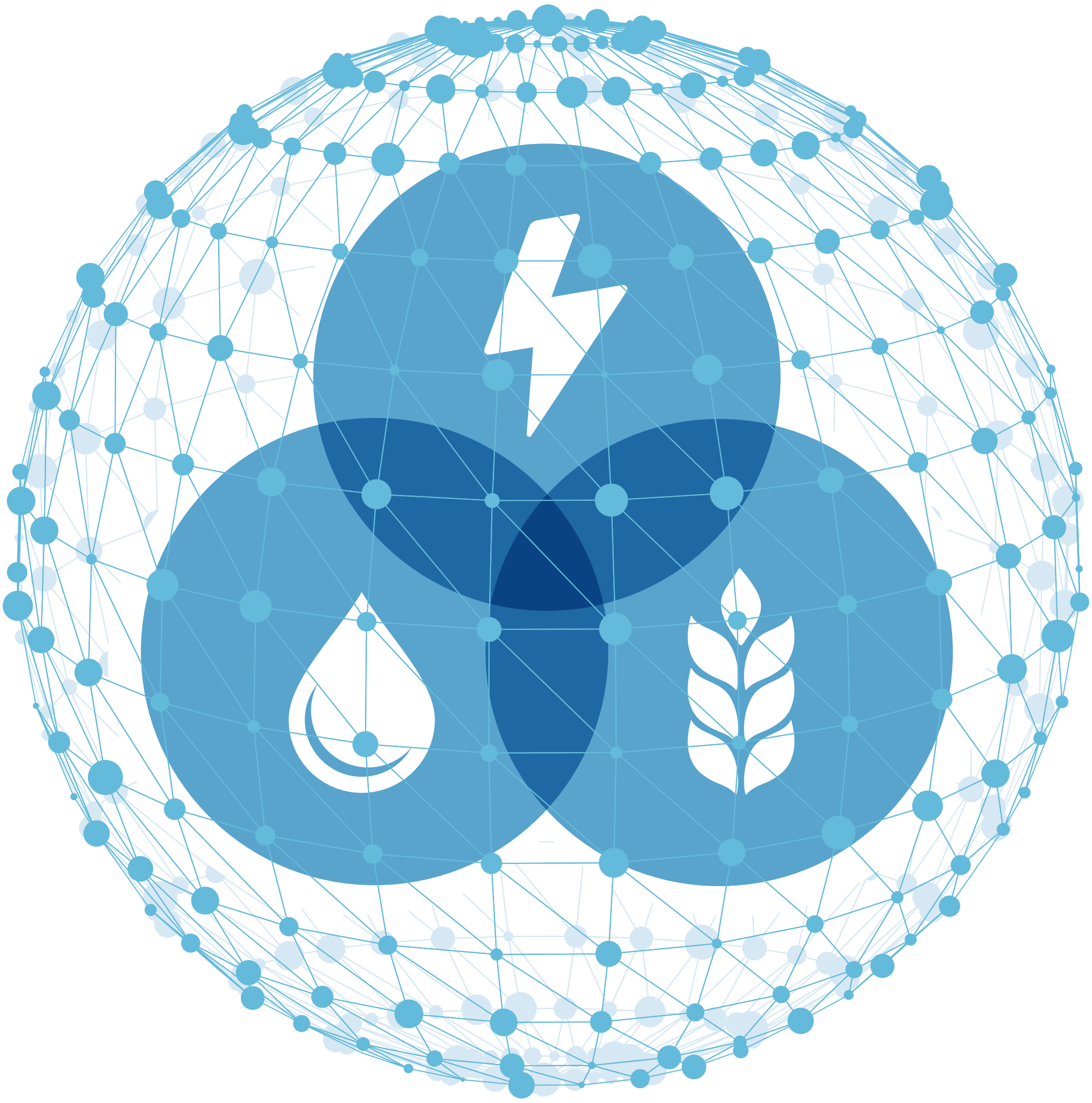
IRENA
International Renewable Energy Agency

RENEWABLE ENERGY IN THE WATER, ENERGY & FOOD NEXUS



JANUARY 2015

About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. www.irena.org

Acknowledgements

This report benefited from valuable comments by the following reviewers: Vaibhav Chaturvedi (Council on Energy, Environment and Water, India); Michele Ferenz (EastWest Institute); Olivier Dubois, Alessandro Flammini, Jippe Hoogeveen and Lucie Pluschke (FAO); Katja Albrecht, Detlef Klein, Jan-Christoph Kuntze, Gerhard Rappold, Ulrike von Schlippenbach (GIZ on behalf of the German Federal Ministry for Economic Cooperation and Development), Karl Moosmann (GIZ), Maria Weitz (GIZ); Jordan Macknick (National Renewable Energy Laboratory); Martin Hiller and Andreas Zahner (REEEP); Jeremy Foster (USAID); Anna Delgado, Diego J. Rodriguez and Antonia Sohns (World Bank); Manisha Gulati (WWF South Africa); Ghislaine Kieffer, Diala Hawila, Salvatore Vinci, Elizabeth Press, Deger Saygin, Linus Mofor, Nicholas Wagner, Henning Wuester, Olivier Lavagne d'Ortigue and Arturo Gianvenuti (IRENA). IRENA would like to acknowledge the contribution of Qatar Foundation to this publication.

Authors: Rabia Ferroukhi, Divyam Nagpal, Alvaro Lopez-Peña and Troy Hodges (IRENA); Rabi H. Mohtar, Bassel Daher, and Samia Mohtar (Texas A&M University); Martin Keulertz (Purdue University).

For further information or to provide feedback, please contact IRENA's policy unit, P.O. Box 236, Abu Dhabi, United Arab Emirates; Email: info@irena.org

RENEWABLE ENERGY IN THE WATER, ENERGY & FOOD NEXUS

FOREWORD

By 2050, global demand for energy will nearly double, while water and food demand is set to increase by over 50%. Meeting this surge of demand presents a tremendous challenge, given competing needs for limited resources amid heightened climate change effects. To overcome the increasing constraints the world faces, we need to fundamentally rethink how we produce and consume energy in relation to the water and food sectors.

Renewable energy technologies provide access to a cost-effective, secure and environmentally sustainable supply of energy. Their rapid growth can have substantial spill-over effects in the water and food sectors. Yet detailed knowledge on the role renewables can play in the nexus remains limited and widely dispersed.

Renewable Energy in the Water, Energy and Food Nexus aims to bridge this gap, providing the broad analysis that has been lacking on the interactions of renewables within those key sectors. Building on existing literature, the study examines both global and country-specific cases to highlight how renewable energy can address the trade-offs, helping to address the world's pressing water, energy and food challenges.

In the Gulf Cooperation Council countries, for example, realising renewable energy plans could reduce water withdrawals for power generation 20% by 2030, the report finds. Water withdrawals in the sector could decline by nearly half for the United Kingdom, more than a quarter for the United States, Germany and Australia, and over 10% for India by 2030 on the back of substantial deployment of renewables, particularly solar photovoltaic and wind power. In addition, renewable-based technologies can make water accessible for domestic and agricultural purposes, improving supply security while decoupling growth in water and food from fossil fuels.

Along different stages of the food supply chain, integrating renewables can improve productivity and reduce losses. The agrifood sector, meanwhile, can further bioenergy development, which, when managed sustainably and efficiently, can transform rural economies, enhance energy security, and contribute to environmental objectives.

I am confident this study will expand the available knowledge base and contribute to an increasingly vigorous global discourse on the challenges and opportunities of renewable energy in the nexus.

Adnan Z. Amin

Director-General
International Renewable Energy Agency

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

List of Boxes

LIST OF ACRONYMS

ATDER-BL	Asociación de Trabajadores de Desarrollo Rural–Benjamin Linder
BMZ	German Federal Ministry for Economic Cooperation and Development
Btu	British thermal unit
CC	Combined cycle
CCS	Carbon capture and storage
CO_2	Carbon dioxide
C-Si	Crystalline silicone
CSP	Concentrated solar power
CT	Combustion turbine
DNI	Direct normal irradiance
ED	Electrodialysis
EGS	Enhanced geothermal system
EJ	Exajoule
EPA	United States Environmental Protection Agency
EU	European Union
EWEA	European Wind Energy Association
FAO	Food and Agriculture Organization of the United Nations
gal	Gallon
GCC	Gulf Cooperation Council
GDP	Gross domestic product
GW	Gigawatt
GWh	Gigawatt-hour
GWth	Gigawatt-thermal
HIO	High-Impact Opportunity
IEA	International Energy Agency
IFPRI	International Food Policy Research Institute
IGCC	Integrated gasification combined cycle
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
IWD	Idyllwild Water District
IWRM	Integrated water resources management
km^2	Square kilometre
KTH	Kungliga Tekniska Högskolan (Royal Institute of Technology — Sweden)

kW	kilowatt
kWh	kilowatt-hour
LPG	Liquefied petroleum gas
m^3	cubic metre
MED	Multi-effect desalination
MENA	Middle East and North Africa
MSF	Multi-stage flash
Mtoe	Million tonnes of oil equivalent
MVC	Mechanical vapour compression
MW	Megawatt
MWh	Megawatt-hour
NPS	IEA New Policies Scenario
NREL	National Renewable Energy Laboratory
OECD	Organisation for Economic Co-operation and Development
OFID	OPEC Fund for International Development
PC	Pulverised coal, sub-critical
PJ	Petajoule
p.u.	Per unit
PV	Photovoltaic
REEEP	Renewable Energy and Energy Efficiency Partnership
RO	Reverse osmosis
RSP	Regional Solar Programme
SE4ALL	United Nations' Sustainable Energy for All initiative
TFC	Total final consumption
TPES	Total primary energy supply
TVC	Thermal vapour compression
TWh	Terawatt-hour
UAE	United Arab Emirates
UN	United Nations
UNCSD	United Nations Conference on Sustainable Development
UNECE	United Nations Economic Commission for Europe
USAID	United States Agency for International Development
USD	United States dollars
VCMWD	Valley Center Municipal Water District
WEF	World Economic Forum

EXECUTIVE SUMMARY

RENEWABLE ENERGY TECHNOLOGIES OFFER SUBSTANTIAL OPPORTUNITIES IN THE WATER, ENERGY AND FOOD NEXUS

The interlinkage between the water, energy and food supply systems - the *nexus* - is a major consideration in countries' sustainable development strategies. Rapid economic growth, expanding populations and increasing prosperity are driving up demand for energy, water and food, especially in developing countries. By 2050, the demand for energy will nearly double globally, with water and food demand estimated to increase by over 50%. The ability of existing water, energy and food systems to meet this growing demand, meanwhile, is constrained given the competing needs for limited resources. The challenge of meeting growing demand is further compounded by climate change impacts. From the rice fields in India to desalination plants in the Middle East, and nuclear power plants in France, the nexus is already posing a significant challenge for improving water, energy and food security, a concern for policy-makers today.

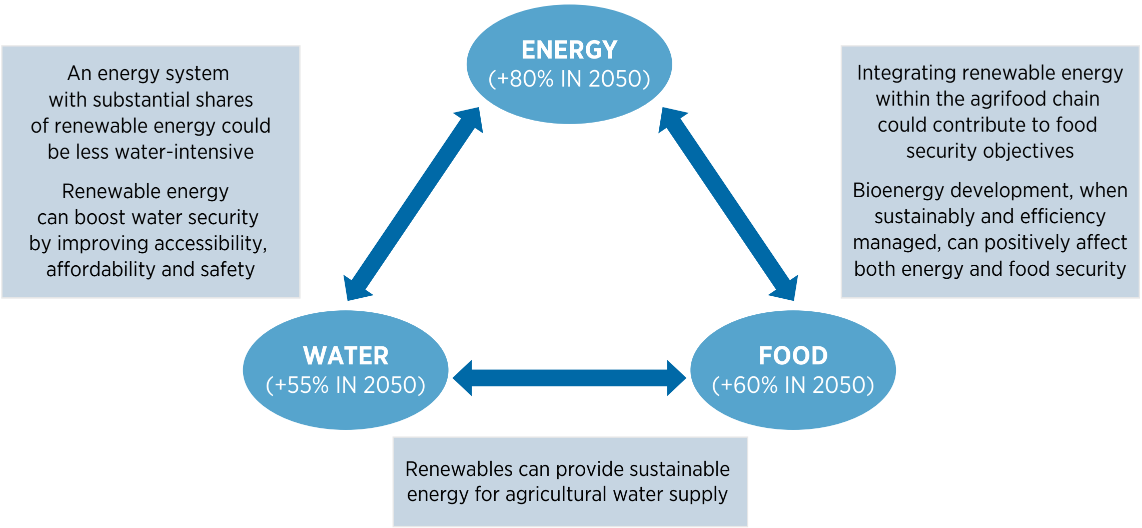
The nexus affects the extent to which water, energy and food security objectives can be simultaneously achieved. Water is required for extracting and processing fossil fuels as well as for generating electricity from various sources. Energy supply presently accounts for nearly 15% of global freshwater withdrawals annually. As a consequence, the availability and accessibility of water resources for fuel extraction, processing and power generation represent a key determinant for energy security. Conversely, disruptions in the provision of energy services, which are essential for water treatment, production and distribution, also have direct implications for water security. Vulnerabilities in water and energy supply also pose critical risks for food security, as severe droughts and fluctuations in energy prices can affect the availability, affordability, accessibility and utilisation of food over time. The agri-food supply chain accounts for 30% of the world's energy consumption and is the largest consumer of water resources, accounting for approximately 70% of all freshwater use. Such interlinkages are compelling governments, the private sector, communities, academia and other stakeholders to explore integrated solutions to ease the pressures and formulate development pathways based on sustainable and efficient use of limited resources.

Renewable energy technologies could address some of the trade-offs between water, energy and food, bringing substantial benefits in all three sectors. They can allay competition by providing energy services using less resource-intensive processes and technologies, compared to conventional energy technologies. The distributed nature of many renewable energy technologies also means that they can offer integrated solutions for expanding access to sustainable energy while simultaneously enhancing security of supply across the three sectors. This report analyses the key opportunities that renewable energy offers, specifically to address the key challenges posed by the water, energy and food nexus (see figure E 1).

LOOKING FORWARD, AN ENERGY SYSTEM WITH SUBSTANTIAL SHARES OF RENEWABLE ENERGY COULD BE LESS WATER-INTENSIVE

Across their life cycle, some renewable energy technologies are less water intensive than conventional options. Renewable energy resources such as solar, wind and tidal are readily available and do not require fuel processing and associated water inputs. Bioenergy, however, could necessitate substantial water inputs depending on feedstock production. Residue-based bioenergy requires relatively less water compared to dedicated energy crops — whose water consumption in turn depends on whether irrigation is necessary and, if so, on the irrigation method adopted, the crop type, local climatic conditions and technology choices.

Figure E 1 Renewable energy opportunities in the water, energy and food nexus



During the power generation stage, water needs for solar photovoltaics (PV) and wind are negligible compared to conventional thermoelectric generation where substantial quantities of water are needed for cooling. During this stage, solar PV or wind could withdraw up to 200 times less water than a coal power plant to produce the same amount of electricity. Geothermal and concentrating solar power (CSP) have higher water needs for operation. Recent projects have shown that application of dry cooling systems in CSP plants, as well as in conventional power technologies, can reduce the water use substantially. Water consumption in hydropower generation occurs primarily due to evaporation from holding reservoirs. Where water is held in reservoirs, it could be used for multiple purposes with different upstream and downstream effects. Depending on the context, attributing water consumption entirely to electricity generation may not be accurate.

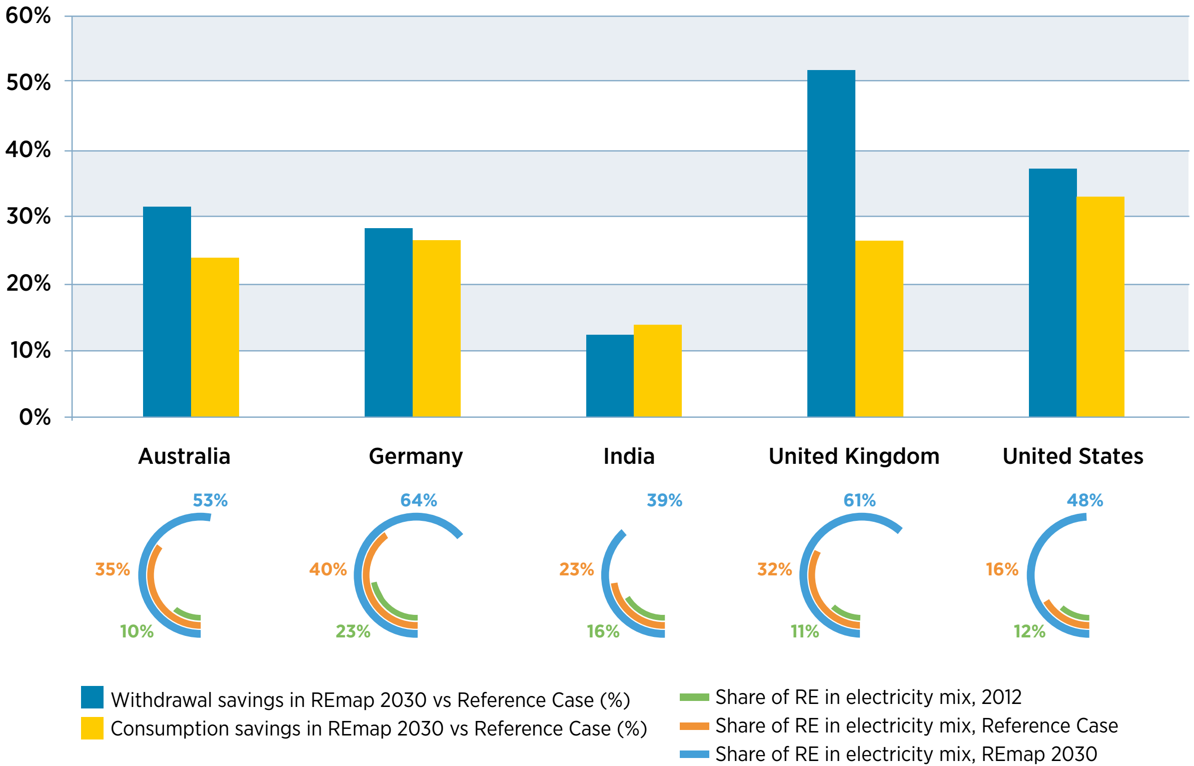
Evidence of water savings from renewable energy deployment to date have been limited to specific technologies and countries/regions. The American Wind Energy Association, for instance, estimates that during 2013 electricity from wind energy in the United States avoided the consumption of more than 130 billion litres of water, equivalent to the annual water consumption of over 320 000 U.S. households. The European Wind Energy Association found that wind energy in the European Union (EU) avoided the use of 387 billion litres of water in 2012 – equivalent to the average annual water use of 3 million EU households.

At an energy-system level, increasing the share of renewable energy can reduce water use substantially. This report conducts a preliminary analysis on select REmap 2030[1] countries (the United Kingdom, the United States, Germany, Australia and India) and finds that increasing renewables penetration leads to a substantial reduction in water consumption and withdrawal in the power sector. On the back of a substantial scale-up in renewable energy deployment, in particular solar PV and wind, water withdrawals in 2030 could decline by nearly half for the United Kingdom, by more than a quarter for the United States, Germany and Australia, and over ten per cent in India (see figure E 2).

Global and regional estimations also showcase a positive impact of increased renewables deployment on water demand in the energy sector. In its *World Energy Outlook 2012*, the International Energy Agency concluded that energy sector scenarios with higher shares of renewable energy require much less water.

[1] *IRENA's REmap 2030 is a roadmap to double the share of renewable energy by 2030 – an objective within the UN's Sustainable Energy for All initiative. REmap analysis presently covers 75% of projected global total final energy consumption in 2030 by analysing 26 countries. Further details are available at www.irena.org/remap.*

Figure E 2 Percentage reduction in water consumption and withdrawal between Reference Case (business as usual) and REmap 2030 (increased renewable energy uptake)



Source: IRENA analysis; Share in 2012 electricity mix from IEA, 2014a.

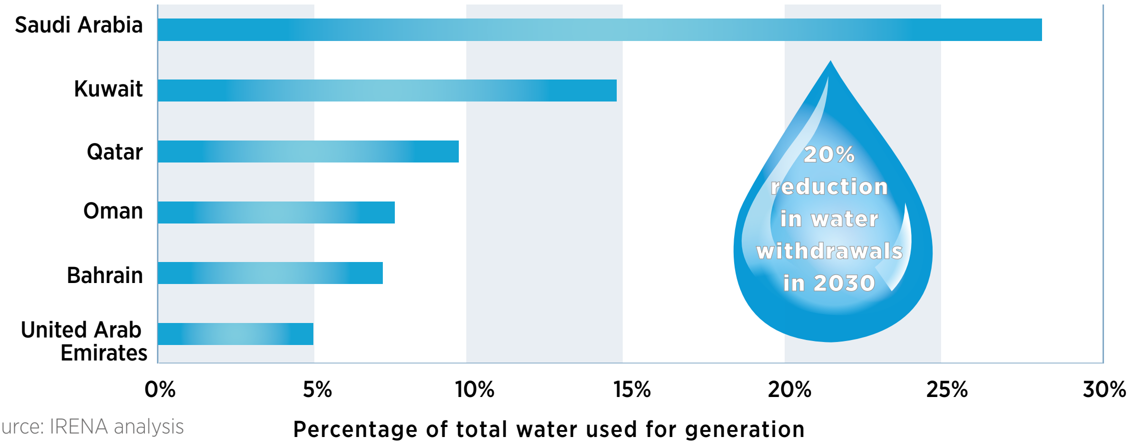
Water withdrawals under the most aggressive low-carbon pathway (the 450 Scenario) will be 4% higher in 2035 than in 2010, compared to 20% higher in the New Policies Scenario and 35% in the Current Policies Scenario. The present report estimates that, at a regional level, realising the renewable energy plans for the Gulf Cooperation Council region (GCC) will result in a 20% reduction in water withdrawal for power generation and associated fuel extraction (see figure E 3). Analysis shows that most of this reduction will come from the largest economy in the region, Saudi Arabia, due to its heavy reliance on crude oil for electricity generation and its ambitious renewable energy plans.

RENEWABLE ENERGY TECHNOLOGIES CAN BOOST WATER SECURITY BY IMPROVING ACCESSIBILITY, AFFORDABILITY AND SAFETY

Renewable energy can provide access to sustainable, secure and cost-competitive energy along different segments of the water supply chain, thereby reducing pressure on existing energy infrastructure. With increasing water scarcity, moving larger volumes of water across longer distances will mean that the hydraulic infrastructure will require substantially more energy inputs, causing an increase in the energy intensity of water provision. Renewable energy is seen as a reliable alternative to meeting growing energy demand for water pumping and conveyance, desalination and heating, while ensuring the long-term reliability of water supply.

Solar-based pumping solutions offer a cost-effective alternative to grid- or diesel-based irrigation pumpsets. Large-scale deployment of solar pumps can support the expansion of irrigation, reduce dependence on grid electricity or fossil fuel supply, mitigate local environmental impacts and reduce government subsidy burdens. Recognising these benefits, several countries have launched programmes to promote solar pumping. India, for example, has announced plans to replace 26 million groundwater pumps for irrigation with solar pumps. Should 5 million diesel pumpsets be replaced with solar systems in India,

Figure E 3 Potential for reduction in water withdrawals for power generation in GCC region by 2030



Source: IRENA analysis

this could lead to savings of nearly 18.7 gigawatts (GW) worth of installed capacity, 23.3 terawatt-hours electricity, 10 billion litres of diesel and 26 million tonnes of carbon dioxide (CO_2) emissions. Despite the compelling case, large-scale adoption of solar-based water pumps is still hindered by a variety of factors, including relatively high capital costs, inertia in the adoption of new technologies, establishing markets for the technology, and ensuring adequate training for installers and operators. Risks are also associated with excessive water withdrawal, since operational costs of PV pumps are negligible.

Water utilities are looking increasingly to distributed renewable energy solutions to improve energy efficiency and the resilience of supply networks. Because energy costs often account for the largest share of a water utility's operating budget (as much as 55%), reliance on expensive or volatile energy sources introduces operational risks. To address this, several utilities are introducing renewable energy solutions along different stages of the supply chain. The Valley Center Municipal Water District in the United States, for example, installed a 1.1 megawatt (MW) solar power system that provides 2.1 gigawatt-hours (GWh) per year, offsetting up to 20% of the electricity required by the utility's largest pumping station. In South Africa, eThekwini Water and Sanitation is seeking to identify tangible and profitable opportunities to install mini-hydro plants ranging from 100 kilowatts (kW) to 1 MW on the existing water supply infrastructure in order to improve system efficiency.

Renewable energy-based desalination technologies could play an increasing role in bridging the water gap. In the Middle East and North Africa (MENA) region, one of the most water-scarce regions in the world, water shortages by 2050 will be met mostly through desalination. More specifically, the Gulf region already relies on fossil fuel-based, energy-intensive desalination to meet its water needs. However, continued dependence on fossil fuels for water production is not sustainable from an economic and environmental perspective. Renewable energy technologies offer the opportunity to decouple water production from fossil fuel supply, and to cater to the heat or electricity needs of desalination plants. Recognising this opportunity, Saudi Arabia announced King Abdullah's Initiative for Solar Water Desalination in 2010, which aims to enhance the country's water security and contribute to the national economy by developing low-cost solar-based desalination technology. Although desalination based on renewable energy still may be relatively expensive, decreasing renewable energy costs, technology advances and increasing scale of deployment, make it a cost-effective and sustainable solution in the long term.

Increasingly, renewable energy technologies are replacing electricity or fossil fuel use for water and space heating. Although the cost of heat production depends on the technology deployed, as well as on the size and location of the installation, solar water heaters generally are competitive with electricity- and

Figure E 4 Examples of renewable energy applications along different segments of the agrifood chain

PRIMARY PRODUCTION	PROCESSING, POST-HARVEST AND STORAGE	DISTRIBUTION, RETAIL AND COOKING
840 GWh	**17** %	**2.7** billion
Energy generated in 2013 by farm-based anaerobic digestors in the United States, utilising agricultural crop residues, animal and food waste	National electricity generation from bagasse cogeneration in Mauritius saving an equivalent 375 000 tonnes of coal imports	Population relying on traditional biomass for cooking for whom modern renewable energy, such as biogas, present key opportunities

gas-based heating. In Europe, the most cost-effective solar thermal application is solar district heating in Denmark, where heat prices are as low as USD 43 per thermal megawatt-hour (MWh_{th}). In China, solar water heaters cost an estimated 3.5 times less than electric water heaters and 2.6 times less than gas heaters over the system lifetime. Globally, solar water heating technologies already have realised substantial energy and emissions savings. In 2012, gross solar thermal energy savings amounted to 284.7 terawatt-hours (TWh) or 24.5 million tonnes of oil equivalent (Mtoe), which is comparable to Bangladesh's primary energy consumption in 2013.

INTEGRATING RENEWABLE ENERGY WITHIN THE AGRIFOOD CHAIN COULD CONTRIBUTE TO FOOD SECURITY OBJECTIVES

Renewable energy can decouple segments of the agri-food supply chain from fossil fuel use. Increased farm mechanisation and expansion in irrigated land, fertiliser production, food processing and transport mean that the agri-food sector has emerged as a significant energy consumer. Going forward, it is clear that energy will be a fundamental input to ensure universal food security. These energy inputs, however, need to be decoupled from fossil fuel use to overcome cost volatility, minimise energy security risks and reduce greenhouse gas emissions, all of which could hamper global efforts to meet the growing demand for food. In this context, the Food and Agriculture Organization of the United Nations, in its Energy Smart Food Programme, proposes a three-pronged approach: improving access to modern energy services, enhancing energy efficiency and a gradual increase in the use of renewable energy.

Renewable energy technologies can provide access to locally available and secure energy along the different stages of the agri-food supply chain (see figure E 4). Renewable energy can be used either directly to provide energy on-site or indirectly as centralised energy supply. On-site renewable energy resources can improve access to modern energy and substitute fossil fuels for the provision of heat, electricity or transportation services within the agri-food sector. In the United States, for example, nearly 840 gigawatt-hours (GWh) equivalent of energy was generated in 2013 by anaerobic digesters placed on farms, which utilise a wide range of agricultural crop residues, animal and food wastes to generate usable energy on-site in the form of electricity or boiler fuel for space or water heating. This could positively affect economic development, bringing co-benefits to farmers, landowners, businesses and communities across all major segments of the agri-food chain. In this manner, renewable energy can enable an integrated food–energy system approach that links food production and natural resource management with poverty reduction in food value chains.

Using renewable energy in post-harvest processing can reduce losses and enhance the sustainability and competitiveness of the industry. One-third of food produced is lost or wasted globally, which also represents a waste of resources used in production such as water, energy and land inputs. Energy is required to preserve food, extend its availability over a longer period of time and reduce post-harvest losses. Food drying, in particular, stands out among other food preservation techniques because it can be performed using low-temperature thermal sources. It is applicable to many different food types (including fruits and vegetables), and the dried food that is produced is light weight, easily stored and transported, and has an extended shelf life.

In Iceland, geothermal energy is used to dry thousands of tonnes of cod heads that are exported to Nigeria. Processing plants also can use biomass by-products for heat and power cogeneration. In India, majority of wet bagasse (a byproduct of sugar mills) is re-used within plants to meet on-site requirements of power and steam. Today, nearly 2.7 GW of bagasse cogeneration capacity has been deployed nationally. Similarly, in Mauritius, bagasse cogeneration contributes to some 17% of national electricity production, saving an equivalent of 375 000 tonnes of coal imports and preventing 1.2 million tonnes of CO_2 emissions.

Substituting traditional biomass for cooking with modern fuels is imperative for social and economic development. Cooking is an energy-intensive activity, especially in developing countries where inefficient cooking practices are commonplace. Around 2.7 billion people rely for cooking on traditional biomass, such as fuelwood, crop residues and animal dung, which are not always sustainably produced and lead to smoke and other emissions that can be detrimental to health. Moreover, traditional biomass is often foraged, which demands considerable labour and time, particularly affecting women. Local modern bioenergy resources, where available, can be used to improve access to modern energy services while also meeting on-site energy demand for electricity and heating in the rural economies.

BIOENERGY DEVELOPMENT, WHEN SUSTAINABLY AND EFFICIENCY MANAGED, CAN POSITIVELY AFFECT BOTH ENERGY AND FOOD SECURITY

Modern bioenergy could play an important role in the ongoing transformation of the energy sector. It has diverse applications across all end-use sectors to provide energy services ranging from electricity, heating and cooling, and transportation fuels. IRENA's REmap 2030 analysis highlights that by 2030, modern biomass demand could double. At present, the majority of bioenergy consumption is for traditional uses in cooking and heating.

Bioenergy can provide a localised solution to transform rural economies while enhancing energy and food security. When managed sustainably and efficiently, bioenergy development could create new markets and generate employment opportunities that could positively affect incomes and poverty reduction, while also contributing to environmental objectives. This transformative potential of bioenergy can be tapped only when a holistic view of social, economic and environmental viability is adopted. The impacts of bioenergy, and specifically biofuels, on food prices, economic growth, energy security, deforestation, land use and climate change are complex and multi-faceted. In general, experience has shown that energy produced from biomass can contribute to food security as long as it is sustainably produced and managed. The production of bioenergy in integrated food–energy systems is one such approach. Intercropping *Gliricidia* (a fast-growing, nitrogen-fixing leguminous tree) with maize in Malawi or with coconut in Sri Lanka is substantially improving yields of agricultural products while also providing sustainable bioenergy feedstock. Such an integrated food-energy industry can enhance food production and nutrition security, improve livelihoods, conserve the environment and advance economic growth.

Land uses for energy and food production are closely related, and can be made compatible. The production of bioenergy feedstock, in particular energy crops, may require arable land, thereby raising the risk of competition for land resources. This conflict can be addressed by improving land-use efficiency by increasing yields, setting the right incentive frameworks, promoting integrated food–energy systems, assessing the use of abandoned or degraded land suitable for certain bioenergy crops, and using non-competing agricultural waste streams and residues as feedstock. Beyond bioenergy, the direct linkages between land for agriculture and energy production become less intense. Energy production technologies have varying land intensities and affect the quality of land differently. It is therefore important to consider both quantitative (*e.g.*, installed capacity per square metre) and qualitative aspects (*e.g.*, duration of impact, changes to quality of land), across the entire life cycle – fuel extraction and processing, installation, production and decommissioning. With technology advancements and efficiency improvements, the land intensity of different power generation technologies reduces, thereby presenting opportunities for repowering existing plants, deploying more capacity with less land. In general, ground-mounted solar PV, when deployed in areas with high insolation, could transform less land than coal coupled with surface mining. Hydropower, however, may have a substantial land footprint where reservoirs need to be developed. Onshore wind land use is higher when the total area of the farm is considered; however, the majority of the land can be suitable for other uses.

