If in 2050 global average per capita fuel demand would reach OECD levels and 7% of this demand would be met by first-generation biofuels, that are produced within each world region, using the currently most common energy crops, total water consumption for energy would increase from 74 km\(^3\)/yr today to possibly 2,012 km\(^3\)/yr, 97% of which for growing biomass. This amount of water would equal the amount of water required for increased food supply when not assuming potential dietary shifts.

9.5 Discussion

In contrast to previous studies our work is able to show that an increase in water demand for food production in future is not inevitable, while a rise in water consumption in the energy sector appears in every scenario we examined. Because the use of water for food is currently in most cases more than one order of magnitude larger than for energy depending on world region, there is an overall potential to save water across the two sectors. At the same time, increased reliance on biofuels could easily change this story, making energy the larger water consumer, overshadowing any potential gains in the food sector.

A globally considerable intensification in water demand of 50% as estimated by us in the first step of this study is comparable to findings of other authors (OECD 2012), and potential mitigation measures are discussed in many WE(L)F studies as cited in the Background section. Indeed, if we were to simply extrapolate current per capita OECD consumption patterns to the global level in 2050, regional and local water competition is likely to increase, and might even lead to potential resource conflicts (Bogardi et al. 2012). Still, on a regional and global scale water demand for energy remains minor when compared to resources used for food supply. Interconnections between the two sectors with regard to water therefore so far appear as a potential environmental and social issue predominantly on a sub-regional and local scale (Aipipalakul, Wirojangud and Ngang 2015).

Regarding the part of our study looking at water requirements for food supply, we investigated how potential changes in food consumption, i.e. changing dietary patterns, and energy
preferences could affect regional and global freshwater consumption. Possible and plausible changes in food preferences, partly in combination with a shift to less water-intensive food sources, both potentially driven by personal health and performance goals, could indeed result in a lower overall water demand for food supply than today despite rising population numbers. The trends we investigated in this study do not fundamentally affect regional and local cuisines and traditions, as mostly broad averages for regional food supply were used that do not compromise food variety and traditional choice of meal ingredients. However, the demand for more nutrient dense diets could also lead to other plausible changes in food preferences such as an increase in vegetable and fruit consumption. This trend would counteract potential water savings, as both food groups show high freshwater consumption rates. It is also worth to look at each world region separately as water footprints can vary significantly between regions. Regarding food sources that provide protein, adequate plant protein does not necessarily require less water than comparable animal protein sources. Another important point to make is that food supply does not equal agricultural production (compare results from Chartres and Sood (2012)). Plant and animal products often satisfy multiple purposes besides delivering food, such as providing seeds, fodder, leather, or ingredients for personal hygiene products. Therefore the losses and waste that occur between the production of the agricultural product and the final food product in retail are difficult to allocate. This is the reason we chose to focus on food supply rather than agricultural production data concerning water requirements for food production within the broader context of the water-energy-food nexus. The largest share of food waste (on average 30%) occurs after the supply stage at retail points and in private households (Gustavson et al. 2011). The data we applied for food supply therefore do not reflect average food consumption, and do not include private food production on a household level. Above, in high-income countries food waste shares after retail are often higher compared to those in low-income countries. A reduction in food waste could therefore additionally lower the intensity of natural resource use without assuming any demand or technological changes in the global food system.

In contrast, in the energy sector water demand will likely grow, even when considering an increasing share of renewable technologies. When assuming high per capita energy intensity in the future on a global average, energy supply capacities have to be expended drastically to satisfy the growing demand. This increase would also likely lead to a non-trivial rise in water demand for energy, as shown by our own estimations as well as other previous studies (Hardy et al. 2012, Stilwell et al. 2011). An increase in first-generation biofuels could easily lead to large additional water requirements, possibly exceeding those for food. Above, also the demand for cropland would rise, which might lead to additional competition for land with food production (Rathmann, Szko and Schaeffer 2010). However, restricting first-generation biofuels as well as the deployment of freshwater-cooled thermal energy technologies in the future would also limit the additional water (and land) demand in the energy sector, an
increase that could be more than offset by changes in the food sector. Due to this potential trade-off, an overall increase in water demand in both sectors is not necessarily an unavoidable trend. Our results provide valuable new insights and information for integrated natural resource management and policy, in particular with respect to biofuel targets. Mitigation measures as discussed in previous studies can further improve water efficiency, especially in regions where water availability might decline over the next decades as a consequence of climate change and other potential ecological changes.

9.6 Acknowledgments

Funding for this work was received from the Institute of Science, Technology and Policy in the form of an ETHZ seed project grant promoting interdisciplinary research. We would like to thank Carmenza Robledo Abad for her valuable assistance and constructive comments.
9.7 References


The Economist (2015). Thin Harvest. Investment in biofuels is dwindling and skepticism is growing. April 18th.


Emerging risks and synergies for water needs in the global energy system


Emerging risks and synergies for water needs in the global energy system


Appendix

Supplementary material for contribution 2: Direct impacts of alternative energy scenarios on water demand in the Middle East and North Africa

Kerstin Damerau, Oscar P.R. van Vliet, Anthony G. Patt
*Climate Change* (2015) 130:171-183

A. Water use data

Table S1 provides a comprehensive overview of the current ranges and average water use requirements for different energy technologies and lists their specific literature sources. For some technologies median instead of mean values were available. However, to be able to present a consistent data set, we only list and apply average data. In bold letters we highlight those technologies that are included in our regional analysis, as not all energy technologies listed in Table S1 are represented in our study for MENA.

<table>
<thead>
<tr>
<th>Table S1</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Extraction technology</td>
</tr>
<tr>
<td>COAL</td>
</tr>
<tr>
<td><em>Mining + washing + slurry pipeline transportation</em></td>
</tr>
<tr>
<td>CRUDE OIL</td>
</tr>
<tr>
<td><em>Primary recovery</em></td>
</tr>
<tr>
<td><em>Secondary recovery</em></td>
</tr>
<tr>
<td>Enhanced recovery (EOR)</td>
</tr>
<tr>
<td><em>Steam injection</em></td>
</tr>
<tr>
<td><em>CO2 injection</em></td>
</tr>
<tr>
<td><em>Caustic injection</em></td>
</tr>
<tr>
<td><em>Forward injection</em></td>
</tr>
<tr>
<td><em>Micellar polymer injection</em></td>
</tr>
<tr>
<td><em>Other</em></td>
</tr>
<tr>
<td><em>Shale oil</em></td>
</tr>
<tr>
<td><em>Oil sand</em></td>
</tr>
<tr>
<td><em>Surface mining</em></td>
</tr>
<tr>
<td><em>In situ</em></td>
</tr>
<tr>
<td><em>Heavy oil</em></td>
</tr>
</tbody>
</table>
Emerging risks and synergies for water needs in the global energy system

### NATURAL GAS

<table>
<thead>
<tr>
<th></th>
<th>Cooling system</th>
<th>Water withdrawal (range)</th>
<th>Water consumption (range)</th>
<th>Average water consumption [m³/GWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Conventional gas + pipeline transportation</strong></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Shale gas</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
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<tr>
<td><strong>URANIUM</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mining</td>
<td></td>
<td></td>
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</table>