Solar and onshore wind technologies offer opportunities for mixed, multipurpose land use. Increasingly, solar PV and onshore wind projects are being developed on land that supports other industries. In Japan, the concept of co-production of food and energy (known as "solar sharing") was first developed in 2004. Special structures are being deployed involving rows of PV panels mounted above ground and arranged at certain intervals to allow enough sunlight for photosynthesis and space for agricultural machinery. Similarly, the areas around solar PV and onshore wind plants are being used for farming and grazing activities, allowing farmers to diversify their income sources. Solar PV is now also being considered for deployment atop canals to minimise allocation of new land resources while at the same time reducing evaporative losses of water. In India, a 1 MW solar plant was developed over a 750 metre stretch of a canal system, producing 1.53 GWh of electricity annually and saving 9 million litres of water from evaporation every day. Covering 10% of the 19 000 kilometre canal network with solar panels could potentially conserve 4 400 hectares and save about 20 billion litres of water every year.

QUANTITATIVE TOOLS HELP TO ASSESS TRADE-OFFS AND SUPPORT NEXUS-ORIENTED DECISION-MAKING IN THE ENERGY SECTOR

Traditionally, policy making has been confined to respective sectors with limited consideration of the influence that one sector could have on another. Lack of coordination between sectors can be attributed to existing institutional arrangements (*e.g.*, separate ministries) as well as the level of decision making (*e.g.*, energy sector decisions may be more centralised than water, which may have a substantial local dimension). A fully integrated approach to resource planning, in line with the concept of integrated resource management, would be desirable to better manage the nexus, but can be a challenging endeavour. A useful starting point could be to analyse how the decisions taken for one specific resource affect the others. From an energy sector perspective, this would imply understanding the implications of policy decisions on water and food sectors.

Analytical frameworks could play a crucial role in assessing the impacts of policies on different sectors. Such frameworks could help inform policy making by quantifying the trade-offs between the resources and providing a sound framework through which potential, and sometimes unexpected, nexus-related risks could be identified and mitigated in a timely manner. Moreover, they could also help identify context-specific integrated solutions that allow the three sectors to expand without compromising long-term sustainability. There are several tools available to support nexus-oriented policy making. These vary in comprehensiveness, scope, questions addressed and outputs they provide.

This report reviewed selected nexus tools resulting in three specific observations:

» Data availability and accessibility is a key challenge for a nexus assessment. The challenge is relevant for specific sectors (*e.g.*, data on water use or energy production) as well as across sectors (*e.g.*, data on water use *for* energy production). When data are available, they are scattered, have limited comparability with other data sets, cover different scales (*e.g.*, local, national, regional) or do not provide temporal trends.

» Most nexus tools are designed for a thorough analysis of the three sectors with a view to quantifying trade-offs, while considering the applicable resource constraints. Hence, such tools have significant data and resource needs, but can be highly effective in informing decision making that is sensitive to the nexus.

» Preliminary or rapid assessment tools are of increasing importance. Such tools, which could precede a more comprehensive analysis, are relatively less data and resource intensive, and can provide inputs within a timeframe that is in line with the policy-making process.

In this context, the report presents the conceptual framework of an energy-focused preliminary nexus tool that provides a snapshot view of the basic resource requirements (water, energy and land) for different energy mix scenarios. The results from such a tool could be used as inputs for a more comprehensive analysis that considers the applicable resource constraints as well as the quality and distribution of the impacts.

INTRODUCTION

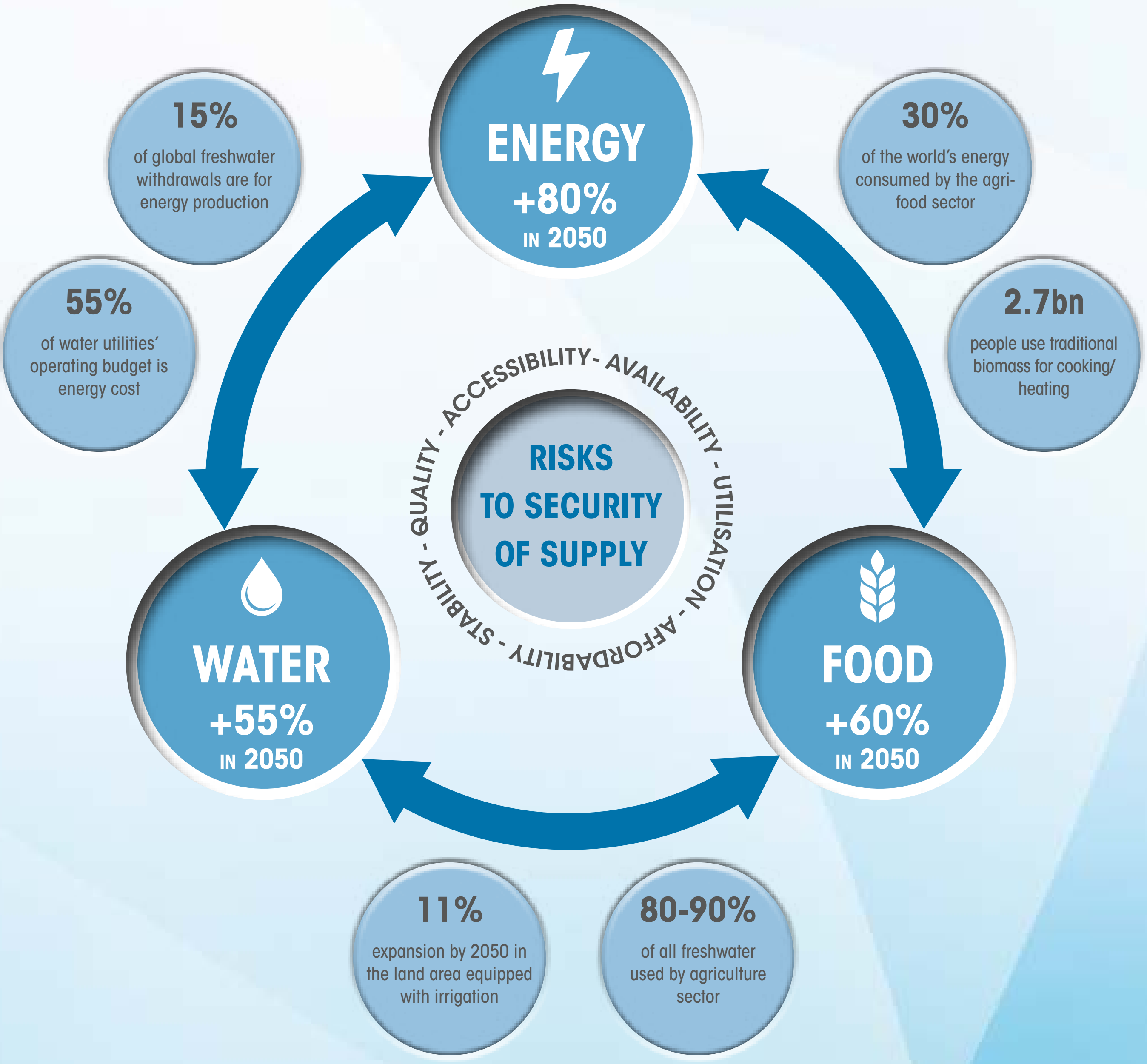
The water, energy and food nexus is at the centre of global policy, development and the research agenda. This focus is testament to the determinant role that the nexus will have in the efforts to meet rapidly growing demand for water, energy and food in an increasingly resource-constrained world.

Energy demand will nearly double, while water and food demand will grow by over 50%, between now and 2050. Rapid economic development, expanding global population and changing lifestyles are among the key drivers of this growth. Global population is projected to surpass 8.3 billion by 2030 (up from 6.8 billion today), with the middle class doubling. Also crucial are the efforts to improve lives of the 1.2 billion people without access to electricity, 783 million people without access to clean water and 842 million people who are undernourished.

Given the interlinkages between water, energy and food, meeting growing demand for resources is increasingly a challenge. An anticipated 35% rise in energy demand by 2035 could increase water consumption for energy by 85%. Similarly, water needs for agriculture, industrial and domestic purposes will rely increasingly on resources that are harder to reach and more energy intensive to exploit. Producing more food will require land, water and energy inputs, with potential trade-offs related to the expanding use of bioenergy. Resource constraints and trade-offs become even more pronounced at a national and local level. Climate change further adds to the challenge by introducing new uncertainties in accessing resources and making existing systems more vulnerable. Policy makers, therefore, need to identify integrated solutions that can address trade-offs and maximise security across all sectors.

Renewable energy technologies offer opportunities to address trade-offs and to leverage on synergies between sectors to enhance water, energy and food security. The changing patterns of energy demand combined with the desire for secure, accessible and environmentally sustainable supply options means that the energy sector is undergoing a transformation led by the rapid adoption of renewables. The United Nations' Sustainable Energy for All initiative lays out an aspirational target of doubling the share of renewable energy in the global energy mix by 2030. This transformation brings new opportunities for the energy, water and food sectors, while also presenting challenges that require adequate consideration. Yet evidence of the role of renewable energy within the water, energy and food nexus remains dispersed and limited, as does quantitative and qualitative knowledge on the impact of expanding renewables on these sectors.

The present report represents a starting point towards bridging the knowledge gap. It begins by briefly introducing the nexus in **chapter 1** and highlighting the risks posed by the interlinkages. It then explores the solutions available to address those risks and introduces the importance of integrated solutions, such as renewable energy technologies, to address the nexus challenge. **Chapter 2** focuses on the role of renewable energy in addressing the trade-offs and making existing energy, water and food supply chains more resilient. It adopts a supply-chain approach to identifying renewables interventions along different segments. The chapter also presents preliminary results from energy-system level quantitative analysis conducted to assess the impact of renewable energy on the sector's water footprint. Finally, **chapter 3** analyses the tools available to policy makers for assessing the role of renewables in the nexus and proposes the conceptual framework of a tool, with energy as the entry point, which intends to bridge identified gaps.



ENERGY
+80%
IN 2050

15%
of global freshwater withdrawals are for energy production

55%
of water utilities' operating budget is energy cost

30%
of the world's energy consumed by the agri-food sector

2.7bn
people use traditional biomass for cooking/heating

RISKS TO SECURITY OF SUPPLY

ACCESSIBILITY - AVAILABILITY - UTILISATION - AFFORDABILITY - STABILITY - QUALITY -

WATER
+55%
IN 2050

FOOD
+60%
IN 2050

11%
expansion by 2050 in the land area equipped with irrigation

80-90%
of all freshwater used by agriculture sector

1

THE WATER–ENERGY–FOOD NEXUS

Water, energy and food systems are closely interlinked. These interlinkages intensify as the demand for resources increases with population growth and changing consumption patterns. Meanwhile, major global trends – notably climate change and competing land-use patterns – restrict the ability of existing systems to meet the growing demand in a reliable and affordable manner. These dynamics pose substantial risks for the sustainable development and resource security ambitions of many governments, businesses and communities.

This chapter introduces the interlinkages between water, energy and food and discusses the implications of this nexus for the security of their respective sectors. It then focuses on the three dimensions that form the nexus: water and energy (section 1.2), water and food (section 1.3) and energy and food (section 1.4). Each section presents the sectoral risks and geographical relevance of the challenges. Section 1.5 identifies the opportunities for adopting integrated solutions for managing the water–energy–food nexus.

1.1 INTRODUCING THE WATER, ENERGY AND FOOD NEXUS

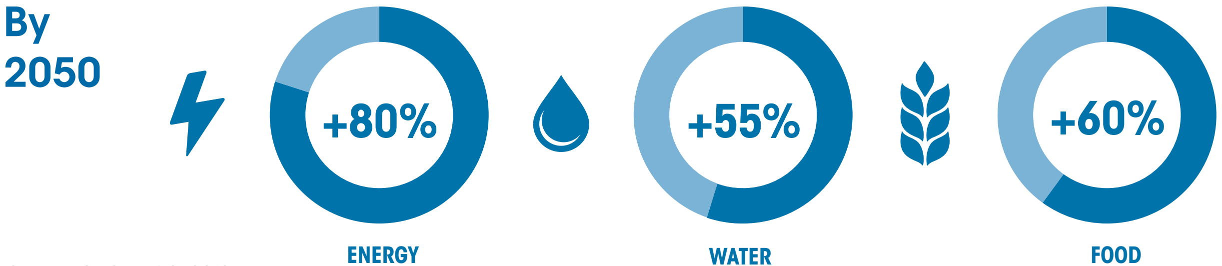
Rapid economic growth, expanding populations and increasing prosperity are driving up demand for energy, water and food. By 2050, the demand for energy will nearly double, and water and food demand is estimated to increase by over 50%.

Developing countries will account for the majority of growth in consumption over the coming decades, concentrated mostly in urban areas. In sub-Saharan Africa, for example, the share of urban dwellers is projected to increase from 37% of the total population in 2010 to nearly 60% in 2050 (OECD-FAO, 2012). Moreover, the drivers of global economic growth are increasingly the developing and emerging economies. This is driving up per capita incomes (still marginal relative to OECD countries), contributing to increasingly resource-intensive lifestyles of significant shares of the population and placing acute strains on resources in specific areas.

Access to resources has not been equitable, and a significant portion of the global population still lacks access to electricity (1.2 billion people), clean water (783 million people) and nutrition (842 million people suffer chronic hunger, according to FAO, 2013a). In addition to meeting growing demands from those who already have access, the water, energy and food systems will need to overcome this access deficit.

Meeting growing demand is becoming more challenging for the energy, water and food

Estimated increase in water, energy and food demand by 2050



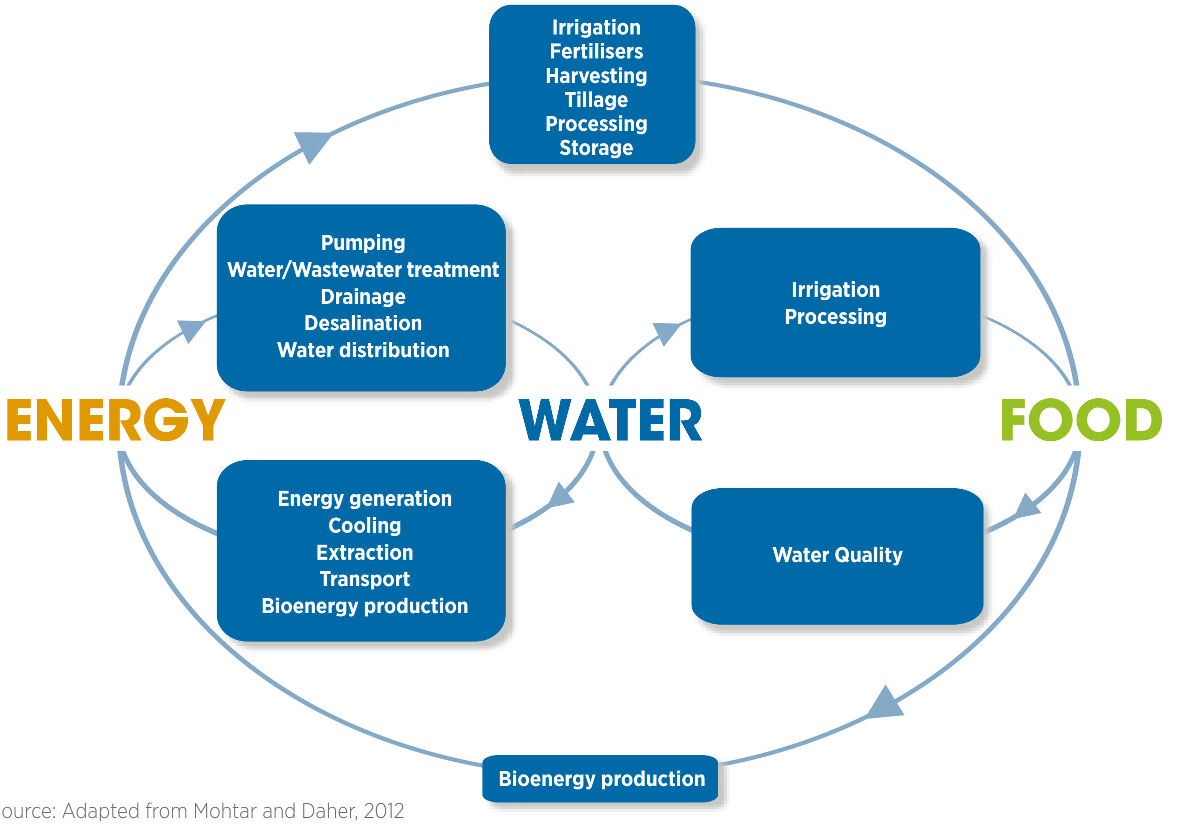
Source: OECD-FAO, 2012

sectors. Traditional growth in energy, water and food demand has been met predominantly by tapping further into fossil fuel, freshwater and land resources. These resources are limited in nature, and their extraction and use often have significant social and environmental impacts. Growing reliance on fossil fuel-based energy, for example, is raising environmental costs and further increases vulnerability to price volatility. Moreover, the intertwined nature of the water, energy and food systems means that competition for limited resources intensifies.

Water is required for extracting, processing and refining fossil fuels, as well as for generating electricity. At the same time, energy plays an important role in pumping, moving, distributing and treating water. In addition, energy and water are crucial inputs for food production, processing, transport and preparation. The agri-food chain accounts for around 30% of the world's energy consumption, and agriculture is the planet's largest consumer of water resources, accounting for 80-90% of all freshwater use (Hoff, 2011). Certain technology choices represent the nexus in particularly stark forms, such as reliance on energy-intensive water desalination, or production of biofuels triggering possible conflicts with food commodity prices. Figure 1.1 illustrates these interlinkages schematically.

The challenge of meeting growing demand for water, energy and food is further compounded by climate change impacts. Extreme weather events, such as intensified droughts and floods, could cause damage to food crops, electrical systems and water infrastructure. All aspects of food security are potentially affected by climate change, including food production, access, use and price stability (IPCC, 2014). Temperature increase in this century is expected to affect crop productivity negatively and significantly, with implications for food security (IPCC, 2007). Regarding water, climate change is projected to reduce renewable surface and groundwater resources in most dry subtropical regions, intensifying competition for water among sectors (IPCC, 2014). Already there is growing evidence of shifting precipitation

Figure 1.1 Schematic illustration of various elements of the water–energy–food nexus



Source: Adapted from Mohtar and Daher, 2012

WATER: WITHDRAWAL AND CONSUMPTION

Withdrawal is defined as the total amount of water taken from a source that may or may not be returned to that source. Consumption is that portion of water withdrawals that is not returned to the original source of water.

Source: Hoff, 2011

patterns that have impacts across all three sectors, affecting hydropower reserves and thermoelectric power plants, agricultural yields and natural replenishment of freshwater reserves (discussed later in the chapter). The impacts of climate change will vary regionally, potentially placing acute strains on delivering services in specific regions and requiring local-level understanding of climate-induced effects on the three sectors as well as the interconnections between them.

The interlinkages between the sectors can affect the extent to which three crucial policy objectives can be achieved: water security, energy security and food security[2] (WEF, 2011) (box 1.1). The interlinkages mean that pursuing security in one sector depends on the developments in other sectors. Energy security, for example, is threatened by the lack of available water resources for thermoelectric power, nuclear power and hydropower plants. Conversely, a disruption in energy supply can affect water security by negatively influencing water pumping, treatment and delivery. Limited water availability also poses critical threats to achieving food security, as severe droughts can catalyse food crisis, particularly in arid and infrastructure-poor areas. Security of drinking water supply of the local population can be threatened or cannot be achieved due to inappropriate prioritisation in water resource allocation.

A better understanding of the trade-offs and risks across the core nexus sectors can help assess the feasibility and impacts of resource allocation choices for energy, water and food security. Table 1.1 maps the risks posed by one sector on the security of the others. As highlighted in Box 1.1, several components, such as availability,

BOX 1.1

DEFINING WATER, ENERGY AND FOOD SECURITY

Water, energy and food security are variously defined. This study will use definitions as provided by international organisations working in water, energy and food because they have been discussed and agreed upon by a large number of stakeholders from the international development community:

The International Energy Agency defines energy security as: “the uninterrupted availability of energy sources at an affordable price” (IEA, n.d.). While there is no single definition of the concept of energy security, it has evolved from a narrow link to the stable supply of oil products to integrate other energy sources, as well as the essential dimension of sustainability.

A working definition of water security by the United Nations is stated as: “the capacity of a population to safeguard sustainable access to adequate quantities of and acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability” (UNU, 2013).

The Food and Agriculture Organization of the United Nations defines food security as existing “when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life” (FAO, 2002).

---

[2] *The concepts of water, energy and food security have been covered substantially in the literature. While there is no commonly regarded definition for each, Box 1.1 highlights the most recognised definitions.*

Table 1.1 Mapping risks posed by one sector on factors that contribute to security of other sectors

		Impacted sectors									
		WATER SECTOR			**ENERGY SECTOR**			**FOOD SECTOR**			
	Security Elements	**Access**	**Safety**	**Affordability**	**Continuity of energy supply relative to demand**	**Physical availability of supply**	**Supply sufficient to satisfy demand at a given price**	**Physical availability of food**	**Economic and physical access to food**	**Food utilisation**	**Stability of the other three dimensions over time**
Impacting sectors/resources	**WATER**	x	x	x	• Shifts in water availability (changing precipitation patterns) and quality (pollution or salinity) • Increasing energy demand for water production, treatment and distribution	Legal/regulatory restrictions on water use for energy production/fuel extraction	Shifts in water availability affecting traditional generation, requiring expensive back-up supply	Increased variability in water availability for food production, particularly due to climate change	Disruptions in global food supply due to regional water variability, given geographic concentration of food production and consumption	Impact of water quality on food production and consumption	Climate change impacts on availability of water resources in long term
	ENERGY	• Limited or unreliable access to energy necessary to extract, transport and treat water • Reallocation of water from other end-uses to energy • Management of dams for hydropower without considering needs of flood risk management	Contamination of water resources due to energy extraction and transformation processes	Fluctuating costs of water supply due to variability in prices of energy inputs (in cost-reflective markets)	x	x	x	• Disruption in energy inputs at production stage: mainly livestock (low risk), mechanised (high risk) • Potential trade-offs between bioenergy production and food crops	• Fossil fuel dependency of upstream and downstream (transport, storage, etc.) food supply chain • Allocation of agricultural products and agricultural land for bioenergy production (impact on food prices)	Social, environmental and health impacts of traditional biomass cooking methods	• Economic and physical volatility of energy inputs • Increasing wastage (lost productivity) due to limited energy access (*e.g.*, storage) • Increasing diversion of food crops for energy production
	FOOD	• Water resource over-utilisation impacts of food security ambitions • Poorly regulated agricultural foreign direct investments (*e.g.*, international land leasing)	Groundwater/surface run-off water contamination from food production and processing activities	Contamination and overexploitation lead to increase in water supply costs	Overall increase in food production and changing diets raises energy demand along the food supply chain	Lack of energy availability hinders food processing and irrigation	Variations in crop-based bioenergy feedstock prices.	x	x	x	x

Source: Based on IISD, 2013; World Bank, 2014; FAO, 2014b accessibility, reliability and utilisation, are used to ascertain water, energy and food security.

Water security elements – access, safety and affordability – are affected by the energy and food sectors (IISD, 2013). Access to water can be jeopardised if there is a limited or intermittent supply of electricity or liquid fuel for critical needs such as pumping, conveying and distributing water. It can also be limited due to competing uses of water for producing, distributing and processing food. The quality of water for consumption can be affected by other sectors as well. Extraction and processing of fossil fuels, such as oil sand extraction and hydraulic fracturing for natural gas and oil, are known to cause pollution of groundwater with hydrocarbons and heavy metals (Water in the West, 2013). The expansion of intensive agriculture practices, such as the use of chemical fertilisers and concentrated animal farming, has led to the pollution of groundwater and surface waters with nutrients and pesticides (FAO, 2008b). Lastly, volatile energy prices can alter the affordability of water supplies that are dependent on energy-intensive infrastructure.

Energy security components (in the narrow sense) – the continuity of energy supply relative to demand, the physical availability of supply, and affordability – all are affected by the water and food sectors. Achieving the key objective of any electricity system operator – meeting energy demand with reliable supply – is imperilled when decreased water flows or increased water temperatures limit production at thermal, nuclear or hydro power plants. Regardless of demand, physical energy supply can be limited when competing needs for water, such as agriculture and domestic use, place a limit on the amount of water that can be dedicated to fuel extraction and energy production. Further, these constraints and trade-offs with water availability can limit energy production and put price pressures on energy supply.

Energy and water supply and demand have an impact on food security elements: the physical availability of food, access (including affordability), utilisation (nutrient content and food safety) and the stability of these elements over time. The physical availability of food can be threatened when water is allocated for other competing needs, when irrigation infrastructure is inefficient, or when the energy supply is unreliable and unavailable to power mechanised farming and food processing practices. These same water and energy resource strains can affect economic affordability and access to food. Utilisation of food can be hampered by the use of contaminated water sources by households, or by shortages in cooking fuel, such as liquefied petroleum gas (LPG) or fuelwood. Lastly, factors such as the impact of climate change on water resources, and the effects of geo-politics and policies on energy sources and pricing, can hamper development goals that aim to achieve food security in the long run.

These risks and impacts are discussed in greater detail in the remainder of this chapter, covering the three key areas of nexus interdependence: water and energy (section 1.2), food and energy (section 1.3) and water and food (section 1.4). The chapter concludes with a discussion of solutions that are being adopted globally in different contexts to address these risks and challenges (section 1.5).

1.2 THE WATER–ENERGY NEXUS

Water and energy are critical resource inputs for economic growth. The correlation between economic growth and energy demand has been widely established (IEA, 2009). Meeting that energy demand, however, requires water. In most energy production processes, water is a key input: fossil fuel production requires water for extraction, transport and processing; thermoelectric generation based on nuclear, fossil fuels or CSP requires water for cooling; hydropower can be generated only if water is readily available in rivers or reservoirs; feedstock production for biofuels, such as ethanol, may depend on water for irrigation; and renewable energy resources such as solar require water for cooling and cleaning panels or collectors for improved efficiency (World Bank, 2013). The technology choice, source of water and fuel type determine the impacts of energy on the withdrawal, consumption and quality of water resources.

Conversely, energy inputs are spread across the supply chain of water. The supply chain for water starts with a source, then water is extracted (*e.g.*, pumping of groundwater), sometimes treated, and conveyed – moving directly to an end-use (*e.g.*, household, irrigation, commercial). Once used, the water is returned back to the environment through discharge – with or without treatment – or through evaporation. In some cases, treated water may be reused (Water in the West, 2013). Along each of these stages, energy inputs are necessary depending on the local conditions. This interaction between energy and water resources is the water–energy nexus (see figure 1.2).

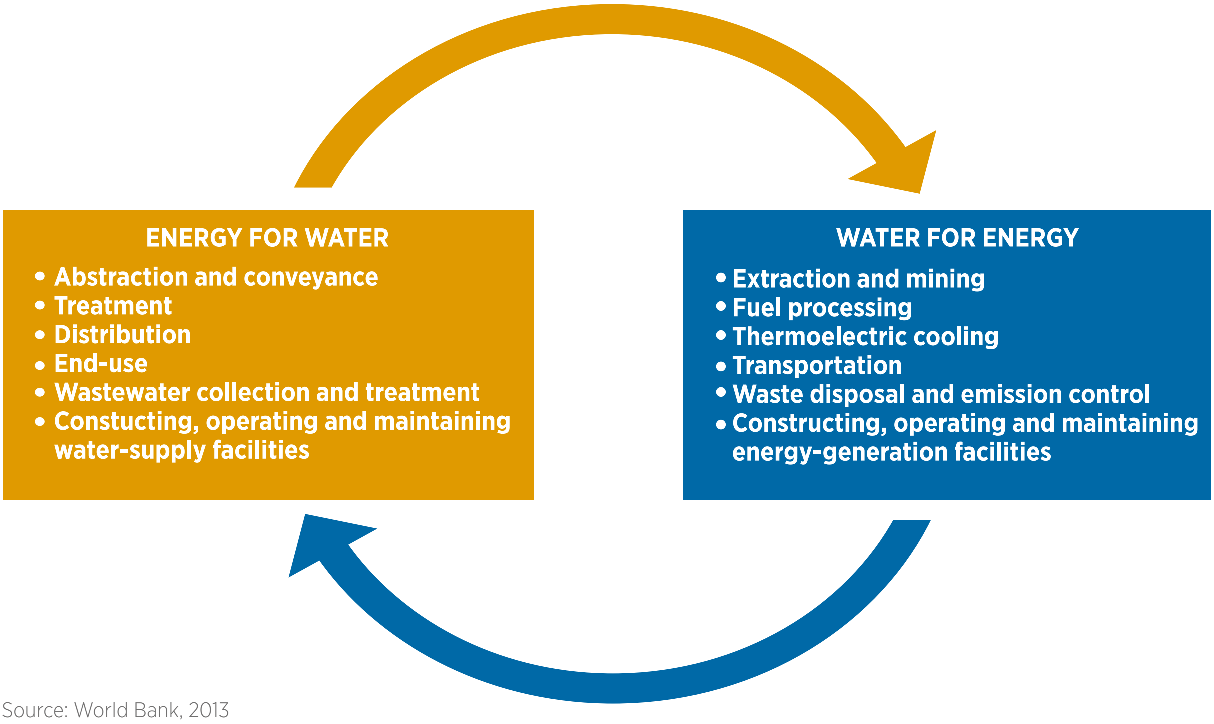
The water–energy nexus represents a critical security, business and environmental issue, which has been recognised increasingly in recent years. In a survey conducted by the Carbon Disclosure Project of 318 companies listed on the FTSE Global Equity Index Series (Global 500), 82% of energy companies and 73% of utilities said that water is a substantial risk to business operations, and 59% of energy companies and 67% of utilities had experienced water-related business impacts in the past five years (Carbon Disclosure Project, 2013). There is general recognition that the starting point of any effort to address the nexus is quantifying the interlinkages and understanding the trade-offs. The International Energy Agency (IEA) included a special section on water and energy in its 2012 World Energy Outlook for the first time in the organisation's history (IEA, 2012). Addressing the nexus, the World Bank established the "Thirsty Energy" initiative to help governments in developing countries tackle issues related to water resources and power services. Additionaly, in response to the growing importance of this nexus, water and energy was the theme of the World Water Day 2014 (UN Water, 2014a).

1.2.1 Quantifying the water–energy nexus

At present, energy production accounts for nearly 15% of global freshwater withdrawals – or 580 billion cubic metres (m^3) of water – every year (IEA, 2012). This includes water use during primary energy production and electricity generation. Of this water withdrawn, nearly 66 billion m^3, or 11%, is not returned to the source and therefore is deemed to be consumed (Lavelle and Grose, 2013).

The share of water withdrawn and consumed for energy significantly varies at the national level. In the United States, for instance, thermoelectric power generation accounts for nearly half of all freshwater withdrawn. In China, where coal continues to be the dominant fuel powering

Figure 1.2 Illustration of the water-energy nexus



Source: World Bank, 2013

economic growth, fresh water needed for mining, processing and consuming coal accounts for roughly 120 billion m^3 a year - the largest share of industrial water use, or a fifth of all water used nationally (Schneider, 2011). The most direct representation of water dependence for electricity production is hydropower generation. Nearly 16% of global electricity production is hydro-based, and hydropower is a major source of electricity in many countries, accounting for nearly 75% of total electricity generation in Brazil in 2012 for instance (REN21, 2014; IEA, 2014a).

Global energy demand is projected to increase 35% by 2035. Meeting this rising demand could increase water withdrawals in the energy sector by 20%, and water consumption in the sector by 85% (World Bank, 2013). China, India and the Middle East will account for most of the growth in energy needs to 2035; however, these are also among the countries with the lowest renewable water resources per capita, meaning that as the demand for energy grows, the strains on limited water resources could intensify.

Energy demand for water services is set to increase. Global data on energy use in extracting, producing, treating and delivering water remain limited. This is primarily because of large variations in the energy intensity of delivering water due to differences in water source (such as groundwater or surface freshwater), water quality (high-salinity seawater is the most energy intensive to treat and use) and the efficiency of water delivery systems. However, some national and regional estimates exist: in the United States, for example, water-related energy use accounts for 13% of total annual energy consumption (River Network, 2009; Sanders and Webber, 2013).

As easily accessible freshwater resources are depleted, the use of energy-intensive technologies, such as desalination or more powerful groundwater pumps, is expected to expand rapidly (World Bank, 2013; WEF, 2011; Hoff, 2011). The Middle East and North Africa (MENA) region, among the regions with the lowest renewable water resources in the world, is home to most of the world's desalination capacity, and the region's capacity is projected to increase more than five times by 2030. This will raise total electricity demand for desalination in the region by three times, to 122 Terawatt-hours (TWh) by 2030 (IRENA and IEA-ETSAP, 2012).

Significant energy is used to heat water for domestic and industry applications. This energy is derived either directly from the combustion of fuels, such as natural gas and fuel oil, or indirectly through electricity. In the latter case, the risks posed by the nexus become more pronounced because of the destabilising impact that increased heating demand can have on the electricity system. In South Africa, nearly 5% of domestic electricity demand comes from electric water heating systems. Even at that level of demand, measures were required to reduce demand from electric water heaters during peak times (see also discussion on solar water heaters in section 2.2.1).

The intensity of the water–energy nexus is a regional, national or sub-national characteristic, which depends on the energy mix, demand characteristics, resource availability and accessibility. For power production, for example, the choice of fuel and technologies holds significant impacts for the quantity of water required (World Bank, 2013; IEA, 2012; Lubega and Farid, 2014). Where water resources are limited, technologies that impose less strain on water resources may be preferable. Renewable energy technologies such as solar photovoltaics (PV) and wind consume little-to-no water during operation compared to fossil fuel-based plants that require large amounts of water during the different stages of energy production (see chapter 2 for a detailed discussion). The risks posed by the water–energy nexus affect all essential elements of water and energy security, as seen in table 1.2.

These risks confront not just governments, but any stakeholder engaging in activities that are affected directly or indirectly by the availability, accessibility and affordability of water or energy. Consequently, these risks and associated impacts manifest at different levels – regional, national and local – causing governments, communities and businesses to increasingly consider the nexus as a key variable affecting the socio-economic sustainability of their operations and long-term objectives.

The first step of the process of managing the water–energy nexus is to understand the entire spectrum of risks that are relevant for a specific country, business or community.

The intensity of each risk will vary depending on the local context, but system-level assessments covered in the literature highlight the following principal risks for water and energy security (summarised also in table 1.2).

1.2.2 Water-related risks to energy security

Water is a critical input for fuel extraction and processing as well as for power generation. The risks that the water sector presents to energy security have been studied widely (UN Water, 2014b; World Bank, 2013; WEF, 2011; IISD, 2013; Hoff, 2011) and can be summarised as follows:

a) Shifts in water availability and quality, resulting in reduced reliability of supply

Different stages of the energy supply chain are extremely sensitive to the availability and quality of the water they require. The ability of thermoelectric or hydropower plants to operate optimally relies in part on the characteristics of the input water, such as temperature, volume flow rates and density. Any deviations can translate into lower output or shutdown of plants. These deviations could be a result of unanticipated weather activity (*e.g.*, changes in precipitation patterns, extreme weather conditions, prolonged heat waves, etc.), re-allocation of water resources (*e.g.*, rising competing water demands for other uses such as agriculture,

Table 1.2 Summary of risks and impacts within the water–energy nexus

	RISKS	IMPACTS
Water-related risks to energy security	Shifts in water availability and quality due to natural or human-made reasons (including regulatory restrictions on water use for energy production/ fuel extraction)	• Reduced reliability of supply and reliance on more expensive forms of generation • Possibility of economic pricing of water and therefore higher costs of energy production • Reduced availability of water for fuel extraction and processing stages, leading to reduced outputs
	Increase in energy demand for water production, treatment and distribution	Strains on the energy system and reduced efficiencies given the different demand profiles for water and energy
Energy-related risks to water security	• Limited or unreliable access to affordable energy necessary to extract water • Re-allocation of water resources from other end-uses to energy	• Disruption in water supply to end-users or diversion of resources away from other core activities such as agriculture • Changes in delivery cost of water due to fluctuating costs of energy inputs
	Contamination of water resources due to energy extraction and transformation processes	Water resources, including for drinking purposes, rendered unsuitable due to contamination, often requiring additional treatment

manufacturing, drinking water, etc.) or regulations (*e.g.*, water pricing, regulatory caps or bans on water extraction and use for fuel processing). This causes the existing water-intensive energy system to operate sub-optimally and, in extreme cases, to switch to more expensive and environmentally unfriendly power generation options. Recent cases illustrating these risks include:

» Because of prolonged drought conditions, hydropower plants in the U.S. state of California generated less power in 2013 than in the previous 21 years. In a state with more than 300 hydropower plants, the share of hydro in the electricity mix dropped to 9% in 2013, compared to a 30-year average of 14% (Garthwaite, 2014). The reliability of the energy system was maintained in part through increased use of natural gas plants.

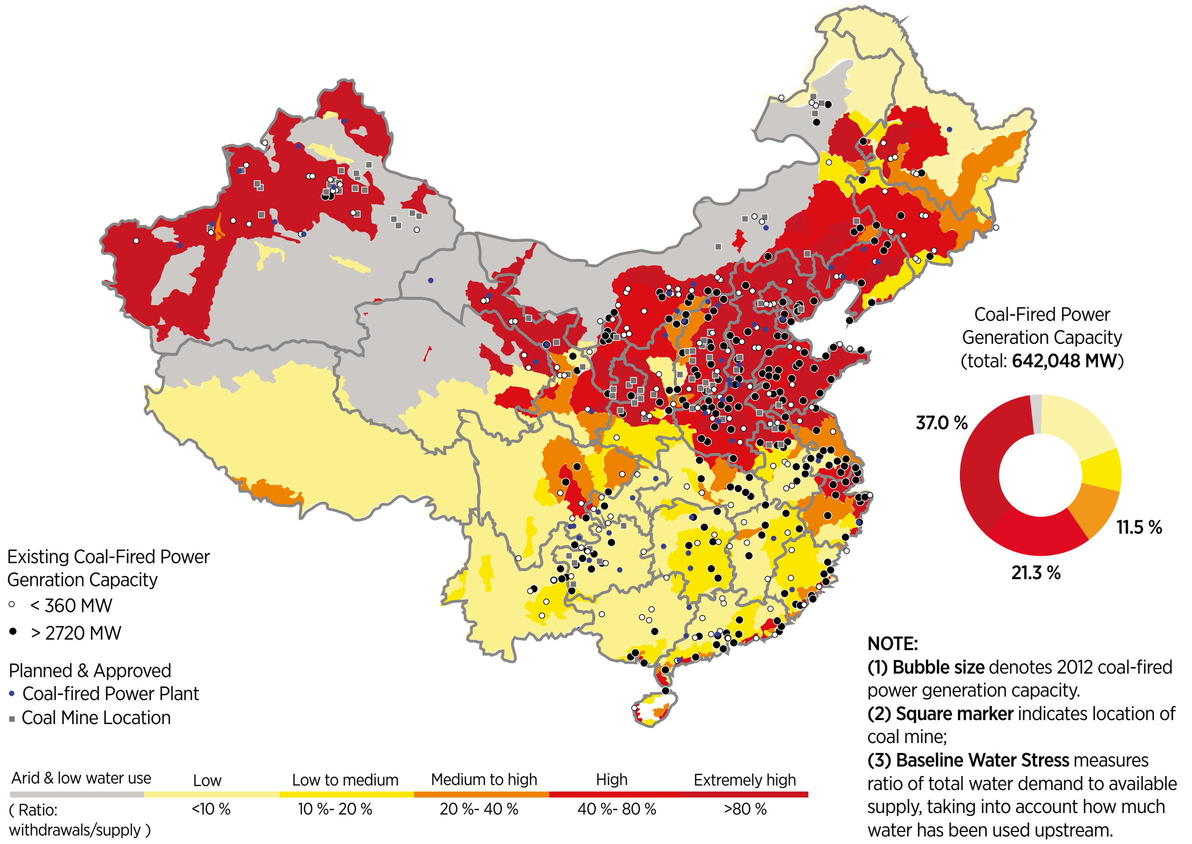
» In 2010-11, thermal power generation in India declined by nearly 4.4 TWh – enough electricity to power nearly 1.3 million Indian households for a year – due to acute water shortage (Central Electricity Authority (CEA), 2011).

» Half of China's proposed coal-fired power plants, which require significant water for cooling, are located in areas already affected by water stress, creating potential conflicts between power plant operators and other water users (see figure 1.3).

» The expansion of shale gas production is transforming several energy markets. As interest in exploring and exploiting shale resources rises, there is growing concern about the environmental impacts of hydraulic fracturing (or fracking), the process used to extract natural gas from shale deposits. These impacts range from the possibility of ground and surface water contamination to competition for water (a key input to the fracking process) with local uses. A recent study indicates that water availability could curtail shale development in many places around the world, as nearly 38%

Figure 1.3 Coal mining and water stress in China

2012 CHINA COAL MINING PRODUCTION AND COAL-FIRED POWER GENERATION VS BASELINE WATER STRESS



NOTE:
(1) Bubble size denotes 2012 coal-fired power generation capacity.
(2) Square marker indicates location of coal mine;
(3) Baseline Water Stress measures ratio of total water demand to available supply, taking into account how much water has been used upstream.

Source: WRI, 2013

of identified shale resources are in areas that are either arid or under high to extremely high levels of water stress (WRI, 2014).

Climate change aggravates these risks greatly, as it can lead to unanticipated disruptions in water availability and cause a gradual, yet significant, change in the quality of water available for cooling and extraction. There is ample evidence suggesting that one of the key impacts of climate change on the energy sector will be an increase in ambient temperatures, which can lead to reduced power operations or even temporary shutdown of power plants. Box 1.2 summarises the key risks that climate change poses to the energy sector.

b) Increase in energy demand for water production, treatment and distribution, with potentially destabilising impacts on the energy system

As demand for water grows and existing renewable water resources are exhausted, more energy-intensive means will need to be deployed. Water needs to be pumped from greater depths due to falling water acquifers and needs to be transported greater distances from centralised, often energy-intensive, water production infrastructure such as desalination plants. Greater impacts on the energy sector from water systems is forcing countries to rethink the archaic norms governing the planning of resource and infrastructure development. The experience of several countries attests to the destabilising impact that energy needs for water supply can have on the energy sector:

- In India, where nearly 20% of electricity generation capacity is used for agricultural water pumping (CEA, 2013), lower-than-usual rainfall accompanied by decreasing water tables is putting tremendous stress on the electricity system during peak seasons. The infamous failure of the Indian grid that affected nearly 670 million people (or 10% of the world's population) in 2012 was a consequence of the lack of rain during the South-West monsoon, which led farmers in North India to resort to excessive electricity-based water pumping (Central Electricity Regulatory Commission, 2012).
- Most of the global desalination capacity resides in the Gulf region. To meet growing power and water demands, natural gas-based cogeneration infrastructure is used for electrical power generation, with fresh water made available by using desalination technology. One of the primary drawbacks of cogeneration lies in differences in water and electricity demand profiles. Water demand has minimal seasonal variations, while electricity demand experiences significant variations on a day-to-day basis and seasonally. In cogeneration plant operation, optimising the supply of a relatively constant output of potable water while varying power output often leads to reduced efficiencies.

1.2.3 Energy-related risks to water security

Existing water systems are predominantly end-users of energy in the form of electricity, but many systems, particularly in developing countries, also rely on primary fuels such as diesel for extracting and delivering water. The availability and type of energy used can either enhance water security or pose risks to it. Further risks emerge from water contamination threats to both underground and surface freshwater resources. Some of the key risks identified in the literature and/or that have been of immediate relevance to communities, utilities and governments include:

a) Limited or unreliable access to affordable energy necessary to extract water

Making water available for a variety of end-uses requires different levels of treatment, depending on the water source. This also has implications for how much and where energy is required. Pumping groundwater for irrigation purposes, for example, requires no treatment; energy needs therefore are lower compared to, say, desalination, which uses substantial amounts of energy to pump and treat seawater or brackish water.

Figure 1.5 provides an overview of the energy required to provide 1 cubic metre or 1 000 litres of water safe for human consumption from various sources (UN Water, 2014b). This energy comes either from fuels directly, such as diesel, or through electricity supply, but in any case can represent nearly 25-30% of a utility's operation and maintenance costs (UN Water, 2014b; EPA, n.d.). Any disruptions in energy supply therefore can affect the availability of water immensely. Water systems dominated by fossil fuel-based energy

BOX 1.2

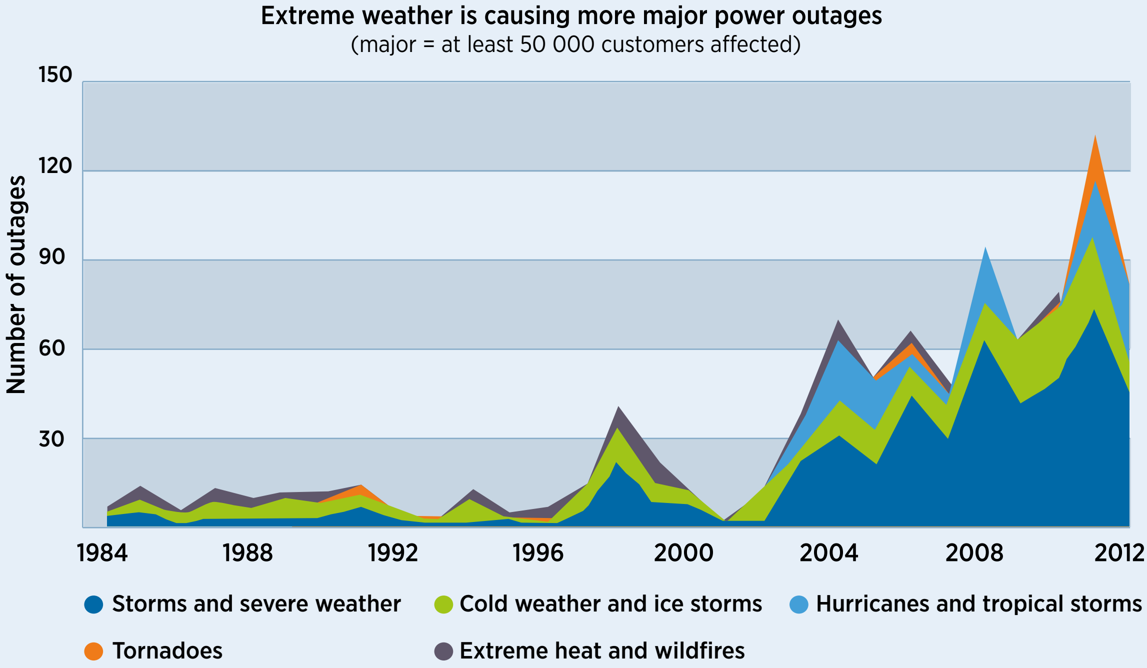
CLIMATE CHANGE IMPACTS ON THE ENERGY SECTOR

Energy supply and reliability are affected by the direct physical impacts of climate change, such as rising temperatures, decreasing water availability and increasing frequency and intensity of storms, droughts and heat waves (King and Gulledge, 2013). These climate trends pose current and future threats to the energy sector in the following areas:

- Elevated water and air temperatures reduce the efficiency of power plant generation and pose risks for power plant operators of exceeding regulations on thermal pollution released to receiving water bodies. Electricity transmission is less efficient with higher air temperatures, weakening the capacity of grid infrastructure.
- Climate change is projected to decrease water availability in many semi-arid and arid regions (IPCC, 2008), with shifting rainfall patterns and intensified droughts threatening water resources necessary for different inputs of energy supply. Thermoelectric power generation, oil and gas production, and renewables such as hydropower and bioenergy are vulnerable to reduced production due to water-dependent processes (DOE, 2013).
- Extreme weather events are a current and growing threat to energy security. In the United States, weather caused 80% of all outages from 2003 to 2012, affecting around 15 million customers each year (Climate Central, 2014). Over this period, the frequency of major blackouts doubled (see figure 1.4).
- Increasingly numerous and intense floods in areas close to energy plants can cause severe harm to power production and energy delivery infrastructure, and can result in more frequent blackouts in regions where power plants are constructed close to surface water resources. In addition, fuel transport by rail and barge faces increased delays and interruption due to flooding of transport routes.

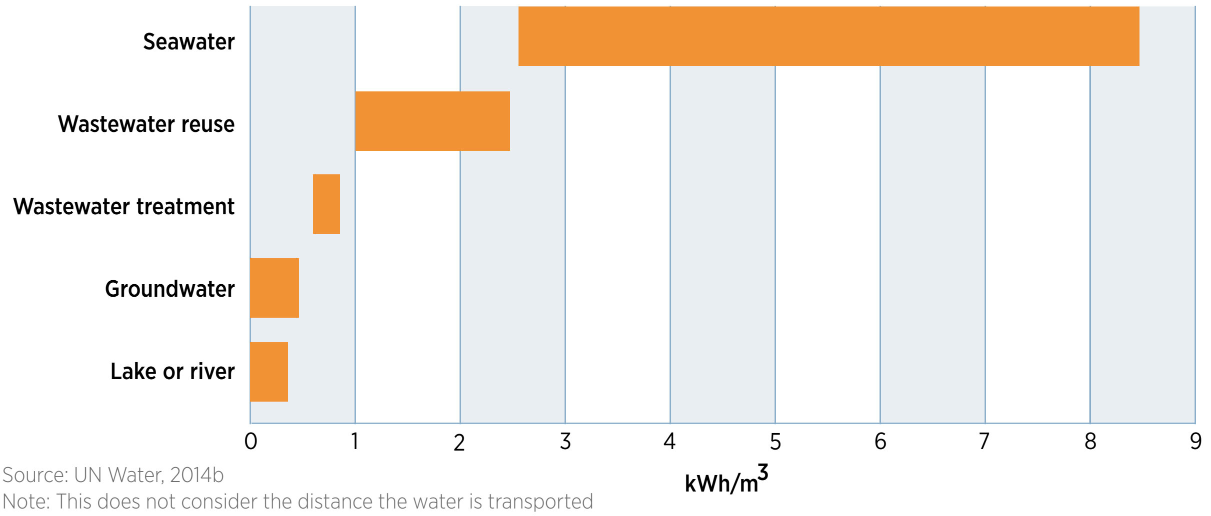
These risks do not exist in isolation, and converging factors can cause additional challenges. For example, persistent droughts coupled with heat waves can curtail electricity production while also spurring increased demand, straining the energy system's ability to deliver services.

Figure 1.4 Frequency of major power outages in the United States, by year



Source: Climate Central, 2014

Figure 1.5 Amount of energy required to provide 1 m3 of water safe for human consumption from various water sources



Source: UN Water, 2014b
Note: This does not consider the distance the water is transported

inputs are especially sensitive to energy price volatility, which can impair access to water and/or negatively impact the financial sustainability of water utilities.

The following examples highlight the impact of energy inputs on water supply and affordability:

- Regions where desalination will play an increasing role will be affected most by the cost of energy inputs into water production. The cost of desalination is dominated largely by the cost of input energy (IRENA and IEA-ETSAP, 2012), with estimates suggesting that energy accounts for more than 50% of the economic cost of desalination plants (2030 WRG, 2009). In the Gulf Cooperation Council (GCC) region, water and electricity cogeneration infrastructure has been developed which utilises waste heat from power plants for distillation. In Dubai in the United Arab Emirates, for example, 95% of water is procured through cogeneration plants that use imported natural gas. Faced with the increasing cost of producing water and unable to ensure cost recovery through prevailing water tariff regimes, the utility (Dubai Electricity and Water Authority) introduced a fuel surcharge that better accounts for the changes in global fuel prices (Gulf News, 2011).
- In Africa's Sahel region, the widespread lack of energy means that many of the region's 68 million inhabitants have to find ways to transport water from as far as 10 kilometres every day. Although the region receives limited annual rainfall (150-600 millimetres per year), the water table is at most 100 metres down (330 feet), making water pumping feasible (Varadi, 2014). Without energy to tap into those groundwater resources, however, the region had great difficulty coping with prolonged drought conditions. In 1986, a programme was launched to deploy solar-based water pumping solutions, which continue to benefit nearly 3 million people in the region today (Africa-EU Partnership, n.d.) (See also discussion on solar pumping in section 2.2.1).

b) Allocation of water resources towards energy production leading to water security risks in other sectors

Water is a critical input for health and livelihoods. As conflicts for limited water resources grow, the risks of re-allocation of water for other applications, particularly energy generation, also increase. There is growing evidence of governments having to make the choice between water, energy and food security given the limited resources available. These choices are expected to become more difficult as the need for meeting rising energy demands, particularly in developing countries, becomes more pressing. The following examples highlight these risks:

- In China, a coal chemical project in the arid region of Inner Mongolia, part of a new mega coal power base, extracted so much water in eight years of operation that it caused the local water table to drop by up to 100 metres, and the local lake to shrink by 62%. The ecological impacts were dramatic, forcing thousands of residents to become "ecological migrants" (Greenpeace, 2014).
- In India, 79% of new energy capacity is expected to be built in areas that already face water scarcity or water stress. Coal will remain a key energy source to meet rapidly expanding power needs despite the apparent water conflicts (WRI, 2010). For example, the country plans to build a cluster of 71 coal plants in the Vidarbha region of Central Maharashtra, a highly water-stressed area where lack of water for irrigation has been documented in the last decade (Greenpeace, 2014).
- A coal power station in South Africa, which is currently under construction and that, once commissioned, will be among the largest plants of its kind, is expected to use 2.9 million litres of water an hour from the nearby Vaal river. Much of this water may be diverted away from current agriculture and residential use. The main utility, Eskom, is classified as a strategic water user under the National Water Act, meaning that it is guaranteed a supply of water despite competing end-uses for the same resource (Greenpeace, 2012).

c) Risks of water contamination from energy-extraction processes

The extraction and transportation of fossil fuels pose risks to the quality of water resources and the health of aquatic ecosystems. Surface-mined coal produces large volumes of mine tailings containing pollutants that can leach into groundwater. During oil and natural gas drilling, seepage and major spills of retention ponds pose threats of polluting water with heavy metals and high-salinity water. There is also growing concern about hydraulic fracturing for natural gas and oil, which can contaminate surface and ground water and render it unfit for consumption for drinking, cooking and other domestic and industrial uses (UN Water, 2014b; IEA, 2012; The Guardian, 2011).

- In the United States, hydraulic fracturing for shale gas and oil produced an estimated 1 billion m^3 of wastewater in 2012. This toxic wastewater has contaminated drinking water resources in states such as Pennsylvania and New Mexico (Environment America, 2013).
- Indonesia, one of the world's largest exporters of coal, is grappling increasingly with the water pollution impacts of coal mining on water, as well as on farmland, forests and local residents. This is particularly acute in Borneo, which accounts for more than 87% of national coal production and where water acidity has increased substantially, with detrimental impacts on aquatic life and the livelihoods of local populations (Hadi, 2014).
- In South Africa's Olifants River catchment, coal mining has contaminated rivers and streams so much that the water no longer can be used in the region's coal-fired power stations. The utility's water either needs to be treated – a costly and energy-intensive process – or must be supplied from another, unpolluted river system (Groenewald, 2012).

1.3 THE WATER–FOOD NEXUS

The relationship between water and food systems is among the most widely covered elements of the nexus. Historically, the accessibility and availability of water resources has greatly influenced the evolution of agricultural practices globally. The type of crops grown, the crop cycles and the irrigation method adopted all vary from arid to wet parts of the world. Today, the water–food nexus is symbolic of vulnerabilities on two fronts: changing patterns of water supply that is influencing the reliability of water-intensive sectors including agriculture, and growing competition for limited water resources in meeting the projected increase in food demand. Moreover, the use of fertilisers and agro-chemicals has grown considerably under usual agricultural practices. Such inputs release chemical compounds that percolate to the groundwater.

1.3.1 Quantifying the water–food nexus

Agriculture is the world's largest user of water, accounting for over 70% of global freshwater withdrawals (and up to 90% in some countries). Water is also used throughout the agri-food chain, including processing, distribution, retailing and consumption. Not only is water used during the different stages, but it is physically part of the goods being handled and traded.

By 2050, a projected 60% increase in agricultural production, will cause water consumption for irrigation to rise by 11% and withdrawal by 6%, despite accounting for modest gains in water efficiency and crop yields (FAO, 2009). Although a seemingly modest increase, much of it will occur in regions already suffering from water scarcity and witnessing intense competition with other sectors, including manufacturing, electricity production and domestic use. In the face of these competing demands, increasing allocation of water for irrigation will be challenging (OECD-FAO, 2012).

Irrigation will have to play an important role in increasing food production. Growth in agricultural production to feed a projected human population of over 9 billion in 2050 will come from 1) increasing crop yields, and 2) expanding arable land area, together with increases in cropping intensities (*i.e.*, by increasing multiple cropping and/or shortening fallow periods). Yields of irrigated crops are well above those of rain-fed ones. To achieve increased production, the expansion of harvested irrigated land area is estimated to rise nearly 12% to 2050, compared to a 9% rise for rain-fed harvested land area (Alexandratos and Bruinsma, 2012).

Agriculture is both a cause and a victim of water pollution. Food requirements in the past have driven expanded use of fertilisers and pesticides to achieve and sustain higher yields (FAO, n.d. a). Although agriculture accounts for 80-90% of global freshwater withdrawals, much of that water flows back into surface and/or ground water (while the rest is lost through evapotranspiration). This allows for the discharge of pollutants and sediment – through net loss of soil by poor agricultural practices, and through salinisation and waterlogging of irrigated land. In total, the food sector contributes 40% and 54%, respectively, to the load of organic water pollutants in high-income and low-income countries (UNESCO, n.d.). At the same time, wastewater and polluted surface water and groundwater are used for irrigation purposes, which can contaminate crops and transmit disease to consumers and farm workers.

Losses along the food supply chain represent waste of resources used in production, such as water and energy. The main challenge facing the food system is not so much expanding agricultural production, but ensuring that existing food stocks reach consumers. Roughly one-third of the edible portion of food produced for human consumption is lost or wasted globally, equivalent to approximately 1.3 billion tonnes per year (FAO, 2011a). This corresponds to a 38% loss of direct and embedded energy (FAO, 2011b).

Although estimates of loss in embedded water and energy remain limited on a global and regional scale, country-level assessments demonstrate its significance. In South Africa, the loss of nearly one third of food production annually wastes enough embedded energy to power the city of Johannesburg for an estimated 16 years. Water wastage amounts to roughly one-fifth of South Africa's total water withdrawals (equivalent to nearly 600 000 Olympic-sized swimming pools) (WWF, 2014). The food losses in Nigeria's cassava and maize value chain contribute to around 2.3 million tonnes of carbon dioxide (CO_2)-equivalent to the atmosphere, representing about 3.3% of total greenhouse gas emissions in the country (GIZ, 2013). Reducing losses in the field, in storage and along the remaining supply chain would go a long way towards offsetting the need for more production and reducing strains on water and energy resources (UNESCO-WWAP, 2012).

Although the majority of the food produced is consumed domestically, trade in agricultural commodities continues to grow. Hence, quantifying the water–food nexus requires due consideration of the virtual (or embedded) water content of agriculture products (see box 1.3). Virtual water refers to the total amount of water needed for food production which changes from country to country depending on agriculture practices. International trade in crops and crop-derived products account for the largest share (76%) of virtual water flows between countries. Trade in animal products and industrial products each contributed 12% to global virtual water flows (Mekonnen and Hoekstra, 2011). This means that countries reduce their

BOX 1.3

QUANTIFYING THE FOOD–WATER NEXUS: THE CONCEPT OF VIRTUAL WATER

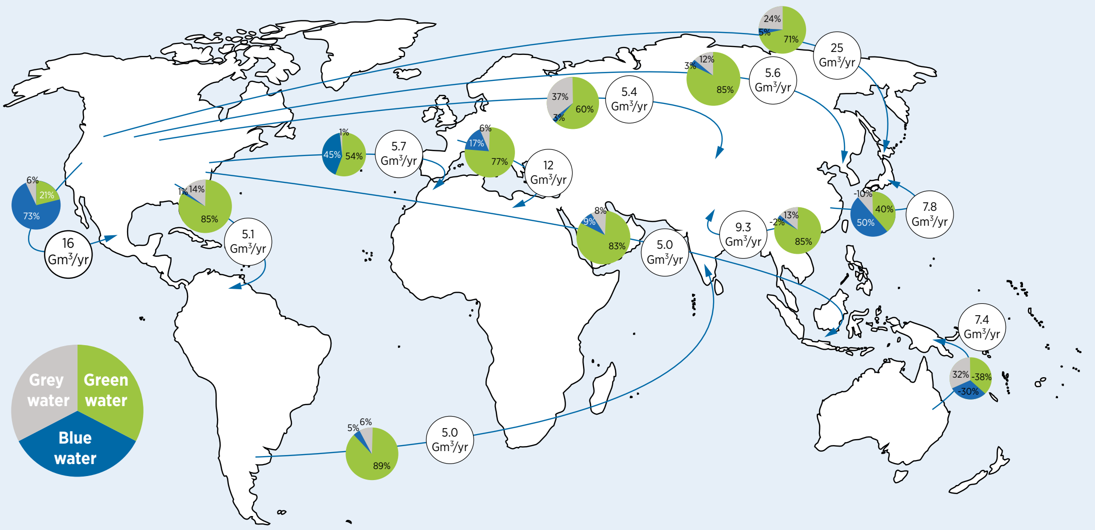
The virtual water concept was introduced in the early 1990s and has been among the most discussed (and debated) methods to quantify the water–food nexus (Allan, 1997). It represents the embedded water content of an agricultural product. The concept has gained prominence recently to capture the global dimension of the water–food nexus and to support sound decision-making on water allocation for agricultural production.

The basic premise of the concept is that some world regions/countries have higher water productivity rates and large swaths of agricultural production than others, creating a hydrological comparative advantage for them in producing water-intensive crops (Hoekstra, 2010). From an economic perspective, this should make them food exporters to countries that are less well endowed with water resources. "Virtual" water trade generates water savings in food-importing economies.

The global water saving related to trade in agricultural products in the period 1996-2005 was 369 billion m^3 per year. Considering only blue water* saving, it would have required an additional 98 billion m^3 per year of blue water to produce the same amount of goods without virtual water trade. Figure 1.6 shows the major global water savings associated with international trade in agricultural products. Exporting agricultural products (mainly maize and soybean products) from the United States to Mexico and Japan comprises the biggest global water savings, contributing over 11% of the total (Mekonnen and Hoekstra, 2011).

Limitations of using the concept as a metric to guide policy-making also have been discussed. These include, for instance, the assumption that all sources of water, whether in the form of rainfall or groundwater, are of equal value. The virtual water metric also does not provide any indication of the environmental harm or if water is being used within sustainable extraction limits (Frontier Economics, 2008). If, for example, livestock are raised under rain-fed conditions on pastureland, the water footprint and environmental impact may be much lower. On the other hand, if livestock is reared in industrial feed lots that use irrigated fodder, the water footprint may be much higher – and much less sustainable (Chapagain and Tickner, 2012).

Figure 1.6 Global water savings associated with international trade in agricultural products, 1996-2005



Source: Mekonnen and Hoekstra, 2011

Note: Only the biggest water savings (>5 billion m^3/yr) are shown. *Blue water refers to fresh surface and ground water; green water refers to water in soil that comes directly from rainfall; and grey water refers to wastewater from households.

use of national water resources by importing agricultural products. Japan, for example, saves 134 billion m^3 per year, Mexico 83 billion m^3, Italy 54 billion m^3, the U.K. 53 billion m^3 and Germany 50 billion m^3 (Mekonnen and Hoekstra, 2011). The term "saving" is used in a physical, and not economic, sense. In water-scarce countries in particular, water saving is likely to have positive environmental, social and economic implications.

Hence, all other things being equal, one might expect that countries under water stress would adopt a trade strategy that alleviates their water scarcity problem, but international trade in agricultural goods is driven largely by factors other than water, such as consumption patterns, market complexities, policy priorities and wealth endowment.

Meeting growing demand for water and food will require careful management of risks and opportunities which are closely related to the interaction between the different attributes of food and water security. Accessibility to water of sufficient quality, for instance, affects several food security concerns. Water is necessary, of adequate quantity and quality, to produce food and further downstream, during the preparation and consumption of food. Similarly, the intensification of certain food production practices – for example, a more aggressive use of soil-enriching nutrients or evolving diets (*e.g.*, growing demand for protein-rich diets involving meat) – has significant implications for water security. The risks posed by the water-food nexus are summarised in table 1.3 and will be discussed further in the following sections.