### B. Electricity generation technology (non-renewable)

<table>
<thead>
<tr>
<th>Technology</th>
<th>Water withdrawal (range) [m³/GWh]</th>
<th>Water consumption (range) [m³/GWh]</th>
<th>Average water consumption [m³/GWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>COAL</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steam turbine <em><em>(w/o FDG</em>)</em>*</td>
<td>on- through closed-loop dry</td>
<td>68,150 – 170,350</td>
<td>360 – 1,116</td>
</tr>
<tr>
<td>Advanced (sub- and supercritical)</td>
<td>on- through closed-loop dry</td>
<td>94,000</td>
<td>250 – 540</td>
</tr>
<tr>
<td>Advanced + CCS</td>
<td>on- through closed-loop dry</td>
<td>210,000</td>
<td>440 – 570</td>
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<tr>
<td>IGCC</td>
<td>closed-loop dry</td>
<td>1,355 – 2,290</td>
<td>1,225 – 1,700</td>
</tr>
<tr>
<td>IGCC + CCS</td>
<td>closed-loop dry</td>
<td>1,815 – 2,590</td>
<td>1,880 – 2,340</td>
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<tr>
<td><strong>NATURAL GAS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas turbine</td>
<td>not required</td>
<td>2.5 – 4.7</td>
<td>3 – 5</td>
</tr>
<tr>
<td>Steam turbine</td>
<td>on- through closed-loop dry</td>
<td>37,855 – 230,050</td>
<td>365 – 1,125</td>
</tr>
<tr>
<td>Steam turbine + CCS</td>
<td>on- through closed-loop dry</td>
<td>-</td>
<td>475 – 1,465</td>
</tr>
<tr>
<td>Combined cycle</td>
<td>on- through closed-loop dry</td>
<td>28,390 – 75,710</td>
<td>75 – 385</td>
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<tr>
<td>Combined cycle + CCS</td>
<td>on- through closed-loop dry</td>
<td>-</td>
<td>350 – 530</td>
</tr>
<tr>
<td><strong>NUCLEAR</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steam turbine</td>
<td>on- through closed-loop dry</td>
<td>95,000 – 230,000</td>
<td>385 – 1,550</td>
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<tr>
<td></td>
<td>3,030 – 8,940</td>
<td>2,250 – 3,275</td>
<td>2,765²</td>
</tr>
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<td></td>
<td>140</td>
<td>0 – 120</td>
<td>60¹</td>
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### Appendix

#### OIL

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<tr>
<th>Steam turbine</th>
<th>once-through</th>
<th>closed-loop</th>
<th>dry</th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>OIL</strong></td>
<td>69,400 - 215,000</td>
<td>2,840 - 6,640</td>
<td>0 - 140</td>
<td>250 - 1,550</td>
<td>900*</td>
<td>2,225 – 4,025</td>
</tr>
</tbody>
</table>

#### C. Electricity generation technology (renewable)

<table>
<thead>
<tr>
<th>Cooling system</th>
<th>Water withdrawal (range) [m³/GWh]</th>
<th>Water consumption (range) [m³/GWh]</th>
<th>Average water consumption [m³/GWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BIOMASS</strong> (excl. crop production)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steam turbine</td>
<td>175,000</td>
<td>1,165</td>
<td>1,165²</td>
</tr>
<tr>
<td>closed-loop</td>
<td>2,175 - 4,385</td>
<td>1,815 – 3,655</td>
<td>2,735²</td>
</tr>
<tr>
<td>dry</td>
<td>0 - 140</td>
<td>0 - 120</td>
<td>60¹</td>
</tr>
</tbody>
</table>

#### GEOTHERMAL

| Steam turbine | closed-loop | 22 - 23,950 | 18 - 19,950 | 9,980² |

#### HYDROPOWER

(water consumption = evaporative loss)

| not required | - | 5,525 – 69,390 | 37,455² |

#### SOLAR

Concentrating solar power

<table>
<thead>
<tr>
<th>power tower</th>
<th>closed-loop (US)</th>
<th>2,910 - 3,570</th>
<th>3,240²</th>
</tr>
</thead>
<tbody>
<tr>
<td>closed-loop (Sahara)</td>
<td>-</td>
<td>2,100 - 2,330</td>
<td>2,240³</td>
</tr>
<tr>
<td>dry (US)</td>
<td>100 - 350</td>
<td>225²</td>
<td></td>
</tr>
<tr>
<td>dry (Sahara)</td>
<td>-</td>
<td>-</td>
<td>340³</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>parabolic trough</th>
<th>closed-loop (US)</th>
<th>2,810 – 4,295</th>
<th>3,555²</th>
</tr>
</thead>
<tbody>
<tr>
<td>closed-loop (Sahara)</td>
<td>-</td>
<td>3,000 - 3,290</td>
<td>3,175³</td>
</tr>
<tr>
<td>dry (US)</td>
<td>165 – 305</td>
<td>235²</td>
<td></td>
</tr>
<tr>
<td>dry (Sahara)</td>
<td>-</td>
<td>-</td>
<td>295³</td>
</tr>
</tbody>
</table>

| dish/ engine | not required | 75 | 75² |
| Fresnel | closed-loop (US) | 3,785 | 3,785³ |