1.3.2 Water-related risks to food security

Water is a critical input along the different stages of the agrifood supply chain. The risks that the water sector presents to food security can be summarised as follows:

Table 1.3 Summary of risks and impacts within the water–food nexus

	RISKS	IMPACTS
Water-related risks to food security	• Increased variability in water availability, particularly due to climate change • Regional concentration of food production and consumption	Changes in supply of food products, leading to higher price volatility, further compounded by regional concentration of food production activities
	Impact of water quality on food production and consumption	Utilisation of poor-quality water along different stages of the food supply chain can have negative impacts, including soil degradation and accumulation of contaminants within the food chain
Food-related risks to water security	Impact of agricultural activities on water resources	Use of external inputs for agriculture and food production can lead to water pollution affecting downstream activities and aquatic life
	Poorly regulated agricultural foreign direct investments (*e.g.*, international land leasing)	Increased agricultural land leasing, when poorly regulated, could lead to expanded use of local water resources, with negative local socio-economic impacts
	Water resource over-utilisation due to food security ambitions	Pursuit of food security ambitions can strain water resources, often leading to substantial depletion in freshwater reserves

a) Increased variability in water availability, particularly due to climate change impacts

Water availability is increasingly becoming a challenge for both rain-fed and irrigated agriculture. Rain-fed agriculture is dependent on seasonal rainfall and decreasing rainfall reliability, and even minor delays and extremes in rainfall can affect crop production significantly. These impacts are felt more strongly in countries that are major domestic consumers of food products and exporters as well, such as India.

» The Indian monsoon, a seasonal event that brings much-needed rains to farmers dependent on rain-fed agriculture, has seen overall rainfall lessen over the past decade while extreme weather events have increased. Between 1981 and 2011, wet spells became more intense and dry spells became more frequent but less intense. The frequency and intensity of extreme weather events during the monsoon season are important, as such periods can lead to floods and crop failures, with negative impacts on local and global food security (Ogburn and ClimateWire, 2014).

For irrigated harvests, water availability is governed by access to water resources, such as groundwater aquifers, rivers, reservoirs or freshwater lakes, and to energy required to pump that water to farms. As competing demands for water grow, the tensions between water for agriculture and for other purposes are becoming more evident, as illustrated by the following two examples:

» In China, competing demands for limited water resources by the energy and food sectors is compelling the government to allocate water more aggressively between the sectors, with government representatives arguing in favour of increased food imports to free up water resources needed for energy generation (Reuters, 2014).

» Italy's Lake Como water system, developed along the Adda River, includes a large storage reservoir which generates 12% of the country's hydropower. Downstream, the river feeds a cultivated area of approximately 1 320 square kilometres (km^2), where maize is grown most widely. Plant operators use the accumulated snowmelt from May-July in the following fall and winter, when the demand for electricity peaks and the production is more valuable. This demonstrates the opportunity cost that the water held in reservoirs represents, resulting in potential conflict between downstream farmers (and other users) and hydropower companies, especially during summer months when farmers face critical water shortages. Such situations are expected to increase as climate change affects the variability of precipitation and temperatures in the Alpine environment, with potentially severe impacts on the stream-flow regime and seasonal snow-cover availability (Anghileri et al., 2013).

The impact of climate change on the long-term availability of water resources is immense. Globally, average temperatures are rising, unusual precipitation patterns are becoming more common and extreme weather events are more frequent. There is no doubt that changes in water quantity and quality due to climate change are expected to seriously affect food availability, stability, access and utilisation – the key constituents of food security (IPCC, 2008).

Climate change-related alterations in the hydrological cycle will affect the quality and quantity of water that is available at a given time for food production, processing, storage and consumption. In-season droughts can greatly reduce output from rain-fed agriculture, and low water availability can negatively affect output from irrigated areas. Box 1.4 provides an overview of the anticipated impact of climate change on food security.

b) Regional concentration of food production and consumption

The regional concentration of food production is evident from figure 1.7, which illustrates the high importance of Asia in producing rice, wheat, cereal and sugar. Such "food bowls" of the world are already facing water stress due to droughts and depletion of blue water resources, which poses significant risks for global food security. River basins that are critical in the water–food nexus – such as the Nile, Colorado, Euphrates and Tigris, Ganges, Murray-Darling and Yellow River – are predicted to be "closed basins" (over-allocated), particularly due to energy and agricultural production, and could face challenges from the

BOX 1.4

CLIMATE CHANGE IMPACTS ON FOOD SECURITY

Agriculture, forestry and fisheries are all sensitive to climate, and climatic changes will likely affect production in all three of these areas. In general, impacts are expected to be positive in temperate regions and negative in tropical ones, but there is still uncertainty about how the projected changes will play out at the local level. The food security implications of changes in agricultural production patterns and performance are as follows:

- Impacts on food production will affect food supply at the global and local levels. In theory, higher yields in temperate regions could offset lower yields in tropical regions. However, because many low-income countries have limited financial capacity to trade and depend largely on their own production to cover food requirements, it may not be possible to offset declines in the local food supply without increasing reliance on food aid.
- Impacts on all forms of agricultural production will affect livelihoods, incomes and therefore access to food. Producer groups that are less able to deal with negative effects from climate change, such as the rural poor in developing countries, risk having their safety and welfare compromised.

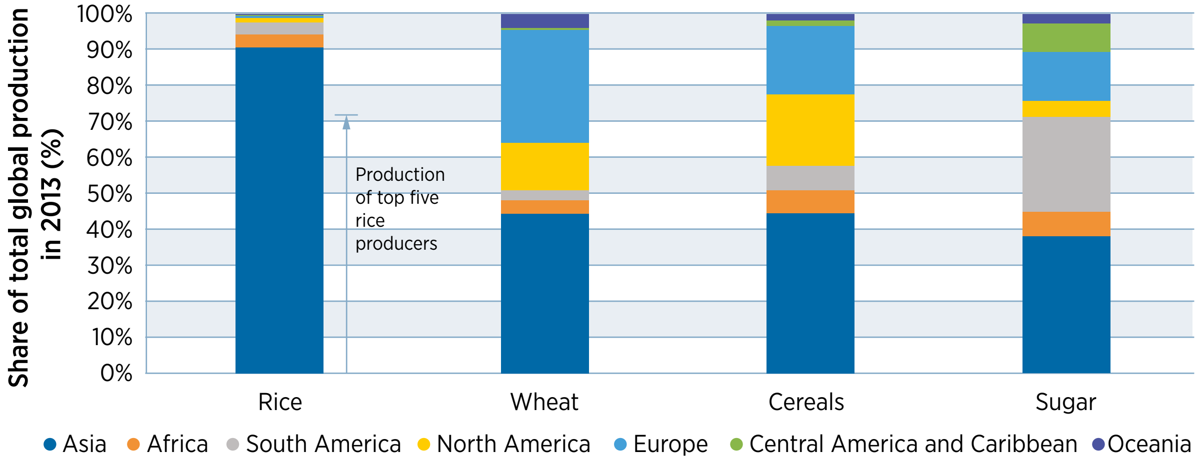
Other food system processes, such as processing, distribution, acquisition, preparation and consumption, are similarly important for food security. Overall, food system performance is far less dependent on climate than it was 200 years ago because of both technological advances and the development of long-distance marketing chains that move foods throughout the world at high speed and relatively low cost. Given a likelihood of increasing fuel costs, this situation may change in the future. As the frequency and intensity of severe weather increase as a result of climate change, there is a growing risk of storm damage to transport and distribution infrastructure, which could disrupt food supply chains.

Source: FAO, 2008a

effects of climate change. Cases are already emerging where variations in water availability in a specific region have major consequences for the security of global food supply, aggravating the already increasing volatility of related commodity prices in the world market.

Drought linked to a 2007 El Niño event sparked a surge in food prices, with the cost of rice rising to

Figure 1.7 Share of global production of rice, wheat, cereals and sugar, by region



Source: Based on data from FAO, 2014a

over USD 1 000 per metric tonne and triggering food riots in 2008 in countries as far afield as Egypt, Haiti, and Cameroon. The 2009 El Niño brought the worst drought in nearly 40 years to India, cutting rice output in the world's second largest rice producer by 10 million tonnes and boosting global sugar prices to their highest levels in nearly three decades (Taylor and Cruz, 2014).

Moreover, the production of many top food commodities is concentrated in just a handful of countries. The top five producers of rice and wheat accounted for 72% and 66%, respectively, of global production of these crops in 2013; and Indonesia and Malaysia produce 88% of the world's palm oil, of which 70% is used in the food system. This introduces additional vulnerabilities associated with geo-political events, domestic changes in policies (*e.g.*, regarding water allocation) and restrictions in trade of food products.

» Export bans introduced on food products by many countries following the global food crisis in 2007-08 or due to isolated domestic events, such as droughts and high inflation, substantially altered the availability of basic food items on the international market. Grain prices surged in 2010 as wheat prices were driven up by a series of weather events including drought in Russia, which introduced an export ban (Kovalyova, 2011; Kramer, 2010) and created a shortage in world markets.

c) Impact of water contamination on food production and consumption

The quality of water needed for irrigation depends on crop properties and on local soil and climate conditions. Careful consideration of hazards related to salinity, sodium contents and other substances, such as chloride and boron, is necessary (TAMU, 2003). There is also growing interest in the use of wastewater resources from domestic and industrial streams for irrigation purposes to complement dwindling fresh water. Wastewater can be a rich source of nutrients and could provide much of the moisture necessary for crop growth, resulting in higher yields and reducing the need for chemical fertilisers. Wastewater irrigation can deliver excess nutrients, such as nitrogen, however, and lead to microbiological contamination that could cause yield losses (IWMI, 2002).

» Worldwide, an estimated 20 million hectares of arable agricultural land is irrigated using wastewater (*i.e.*, direct use of raw or untreated wastewater, direct use of treated wastewater, as well as indirect use of untreated wastewater), with unreported use projected to be even higher (World Bank, 2010b; UN Water, 2013).

» In the U.S. state of California, a fresh bagged spinach from a single farm was discovered to be the source of a 2006 E. coli outbreak that resulted in 200 illnesses and 5 deaths. An investigation found the most likely cause of the outbreak to be contamination of the groundwater used for irrigation. The groundwater contamination in turn was a result of aquifer recharge with polluted surface water (Gelting and Baloch, 2012).

The quality of water available for processing and cooking food is also an important determinant of food security. Water is needed for washing, rinsing, scalding, chilling, pasteurising, cleaning, sanitation, disinfection and cooking, among other applications (Uyttendaele and Jaxcsens, 2009). In the absence of appropriate measures being taken, the use of unsafe water during food processing and preparation can lead to food contamination.

1.3.3 Food-related risks to water security

As the largest consumer of freshwater resources globally, agricultural practices have substantial impacts on water security for a broader set of stakeholders. Some of the key risks can be summarised as follows:

a) Impact of agricultural activities on water resources

Agricultural contamination remains a major source of water pollution. Different agricultural activities, such as ploughing, fertilising, manure spreading and irrigation, have different impacts on surface water and groundwater. FAO's Control of water pollution from agriculture provides a detailed account of those impacts (FAO, 2002). In general, the degradation of water quality downstream by salts, agrochemicals and toxic leachates is a serious environmental problem. Many of these impacts are being experienced today and are affecting water security at a significant scale:

- In August 2014, nearly 400 000 people were left without access to safe drinking water for two days in the U.S. city of Toledo, Ohio. This was a result of a massive algae bloom in the freshwater lake from which the city draws its water supply. The primary cause of such algal blooms has been found to be excessive quantities of phosphorus, with two-thirds of this amount entering the water system as run-off from agriculture. Climate change could add to the challenge as heavier rains bring more phosphorus into the lake through agricultural run-off, and as warmer temperatures cause algal blooms to spread more intensely (Goldernberg, 2014).
- About 70% of the water pollution in China comes from agriculture, as run-off from fertilisers, pesticides and animal waste. China is the world's largest producer and consumer of fertilisers and pesticides, making the agriculture sector the biggest source of water contamination (Aulakh, 2014). In addition, water contamination from industrial waste is increasingly affecting the food supply chain, in the form of heavy metals present in seafood and rice (Hsu, 2014).

b) Poorly regulated agricultural foreign direct investments in agriculture

Domestic food security is high on the agenda of many governments around the world. In the wake of the 2008 food crisis, when at least 25 countries imposed export bans or restrictions on food commodities, many food-importing countries realised the grave food security risks that such situations posed. Several countries for which food self-sufficiency is very difficult to achieve, due mostly to limitations on water availability, began buying or leasing land in relatively water-rich countries such as Sudan and Ethiopia (Bossio et al., 2012). In 2009, it was estimated that about 56 million hectares worth of large-scale farmland deals were announced in less than a year (World Bank, 2010a).

In this context, concerns emerge regarding the effectiveness of regulations that govern water rights, extraction and utilisation, with some asserting that, in effect, this land acquisition amounts to de facto water acquisition. This is particularly relevant given that many of the recipient countries are home to significant populations of malnourished and are often on the receiving end of food aid.

- An analysis conducted by the FAO to assess the impact of international investment on the host country found that, in many cases, the water security of local communities can be negatively affected, as local farmers face off against competing water users (FAO, 2010a).
- In Sudan, land investments are occurring on the banks of the Blue Nile. As large-scale commercial farmland expands in the region, small holders are losing access to both land and water. As a result, Sudan has become a major exporter of food commodities produced by large-scale farmers, but the local population is increasingly dependent on food aid and international food subsidies (Rulli, 2013).

c) Over-utilisation of water resources due to food security ambitions

Countries in their quest to maximise food self-sufficiency are known to adopt policies that are detrimental to water security in the long term. These policies allow unrestricted utilisation of renewable and non-renewable freshwater resources for agriculture purposes by making available highly subsidised energy for pumping and because of a lack of proper pricing of water resources. This leads to overdrawing of water with long-term implications for water, energy and food security.

- Agricultural water demands in Saudi Arabia represented 83-90% of domestic water demand between 1990 and 2009. This demand was backed by a self-sufficiency goal for wheat and other products such as milk, meat and eggs. As a result of highly subsidised water availability for agriculture, it is estimated that more than two-thirds of Saudi Arabia's non-renewable groundwater resources may have been depleted (Chatham House, 2013). Realising the infeasibility of such an endeavour, the government now aims to phase out domestic wheat production completely by 2016 and instead is focusing on overseas investments to boost food security.
- In India, the number of electric tubewells (pipes that are bored into the ground and pump water to the surface) has increased from 12 million in 2001 to nearly 20 million today. Much of

the electricity consumed by these tubewells is highly subsidised, with farmers paying less than 13% of the true cost of electricity. This has prompted inefficient water use in agriculture as farmers resort to inexpensive flood irrigation techniques, wherein half of the water is lost to evaporation and run-off (Casey, 2013). In the state of Punjab, over-pumping of groundwater is directly related to the energy subsidies provided by the government to the farmer, which encourages intensive agriculture and consequent impact on underground aquifers (FAO, 2014b). The impacts of this practice on the energy sector were discussed in section 1.2.2.

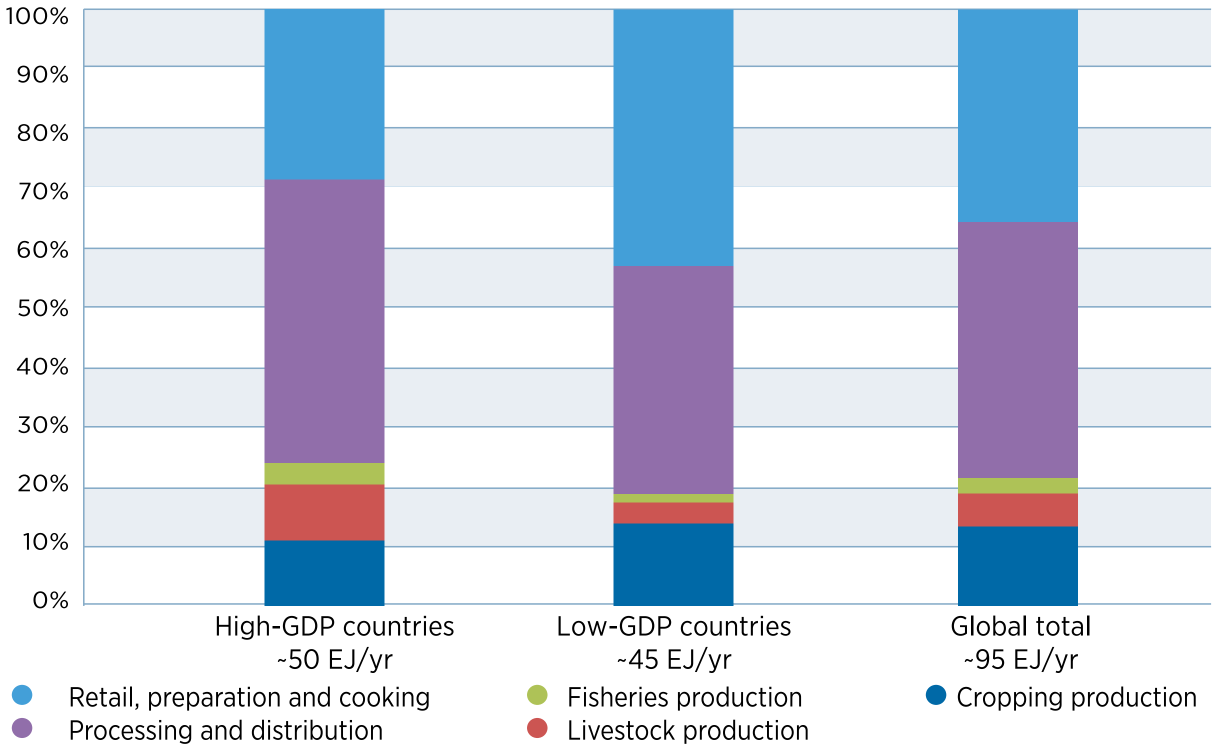
1.4 THE ENERGY–FOOD NEXUS

Discussions surrounding the energy–food nexus relate mainly to energy use within the food supply chain. Depending on the extent of mechanisation, agricultural production consumes energy directly in the form of fuels for land preparation and tillage, crop and pasture management, and transportation or electricity supply, and indirectly through the use of energy-intensive inputs, such as fertilisers and pesticides, or energy for manufacturing agricultural machinery. Energy is also needed during processing, distribution, storage, retail and preparation of food products. This makes food security particularly sensitive to the quality and price of energy inputs: in some countries, the price of oil has a rather direct effect on the price of food. Another dimension of the energy–food nexus that is gaining prominence is the impact of the growing share of modern bioenergy in the world's energy mix. In the face of rising energy security and climate change challenges, bioenergy has emerged as a viable renewable energy option for many countries. In this context, this section explores the interlinkages between the energy and food sectors and highlights the key risks posed by the nexus.

1.4.1 Quantifying the energy–food nexus

The food chain requires significant amounts of energy, with variations in where that energy is consumed. The food sector currently accounts for some 30% of global energy consumption, met largely with fossil fuels (FAO, 2011b). The bulk of energy needs in the food supply chain comes from processing, distribution, preparation and cooking of foods (see figure 1.8). Not surprisingly, more energy is consumed in the retail, preparation and

Figure 1.8 Direct and indirect energy inputs at different stages of the food sector



Source: FAO, 2011b

cooking stages in low-GDP countries owing to limited and less-efficient infrastructure compared to high-GDP countries. The increased livestock production in high-GDP countries symbolises the changes in diets towards protein-rich products as incomes rise.

As world demand for food grows (by a projected 60% by 2050), the bulk of demand for more energy inputs to the food system will come from emerging economies in Asia, Latin America and sub-Saharan Africa. The estimated increase in energy demand will be a result of growing population, higher calories consumed per capita, changing diets towards more energy-intensive meat production, and increasing mechanisation throughout the food supply chain. Emerging economies, for instance, are expected to account for 80% of the growth in meat production by 2022 (OECD-FAO, 2012). An important consideration is also the energy embedded in the substantial amounts of food wasted.

A large amount of food, with a significant energy footprint, ends up as waste. Approximately a third of all food produced is lost or wasted each year, resulting in a waste of 1 to 1.5% of total global energy use (Aulakh and Regmi, 2014). In developing countries, 40% of losses occur during post-harvest and processing, whereas in industrialised countries more than 40% of losses happen at the retail and consumer levels (FAO, n.d. b). This wastage represents a loss of valuable water, land, energy and labour inputs that have gone into producing the food, while at the same time contributing to greenhouse gas emissions.

Bioenergy, both traditional and modern, plays an important role in the world's energy mix. In 2013, biomass constituted about 10% of global primary energy supply, with 60% from traditional biomass (REN21, 2014). Globally, 2.7 billion people use traditional forms of biomass, such as fuelwood, agricultural waste and animal dung, for cooking and heating. When harvested unsustainably and used with inefficient cooking technology, this contributes to environmental, health and economic concerns such as deforestation and chronic pulmonary diseases through indoor air pollution.

Demand for modern bioenergy is growing for use in transport, heating and electricity. Liquid biofuels in particular have seen a surge, with global production expanding from 16 billion litres in 2000 to more than 100 billion litres in 2011. This growth has raised real concerns about competition with food crops. For example, maize used for ethanol in the United States totals 127 million tonnes, or 15.6% of world maize production (Alexandratos and Bruinsma, 2012). Liquid biofuels also provide around 3% of total road transport fuel worldwide, or 1.9 million barrels per day in 2012 (IEA, 2013a). The IEA predicts that this number will increase to 2.4 million barrels per day by 2018. With 62 countries having biofuels mandates or targets globally (Lane, 2014), the growing profile of liquid biofuels will need to be managed carefully to avoid conflicts with food.

Understanding the various risks and synergies of the energy–food nexus as well as the impacts on different stakeholders is paramount to pursuing energy and food security goals in tandem. According to the literature, the risks summarised in table 1.4 pose the greatest challenges to managing the interlinkages between the energy and food sectors (FAO, 2012a and b; FAO 2014b; SEI, 2012; UN ESCAP, 2013; Hazell and Pachauri, 2006). These risks cover threats to the overall physical resource availability of energy and food, acute failure points in the supply chain and possibilities for political and economic disruption.

1.4.2 Energy-related risks to food security

The nature of energy supply into the agrifood sector can substantially influence food security. The key risks posed by the energy sector on food security can be summarised as follows:

a) Dependence on fossil fuels increases volatility of food prices and affects economic access to food

Fossil fuels continue to provide the majority of the energy inputs for conventional development of the agri-food sector, ranging from electricity and/or diesel for pumping, food processing and storage, to fuel for agro-machinery. This reliance on fossil fuels comes at a cost – related not only to climate change but also to fluctuations in fossil fuel prices, which can cause dramatic changes in food prices (see figure 1.9). The 2007-08 global food crisis was due in part to increasing oil prices,

Table 1.4 Summary of risks and impacts within the energy–food nexus

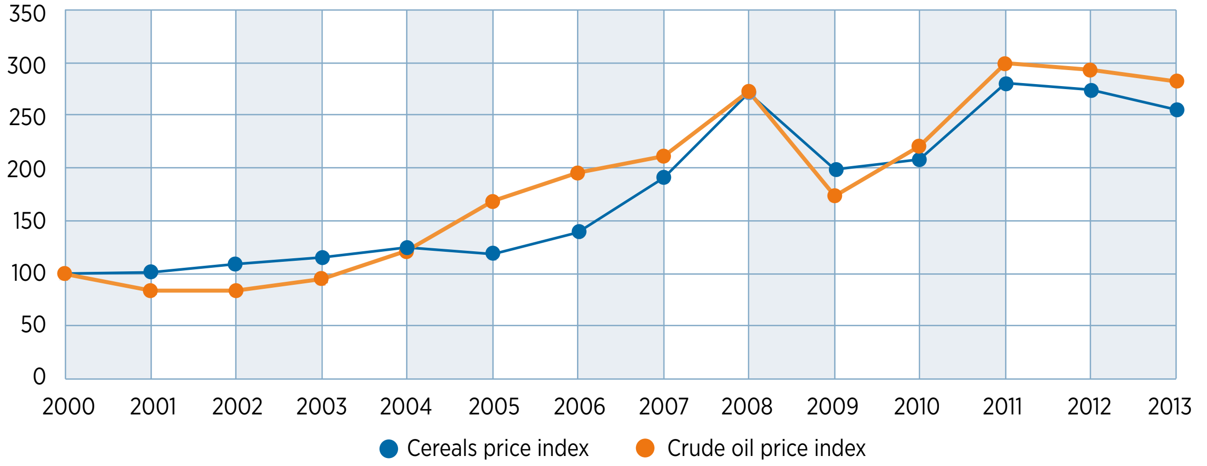
	RISKS	IMPACTS
Energy-related risks to food security	Dependence on fossil fuels increases volatility of food prices and affects economic access to food	• Fossil fuel dependency of upstream (*e.g.*, production) and downstream (*e.g.*, transport, storage, etc.) food supply chain • Price volatility and supply shortages of energy inputs introducing economic and physical risks in the food supply chain • Social, environmental and health impacts of traditional biomass cooking methods
	Potential trade-offs between bioenergy production and food crops	Allocation of agricultural products for bioenergy production with possible impacts on food prices
	Risks of energy production on food availability	Possible negative impacts of energy technologies (*e.g.*, hydropower, thermal power generation) on river and marine life
Food-related risks to energy security	Overall increase in food production and changing diets raises energy demand along the food supply chain	Rising demand for energy needs for agriculture can strain the energy system, particularly in regions with a potential to expand irrigated agriculture with pumped water
	Quality and affordability of energy supply can depend on feedstock availability	In energy mixes with bioenergy, quality and affordability of food-crop-based feedstock can affect energy supply

which had a cascading effect that led to greater demand for biofuels and to trade shocks in the food market (European Commission, 2011). Another component of the food supply chain that is affected by energy prices is packaging (containers, boxes, etc.), for which fossil fuels are a key input.

b) Potential trade-offs between food security and bioenergy production

Bioenergy and food security are connected at several levels. The first pillar of food security – availability – is affected by biomass feedstock production through land and farm-gate producer prices (decreasing food production

Figure 1.9 Oil–cereal price interlinkage, 2000-2013



Source: Based on FAO Food Price Index and BP Statistical Review of World Energy 2014 (Base 2000 = 100) increases food prices and provides an incentive to grow more food). Regarding food accessibility (which includes affordability), an improvement of the local economy could bring additional income and hence improve food affordability. Biofuel developments may contribute to overall improved macroeconomic performance and living standards because biofuels production may generate growth linkages (*i.e.*, multiplier or spill-over effects) to the rest of the economy (Urbanchuk, 2012).

It is important to carefully manage any negative impacts of biofuels promotion. Although liquid biofuels currently cover only around 3% of transport fuel demand, a significant increase in the volume of first-generation liquid biofuels in the energy mix could cause interactions with food prices if not properly managed by cross-sectoral policy formulation.

Whether the price correlation is as strong as that being experienced with crude oil prices remains to be seen. In the interim, strong adherence to sustainability standards and regulation will be necessary to align biofuel growth with other environmental, economic and social goals.

c) Risks of energy production on food availability

Some specific technologies for energy production can affect food availability. Thermal power generation using cooling water from a river can affect the river's ecosystem (*e.g.*, increasing the temperature of the water), altering fish availability and potentially affecting local food supply. Hydropower also can impose burdens on fish (*e.g.*, on migratory species, which represent a large share of commercial fish), as has been observed in the Mekong Basin in Southeast Asia and in the Columbia River Basin in western North America. Moreover, as seen in section 1.3.2, water held in hydropower reservoirs can affect availability of water for irrigation both upstream and downstream.

Marine fisheries can be affected by energy technologies as well (FAO, 2014b). A clear example is the 2011 Fukushima nuclear accident in Japan, which significantly affected the fishing activity in eastern Japan (Kiger, 2013).

1.4.3 Food sector-related risks to energy security

The risks posed by the food sector on energy security, especially in contexts where bioenergy plays a crucial role, can be summarised as follows:

a) Overall increases in food demand raise energy inputs required in the food supply chain and put strains on energy systems

Population growth and changing diets in emerging economies will place increased burdens on energy and food production systems due to higher demand for fertilisers and agrochemicals, higher levels of livestock production, and demand for more sophisticated retail, distribution, processing, cooking and food preparation. Energy inputs into the food supply chain are likely to increase in the coming decades, leading to increased energy production necessities and likely strains on energy delivery systems. As food demand rises, so will water needs, which have their own energy footprint impacts.

Livestock production is projected to increase from 218 million tonnes in 1997-99 to 378 million tonnes by 2030. Producing 1 kilogram of meat requires 2-10 kilograms of fodder. Increasing meat production and other dietary changes therefore will have significant impacts on land and energy use. This will take its toll on the energy system, which will have to provide additional supplies to produce feed, process meat, distribute, retail and cook the food (OECD-FAO, 2012).

b) Quality and affordability of energy supply can depend on bioenergy feedstock availability

In energy systems dominated by bioenergy (whether traditional or modern), reliability of the energy supply will depend greatly on the quality and availability of biomass feedstock.

In the rural context, reliance on traditional biomass for cooking and heating places substantial strains on local ecosystems where overexploitation of the biomass resource, such as fuelwood or charcoal, could lead to deforestation and degradation of forests as well as destruction of potential water catchments for other water uses. This can reduce the accessibility of biomass and further add to the drudgery of walking long distances to collect fuel for cooking and heating.

Efforts are under way to promote modern fuels, such as biogas and LPG, as well as the use of improved cook stoves to enhance efficiencies and reduce environmental and health impacts. In the developed context, similar risks also apply, where a reliable and affordable biomass feedstock supply chain is one of the key sustainability determinants for power-generation or biofuel projects. Any disruptions, fluctuations in feedstock prices or changes in quality could substantially alter the characteristics of energy supply, especially in rural areas where these represent the primary source of energy.

1.5 IDENTIFYING INTEGRATED SOLUTIONS TO MANAGE THE WATER–ENERGY–FOOD NEXUS

This chapter has shown that water, energy and food together form a highly complex and entwined resource nexus. It is clear that each of the three sectors has impacts on the security of supply in the other sectors, in a variety of ways. As demand for resources is expected to increase, competition and scarcity will become more acute, affecting the security of supplies across all sectors. The examples presented in this chapter illustrate that several countries already face clear nexus challenges, thus threatening sustainable development objectives.

Decision makers should take steps to promote growth while being sensitive to social, economic and environmental implications. The energy sector is undergoing important changes, with renewable energy technologies accounting for the majority of new capacity additions (IRENA, 2014a). Meanwhile, the concept of integrated water resources management has been adopted widely, with nearly two-thirds of countries having developed such plans and one-third in advanced stages of implementation (UN Water, 2012). Measures are also being taken to adopt more sustainable and efficient agricultural practices, such as shifts towards integrated "agro-ecosystems" (Hoff, 2011). Yet despite overall progress, challenges remain.

As the world reaches – and in some cases has already exceeded – the sustainable limit of resource availability, and is at risk of exceeding planetary boundaries (Rockström et al., 2013; BMU, 2012), water security, energy security and food security will become more elusive. It is increasingly evident that development strategies and national policies can no longer be formulated for individual sectors alone, but must cut across the different sectors to better manage trade-offs. Some argue that managing the nexus at the local or national level does not require a major institutional restructuring, but rather appropriate changes to protocols, procedures and processes that improve interactions among the relevant governance entities. Others, on the contrary, affirm that lack of co-ordination among institutions (silo decision making) could be a key cause of the nexus pressures that are being experienced today.

The consultations that took place around the landmark Bonn 2011 Nexus Conference[3] clearly highlighted the importance of integrated solutions for a green economy – a paradigm wherein economic growth is decoupled from resource depletion. The conference laid out a set of "Nexus Opportunity Areas", highlighted below, intended to *"support sustainable growth and achievement of water, energy and food security by cutting across interlinked decision spaces and identifying win-win solutions"* (BMU, 2012).

- Increase policy coherence
- Accelerate access
- Create more with less
- End waste and minimise losses
- Value natural infrastructure
- Mobilise consumer influence

In essence, the objectives of most measures being discussed and implemented by governments, the private sector, development agencies and

---

[3] The conference, titled "The Water, Energy and Food Security Nexus: Solutions for the Green Economy", marked a key milestone in the international discussions around the nexus. It was organized by the German Federal Government in collaboration with the World Economic Forum (WEF), WWF and the International Food Policy Research Institute (IFPRI). It aimed to contribute to the run-up to the UN Conference on Sustainable Development (UNCSD, or Rio+20), that took place in Rio de Janeiro, Brazil, in June 2012.

communities to address nexus challenges fall within at least one of the six identified action points. Adopting integrated solutions is a compelling case for each of the stakeholders from a social, economic and environmental standpoint. Minimising wastage and losses in distribution of water, energy and food can help bridge the projected demand increases, save substantial amounts of embedded resources consumed in production and reduce environmental impacts.

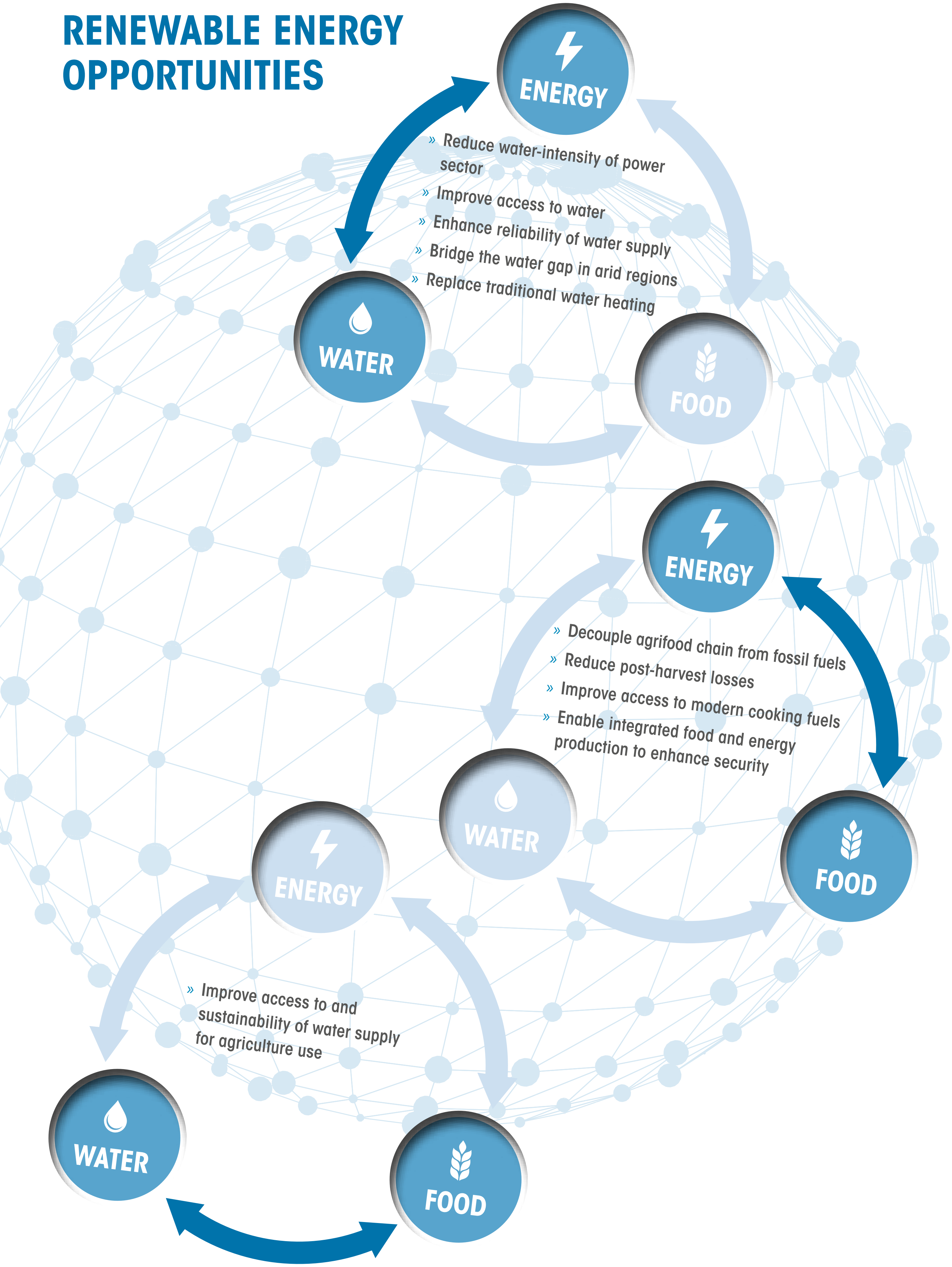
This thinking is also reflected, for instance, in the Urban NEXUS approach which provides a framework for municipalities and other cities to shift from conventional sectoral planning towards utilising the opportunities offered by the interlinkages. A growing number of cities, such as Curitiba (Brazil), Durban (South Africa) and Nashik (India), have started to turn away from *silo* planning in the recent years to harness the abundant potential of an innovative, cross-sectoral nexus approach (GIZ and ICLEI, 2014).

Revisiting the concept of nexus thinking from more of a supply-side perspective, there is growing importance of integrated solutions that enhance security and sustainability across all three sectors (Barrett, 2014), while supporting global climate ambitions. What contributes greatly to the sustainability of an existing (water, energy or food) system is essentially the sustainability of the resource inputs along different stages of the supply chain. Energy, for example, is a critical input along different stages of the water and food supply chain, and the negative impacts of growing reliance on unsustainable energy sources are increasingly evident.

These energy sources are characterised by increasingly volatile prices, they cause damage to the environment and they are intrinsically more resource intensive to extract, process and deliver. Until lately, the alternatives did not exist, and growing demand for energy in different end-use sectors has been met by fossil fuels. But today, renewable energy technologies could provide integrated solutions that simultaneously enhance water, energy and food security by addressing trade-offs and leveraging on synergies between sectors.

Renewable energy technologies now represent a mainstream energy source. Their distributed, environmentally friendly and less-resource-intensive nature means that they are compatible with the broader green growth objectives towards sustainable development. The benefits brought by renewable energy range widely and include enhancing energy security, mitigating climate change, increasing energy access and stimulating socio-economic development. There is now growing recognition that renewables also can play a significant role in reducing some of the strains across the nexus elements. It is expected that the benefits of renewable energy can spill over to other sectors and that such technologies come with the potential to enhance water and food security under specific conditions. Chapter 2 explores this dimension further and analyses the benefits that renewables bring in the water, energy and food sectors.

RENEWABLE ENERGY OPPORTUNITIES



- Reduce water-intensity of power sector
- Improve access to water
- Enhance reliability of water supply
- Bridge the water gap in arid regions
- Replace traditional water heating

- Decouple agrifood chain from fossil fuels
- Reduce post-harvest losses
- Improve access to modern cooking fuels
- Enable integrated food and energy production to enhance security

- Improve access to and sustainability of water supply for agriculture use

2

RENEWABLE ENERGY IN THE NEXUS

The previous chapter presented the interlinkages between the three key elements of the nexus: water, energy and food. It highlighted the importance of identifying integrated solutions that are aligned with the nexus concept of analysing challenges and solutions more holistically across the three sectors. As the deployment of renewable energy technologies accelerates, there is a need to evaluate the impact of this growth on the nexus and to identify opportunities for enhancing security of supply across the three sectors.

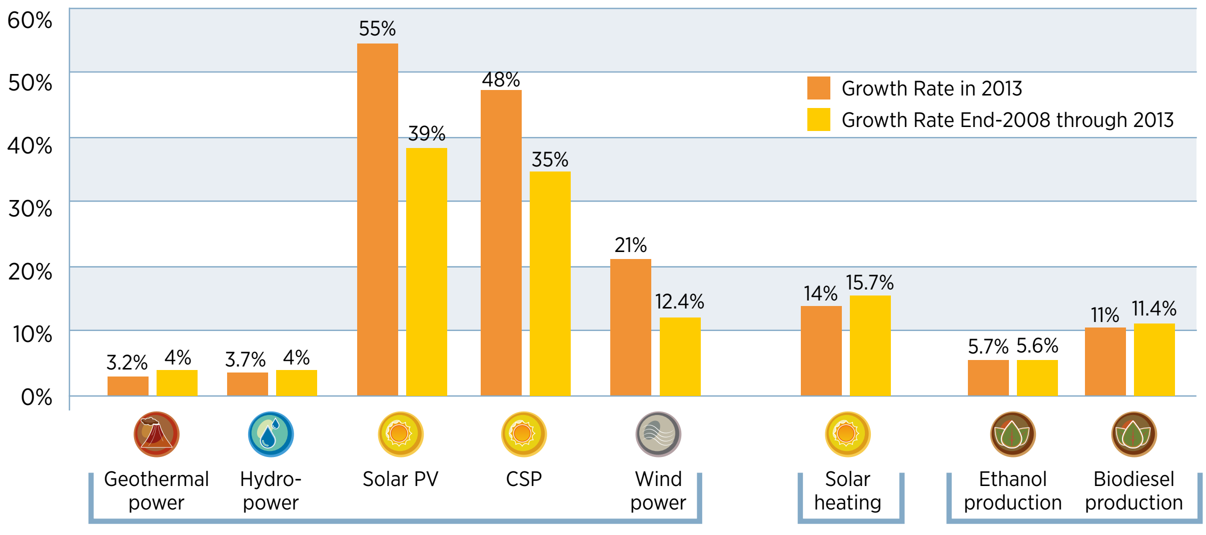
This chapter begins by introducing the renewables growth story and highlighting its relevance to the nexus discussions. Based on cases from the literature, it then presents the experience with deploying renewables along different segments of the water, energy and food supply chain. The chapter also presents country-level quantitative analysis conducted by IRENA to understand the impact of growing renewables use in the power sector on water consumption and withdrawal.

2.1 INTRODUCTION

Renewable energy deployment has expanded immensely over the past decade. Figure 2.1 shows the average annual growth in capacity additions and biofuels production between 2008 and 2013. In the power sector, for example, 120 gigawatts (GW) of renewable energy capacity was deployed in 2013, which is comparable to all of Brazil's electricity generation capacity and accounts for more than half (58%) of all new capacity deployed globally.

Together, renewables generated 22.1% of electricity globally in 2013. Robust growth is also being seen in the heat and transport sectors. The share of modern renewables in meeting final global heat demand is now 10% and gradually rising. Liquid biofuels (including ethanol and biodiesel), which account for the largest share of transport fuels derived from renewable energy sources, met 0.8% of global transport fuel needs in 2013 (REN21, 2014).

Figure 2.1 Average annual growth in renewable energy capacity and biofuels production across the three end-use sectors



Source: REN21, 2014

The share of renewables in the global energy mix is poised to grow substantially. At present, renewable energy makes up 19% of global final energy consumption, of which 9% is traditional biomass (REN21, 2014). This share will grow for two primary reasons: 1) countries are increasingly realising the benefits of adopting renewable energy in terms of enhanced energy security, improved energy access, socio-economic development and climate change mitigation, and 2) there is a growing consensus that, globally, any solution to address catastrophic climate change will involve a substantial expansion of renewable energy deployment.

The United Nations' Sustainable Energy for All initiative aims at doubling the share of renewable energy in the global energy mix by 2030, as one of its three objectives. This would involve raising the renewables share from 18% in 2010 to 36% in 2030. IRENA's REmap 2030 analysis charts out pathways to meeting that target and finds that under business-as-usual the share will increase to only 21% by 2030, but with realistic potential to accelerate deployment in the buildings, transport and industry sectors– the share can reach and exceed 30% by 2030. Energy efficiency and improved energy access can further advance the share of renewables in the global energy mix, to as much as 36% (IRENA, 2014b).

The interlinkages between the sectors mean that changes in one can have spill-over effects, both desired and undesired, on the others. When deployed with a view towards sustainable use of land and water resources, renewables can have reduced negative local and global environmental impacts and enhance energy security by decreasing dependence on fuel imports. Water and food security also can improve indirectly if suitable renewable energy technologies are deployed to expand access to modern energy services and to meet growing energy needs along the different segments of the water and food supply chain.

An energy system with a substantial share of renewables would affect the food and water sector differently than one based mainly on fossil fuels. Many renewable energy resources, such as solar, wind and tidal, are freely available and require minimal resource inputs (*e.g.*, water) during the fuel extraction, processing and transportation phases. During the transformation stage (converting primary energy into electricity or transport fuels), water use varies by renewable technology, but can generally be lower than for conventional technologies (discussed further in section 2.2).

In the case of bioenergy, concerns arise due to potential impacts on land use and food and water security, particularly with the use of irrigated food crops as feedstock, but these concerns can be addressed by adopting sustainable practices and specific safeguard measures.

A number of risks could be mitigated through a better understanding of trade-offs, utilisation of existing tools and adoption of sustainability standards and effective regulations. Substantially increasing the share of bioenergy in the global energy mix, however, will require a transition to using biomass feedstock and processes that are environmentally sustainable and do not compete, directly or indirectly, with food production.

The remaining sections of this chapter delve deeper into the role of renewable energy in the energy–water (section 2.2) and food–energy (section 2.3) nexus. The impacts on the food–water nexus are spill-overs from the other two elements being discussed, where energy is a common denominator. Land is yet another critical resource input, particularly within the energy and food sectors, and will be dealt with accordingly in the following sections.

2.2 RENEWABLE ENERGY IN THE WATER–ENERGY NEXUS

The water–energy nexus, as seen in chapter 1, is emerging as a key security-of-supply risk for both the energy and water sectors. Variability in the water supply and competing needs are forcing traditional power plants to reduce generation in many countries; meanwhile, securing reliable and affordable energy inputs for water systems is increasingly a challenge. Renewable energy technologies are capable of playing a key role in addressing some of the most challenging aspects of the water–energy nexus. This section reviews practical applications of renewable energy in managing the water–energy nexus.

2.2.1 Renewable energy for water supply

Water use is inextricably linked to energy supply, requiring energy inputs for every step. The supply chain for water starts with a source, then water is extracted (*e.g.*, pumping of ground water) and conveyed – moving directly to an end-use (*e.g.*, irrigation, commercial) or to a treatment or desalination plant, from where it is distributed to customers. Once used, the water is discharged back to a source – with or without treatment. In some cases, treated water may be re-used for tertiary use by industries, as in the case of eThekwini Municipal Water and Sanitation Unit in South Africa (WSP, 2009). Energy inputs (and outputs) are spread across this supply chain, and renewable energy can be utilised at different stages. Although renewable energy may not reduce the energy intensity of the processes, it may reduce the environmental footprint and can be particularly useful in off-grid applications to increase access to reliable water services.

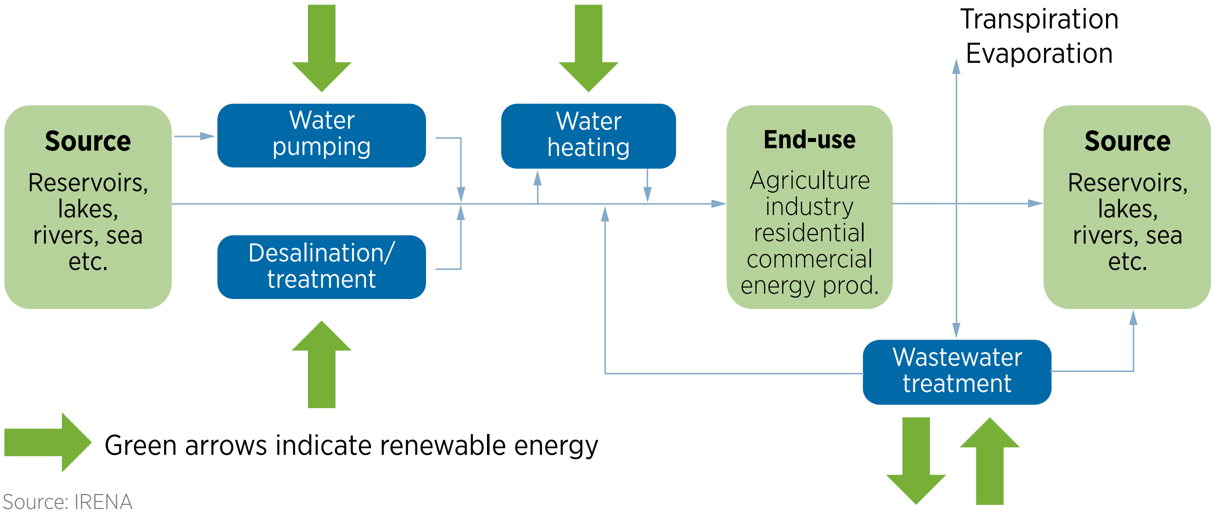
Renewable energy intervention along different segments of the water supply chain can enhance water security and ease the water–energy nexus. Figure 2.2 depicts the water supply chain and identifies the various segments – water pumping and conveyance, desalination and heating – where renewable energy can provide access to sustainable and secure energy and replace conventional energy sources. Additional opportunities for renewable energy integration also emerge from wastewater treatment (see box 2.1).

It is important to note that the water supply chain could cover vast geographical spaces between source and end-use. Given the water scarcity situation, large-scale inter-basin water transfers at the national level (and increasingly at the regional level) are becoming the norm to meet growing water needs. The transfer of larger volumes of water across longer distances likely will mean that the hydraulic infrastructure will require substantially more energy inputs, causing an increase in the embodied energy intensity of water provision.

Water pumping and conveyance

Water pumping is a major energy consumer within a traditional water supply chain. Delivering water originating from surface or underground water sources to treatment plants requires significant energy inputs. Within the water sector, two distinct contexts exist. The first is remote areas where access to energy is limited or non-existent and where water sources are far from rural communities, requiring locals either to travel long distances to procure water or to rely on intermittent and expensive delivery mechanisms such as diesel pumps or periodic water deliveries. The second context is relatively developed water supply chains where energy, most notably in the form of grid electricity, is available, but concerns

Figure 2.2 Renewable energy across the water supply chain



Source: IRENA

about affordability and the environmental impact of water supply are compelling utilities to explore alternate energy solutions.

Around 1.2 billion people, or nearly one-fifth of the world's population, live in areas of physical water scarcity. Another 1.6 billion people, or almost one-quarter of the world's population, face economic water shortage, meaning that their countries lack the necessary infrastructure to take water from rivers and aquifers (UNDESA, n.d.). Groundwater, in particular, is an essential source of life and livelihood. It serves as a vital source of freshwater for domestic and agriculture uses. Extracting groundwater, however, requires pumping, which in turn requires large energy inputs, commonly in the form of electricity and diesel fuel.

India is the largest user of groundwater for agriculture accounting for nearly 80% of all freshwater use. Most of India's estimated 26 million agriculture pumps are driven by highly subsidised electricity or diesel, including at least 12 million grid-based (electric) pumps and 10 million diesel-operated irrigation pumpsets (Tweed, 2014; IGEP, 2013; CEEW, 2013). This poses a tremendous challenge for the long-term socio-economic stability of the country's energy and water supply systems. India alone spends over USD 6 billion on energy subsidies annually, and farmers pay only an estimated 13% of the true cost of electricity (Casey, 2013). This subsidised energy for groundwater pumping also contributes to overdraft of groundwater. As water levels drop, more power is needed to retrieve water, thus increasing the energy intensity of water extraction.

Solar-based pumping solutions offer a cost-effective alternative to pump sets that run on grid electricity or diesel. The large-scale deployment of solar pumps can bring multiple benefits including expansion of water services to underserved communities and unirrigated lands, while reducing dependence on grid electricity or fossil fuel supply. Their use also helps mitigate the local environmental impacts of using diesel, enhance

BOX 2.1

WASTEWATER TREATMENT

Following its use, water is either treated or discharged directly into the environment. Synthesising what data there are on wastewater treatment, on average, high-income countries treat 70% of the waste water generated, upper-middle-income countries 38% and lower-middle-income countries 28%. In low-income countries, just 8% of the waste water generated undergoes any kind of treatment (UNU, 2013).

Wastewater treatment includes energy inputs for collection, treatment and discharge. In the United States, these processes consume a combined 3% of total electricity use, with similar rates in other developed countries (Water in the West, 2013). Most of this energy goes into pumping water from the source and to the practice of aerating waste during aerobic treatment. The solids recovered after treatment are usually treated, re-used for fertiliser, or incinerated or deposited in landfills. The higher the production of solids, the more energy is needed for disposal or incineration. In developing country settings, the inability to provide the required stable energy supply has been a major contributor to the failure or abandonment of wastewater treatment plants.

Waste water itself holds immense potential for energy production. The energy contained in waste water and biosolids exceeds the energy needed for treatment by 10-fold (WERF, 2011). Biogas from anaerobic treatment and the end-product biosolids are a large source of energy and can be used to generate energy on-site. Biogas can be used directly for combined heat and power (CHP) production. Significant amounts of biosolids already are incinerated (without energy production) or put in landfills, and could be utilised for energy production. These technologies have received significant attention, are proven to be cost effective and known to be predictable.

overall grid stability in agrarian economies and reduce electricity and fossil fuel subsidy burdens. The technology is mature and has been successfully deployed at scale. The two phases of the Regional Solar Programme (RSP), launched by the Permanent Interstate Committee for Drought Control in the Sahel in 1986, have deployed 995 solar pumping stations and 649 community systems, providing improved access to water and electricity to 2 million people. These systems have been operating successfully and reliably for over 10 years. By the end of the second phase in 2009, the population without access to safe drinking water had dropped by 16% in the Sahel countries of West Africa (IRENA, 2012a).

Recognising the benefits, several countries have launched programmes to promote solar pumping (see also box 2.2). For example:

- India announced plans to replace many of its 26 million groundwater pumps for irrigation with solar pumps (Tweed, 2014). Should half of the

BOX 2.2

SOLAR IRRIGATION IN KENYA

A viable alternative to manual pumping and to environmentally polluting fossil fuel-powered generators

There are an estimated 2.9 million smallholder farmers in Kenya, and only 6% of the farmland is irrigated. Lack of access to energy for irrigation is one of the main factors limiting the productivity of small farms. Different forms of manual pumping technologies, such as treadling pumps, exist, but they are labour-intensive, physically exhausting and appropriate only where water tables are shallow.

Diesel or petrol-powered engine pumps offer an alternative, but they also pose environmental risks and have volatile operational costs depending on the price of fuel, along with a limited lifespan of 3-5 years. Small-scale irrigation systems based on renewable energy could provide a viable alternative. Solar-powered pumps can provide decentralised pumping for the expansion of irrigation and hence cultivated areas, which directly translates into increased income for small holders due to increased and/or more stable yields.

One of the solar-based irrigation solutions is the Sunflower solar-powered water pump. Field trials involving ten pumps at pilot farms in Ethiopia and Kenya (supported by the Renewable Energy and Energy Efficiency Partnership, REEEP) demonstrate that the system is able to provide water yields up to 20 000 litres per day and can operate at pumping depths of 0–15 metres (ideally 6 metres). The system has a low capital cost of around USD 400, which can be offset by savings on fossil fuels, depending on local prices and availability of fossil fuels. With a lifespan of 20 years, the financial break-even point is usually two years.

The programme is targeting 5 000 pumps by 2015 and 30 000 by 2018, resulting in 56 000 tonnes of CO_2 displaced. In addition to displacing fossil fuels, solar pumps free children and women from the time-consuming task of manually pumping and carrying water, while also resulting in employment generation from manufacturing, assembly, repairs and sales of pumps.

To ensure the adoption of solar pumping solutions, financing schemes, such as credit mechanisms, need to be in place as well as capacity-building programmes to ensure that technical skills are available for system maintenance needs over time. Moreover, a key risk is the possibility of over-pumping. Although groundwater represents an invaluable source of irrigation water, it has proven to be difficult to regulate. Locally intensive and continuous groundwater withdrawals could exceed rates of natural replenishment, which would have negative consequences for local and global food production and therefore need to be managed adequately.

Source: REEEP, 2014; FAO, 2014b

country's 10 million diesel pumpsets be replaced with solar systems, it could lead to savings of nearly 18.7 GW worth of installed capacity, 23.3 billion units of electricity, 10 billion litres of diesel and 26 million tonnes of CO_2 emissions (CEEW, 2013). India has also recently announced a solar energy-based pump piped water supply programme to deploy 20 000 solar pumps in select tribal and backward districts to expand access to piped water (Indian Ministry of New and Renewable Energy, 2014).

- Under the Moroccan Green Plan (Plan Marocain Vert), the government-owned bank Crédit Agricole of Morocco will distribute a USD 300 million grant to install 100 000 solar pumps by 2020 (IFC, 2014).
- In South Africa, where 67% of agri-energy use comes from diesel, solar pumping represents a USD 195 million market, assuming just a 10% conversion of the 265 000 traditional pumpsets currently deployed (IFC, 2014).
- Tunisia's 2008 Renewable Energy plan included measures to develop renewable energy in the agricultural sector, with 200 large water-pumping stations for irrigation systems powered by hybrid technologies (REN21, 2013).

The large-scale adoption of solar-based water pumps is still hindered by a variety of factors. The relatively high capital cost of solar pumping systems is a key barrier, requiring end-users to have access to affordable credit or other forms of financial support. Other challenges include initial inertia associated with introducing new technologies, establishing distribution channels for technology and post-sales services, and ensuring adequate training for installers and operators.

There is also evidence of risks that solar-based pumping poses for water resources. In India and China, for instance, where a substantial number of solar PV-based pumping systems have been deployed, additional risk associated with excessive water use has emerged. Since the operational cost of PV pumps is negligible and the availability of energy is predictable, it could result in overdrawing of water. To mitigate this risk, many of the solar pumping promotion programmes package financial support with deployment of drip irrigation technology. Although drip irrigation technology can improve the efficiency of water use, it also is more capital and energy intensive, may not be the most suitable irrigation option for all contexts and may limit the amount of water that seaps to acquifers, which could in turn reduce the replenishment of groundwater sources.

In more developed contexts, water utilities are increasingly exploring ways to reduce energy consumption and enhance the resilience of their supply networks. Improving efficiency of water supply infrastructure by fixing leakages is among the most effective ways to reduce expenditure on energy. Energy costs account for the largest share of a water utility's operating budget – as much as 30% to 55% by some estimates (Atkinson, n.d.; ESMAP, 2012). Variation in the cost of electricity supply introduces risks for the cost structures of water utilities, especially in contexts where decision-making processes for water and electricity pricing are independent. To decouple water supply from external energy inputs, several utilities are beginning to introduce renewable energy solutions along different stages of the supply chain. Box 2.3 gives examples of two water utilities in the United States that have deployed solar technologies to meet part of their electricity needs for water pumping and to improve the reliability of their supply.

Powering desalination

Desalination technologies will play an increasing role in bridging the water gap in many countries. There are 16 000 desalination plants operational worldwide today, with a total operating capacity of 70 million m^3 per day. Desalination capacity is poised for substantial growth in the coming decades as countries explore alternate solutions to meet growing water demand. In the MENA region, for instance, the shortage of water (approximately 9.3 billion m^3) will be met mostly through desalination by 2050 (World Bank, 2012). The expansion of desalination will require a careful consideration of its social, economic and environmental impacts as well as its associated energy demand.

Desalination is the most energy-intensive water production technique available today. It consumes at least 75.2 TWh of electricity per year, equivalent to around 0.4% of global electricity consumption (UN Water, 2014c). Most of the energy required for desalination presently comes from fossil fuels, with less than 1% of capacity dependent on renewables (IRENA and IEA-ETSAP, 2012). As the number of desalination plants increases, dependence on fossil fuels is no longer sustainable from an economic and environmental perspective. Considering that energy and water pricing frameworks in most countries do not reflect the full production costs, the burden on governments of using expensive desalination techniques will likely increase further.

Renewable energy technologies offer the opportunity to decouple water production from fossil fuel supply. Major desalination technologies consist of thermal processes using either thermal power or electricity as energy input, or membrane-based processes that use only electricity (see box 2.4 for an overview of the major desalination technologies). Depending on the desalination technology, there are different ways in which renewable energy can provide the thermal or electricity inputs. Figure 2.4 illustrates the potential pathways for integrating different renewable energy technologies with desalination technologies. As seen in box 2.4, the type and intensity of energy required for desalination depends on the technology adopted and hence,

BOX 2.3

WATER UTILITIES GOING RENEWABLE

The case of water utilities in the United States and South Africa

In the United States, the Valley Center Municipal Water District (VCMWD), which has a service area of over 260 km^2 in San Diego County, California, announced the installation of a 1.1 MW solar power system in 2009. The system provides 2.1 GWh per year, offsetting up to 20% of the electricity required by the utility's largest pumping station. The project was financed through a 20-year power purchase agreement with a developer, and VCMWD procures the electricity generated by the system at a rate below the utility's price.

The Idyllwild Water District (IWD) near Palm Springs, California, deployed a 44.1 kW solar PV system to run 57 horsepower of pumping capacity for 11 different well pumps and booster motors, ranging in size from 1.5 to 15 horsepower. The system provides 83% of the district's electricity. The main value of the system is in increasing the reliability of water supply. In times of high wind speeds, the electricity utility used to give IWD only 10-15 minutes' notice when it would shut off electricity, so that trees falling on power lines did not start fires. Without electricity, IWD was unable to pump drinking water to its customers, unless it resorted to back-up diesel power generation. In addition, IWD would receive requests from the electricity utility to shut down pumps to ensure grid reliability. Switching to solar has allowed the utility to shield itself from many such dynamics that can affect its reliability of supply. The solar system also brings in credits for IWD by feeding back power into the grid that can be utilised when night-time pumping is necessary.

In South Africa, eThekwini Water and Sanitation is a utility that serves over 3.5 million people living in the Durban metropolitan area. With active support from REEEP, the utility is taking efforts to identify tangible and profitable opportunities to install mini-hydro plants ranging from 100 kW to 1 MW on existing water supply infrastructure. Instead of using pressure-reducing valves in pipes running down steep hillsides, the company is installing mini turbines, using the excess pressure to generate power for the city's low-tension grid. In this manner, the project aims to realise the potential for renewable energy in water treatment and supply, maximise overall benefits from the infrastructure and its impacts, reduce greenhouse gas emissions and provide a replicable model for other regional water managers nationwide. It would also allow the process/framework to be shared with other council areas, including rural areas of northern Kwazulu-Natal where water and power availability is limited.

Source: Breslin, n.d.; IWD, n.d.; REEEP, 2014 specific pairings between renewable energy and desalination technologies have emerged, such as PV or wind reverse osmosis (RO), and CSP multi-effect desalination (MED).

Renewable energy-based desalination covers a wide array of technologies that are at various stages of technological development and address different market segments. Figure 2.5 compares

BOX 2.4

SUMMARY OF MAJOR DESALINATION TECHNOLOGIES

Thermal desalination technologies involve distillation processes where saline feed-water is heated to vapour, causing fresh water to evaporate and leave behind a highly saline solution (brine).

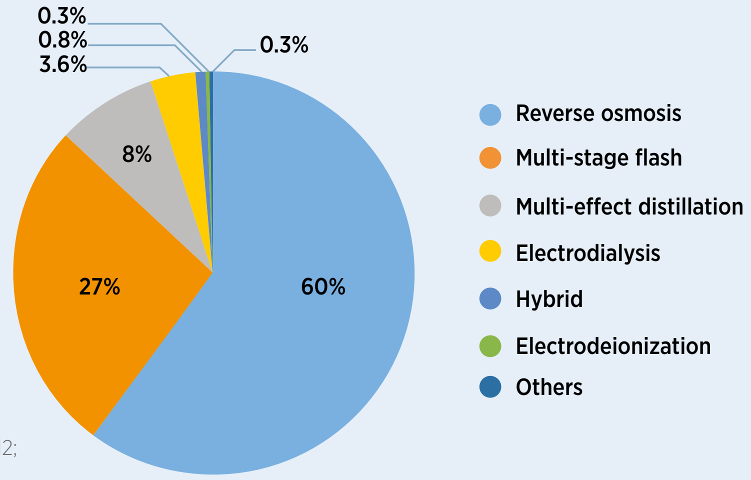
- The **Multi-stage flash (MSF)** process is divided into sections or stages. Saline water is heated at the boiling temperature with a decreasing pressure through the stages. Part of the water flashes (quickly vaporises) at each stage, while the rest continues to flow through the remaining stages. Because the MSF process can be powered by waste or by-product heat, it enables the combined production (cogeneration) of power, heat and desalinated water.
- **Multi-effect distillation (MED)**, similar to MSF, is a multi-stage process wherein vapour from each vessel (stage) is condensed in the following vessel and vaporised again at reduced ambient pressure. MED, unlike MSF, allows the feed-water to be processed without the need to supply additional heat for vaporisation at each stage.
- **The vapour compression (VC)** distillation process, where the heat for water evaporation comes from compression rather than from direct heating, generally is used in combination with other processes, such as MED, to improve overall efficiency.

Membrane desalination technologies use membranes to separate fresh water from saline feed-water. Feed-water is brought to the surface of a membrane, which selectively passes water and excludes salts.

- **Reverse osmosis (RO)** involves passing saline water through a semi-permeable membrane at a pressure greater than the osmotic pressure, thereby leaving the solid salt particles behind. RO plants are very sensitive to the feed-water quality (salinity, turbidity, temperature), while other distillation technologies are not as sensitive.
- **Electrodialysis (ED)** is another membrane processes that uses electrical potential to move salt through the membrane, leaving fresh water behind. Currently, ED is used widely for desalinating brackish water rather than for seawater.