#### Photovoltaic

| not required | negligible |

#### WIND

| not required | negligible |
### D. Fuel technology: Water consumption (range) [m³/TJ]

<table>
<thead>
<tr>
<th>Technology</th>
<th>Water Consumption</th>
<th>Average Water Consumption [m³/TJ]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BIOFUELS</strong> (excl. crop production)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bioethanol</td>
<td>0 - 32</td>
<td>16¹</td>
</tr>
<tr>
<td>Bioethanol + CCS</td>
<td>210 - 238</td>
<td>224</td>
</tr>
<tr>
<td><strong>BTL (Fischer-Tropsch) (w/ + w/o CCS)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>34⁸</td>
</tr>
<tr>
<td><strong>COAL</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methanol (w/ + w/o CCS)</td>
<td>-</td>
<td>37**,⁸</td>
</tr>
<tr>
<td>CTL (w/ + w/o CCS)</td>
<td>40 - 93</td>
<td>67.⁵,⁷</td>
</tr>
<tr>
<td><strong>HYDROGEN</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bio gasification (w/ + w/o CCS)</td>
<td>-</td>
<td>46⁵,⁸</td>
</tr>
<tr>
<td>Coal gasification (w/ + w/o CCS)</td>
<td>-</td>
<td>53⁹</td>
</tr>
<tr>
<td>Electrolysis</td>
<td>-</td>
<td>64</td>
</tr>
<tr>
<td><strong>Steam methane reforming (SMR)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(w/ + w/o CCS)</td>
<td>-</td>
<td>37⁹</td>
</tr>
<tr>
<td><strong>NATURAL GAS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methanol</td>
<td>4 - 34</td>
<td>19¹⁰,⁵</td>
</tr>
<tr>
<td>Methanol + CCS</td>
<td>210 - 264</td>
<td>237¹⁰,⁵</td>
</tr>
<tr>
<td><strong>OIL PRODUCTS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Petroleum distillation</strong></td>
<td>2 - 3</td>
<td>2.5¹¹</td>
</tr>
</tbody>
</table>


Table S1: Water consumption associated with energy technologies (technologies used in this study are highlighted in bold letters). (A) Water consumption in energy resource extraction, presenting ranges and average water consumption for various technologies. (B) Water consumption in non-renewable electricity generation, distinguishing ranges for water withdrawal and consumption as well as average consumption for various technologies. For seawater cooling same values apply as for dry cooling. (C) Water consumption in renewable electricity generation, distinguishing ranges for water withdrawal and consumption as well as average consumption for various technologies. For seawater cooling same values apply as for dry cooling. (D) Water consumption in fuel production, presenting ranges and average water consumption for various fossil and renewable fuels.
B. Detailed scenario results

Figure S1 and Tables S2a and S2b present the water demand for coal, gas and oil extraction including the shares of water demand for unconventional recovery methods and those that go into export fuels through 2100. In the RCP8.5 scenario both the higher reliance on fossil fuels to meet a higher energy demand, as well as the resulting exploration of unconventional resources, lead to a water demand for resource extraction up to 26 times higher than in the RCP2.6 scenario (in 2080).

Figure S1 and Tables S2a and S2b
Figure S1: Water consumption for resource extraction in MENA through 2100, comparing the RCP2.6 and RCP8.5 scenario. The hybrid scenario is identical with the RCP2.6 scenario. Darker shades indicate domestic consumption, lighter shades the water requirements for export resources; conventional and unconventional resources are segregated. Table S2a shows extracted resources in EJ, Table S2b gives an overview of exactly calculated water demand values.