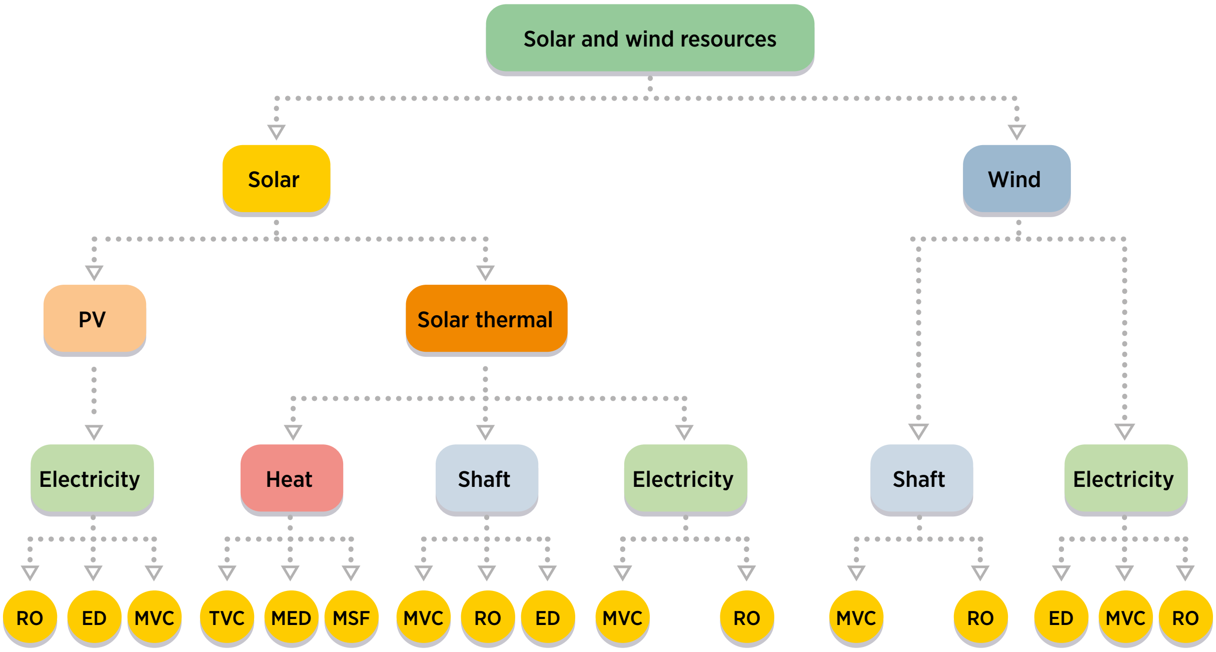
The dominant desalination processes in use today are RO and MSF (see figure 2.3).

Figure 2.3 Desalination capacity by technology



Source: IRENA and IEA-ETSAP, 2012; IDA in Koschikowski, 2011

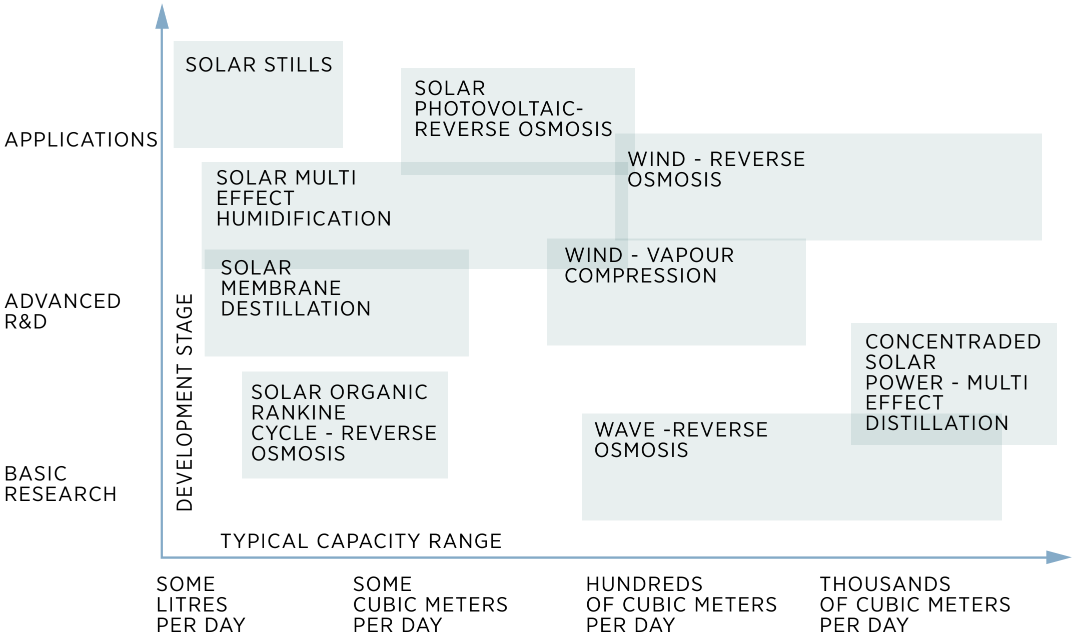
Figure 2.4 Pathways for integrating solar and wind resources with different desalination technologies



Source: Karaghouli, Renne and Kazmerski (2009)
Note: MED = multi-effect desalination, MSF = multi-stage flash, TVC = thermal vapour compression, ED = electrodialysis, RO = reverse osmosis, MVC = mechanical vapour compression

the main renewable energy-based desalination technologies based on the development stage and typical capacity scale. As such, solar stills, solar PV and wind-based RO plants are commercially available and deployed at scale. Most of the renewables-based desalination capacity deployed today is based on solar RO technology (IRENA and IEA-ETSAP, 2012).

Figure 2.5 Development stage and capacity range of the main renewable energy-based desalination technologies



Source: ProDes, 2010

Such technologies are generally deployed at the community level (see box 2.5), but they are increasingly being deployed at a larger scale for island applications[4]. Additional uses are emerging in the food sector, with seawater desalination meeting water needs for irrigation in arid regions (see box 2.6). An area of substantial research is the use of CSP-based desalination, which has the potential to cater to large water needs, especially in the MENA region.

Concentrated solar power (CSP) with thermal energy storage shows significant potential for combined production of electricity and fresh water in the MENA region. If used, CSP-based desalination could become a major source of water in the MENA region, potentially accounting for about 16% of total water production in 2030 and 22% in 2050 (DLR, 2011). The benefits offered by CSP-based desalination include:

- By design, CSP plants collect solar radiation and provide high-temperature heat for electricity generation, making it possible to integrate them with both membrane desalination technologies, such as RO, and thermal desalination units.
- CSP plants can be equipped with thermal storage systems. This allows cogeneration plants to better cope with the different load profiles of water and electricity demand without affecting plant efficiency.

Despite tremendous potential, the development of large-scale CSP-based desalination plants has limitations that need to be overcome. The smooth and efficient coupling of existing desalination technology with CSP plants is a technological challenge (World Bank, 2012). Most utility-scale desalination technologies require continuous energy supply, which CSP plants can provide when equipped with thermal storage systems and/or combined with conventional power plants for hybrid operation. Desalinated water itself can provide a storage opportunity in the case of electricity generation exceeding the demand (IRENA and IEA-ETSAP, 2012).

From an economic point of view, continued focus on research, development and innovation is necessary to reduce costs, increase reliability and demonstrate the effectiveness of the technology in sustainably meeting water and energy needs.

Energy is the largest single expense for desalination plants, representing as much as half of the production cost (Herndon, 2013). In general, desalination based on renewable energy sources is still expensive when compared to conventional desalination (see figure 2.6).

BOX 2.5

SOLAR-POWERED REVERSE OSMOSIS DESALINATION PLANT: VILLAGE-LEVEL INTERVENTION

Nearly 100 villages surround India's Sambhar Lake, a large saltwater lake that drives the rural economy, which relies on salt production. Salinity levels are high, and, despite significant evaporation, the water remains too brackish to drink or to use for cooking and cleaning.

A solar-based RO plant was set up at Kotri, a small village of 300 families in the Ajmer District of Rajasthan. The plant meets the drinking water needs of more than 1 000 residents from Kotri and surrounding villages. The brackish water from Sambhar Lake is pumped through the RO plant and stored in a 5 000 litre tank. The RO plant runs on a 2.5 kW power plant that allows it to produce 600 litres of water an hour for six hours each day, reducing the salinity levels enough to make the water safe for consumption.

The village, although connected to the grid, receives erratic power supply (often no more than three hours per day). Integrating RO plants with solar ensures an uninterrupted supply of electricity for six hours, including power to spare for running a computer, a solar workshop, fans and light.

Source: Barefoot College, n.d.

---

[4] The specific aspect of renewable energy-based desalination in island contexts will be dealt with in greater detail in IRENA and Fraunhofer ISE's forthcoming publication, Technology Options for Renewable Desalination on Islands.

BOX 2.6

SOLAR THERMAL-BASED GREENHOUSE DEVELOPMENT

Meeting water, energy and food security objectives

In arid environments where fresh water is in short supply and domestic food security is a concern, the development of greenhouses is being seen as a key opportunity. Greenhouses can produce the same yields as open farming, but using only 10% of the water (Masudi, 2014). To make projects more viable, solar power can be used to run the greenhouses and provide both energy and water needs.

One such technology is the Sundrop System, which harnesses solar thermal energy to desalinate seawater to produce fresh water for irrigation; to produce electricity to power a greenhouse; and to provide the energy to heat and cool the greenhouse (Saumweber, 2013). Moreover, nutrients that end up as by-products from the desalination process can be converted into fertiliser that in turn can be used within the greenhouse (Kaye, 2014).

Such systems can have a competitive advantage over traditional greenhouses that generally are very energy intensive and rely primarily on fossil fuels to regulate the interior climate. Building a solar field and the necessary auxiliary equipment for desalination, heating and cooling provides the project with free climate control and water throughout its lifetime. The upfront costs of solar-based greenhouses are known to be lower than the present-value annual cost of fossil fuels for traditional greenhouses in the same location (Saumweber, 2013). These systems can be located on marginal land in regions with high sunshine, possibly between the desert and ocean, where climatic conditions are suitable.

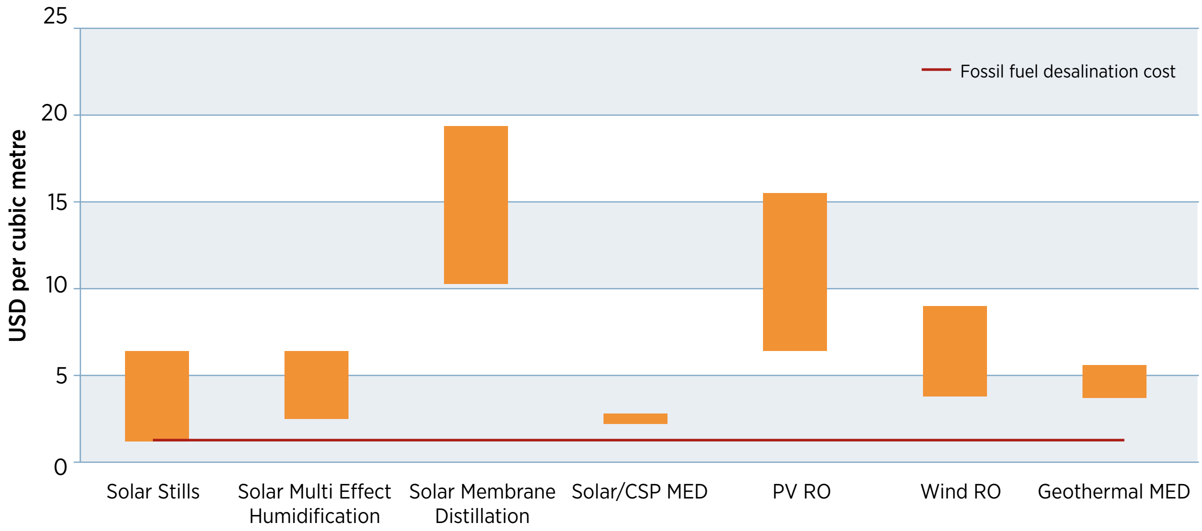
The Australian Government's Clean Energy Finance Corporation is co-financing the construction of a 20-hectare greenhouse facility in Port Augusta that, when completed in 2015, will have a capacity to produce 10 000 litres of desalinated water per day and over 15 000 tonnes of vegetables a year for metropolitan markets across Australia (WWF and CEEW, 2014). Such technology solutions can be replicated in the Middle East, which faces extreme constraints on arable land and water resources and is experiencing food security risks. In such regions, the cost-effectiveness of solar desalination is enhanced when irrigation use is combined with climate control or electricity production (Saumweber, 2013).

With decreasing renewable energy technology costs, technology advances and increasing scale of deployment, renewable desalination is likely to become significantly more cost effective and to represent a key solution to mitigate growing development risks posed by resource constraints. The competitiveness of renewable desalination is further enhanced when volatile fossil fuel costs are taken into account.

Desalination plants are already proving cost effective in remote regions where the cost of delivering fossil fuel-based energy is high (Shatat, Worall and Riffat, 2013). In Milos Island (Greece), for example, a RO desalination plant constructed in 2008 integrates wind energy. The plant is designed to cover the island's rising demand for potable water and to supply high-quality water on a 24-hour basis at a lower cost than before the plant's establishment. Utilising locally sourced wind energy has meant that the island does not have to rely on expensive ship-based deliveries of water and fuels from the mainland (Regions202020, 2011).

Countries are increasingly recognising the opportunity for deploying renewable-powered desalination. In 2010, Saudi Arabia announced the King Abdullah Initiative for Solar Water Desalination, which aims to enhance the country's water security and support the national economy by developing low-cost solar-based desalination technology (see box 2.7). The UAE is also assessing solar power for desalination. In May 2014, Masdar signed contracts for four pilot projects that use highly energy-efficient membrane technologies

Figure 2.6 Technology cost comparison of renewable energy-based desalination versus fossil fuel-based plants



Source: Based on IEA-ETSAP and IRENA, 2012 and CEBC, 2013

to produce around 1 500 m^3 of water per day. If successful, they are expected to pave the way for renewable energy to power electricity-driven desalination at a large scale.

Water heating

Heating water for domestic and commercial use is among the most energy-intensive parts of the water cycle (Plappaly and Lienhard V, 2012). On average, water heating constitutes 15% of household energy use in Europe, 18% in the United States and around 30% in Japan (Leonardo Energy, 2012). In developing countries, water heating is often the most energy-intensive process and accounts for a relatively high share of the energy budget. Depending on the energy source used (electricity, natural gas, oil), water heating can make up over 90% of the total energy inputs along the water cycle (from source to end-use to treatment) for households and business (based on data from Plappaly and Lienhard V, 2012). Moreover, substantial use of electricity for water heating can increase peak demand, having a destabilising impact on the power system and represents an inefficient energy-conversion process, especially in developing countries where transmission and distribution grid losses can be high.

Renewable energy sources, such as geothermal and solar, are being adopted increasingly to replace electricity and fossil fuel use for water heating. In particular, the global capacity of solar water heating grew to 326 gigawatts-thermal (GW$_{th}$) in 2013 (see figure 2.7). Most solar thermal systems are used for domestic water heating, where they typically meet 40-80% of demand. Emerging applications include deployment of larger water heating systems for community centres, hospitals, hotels, etc., as well as of hybrid systems that provide both water and space heating.

Hybrid systems are common across Europe, representing about 40% of installed systems in Austria and Germany. District heating systems that rely on solar thermal technology and that are often combined with other renewable heat sources, such as biomass, are also rising in prominence. At least 17 plants larger than 700 kilowatts-thermal were constructed in 2013 and the world's largest solar district heating plant began operating in Dronninglund, Denmark[5] in early 2014 (REN21, 2014).

Globally, solar water heating technologies already have realised substantial energy and emissions savings. In 2012, gross solar thermal collector yield totalled 227.8 TWh worldwide, with the majority (82%) of this going to domestic hot water applications. The annual energy savings in 2012 amounted to 284.7 TWh, or 24.5 million tonnes of oil equivalent (see figure 2.8) (IEA SHC, 2014).

---

[5] The system, which is planned to provide about 15 000 MWh per year, consists of 2 982 collectors with a total solar thermal capacity of 26 MWth (37 573 m^2) and a 61 700 m^3 seasonal pit heat storage. Its output will meet half of the annual heat demand of the plant's 1 350 customers (Solarthermalworld, 2014).

BOX 2.7

SAUDI ARABIA: KING ABDULLAH INITIATIVE FOR SOLAR WATER DESALINATION

Desalination is regarded as a strategic choice to meet growing demand for water in an environment of scarce conventional water sources. The high cost of energy used in desalination plants is the primary cause of higher water production costs. In Saudi Arabia's case, many of the 35 desalination plants that presently generate over 5 million m^3 of drinking water (equivalent to more than 18% of the global daily desalination output) consume valuable oil resources. Given the country's abundant solar resources, utilising solar energy for desalination can reduce the cost of energy inputs and in turn the cost of water production.

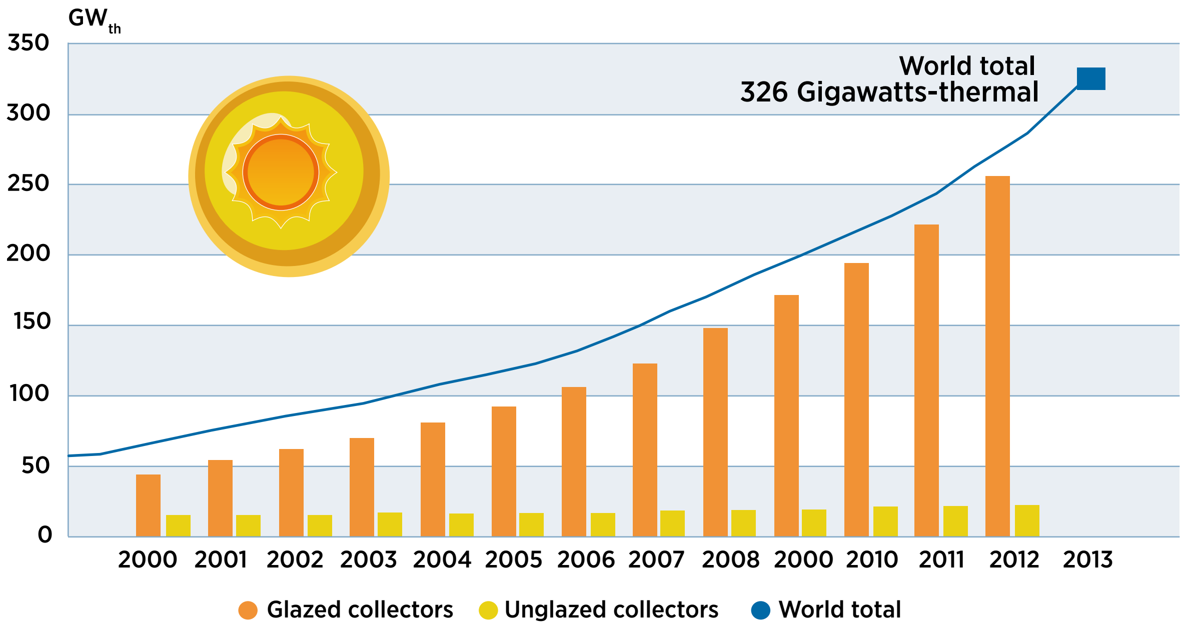
The King Abdullah Initiative for Solar Water Desalination is a key initiative of the National Plan for Science, Technology and Innovation led by King Abdulaziz City for Science and Technology.

The initiative is to be executed in four phases:

- Building a desalination plant powered by solar energy with a capacity of 30 000 m^3 per day of water to meet the drinking water needs of Al Khadji city. The project will use 10 MW solar systems as well as domestically developed membranes.
- Building a desalination plant capable of producing 300 000 m^3 of drinking water per day, enough to meet the needs of 1 million inhabitants.
- Building a series of solar-powered desalination plants in various parts of the country.
- Implementing the initiative in the agricultural sector.

Source: KACST, 2014

Figure 2.7 Solar water heating collectors global capacity, 2000-2013



Data are for solar water collectors only (not including air collectors)

Source: REN21, 2014

The cost of heat production depends on the technology deployed, as well as on the size and location of the installation, solar water heaters are generally competitive with electricity and gas-based heating (see figure 2.9). In Europe, the most cost-effective solar thermal application is solar district heating in Denmark, where heat prices as low as USD 43/MWh$_{th}$ can be reached for ground-mounted collector fields of 10 000 square metres (m^2) and more (IEA, 2014b).

As with most renewable energy technologies, solar water heating systems are upfront-cost heavy, meaning that the ratio of capital to operational cost is relatively higher compared to conventional systems. Over a life cycle, however, solar water heaters are markedly cheaper. In China, solar water heaters cost an estimated 3.5 times less than electric water heaters and 2.6 less than gas heaters over the lifetime of the system (REN21, 2013). In South Africa, solar water heating systems typically pay back within five years (Eskom, 2011).

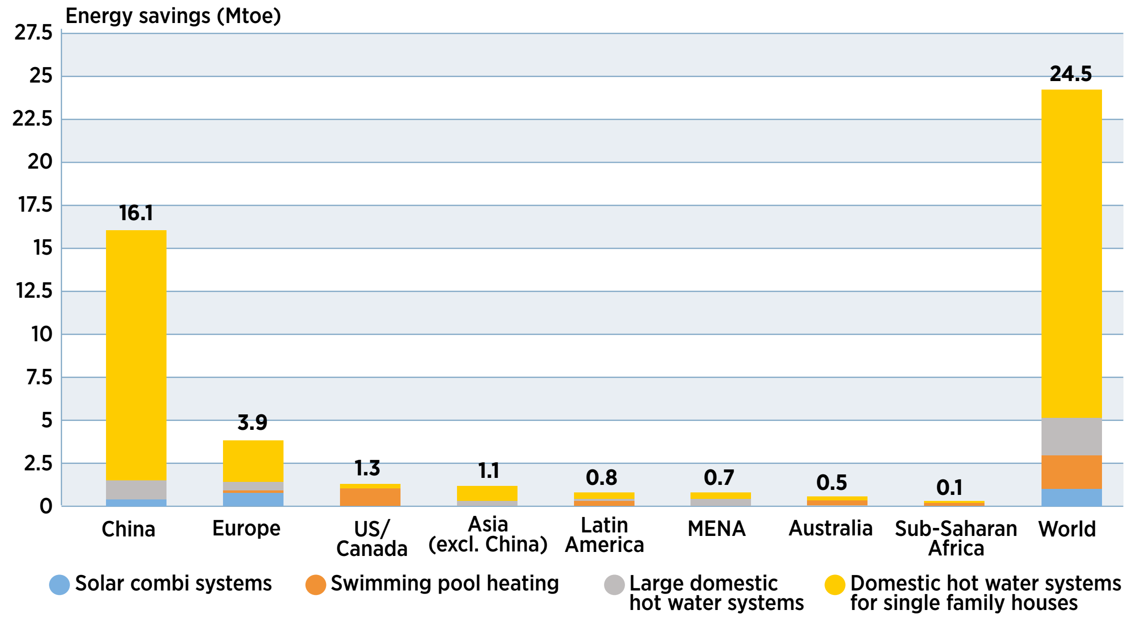
Many governments have pursued ambitious programmes to promote solar water heating to reduce electricity and fuel demand, improve energy services and build a domestic industry. China has the world's highest installed capacity of solar water heaters, accounting for nearly two-thirds of global capacity. Between 2000 and 2012, installations increased nearly 10-fold from 26 million m^2 to more than 250 million m^2 (IRENA, 2014a). In 2012, Brazil had over 5.7 GWth of solar water heating capacity deployed, aiming to avoid the equivalent of 1.2 GW of additional electricity capacity (IEA SHC, 2013; REEEP, 2010).

Several programmes have been launched to support market development, including Minha Casa, Minha Vida ("My House, My Life") which, along with several municipal building codes (*e.g.*, São Paolo, Belo Horizonte and Porto Alegre), mandates solar water heaters to be built in new housing for low-income families (IRENA, 2012b; Cardoso, 2013).

In Tunisia, the PROSOL programme, launched in 2005, has contributed to a near 10-fold increase in installations from 2004 to 2011, producing a market turnover of USD 25 million in 2011 for the country's solar thermal industry. A nascent domestic industry has sprung up, with 49 solar water heater suppliers (of which 10 are manufacturers) and over 400 qualified installers – creating a total of 7 000 direct jobs since the start of PROSOL (REN21, 2013).

South Africa targets replacing 10 000 gigawatt-hours (GWh) of current electricity generation by

Figure 2.8 Annual energy savings in oil equivalent from unglazed and glazed water collectors in operation by the end of 2012



Source: IEA SHC, 2014

switching electric water heating systems to solar, while island countries, such as Cyprus, are adopting solar water heating to reduce the cost of energy supply and enhance energy security. Cyprus has the highest solar water heating capacity installed per capita globally. More than 93% of households and 52% of hotels are equipped with solar water heating systems, and nearly 750 000 m^2 of solar thermal collectors are installed (Epp, 2014). These have contributed to increasing the share of renewables in the energy mix from 3.8% in 2005 to almost 9% in 2013, thus reducing dependence on foreign imports to meet domestic energy demand (IRENA, 2014c).

2.2.2 Water for energy production

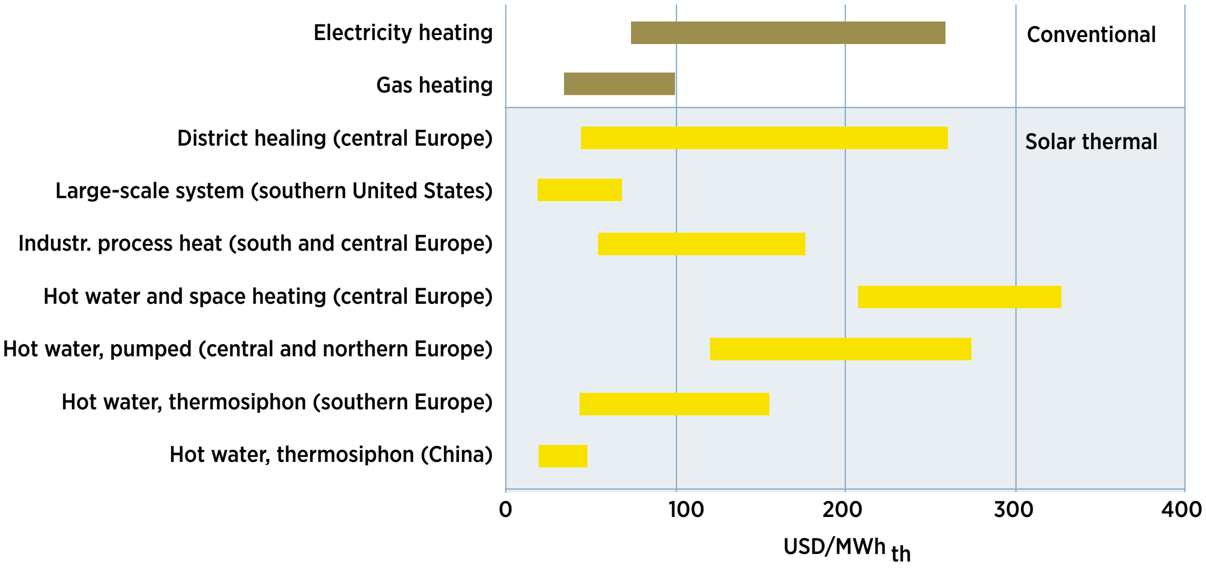
Water use for energy production represents a critical element of the water–energy nexus. As highlighted in chapter 1, energy production globally accounts for about 15% of total freshwater withdrawals, second only to agriculture. The energy system of today, dominated by oil, coal and natural gas, is water intensive in nature, requiring substantial water inputs for fuel extraction, processing, transport, transformation, end-use and, where applicable, decommissioning. Although measures are being taken within the energy sector to reduce water use, the availability and accessibility of water resources will remain a key constraint as the sector scales to meet growing demand. This section delves deeper into the overall impact of a transforming energy mix on the water–energy nexus, based on the literature and on preliminary quantitative analysis conducted by IRENA.

Water intensity of different energy technologies

Evaluating the water intensity of different energy technologies requires an understanding of water inputs along the different stages of the energy supply chain. As illustrated in figure 2.10, the energy supply chain can be divided into three basic stages: fuel extraction, processing and transportation; energy transformation (*e.g.*, generation of electricity) and end-use. The impacts on withdrawal, consumption and quality of water resources along these different stages is dictated by how, where and what energy sources characterise the supply chain, as well as by other factors such as the technology choice, water source and fuel type.

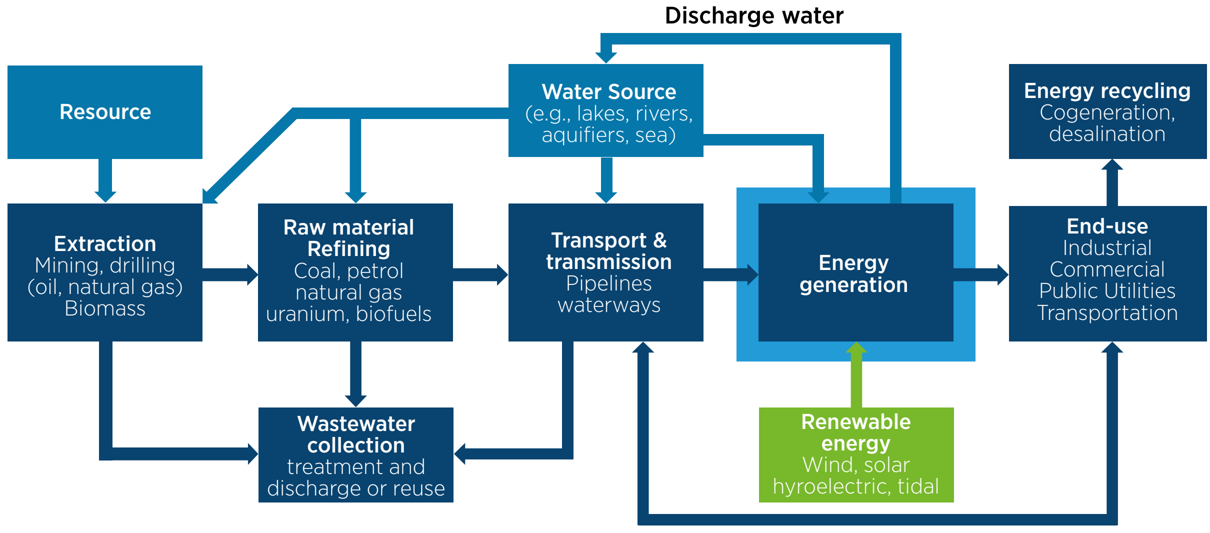
Renewable energy resources are often freely available and require minimal fuel extraction, refining or transportation. Water inputs for solar, wind, geothermal, tidal and hydropower

Figure 2.9 Solar heat production costs compared with electricity and natural gas-based heating in different regions



Source: IEA, 2014

Figure 2.10 Flow chart of embedded water in energy



Note: Water inputs and outputs may be in different water bodies.

Source: Water in the West, 2013

development during these stages can be considered negligible[6]. Bioenergy, however, requires water inputs for feedstock production, processing and transportation. These water inputs vary depending on whether irrigation is necessary, and, if so, on the irrigation method adopted, crop type, local climatic conditions and technology choices (see figure 2.11). Irrigated feedstock production, for example, could require substantial volumes of water, whereas rain-fed production or agricultural and forestry residues may not be as water intensive.

Even when considering the ranges for water inputs, bioenergy feedstock production could drive a substantial increase in overall water demand, depending on energy and climate scenarios (Chaturvedi et al., 2013). However, impacts of bioenergy production on water availability and quality could be managed by implementing judicious water policy instruments and legislation for both feedstock production and energy conversion, as well as by effectively monitoring the competition between sectoral uses of water (UNEP, 2011). At the same time, continued focus on the development of technologies and processes is necessary to enhance the water efficiency of traditional bioenergy production and to tap into other forms of feedstocks, such as second-generation fuels and algae, which may have lower water needs (IRENA and IEA-ETSAP, 2013).