Comparing the refining of fossil and renewable fuels, the RCP2.6 scenario shows a peak in oil refinery around 2030 with 52 EJ, the RCP8.5 scenario in 2080 with 77 EJ/yr, respectively. In the RCP2.6 scenario, the refining of oil products falls below the initial (2010) amount of 24 EJ/yr around 2060. In both scenarios small amounts of fossil and renewable synthetic fuels are complementing the fuel supply. Besides oil products, methanol from mainly gas and to some degree coal, with and without CCS, but also liquid biofuels along with hydrogen derived from coal or via steam methane reforming get introduced, and all of these include CCS. As all of the technologies named above are inherently providing CO$_2$ separation, no additional water is required for treating exhaust gases. Figure S2 and Table S3b present the development of the water consumption in the fuel sector for both scenarios, which show that overall water consumption in the RCP8.5 scenario remains in the long run higher than in RCP2.6 despite a greater reliance on water-intensive new synthetic fuels and hydrogen of the latter; compared to today the water demand for fuel production rises to nine to ten times the amount of 2010.
Figure S2 and Table S3a and S3b

Figure S2: Water consumption for fuel production in MENA through 2100. Lighter shades indicate shares for export fuels. The hybrid scenario is identical with the RCP2.6 scenario. Table S3a shows produced fuels in EJ, Table S3b gives an overview of exactly calculated water demand values.
In all scenarios, cost minimization leads to the result that increasing domestic electricity demand will be primarily met by new capacities of concentrating solar power (60% in RCP8.5, and 70% in RCP2.6 and the hybrid scenario, respectively, in 2100), photovoltaic and to some extent wind and hydropower. In the RCP8.5 scenario the use of gas plants also increases to meet the higher demand while being less strict on GHG emissions; there are no added CCS capacities in the electricity sector. In the RCP2.6 scenario natural gas capacities increase at first while relying in part on CCS to lower GHG emissions. Most fossil fuel capacities are phased out by 2100 leaving the electricity sector primarily relying on solar technologies (25% photovoltaics in 2100 for RCP2.6 and the hybrid scenario, no significant capacities used in RCP8.5), small amounts of wind, hydro and for some decades geothermal plants. Gas power plants continue to play an important role in RCP8.5 scenario by meeting 36% of the power demand in 2100, while they play a marginal role in RCP2.6 and the hybrid scenario. In all scenarios renewable energy technologies are considered GHG emission-free. The water demand rises for the fossil capacities but declines again towards the end of the century. CSP constitutes the potentially major electricity technology in future for MENA. Thus, the decision on which cooling technology will be built in those CSP plants, wet, dry or hybrid systems, can have a substantial impact on the future water demand for electricity supply. Once-through cooling with sea or brackish water, as currently preferred for MENA’s fossil power plants, seems unlikely for the majority of new CSP capacities, as a coastal siting would reduce the plants’ power output potential. Figure S3 and Table S4b compare the water demand in the electricity sector for the RCP2.6, hybrid and RCP8.5 scenario. They present the shares of water demand for fossil and renewable capacities, and moreover a range of water demands for renewables depending on how CSP capacities are cooled, wet or dry. Overall, water demand increases to maximum 22 billion m$^3$/yr (using dry-cooled CSP) in our hybrid scenario in 2080, roughly 5.5-8.5 billion m$^3$/yr more than in the RCP2.6 and RCP8.5 scenario, but declines thereafter again slightly.
Figure S3 and Table S4a and S4b