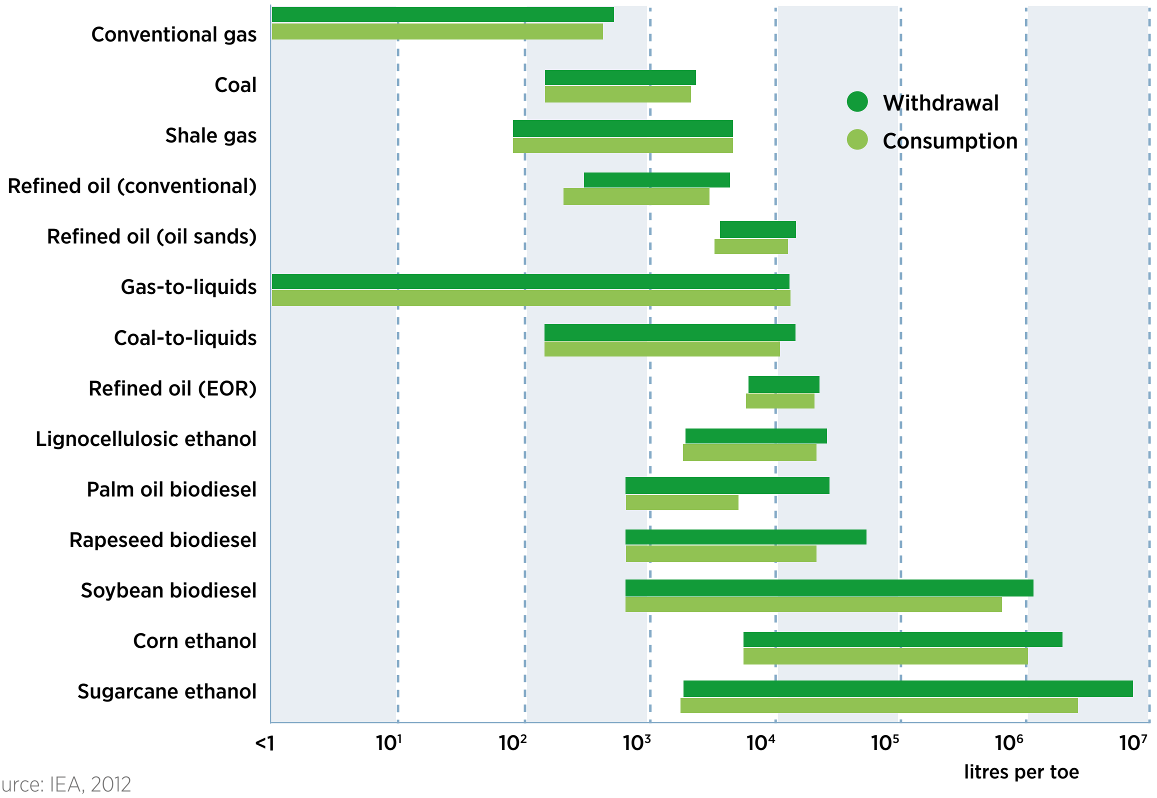
Developing nuclear energy and fossil fuels such as oil, natural gas and coal involves fuel extraction, including mining and drilling, requiring water. A broad range of literature, which takes into account different geography, geology, extraction methods and well-depletion levels, estimates that oil extraction requires 3.0-8.3 litres per million Btu for drilling, flooding and treatment (Water in the West, 2013). Water requirements for conventional oil extraction are relatively minor. Secondary recovery techniques that use water flooding to support reservoir pressure have water needs about 10 times those of primary recovery. Similarly, producing synthetic crude oil from oil sands is comparatively more water intensive (IEA, 2012). On average, oil extraction, processing and transport uses more water than for natural gas, coal or uranium (Wu et al., 2009; Gleick, 1994; NREL, 2011), as also confirmed in IEA's World Energy Outlook 2012 (see figure 2.11).

Shale gas development generally requires substantially more water than conventional gas, with specifics depending on the gas recovery

---

[6] *Water inputs may also be necessary to extract raw materials, develop the infrastructure and manufacture the equipment to tap into the resources such as solar panels, turbines, constructing wells or dams, conducting resource assessment, etc.*

Figure 2.11 Water withdrawal and consumption for primary fuel extraction, processing and transportation



Source: IEA, 2012

rates, the number of hydraulic fracturing treatments performed and the use of technologies for water recycling (IEA, 2012). There are also concerns about contamination of water resources, specifically the leakage of fracturing fluids, saline water or hydrocarbons into groundwater supplies and the disposal of waste water. Similar concerns arise from the use of water for coal production and washing (a common practice to raise the quality of coal and hence power plant efficiency).

During the energy generation stage, thermal power plants are the most water-intensive users, requiring water mostly for cooling. These plants are based primarily on fossil fuels, such as coal and natural gas, as well as on nuclear and some renewables such as geothermal and CSP. The amount of water withdrawn and consumed per unit of electricity generated depends heavily on the cooling technology employed[7]. On the one hand, once-through cooling technologies withdraw 10 to 100 times more water per unit of electric generation than recirculating cooling technologies. On the other hand, recirculating cooling technologies consume at least twice as much water as once-through cooling technologies (NREL, 2011). Overall, almost all cooling technologies are adopted at scale globally, with specific applications depending on the local availability of water, impact of discharge on water source quality and capital cost considerations.

Several studies have been conducted to quantitatively assess the water intensity of different electricity production technologies. While some have undertaken an analysis at specific stages of energy production (Macknick et al., 2012a; NREL, 2011), others have considered water intensity along the full life cycle of energy production, which includes fuel extraction, processing and transformation, among other intermediate steps (Meldrum et al., 2013; Mielke, Anadon and Narayanamurti, 2011). These studies indicate that there is almost unequivocal agreement that wind and solar PV use practically no water to operate

---

[7] While pursuing carbon reduction goals, it also is important to consider that deployment of carbon capture and storage (CCS) technologies at future power plants could add substantial water consumption demands. The application of a CCS system in a coal plant would lead to an estimated 50-90% increase in water consumption (Gerdes and Nichols, 2009).

and have minimum life-cycle water usage, and hence could offset negative water consumption trends. Figure 2.12 provides a summary of the outputs to demonstrate the standing of different energy-producing technologies as well as the variations for different cooling technologies which can dramatically change the water consumption and withdrawal factors (Meldrum et al., 2013).

Some renewable energy technologies – such as geothermal and CSP – use thermoelectric generation and could require substantial amount of water during operation. For geothermal, water use estimates vary widely depending on the technology and whether water required for cooling is sourced externally or drawn from on-site geothermal fluids. When geothermal fluids are included in water needs for operational water requirements, estimates for water consumption range from 7600 to 13 100 litres per MWh and higher in some cases (Davies et al., 2013; Meldrin et al., 2013). CSP is found to be water intensive during the operations stage, particularly where steam turbines are the prime mover, and water consumption levels (up to 4 700 litres per MWh) are comparable to conventional thermoelectric power plants (Burkhardt et al., 2011).

Technology choices to reduce the water demand are available: for example, the use of dry cooling systems can reduce total water consumption by as much as 90%, as evident from figure 2.12. Such systems are being increasingly deployed in Morocco, the United Arab Emirates, the United States and South Africa. Studies find that dry-cooled CSP power plants are an attractive economic and technical option in sites with significantly high direct normal irradiance (DNI) values (Liqreina and Qoaider, 2014). As such, wet-cooled plants are more efficient, and a trade-off exists between the cooling technology and levelised cost of generation. A study by an Indian electricity regulator found that the most water-efficient technologies reduce consumption by 90% but result in an 8-9% increase in the electricity tariff (CEEW and NRDC, 2012). Nevertheless, there has been a consistent push within the sector to promote water efficiency measures and to encourage innovation in developing improved storage and more water-efficient cooling systems to allow the technology to fulfil its potential.

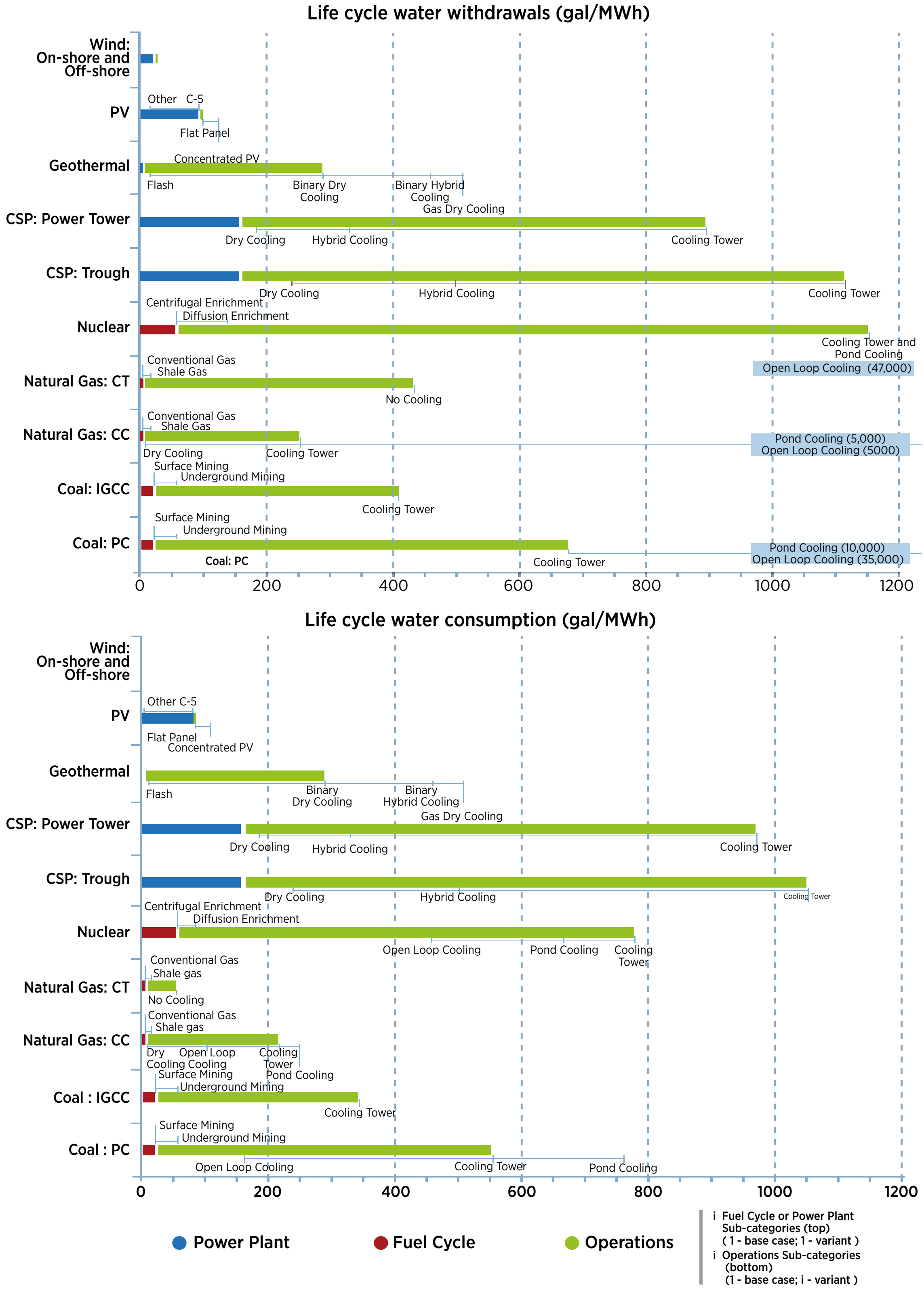
In the process of hydropower generation, water losses occur due to evaporation from holding reservoirs. Once evaporation is accounted for, large hydropower can be very water intensive (Mielke, Anadon and Narayanamurti, 2011). However, water held could be used for multiple purposes such as irrigation, water supply, flood control or recreation, in addition to power generation. Therefore, allocating the entire evaporation from reservoirs to electricity generation may not be entirely accurate. Small hydropower and run-of-the-river technology may evade the need for creating large dams, avoiding the large amounts of water evaporation and socio-economic impacts associated with large hydropower.

Assessing the energy-system-level impacts of renewable energy deployment on water use

The previous section demonstrated that, from a “litres per MWh” point of view, some renewable energy technologies offer comparative advantages over conventional generation technologies. The focus now shifts to an energy-system level to better understand whether increased renewable energy deployment can lead to a substantial reduction in water footprint to address the water–energy nexus in different contexts.

Global projections that assess the impacts of expanding renewables on water use in the energy sector find that a renewables-dominated energy system will be less water intensive compared to a business-as-usual expansion. For instance, under all three of the IEA’s energy sector scenarios (IEA, 2012) – the Current Policies Scenario, the New Policies Scenario (NPS) and the 450 Scenario – water consumption will increase between 2010 and 2035 (see figure 2.13). Meanwhile, withdrawals will be more variable depending on trends related to energy demand, power generation mix, cooling technologies used and rate of biofuels growth. The expanded role of renewables in the NPS – in which wind generation is 25% higher and solar PV is 60% higher in 2035 than in the Current Policies Scenario – contributes to reducing water withdrawals. The 450 Scenario could be even less water intensive,

Figure 2.12 Estimated life-cycle water consumption and withdrawal factors for selected electricity generation technologies

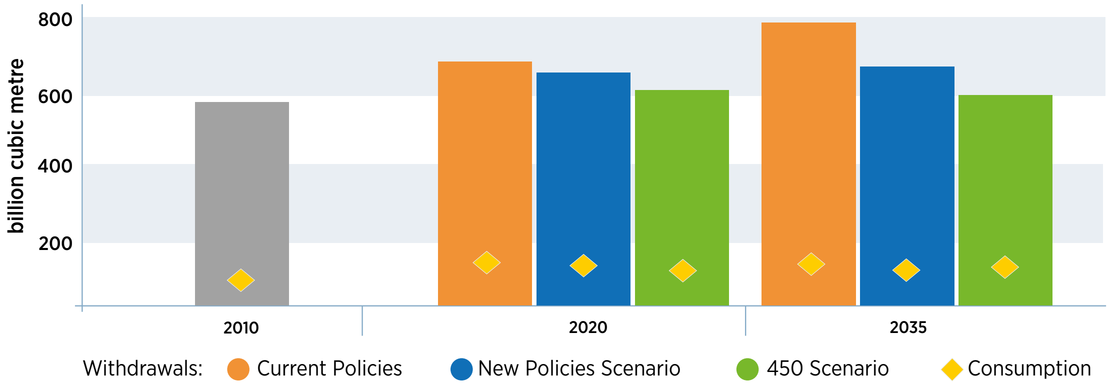


Base-case estimates for each life-cycle stage, presented in bold font, are held constant for estimating life-cycle water consumption factors for other life-cycle stages. Estimates for production pathway variants in fuel cycle or power plant (labelled on top of the bars) or operations (bottom) are labelled at points connected to the base-case estimate with horizontal lines. The figure also presents water factors for different cooling technologies marked along the green bars.

Note: PV = photovoltaics; C-Si = crystalline silicone; EGS = enhanced geothermal system; CSP = concentrated solar power; CT = combustion turbine; CC = combined cycle; IGCC = integrated gasification combined cycle and PC = pulverised coal, sub-critical.

Source: Meldrum et al., 2013

Figure 2.13 Global water use in the energy sector for different IEA scenarios, 2010, 2020 and 2035



Source: IEA, 2012

owing in part to a marked shift in the power sector away from coal-fired plants towards renewables.

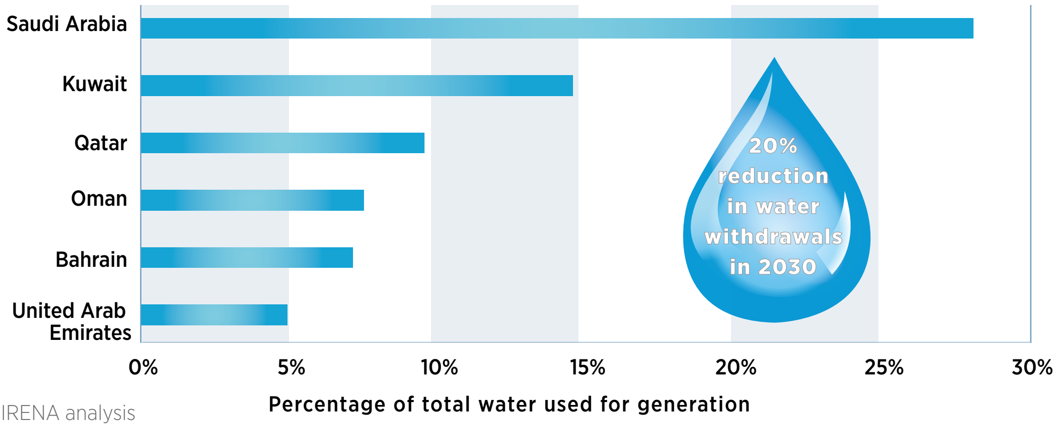
Regional-level projections also showcase a positive impact of increased renewables deployment on water resources. In the European Union, for example, the European Wind Energy Association (EWEA) estimates that wind energy avoided the use of 387 billion litres of water in 2012 - equivalent to the average annual household water use of 3 million average EU households (EWEA, 2014).

The GCC region has among the world's lowest renewable water resources, and the demand for water is expected to increase fivefold by 2050. Extraction of fossil fuels and cooling during power generation requires withdrawal and consumption of water. As treated water is needed for extraction, this results in a demand for desalination and associated risks.

The GCC region is looking to develop its vast renewable energy potential given the economic rationale in domestic hydrocarbon savings and associated opportunity costs that come with the diversification of the energy mix. Each country has announced a renewable energy plan - Bahrain (5% by 2020), Kuwait (10% by 2030), Oman (10% by 2020), Qatar (2% by 2020), Saudi Arabia (54GW by 2032), United Arab Emirates (7% by 2020 in Abu Dhabi and 5% by 2030 in Dubai), all of them in capacity terms except for Qatar (MoFA, IRENA and REN21, 2013). These plans primarily focus on solar energy.

Realising the renewable energy plans for the GCC could result in an estimated overall reduction of 20% and 22% in water withdrawal and consumption, respectively, in the power sector[8] (see figure 2.14). This is equivalent to an annual reduction of 18 trillion litres of water withdrawn and 220 billion litres of water consumed. Analysis shows that most of this

Figure 2.14 Potential for reduction in water withdrawals for power generation in GCC region by 2030



Source: IRENA analysis

---

[8] *The analysis considers water consumption for power generation in all GCC countries and includes water use during fuel extraction only for those countries using high shares of domestic oil resources for generation (Saudi Arabia, Kuwait and Oman). Water consumption factors for different technologies are derived primarily from NREL (2011), using median values. Total water use does not consider the sources of water due to lack of available data. The analysis does not account for financial considerations.*

reduction will come from the largest economy in the region, Saudi Arabia, due to its heavy reliance on electricity generation from crude oil, which requires significant amount of water for extraction and plans to add large shares of renewable energy in the power sector. It is, however, important to note that majority of the power plants in the region rely on seawater cooling while crude oil extraction uses treated water. Depending on the technology and other factors, such as plant location, renewables may require substantially less water. It should be noted, however, that the water may be procured from other water sources than those used for conventional generation. Therefore, a shift towards renewable energy needs to be guided by a careful examination of the opportunities and risks for the sustainability of water sources in specific contexts.

At a national level, as lower-water-intensity renewables expand, their cumulative positive impact on the water–energy nexus is becoming more significant. During 2013, electricity from wind energy in the United States avoided the consumption of more than 130 billion litres of water, equivalent to the annual water consumption of over 320 000 households (AWEA, 2013). A scenario with 20% wind energy in the U.S. energy mix in 2030 could reduce cumulative water use in the electric sector by nearly 8% (NREL, 2008). There is growing evidence that a pathway focused on renewable energy and energy efficiency could reduce carbon emissions and water effects from the power sector (Union of Concerned Scientists, 2013; Faeth, 2014; Foeth and Sovacool, 2014).

In China, where the coal industry accounts for more than 22% of total water consumption, massive renewables deployment is expected to reduce the reliance of power generation on water from 97% to under 87% by 2030 (Cho, 2011; Tan, 2012).

Projecting the cumulative benefits on water use of a renewables-dominant energy system depends on several factors, such as improvements in water efficiency, changes in cooling technologies, and the changing energy mix. Preliminary analysis is, however, important to gauge the overall impacts on water use within the sector and to mitigate conflicts arising out of competing needs with other end-uses. In this report, the water footprint of the electricity sector of five different countries is assessed for 2030. The analysis uses IRENA's REmap 2030 roadmaps[9] for two potential options: the Reference Case and REmap 2030. The Reference Case represents policies in place or under consideration, including energy efficiency improvements. REmap 2030 represents the energy mix that would enable a global doubling in the share of renewable energy by 2030.

The analysis presented here is based on three fundamental inputs: 1) the projected electricity mix in 2030 from IRENA's REmap 2030 analysis, 2) the water-intensity factors available in the literature for different power generation options and cooling technologies[10] and 3) the country-specific information available on potential shifts in regulations governing the cooling technology adopted, type of water use and availability. The output is the total water consumption and withdrawal for the two 2030 cases by power generation source (excluding hydropower)[11]. The analysis does not account for financial considerations.

In all countries analysed, increasing renewables penetration leads to a reduction in water consumption and withdrawal. Figure 2.15 provides a summary of the results of the analysis conducted for Australia, Germany, India, the United Kingdom and the United States.

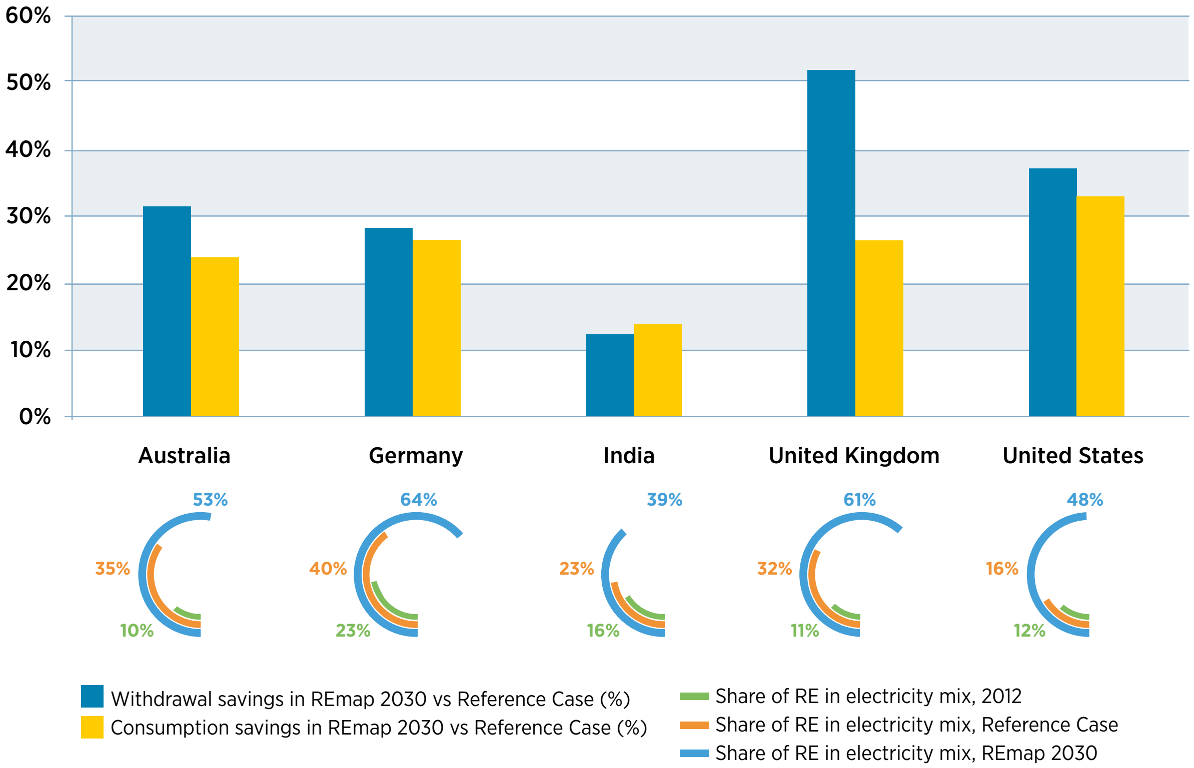
---

[9] *IRENA's REmap 2030 is a roadmap to double the share of renewable energy by 2030 – an objective within the UN's Sustainable Energy for All initiative. REmap analysis presently covers 75% of projected global total final energy consumption in 2030 by analysing 26 countries. Further details are available at www.irena.org/remap.*

[10] *Water consumption and withdrawal factors are based primarily on data from power plants in the United States (NREL, 2011), using median values. The analysis accounts for water used during power plant operations and does not consider water used during other stages of fuel extraction, processing or transport. Water usage for coal, biomass, natural gas and oil thermal power plants is calculated based on country-specific shares of power plants using once-through, closed-loop, hybrid and dry cooling systems. The mix of power plant cooling technologies for 2030 is based on announced policies and industry trends for each country, considering shifts towards closed-loop, dry cooling or hybrid cooling technologies in select countries for relevant energy sources. This mix for the countries analysed is reported in the Annex.*

[11] *Hydropower has been excluded from this analysis given that water consumption and withdrawal metrics for large-scale hydro plants vary widely and can have a distorting effect on the results. Evaporative losses in reservoirs are difficult to attribute between end-uses given the multiple purposes of the water held in catchments such as recreation, flood control, power generation, irrigation and potable water supply.*

Figure 2.15 Percentage reduction in water consumption and withdrawal between Reference Case and REmap 2030



Source: IRENA analysis; Share in 2012 electricity mix from IEA, 2014a.

These REmap 2030 countries were chosen for this preliminary analysis based on their geographic and energy sector diversity, relevance of the energy–water nexus challenge and renewable energy plans. The intensity of reduction varies substantially depending on the projected increase in energy demand, the fuel being displaced until 2030 and policy changes. More detailed results from the quantitative analysis for each country is provided in the Annex to this report.

Key findings from the analysis include:

United Kingdom. In REmap 2030, total water consumption is estimated to be 27% lower than in the Reference Case, at 0.31 billion m^3 compared to 0.42 billion m^3. For total water withdrawals, REmap 2030 also sees a 52% reduction compared to the Reference Case, with water withdrawals of 20.1 billion m^3 and 9.7 billion m^3, respectively. The reductions in water consumption and withdrawals are due largely to the large scale-up of wind and solar PV energy, which will decrease shares of nuclear energy and coal thermal power plants. These results are in line with a study by Byers et al. (2014) comparing water use under different decarbonisation pathways to 2050 for the U.K.'s electricity sector.

United States. In REmap 2030, electricity generation consumes 3.9 billion m^3 of water, compared to 5.8 billion m^3 in the Reference Case – a 33% reduction. The majority of this reduction comes from substantial deployment of wind and solar PV energy, which replaces existing coal plants and avoids new coal generating capacity. Withdrawals are 37% lower in REmap 2030 compared to the Reference Case, with 102 billion m^3 and 162 billion m^3 of withdrawals, respectively. The reduction in coal and nuclear in REmap 2030 compared to the Reference Case accounts for the majority of water withdrawal savings. This analysis draws similar conclusions to a study by Macknick et al. (2012b) simulating water consumption and withdrawal requirements for different U.S. energy pathways to 2050.

Germany. The analysis shows 27% less annual water consumption in REmap 2030 than in the Reference Case, with 0.37 billion m^3 and 0.50 billion m^3 of water consumed, respectively. This can be attributed to a larger share of wind energy in REmap 2030 and a reduction in the share of coal power. Similarly, total water withdrawals are 28% lower in REmap 2030 (6.2 billion m^3) compared to the Reference Case (8.7 billion m^3). Water withdrawals for coal power comprise the large majority of total withdrawals, with the modest share of plants with once-through cooling systems having the greatest withdrawal amounts.

Australia. REmap 2030 consumes 24% less water than the Reference Case, at 0.21 billion m^3 and 0.27 billion m^3, respectively. The decrease is caused by the larger shares of wind and solar and the reduction in coal thermal power plants in REmap 2030. Water withdrawals total 2.1 billion m^3 in REmap 2030 compared to 3.0 billion m^3 in the Reference Case scenario, with savings of 32%. This also can be attributed to lower shares of electricity generated by coal and higher shares from solar PV and wind in REmap 2030 compared to the Reference Case.

India. In REmap 2030, water consumption is reduced by 14% compared to the Reference Case, consuming 2.8 billion m^3 and 3.2 billion m^3, respectively. This can be attributed to the higher shares of solar PV and wind, with minimal water footprints. Biomass thermal power has a relatively higher water footprint and is not estimated to contribute substantially to reductions in water consumption. For water withdrawals, REmap 2030 results in 117 billion m^3 of water withdrawn, while the Reference Case results in 134 billion m^3 of water withdrawn – a 12% reduction. Reductions are due to a lower share of coal, with high withdrawal rates from the share of coal plants using open-loop cooling technology.

The estimations of reduction in water consumption and withdrawal do not consider the sources of water. The analysis presented in this report is limited to cumulative water savings due to lack of data and information on the source of water currently used for power plant cooling. Moreover, the analysis does not consider the local impacts of water use in these countries while acknowledging that many of the countries studied have high degrees of local variability in water resource availability. A better understanding of these aspects can help decision makers in more accurately assessing the impact of growing shares of renewable energy in the energy mix on different water resources and in applying physical water constraints to energy sector projections and strategies.

2.3 RENEWABLE ENERGY IN THE FOOD–ENERGY NEXUS

The constituents of the food–energy nexus provide insights into the different prisms through which the role of renewables within this nexus should be analysed. These are:

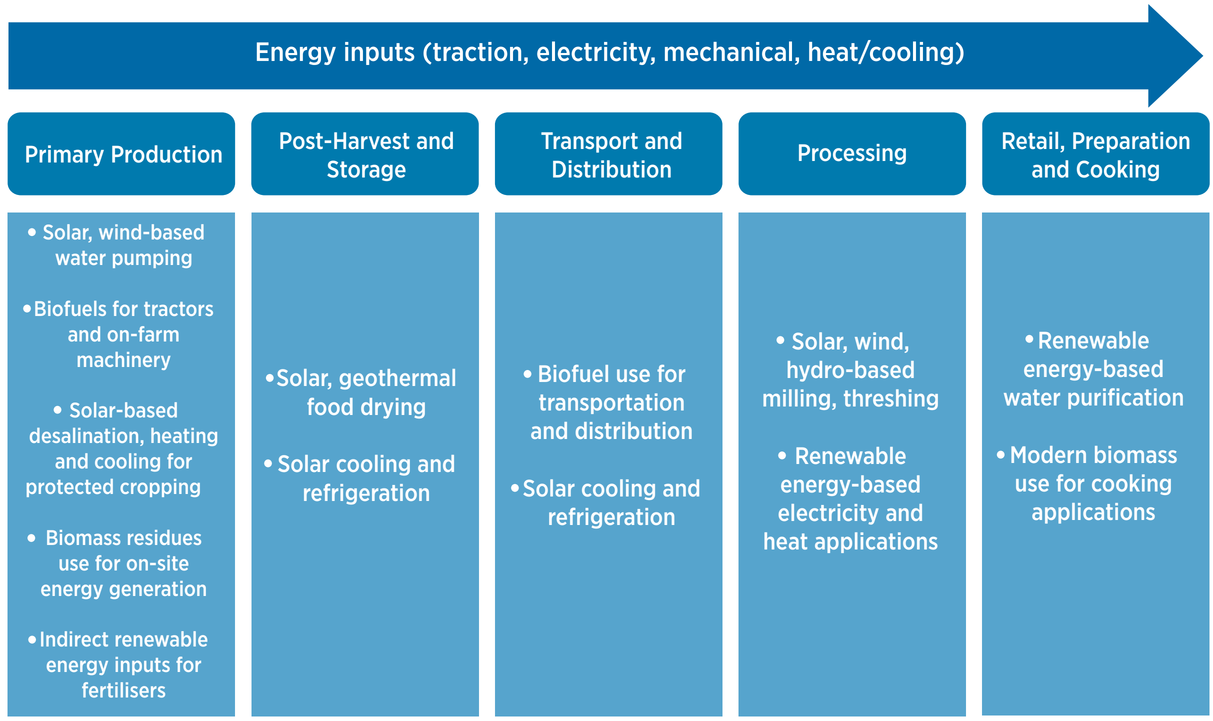
- Renewable energy technologies meeting energy demand along the different stages of the food supply chain; and
- Increasing the use of bioenergy in the global energy mix.

2.3.1 The role of renewable energy in the food supply chain

The growth in food production in past decades has been driven largely by fossil fuel energy inputs. Increases in farm mechanisation, fertiliser production, food processing and transport have meant that the food system has emerged as a significant energy consumer, with growing dependence on fossil fuels (FAO, 2011b). In its Energy Smart Food Programme, the FAO proposes a three-pronged approach to becoming “energy smart” in the agri-food chain: improving access to modern energy services, enhancing energy efficiency and gradually increasing the use of renewable energy (FAO, 2014c).

Emphasis has been placed on the gradual introduction of renewable energy to give priority to improving access to modern energy services, even if it is through fossil fuels. In the long term, however, options for increasing productivity in agriculture may become severely limited if an inexpensive and reliable supply of fossil fuels is not available, and if climate change impacts are not mitigated. This highlights the necessity to gradually decouple increases in food production from fossil fuel availability, requiring fundamental changes in the way energy is produced, distributed and consumed within the global food system.

Figure 2.16 Illustration of different entry points for renewable energy into conventional energy supply systems



Energy inputs (traction, electricity, mechanical, heat/cooling)

Primary Production	Post-Harvest and Storage	Transport and Distribution	Processing	Retail, Preparation and Cooking
• Solar, wind-based water pumping • Biofuels for tractors and on-farm machinery • Solar-based desalination, heating and cooling for protected cropping • Biomass residues use for on-site energy generation • Indirect renewable energy inputs for fertilisers	• Solar, geothermal food drying • Solar cooling and refrigeration	• Biofuel use for transportation and distribution • Solar cooling and refrigeration	• Solar, wind, hydro-based milling, threshing • Renewable energy-based electricity and heat applications	• Renewable energy-based water purification • Modern biomass use for cooking applications

Source: Based on FAO, 2011b; Practical Action, 2012

The deployment of renewable energy systems at different stages of the food supply chain offers several benefits. These include: 1) improved access to modern energy services, particularly in rural areas; 2) reduced dependence on fossil fuels; 3) allayed energy security concerns; 4) diversified farm and food processing revenues; 5) lowered greenhouse gas emissions and 6) support for sustainable development goals (FAO, 2011b).