<table>
<thead>
<tr>
<th>Technology</th>
<th>2010</th>
<th>2030</th>
<th>2050</th>
<th>2070</th>
<th>2090</th>
<th>2100</th>
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<tr>
<td>CSP</td>
<td>2.6</td>
<td>8.5</td>
<td>2.6</td>
<td>8.5</td>
<td>2.6</td>
<td>8.5</td>
</tr>
<tr>
<td>CSP dry</td>
<td>0.00</td>
<td>0.00</td>
<td>0.38</td>
<td>0.38</td>
<td>2.00</td>
<td>2.00</td>
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<tr>
<td>Solar</td>
<td>0.50</td>
<td>0.50</td>
<td>0.73</td>
<td>0.73</td>
<td>1.10</td>
<td>1.10</td>
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<tr>
<td>CSP wet</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.08</td>
<td>0.11</td>
<td>0.11</td>
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<tr>
<td>CSP hybrid</td>
<td>2.6</td>
<td>8.5</td>
<td>2.6</td>
<td>8.5</td>
<td>2.6</td>
<td>8.5</td>
</tr>
<tr>
<td>Geothermal</td>
<td>2.6</td>
<td>8.5</td>
<td>2.6</td>
<td>8.5</td>
<td>2.6</td>
<td>8.5</td>
</tr>
<tr>
<td>coal</td>
<td>4.33</td>
<td>4.33</td>
<td>4.33</td>
<td>4.33</td>
<td>4.33</td>
<td>4.33</td>
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<tr>
<td>Gas (steam turbine)</td>
<td>1.85</td>
<td>1.85</td>
<td>1.85</td>
<td>1.85</td>
<td>1.85</td>
<td>1.85</td>
</tr>
<tr>
<td>Gas (combined cycle)</td>
<td>4.02</td>
<td>4.02</td>
<td>4.02</td>
<td>4.02</td>
<td>4.02</td>
<td>4.02</td>
</tr>
<tr>
<td>Gas (combined cycle, CCS)</td>
<td>4.02</td>
<td>4.02</td>
<td>4.02</td>
<td>4.02</td>
<td>4.02</td>
<td>4.02</td>
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<tr>
<td>Geothermal</td>
<td>0.89</td>
<td>0.89</td>
<td>0.89</td>
<td>0.89</td>
<td>0.89</td>
<td>0.89</td>
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<tr>
<td>Wind</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
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<td>Coel (i.e., FGD)</td>
<td>0.44</td>
<td>0.44</td>
<td>0.44</td>
<td>0.44</td>
<td>0.44</td>
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<tr>
<td>Photo voltaic</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
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<tr>
<td>Photovoltaic</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Wind</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
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<tr>
<td>Sum</td>
<td>0.48</td>
<td>0.48</td>
<td>0.48</td>
<td>0.48</td>
<td>0.48</td>
<td>0.48</td>
</tr>
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</table>
Figure S3: Water consumption in the electricity sector in MENA through 2100, comparing the RCP2.6, hybrid and RCP8.5 scenario. Hydro refers to evaporative losses. Error bars show additional water demand when installing wet cooled instead of dry cooled CSP, caps indicate exact values for auxiliary water need. Table S3a shows electricity generated in EJ, Table S4b gives an overview of exactly calculated water demand values, highlighting wet-cooled CSP in italic letters.
### Additional publications, posters and presentations

#### Additional publications

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Title</th>
<th>Journal/Proceedings</th>
</tr>
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<tbody>
<tr>
<td>Pfenninger S., Gauché P., Lillistam J., Damerau K., Wagner F., Patt A.G.</td>
<td>The potential for concentrating solar power to provide baseload and dispatchable power</td>
<td><em>Nature Climate Change</em> 4(8), 689-692</td>
</tr>
<tr>
<td>Honey K., Damerau K., Strohecker C.</td>
<td>The Ocean Inside Us. A complex adaptive systems approach to considering the role of marine ecosystems in sustaining human health</td>
<td>SFI 2013 CSSS Proceedings</td>
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<tr>
<td>Damerau K.</td>
<td>Climate change and energy security - a losing deal? Impacts, trade-offs and adaptation possibilities for metropolitan areas. A scenario approach for long-range energy planning in the greater Vienna region.</td>
<td>Diploma thesis, University of Vienna</td>
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#### Presentations and posters

<table>
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<tr>
<th>Event</th>
<th>Title</th>
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<tbody>
<tr>
<td>Annual Conference SGLUC/SGLH/SGLWT &amp; SVIAL – Water in Food Production, Solothurn, Switzerland, September 2014.</td>
<td>Poster presentation: Water consumption in meat- and plant-based diets</td>
</tr>
<tr>
<td>2nd Dii Desert Energy Conference, Cairo, November 2011.</td>
<td>Poster Presentation: Costs of reducing water use of concentrating solar power to sustainable levels: Scenarios for North Africa</td>
</tr>
</tbody>
</table>
Emerging risks and synergies for water needs in the global energy system
Curriculum vitae

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University of Vienna, Austria. Tutor for Economic Geography (2008)

Awards