Renewable energy can be used either directly to provide energy on-site or indirectly by integrating this energy into the existing conventional energy supply chain (see figure 2.16). The distributed nature of renewable resources means that they can substitute fossil fuels to generate heat and electricity or they can be used as transport fuels in farms. If excess energy is produced, it can be exported to nearby communities or to the national grids (where possible) to gain additional revenue. This enables an integrated food–energy system approach that links food production and natural resource management with poverty reduction in food value chains (FAO, 2011b).

This is especially feasible in low-GDP countries, where extension of the national grid to remote and rural areas is costly and maintenance of such grid infrastructure is expensive. Decentralised renewable energy solutions could not only supply energy for subsistence and small-scale farming, but also provide attractive energy supply solutions for large-scale farming, small and medium-sized enterprises and industry-sized agro-processors such as rice mills and fruit processing companies. Therefore, they have the potential to support rural economic development, bringing co-benefits to farmers, landowners, businesses and rural communities.

For a better understanding of how renewable energy can be integrated into the agri-food system, it is important to look at the different segments: production, processing, transport and distribution, as well as retail, preparation and cooking. The remainder of this section focuses on renewable energy interventions in the production, processing and cooking stages of the food supply chain, where renewable energy impacts are most relevant.

During the primary production phase, direct energy inputs are required for different activities, including land preparation (also referred to as tillage), crop cultivation, lifting and distributing irrigation water. The magnitude of energy use depends on the type of farming. Small-scale subsistence agriculture often involves little external energy input (relying mostly on human and animal power), while modern large-scale agricultural supply chains are increasingly becoming more mechanised, sophisticated and energy intensive (FAO, 2011b).

The pace of mechanisation varies between different developing regions. In sub-Saharan Africa, where up to 80% of primary land preparation relies entirely on human muscle power, tractor use has actually shrunk from 2 per hectare in 1989 to 1.3 per hectare in 2003. Meanwhile, South Asia has seen an increase in tractor use from 7.8 per hectare of arable land in 1989 to 14.9 per hectare in 2003 (FAO, 2011c). Moreover, indirect energy inputs also are required to account for the production of agricultural inputs such as fertilisers and pesticides.

Renewable energy resources can be converted into the full range of energy uses and carriers, including electricity, heating, cooling, liquid and gaseous biofuels. As mechanisation of agricultural activities expands and reliance on non-local energy sources grows, risks associated with disruption of the fuel supply or fuel price fluctuations also increase. Renewable energy resources can meet energy demand for primary food production both directly and indirectly. Where adequate renewable energy resources exist, they can be used as a substitute for fossil fuels to generate traction, heat or electricity for use on farms.

A case in point is the increasing use of biomass resources available on-site for generating electricity and/or heat through small-scale digesters (see box 2.8). In the United States, nearly 240 anaerobic digester systems were operating at commercial livestock farms, mostly on dairy farms, as of January 2014. Many of these farm-level plants utilise a wide range of agricultural crop residues, animal and food wastes to generate usable energy on-site in

BOX 2.8

TRANSFORMING RURAL ECONOMIES THROUGH BIOENERGY

The state of Paraná in Brazil

Small-scale family farming represents 85% of the agrarian structure in the Brazilian state of Paraná. The region's roughly 4.1 million family establishments produce almost 40% of the gross value of agricultural and livestock production, or 60% of the food consumed by the Brazilian population. Both family and industrial farming in Brazil have become highly dependent on chemical inputs, such as fertilisers, over the past four decades, making them susceptible to price unpredictability and to a general dearth of surplus funds for investing in the sector's modernisation.

Given the substantial amounts of solid residues and other wastes produced from agricultural activities, there is tremendous opportunity to utilise the bioenergy resource to produce energy and bio-fertilisers. Adding bioenergy generation to small-scale family farming production has a transformative impact on rural agrarian economies. A new local economy is mobilised that includes design, engineering, electrical and mechanical maintenance, assistance for biological control of the biodigesters, trade of equipment, raw materials, machinery, engines, generators, piping, control panels and electrical grid connections of low, medium and high tension.

A project, Agri-energy Cooperative for Family Farming, has been launched in the Municipality of Marechal Cândido Rondon in the state of Paraná. This project involves 33 small-scale family farms where individual biodigesters (biogas plants) are installed to produce biogas. The biogas is transported through a 22-kilometre-long gas pipeline from each biogas plant to a centralised power plant to produce electricity and heat and/or biomethane vehicle fuel after upgrading. Finally, to close the production loop, the biofertiliser originating from the biodigesters is used on the 33 co-operative farms, and any surplus can also be sold to provide additional income.

Source: IEA, 2013b

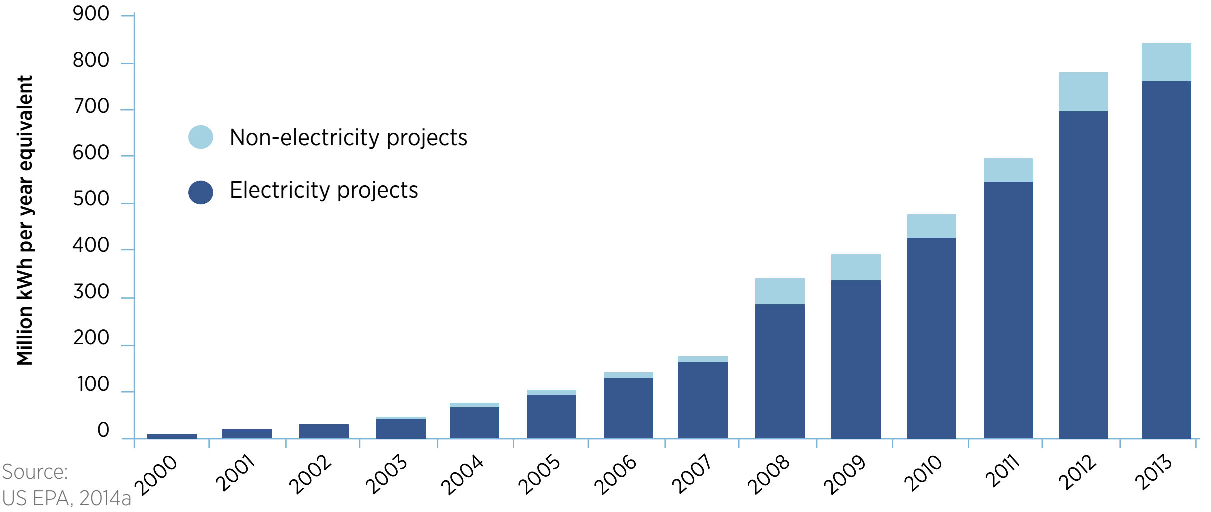
the form of electricity, or as boiler fuel for space or water heating. In 2013, approximately 840 GWh equivalent of energy was generated by anaerobic digester systems on livestock farms tracked under the U.S. Environmental Protection Agency's (EPA's) AgSTAR programme[12] (see figure 2.17), with combined heat and power being the most common use of biogas (see figure 2.18) (US EPA, 2014a). The use of on-site agriculture residues for energy production should, however, carefully consider the competing use of residues, especially in developing countries, for other on-site purposes such as maintaining soil quality (fertility and protection), animal feed and increasingly biomaterials.

Between harvesting and consumption, agricultural food products undergo a certain degree of transformation or processing. During this stage, energy is required to preserve food, reduce post-harvest losses and extend the availability of food over a longer period of time. The lack of access to reliable and affordable energy is a key challenge for the food processing industry, as it affects its competitiveness (FAO, 2011b). This highlights the need for the food processing sector to reduce energy consumption, increase energy efficiency and integrate renewable energy to enhance sustainability and economic competitiveness.

Boxes 2.9 and 2.10 provide examples of how renewable energy technologies are supporting rural agro-processing industries. Existing food processing plants can also use biomass by-products for co-generating heat and power, which are usually consumed on-site (FAO, 2011b). In India, the world's second largest producer of sugar cane, wet bagasse, a bio-product of sugar mills, is re-used in the plants to generate power and steam. Bagasse cogeneration has emerged as a crucial option for supplying low-cost and reliable energy, and India has deployed nearly 2.7 GW of such capacity nationally (MNRE, 2014). Similarly, in Mauritius bagasse cogeneration contributes to some 17% of national electricity production. By using bagasse, Mauritius saves on importing the equivalent of some 375 000 tonnes of coal, thereby preventing 1.2 million tonnes of CO_2 emissions (MSPA, n.d.).

A significant share of total energy inputs is embedded in food losses that occur at the harvest and storage stages. As a result, significant attention is given to renewable energy in developing decentralised processing and storage infrastructure. For instance, solar energy and biomass have been used successfully for both dry and cold storage. Compared to other food preservation techniques, food drying can be performed using low-temperature thermal sources and is applicable to many different types of food (including fish, fruits and vegetables). The dried food produced is light weight, is easily stored and transported and has an extended shelf life. In Sri Lanka, the use of wood biomass to dry spices has diversified income streams and increased revenue for local operators in the spice market chain. In addition to selling the fuelwood by-product from

Figure 2.17 Energy generation by anaerobic digester systems in the United States, 2000-2013

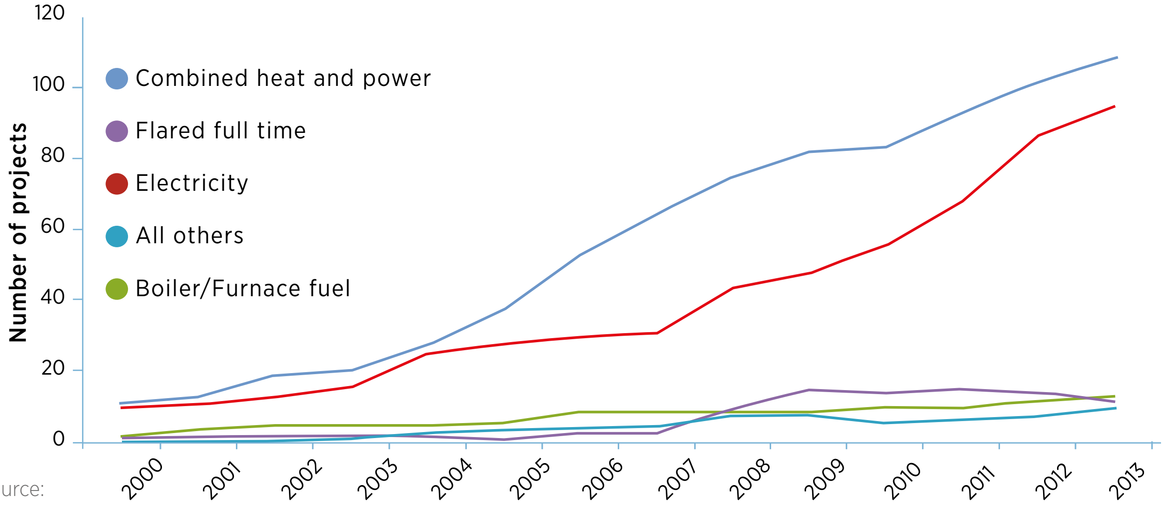


Source: US EPA, 2014a

---

[12] *AgSTAR is one of the EPA's climate-protection partnership programmes, which promotes investments in alternative energy technologies by encouraging the development and adoption of anaerobic digestion technology in the livestock sector. Details for farm-level anaerobic digester projects in the United States are available at http://www.epa.gov/agstar/projects/.*

Figure 2.18 Trends in end-uses of biogas in the United States, 2000-2013



Source:
US EPA, 2014a

pepper plants to the dryer operators, small-scale growers are able to sell mature spices that can be dried and preserved (FAO, 2011). Geothermal food drying also presents tremendous potential for reducing food losses and enhancing food security (see box 2.11).

BOX 2.9

USING BIOENERGY AND HYDROPOWER FOR RICE PROCESSING

The case of Nicaragua

The town of San José de Bocay, in the department of Jinotega, is located 75 kilometres from the capital city of Managua, Nicaragua. A locally owned and operated mini hydroelectric plant provides 260 kW of electricity for the 800 families in this community and its surroundings. A rice thresher was put into service immediately after the inauguration of the hydroelectric plant in San José de Bocay, with the objective of strengthening and diversifying the use of electricity and providing alternative work to the labourers and farmers in this municipality. A rice processing centre, which includes a rice thresher and a biomass rice dryer, provides service to 220 small farmers who do not have the means, or the economic resources, to transport their products to larger cities for processing. The services offered are drying the grain, threshing and storing the rice.

This project has motivated farmers in the municipality to plant rice, as local opportunities now exist to add value to this production and to obtain a better price for the product at the municipal market. Locally processed rice is also less expensive for consumers, which improves the family economy and allows the entire population to consume rice, improving the diet of poor families. To avoid the possible negative ecological side effects of rice cultivation (it is very demanding of nutrients and can lead to rapid soil depletion), ATDER-BL (Asociación de Trabajadores de Desarrollo Rural–Benjamin Linder) supports communities in making the transition to organic agriculture and promotes sustainable practices such as terracing, reforestation, leaving an uncultivated border along streams and agro-forestry. The project already has served as a model to be replicated in other communities, viable in various locations due to the general high demand for rice processing, its financial sustainability and the use of locally available materials.

Source: WISIONS, 2007

BOX 2.10
BIOGAS USE FOR TOFU AND TEMPEH PROCESSING

The case of Indonesia

In urban Jakarta and the surrounding cities in Java, tofu and tempeh are fundamental staples of the Indonesian diet and an important source of protein and other critical nutrients, especially for low-income households. Tofu and tempeh are produced locally throughout Indonesia by approximately 85 000 informal micro, small, and medium enterprises, which collectively employ 285 000 workers and generate around USD 78 million per year.

Tofu and tempeh are traditionally produced using firewood to heat soybeans. Firewood is typically gathered in parks, forests around town or from secondary sources such as furniture factories and construction sites. In many locations, firewood has become increasingly scarce, resulting in rising costs (money and time expenditure) to collect adequate supplies. Moreover, lack of regulation has led to poor sanitation, safety and health conditions, and high environmental impacts.

In short, the tofu and tempeh sector is in need of suitable, scalable, and sustainable production technologies. In this context, a Mercy Corps project is promoting biogas reactors in the tofu industry in peri-urban areas, with the following benefits: 1) avoided fuel costs in the long term, 2) avoided risk of price fluctuations for LPG and firewood, 3) avoided risk of firewood scarcity, 4) avoided community opposition due to reduction of smoke and water pollution, 5) time savings and improved health conditions, and 6) option to produce electricity from biogas.

The project has selected large- and small-scale fixed-dome biogas technology provided by a local company (digesters made of fibreglass to be used for individual tofu and tempeh producers or groups up to four producer units; waste input requirements are 90% liquid waste plus 10% solid waste or kitchen garbage). The biogas reactors convert the liquid waste of tofu and tempeh production into methane gas and are able to substitute the LPG usage in the production process by up to 30%. Additionally, the effluent (waste) produced by the biogas reactor can be used as fertiliser or fish feed without any treatment. This means that there is a potential income opportunity for selling the waste products to the farming sector.

Source: REEEP, 2014

Cooking is an energy-intensive activity, especially in developing countries where inefficient cooking practices are commonplace. Around 2.7 billion people worldwide rely on traditional biomass for cooking, such as fuelwood, crop residues and animal dung (FAO, 2011). Traditional sources of biomass, however, are not always produced sustainably, and emissions of smoke and carbon monoxide can lead to health and safety issues (IPCC, 2011). Moreover, traditional biomass is often scavenged, which usually demands considerable labour and time.

Several measures have been undertaken to address this situation. Efforts are under way to enhance the energy efficiency of cooking processes through the use of improved cookstoves. Compared with open fires, using more efficient cooking stoves can reduce the demand for fuelwood by half. A longer-term solution is to expand access to modern cooking fuels such as LPG and biogas[13]. Tapping into local bioenergy resources to sustainably provide clean cooking fuels to rural communities is expected to be central to achieving universal access to modern energy services.

2.3.2 Increasing use of bioenergy in the global energy mix

The majority of bioenergy consumption today is for traditional uses in cooking and heating. In 2010, more than 60% of total global biomass demand was in the residential and commercial buildings sector, mostly for cooking and heating. The manufacturing

---

[13] *The barriers to the adoption of improved cookstoves and biogas solutions have been discussed in greater detail in IRENA's other streams of work such as Renewable Energy Jobs and Access (IRENA 2012c).*

BOX 2.11

POTENTIAL FOR GEOTHERMAL FOOD DRYING

The case of Iceland

Drying is an important technique for preserving food in developing countries; however, traditional methods can result in spoilage, contamination and low product quality. Effective solar and geothermal food drying technologies are now available to reduce such losses and increase food quality, resulting in greater productivity and income for farmers. The use of renewable energy sources generally reduces fuel costs.

Iceland currently exports 15 000 tonnes of cod heads annually, mostly to Nigeria, that are dried using heat from geothermal energy. This allows for a reduction in wastage, stimulates businesses within Iceland's fishing industry and helps boost food supplies in Nigeria. The same technology (renewable geothermal heat) could also be used to dry and preserve a broad variety of foods such as meats and fruits.

Source: IRENA, 2013; Shankleman, 2013

industry (15%), transport (9%) and the power and district heating (8%) sectors accounted for about one-third.

Modern bioenergy could represent a substantial share of the global energy mix moving forward. It has diverse applications across all end-use sectors to provide energy services including electricity and heating, and transport fuels. In particular, modern bioenergy provides a key pathway to alleviate energy poverty and enhance access to modern energy services, including clean cooking fuels and electricity. Indeed, IRENA's REmap 2030 analysis highlights that by 2030, modern biomass demand could double to 108 exajoules, accounting for 60% of total final renewable energy use. This estimate is comparable to other scenario analyses such as IEA (450 ppm), IPCC (440-600 ppm) and Greenpeace (Alternative) (IRENA, 2014d).

Bioenergy development needs to be managed sustainably and efficiently. The opportunities offered by the development of bioenergy resources create a compelling case for their rapid adoption. Bioenergy development can enhance energy security and provide a localised solution, with potential positive effects on food security. Moreover, a bioenergy sector could create new markets for producers as well as create new employment opportunities that positively affect rural incomes, poverty reduction and economic growth. Bioenergy also has the potential to help meet environmental objectives such as reducing greenhouse gas emissions (FAO, 2010b).

Yet the bioenergy sector also has been a cause of concern because of potential negative impacts on food security and the environment caused by intensive agriculture production and by competition between food production and natural resources (FAO, 2010b). The impacts of bioenergy – specifically liquid biofuels – on food prices, economic growth, energy security, land use, deforestation and climate change are complex and multi-faceted. These impacts vary widely depending on the feedstocks and production methods used, and on the location (FAO, n.d. c).

In general, experience has shown that energy produced from biomass can contribute to food security as long as it is sustainably produced and managed (FAO, 2014d). To enable this, a broad array of approaches, tools and sustainability frameworks (*e.g.*, Sustainability Indicators for Bioenergy developed by the Global Bioenergy Partnership, European Commission or the FAO Sustainable Bioenergy Support Package) are being developed and implemented to better inform decision making on bioenergy development by quantifying trade-offs and supporting wider cost-benefit analysis.

The production of primary bioenergy from agricultural resources is closely related to food demand and supply because both energy and food crops are produced using the same agricultural land resources. There are several ways that energy crops can be produced in a manner that minimises impacts (NL Agency, 2013):

- **Increased efficiency in land use.** The need to expand the cultivated area can be reduced by increasing the yields of energy and food crops, and by promoting integrated food energy systems that include rotations of energy and food crops, mixed energy/food crop systems, and the cascading use of residues from agriculture (see box 2.12).
- **Crop production on abandoned or degraded lands.** Land-use change impacts of bioenergy production could be limited by using abandoned or degraded lands that typically are characterised by lack of water, low soil fertility or high temperatures. There are bioenergy crops that are tolerant to such environmental conditions, where food crops might fail. Any such development, however, should carefully consider potential competition with other uses of degraded land and be backed by a thorough cost-benefit analysis.
- **Producing bioenergy from wastes or residues.** Using agricultural waste streams and residues (*e.g.*, bagasse for energy from sugar production, biogas from manure) for bioenergy production

BOX 2.12

INTEGRATED FOOD-ENERGY SYSTEMS

The case of simultaneous intercropping in Sri Lanka and Malawi

The production of bioenergy in integrated food–energy systems makes it possible to meet both food and energy demand. It involves combining the sustainable production of food and other biomass across different ecological, spatial and temporal scales, through multiple-cropping systems or systems mixing annual crop species with perennial plants, *i.e.*, agro-forestry systems (FAO, 2014d). Agro-forestry is a set of tools that farmers use to increase yields, build soil fertility, raise income and boost food security. Simultaneous intercropping is an agro-forestry technique whereby nitrogen-fixing woody trees are grown simultaneously with annual crops on the same piece of land.

Gliricidia sepium is a fast-growing, nitrogen-fixing leguminous tree that is used to add nitrogen and organic matter to the soil and that can dramatically increase crop yields. In Malawi, intercropping maize with Gliricidia yielded more than 5 tonnes per hectare in good years, and an average of 3.7 tonnes per hectare overall, in the absence of mineral fertilisers (compared with an average of 0.5-1.0 tonnes per hectare without Gliricidia or mineral fertiliser) (FAO, n.d. d). Similarly, in Sri Lanka Gliricidia is intercropped with coconut.

A food–energy system for rural electrification has been commercially developed that uses Gliricidia as the feedstock for electricity production. A 1 to 10 MW power plant is sited in a rural area composed of smallholder farmers who grow predominantly food crops in a maize-mixed farming system. Gliricidia trees are intercropped in the maize fields in a grid pattern. The trees produce wood and foliage that is harvested periodically during the year by pollarding the trees. The foliage is stripped from the branches for high-protein livestock fodder and/or biofertiliser for the crops. The branches are removed and transported to the power plant as feedstock for electrical power generation, with the electricity provided to local rural consumers and any excess going to the national grid.

The Gliricidia systems also increase the on-farm production of firewood, a resource that is increasingly in short supply in Africa smallholder agricultural systems. Farm production of adequate fuelwood saves the drudgery of women and children in travelling long distances to collect it, and this releases time and energy for other income-generating activities. It also reduces the destruction of natural forests by reducing the need to collect firewood from public lands.

Such an integrated food–energy industry is envisioned to provide electrical power while at the same time enhancing food production and nutrition security, improving livelihoods, conserving the environment and advancing economic growth.

Source: EverGreen Agriculture, 2014

can save land otherwise needed to produce energy crops as well as contribute to value-added within the supply chain. However, a key point of consideration is the competing use of agricultural residues or waste for maintaining soil quality (fertilising and protection), animal feed and increasingly biomaterials. These multiple uses often limit the availability of residues for energy production.

- Production of co-products. Co-products, such as press cakes of biofuel production, are often used as livestock feed. To a certain extent, this can offset the use of land and water resources for feed production and makes resources available for food production. Co-products usually have high added value. At the same time, market drivers determine whether they generate most value as feed or as industrial or energy feedstock.

To overcome the limitations of first-generation biofuels that depend on energy crops that could compete directly with food production, substantial research and development efforts are focusing on second- and third-generation biofuels. These are produced from non-food, cellulosic biomass, such as woody and straw residues from agriculture and forestry, the organic fraction of urban waste and algae-based feedstock. These feedstocks require advanced, capital-intensive processing to produce biofuels, but they could hold the potential to be more sustainable, offering higher emissions reductions and less sensitivity to fluctuations in feedstock costs (IRENA and IEA-ETSAP, 2013). Even if second-generation biofuels use non-food feedstocks, the trade-offs between food and fuel are not entirely resolved because of indirect land-use changes, and due to the potentially huge market demand for renewable energy in comparison to agriculture (FAO, 2013b).

As with bioenergy, the energy sector as a whole requires land inputs across different stages of the supply chain, depending on the resource being harnessed. Fossil fuels and nuclear, for instance, convert highly concentrated, mined resources into useful energy in power plants or refineries. But the land requirements of these energy sources are significant, including the footprints of mines and drilling sites, associated support infrastructure, transportation routes from extraction to conversion sites, the footprint of the conversion (transformation) site, and the footprint of any needed waste depository (Andrews et al., 2010).

A number of metrics and methodologies are available for evaluating land-use impacts, focusing mainly on the area affected and the duration and quality of the impacts (also called the “damage function”) (NREL, 2009; Koellner and Scholz, 2008). For a sound assessment of the land impacts of different energy technologies, it is important to consider all three aspects on a life-cycle basis, including fuel extraction and processing, transformation and decommissioning, if any (Steger, 2011). Such an assessment utilises land-intensity metrics that include an analysis of how much land is needed, for how long and whether it can be restored after use.

The land intensities (area per unit generation) of different renewable energy technologies are highly context specific due to their distributed and diffused nature. They depend on the renewable resource available, technology deployed and local environmental factors. National-level efforts are under way to improve the understanding of the land intensity of different technologies. In 2009, the U.S. National Renewable Energy Laboratory undertook a comprehensive land-use analysis of 172 projects representing more than 26 GW of wind capacity (NREL, 2009). The study focused on quantifying the area of impact, recognising that the quality and duration of the impact must be evaluated on a case-by-case basis. The average area requirement for wind power plants was 0.74 (± 0.74) acres/MW for permanent direct impact[14], 1.72 (± 1.48) for temporary direct impact and 85.25 (± 55.35) acres/MW for total area. In 2013, NREL analysed land-use data for 217 solar PV and CSP projects (NREL, 2013a). The study found that the direct land-use requirements for small and large PV installations range from 2.2 to 12.2 acres/MW, with a capacity-weighted average of 6.9 acres/MW. For CSP installations, direct land-use intensity ranges from 2.0 to 13.9 acres/MW, with a capacity-weighted average of 7.7 acres/MW (NREL, 2013a).

Several studies have been undertaken to compare estimates of the land intensity of renewable energy

---

[14] Direct impact is defined as the disturbed land due to physical infrastructure development. The total area is more challenging to define and subjective in nature. Generally, the total area of a wind plant consists of the area within a perimeter surrounding all of the turbines in the project. However, the perimeter depends highly on terrain, the size of turbines, current land use, setback regulations, and other considerations (NREL, 2009).

technologies with other conventional technologies. Fthenakis and Kim (2009) studies land-use requirements of different power generation technologies in the United States. Although estimates can vary with regional and technological conditions, the study finds that solar PV requires the least amount of (total) land among renewable energy-options. Moreover, ground-mounted PV deployed in areas with high insolation transform less land than coal coupled with surface mining. Onshore wind appears higher given that the total area of the farm is considered; however, as the data from NREL indicate, the direct area in use is minimal, leaving the majority of the land suitable for other uses (see box 2.13) (NREL, 2013c). The same is increasingly applicable for solar PV, where systems are being deployed on roof-tops or co-exist with agricultural production, as in the case of Japan (see box 2.14) and Italy (see box on agrophotovoltaic farms in FAO, 2013c). It is also important to consider the potential for deploying renewable energy technologies on marginal lands that are generally underused, difficult to cultivate, have low economic value, and varied developmental potential. Developing solar power on contaminated and disturbed lands can help create jobs and revitalise local and state economies, and selecting these sites over greenfield sites can potentially have permitting and environmental mitigation advantages. In the United States, for instance, the development of solar PV on marginal lands present the highest opportunity (Milbrandt et. al., 2014). In fact, there is sufficient disturbed and environmentally contaminated land area suitable for utility-scale solar power development to meet the SunShot goals of 632 GW of PV and 83 GW of CSP by 2050 (NREL, 2013b).

Using the total area metric without qualification may distort the land impacts of some renewable energy technologies compared to other sources. Many comparisons of total land use associated with energy production include only the total area affected, and provide little discussion of the impact on land quality (damage function) as a comparative metric. For instance, a wind plant in an agricultural area with low population and minimum avian

BOX 2.13

DUAL USE OF LAND FOR POWER PRODUCTION AND AGRICULTURE

In many regions, land under cultivation could simultaneously be used for renewable energy production. Multi-use of land for agriculture and energy purposes is becoming common, such as wind turbines constructed on grazing land; biogas plants used for treating animal manure with nutrients recycled to the land; crop residues collected and combusted for heat and power; and energy crops grown and managed specifically to provide a biomass feedstock for liquid biofuels, heat and power generation (with co-products possibly used for feed and fibre) (IPCC, 2011).

Given that farmers are most vulnerable to fossil fuel price volatility and can receive the lowest share of the final product sale value, leasing farm land to renewable energy developers, such as wind, can be a source of additional income. In Germany, for instance, 11% of renewable energy capacity (as of 2012) is owned by farmers. Solar farms may also enhance the agricultural value of land, where marginal or previously developed land (*e.g.*, an old airfield site) has been brought back into more productive grazing management. It is desirable that the terms of a solar farm agreement include a grazing plan that ensures the farmer continued access to the land.

Many solar farm developers actively encourage multi-purpose land use, through continued agricultural activity or agri-environmental measures that support biodiversity, yielding both economic and ecological benefits (BRE, 2014).

It is commonly proposed in planning applications for solar farms that the land between and underneath the rows of PV modules be available for grazing small livestock. Sheep and free-ranging poultry already have been successfully employed to manage grassland in solar farms while demonstrating dual-purpose land use.

BOX 2.14

PRODUCING CROPS AND SOLAR ENERGY SIMULTANEOUSLY

The case of solar sharing in Japan

The concept of co-production of food and energy, known as “solar sharing”, first came to Japan in 2004. The guiding principle lies in understanding the point beyond which an increase in the level of sunlight incident on the plants does not cause any further rise in the rate of photosynthesis. Special structures are being deployed involving rows of PV panels mounted above ground and arranged at certain intervals to allow enough sunlight for photosynthesis and space for agricultural machinery to be used.

The Ministry of Agriculture, Forestry and Fisheries recently has allowed installation of solar PV systems on crop-producing farms and has introduced guidelines to ensure that farmlands are not fully converted to solar plants. Farmers are required to report their annual crop cultivation, and if the amount cultivated falls below 80%, they will be required to dismantle the PV system.

Several “solar sharing” plants have been developed. In Chiba Prefecture, the 34.4 kW Kazusatsurumai Solar Sharing Project has 348 PV panels on a 750 m^2 farm mounted 3 metres from the ground. Under the panels, peanuts, yams, eggplants, cucumber, tomatoes and cabbages are grown. The PV produces 35 000 kWh of electricity per year and benefitted from an attractive feed-in tariff. Similar projects have emerged in the Aichi and Fukushima Prefecture.

Source: ISIS, 2013

impacts, or a GW of solar PV deployed on roof tops, would have a much lower damage function than an area mined for coal where all natural habitat is cleared (McDonald et al., 2009).

Other energy production technologies with a relatively small infrastructure footprint could affect a larger area through habitat fragmentation and other secondary wildlife effects. For example, production techniques involving wells, such as geothermal, petroleum and natural gas, have about 5% of their impact area affected by direct clearing, with the remainder coming from fragmenting habitats and species avoidance behavior (McDonald et al., 2009). For solar technologies in particular, these aspects will be discussed in greater detail in IRENA’s forthcoming study Environmental Impact from Deployment of Solar Energy Technologies.

2.4 CONCLUSION

Renewable energy technologies are poised for substantial growth in the coming decades. A combination of drivers, including energy security, climate change mitigation, socio-economic considerations and energy access, will propel the ongoing transformation of the energy sector away from traditional fossil fuel options. This dynamic presents both opportunities and challenges for the water and food sector. The distributed and environmentally sustainable nature of most renewable energy technologies means that they could address trade-offs between the water, energy and food sectors and leverage on synergies to enhance sustainability across these sectors.

A shift towards relatively less resource-intensive renewables, such as solar PV and wind, can address challenges posed by the water–energy nexus. Analysing projections for water use by the energy sector shows that, at a global, regional and national level, an energy system with substantial shares of renewable energy could be less water intensive compared to one based on conventional fuels.

In an increasingly water-constrained environment, renewable energy could offer a low-carbon and less water-intensive path to expanding the energy sector. While the cumulative benefits are estimated to be positive, due attention is necessary to assess the water impacts of individual technology solutions. Whereas solar PV and wind have minimal water needs, technologies such as CSP and bioenergy development could have a substantial water footprint that needs to be adequately considered in energy sector planning.

The chapter has shown that renewables are also considered as a means to enhance water security. Distributed renewable energy systems are being deployed increasingly to expand access to water services in remote communities while also expanding water availability for irrigation, with positive impacts on food security. In urban settings, renewable energy technologies are being deployed to enhance the resilience of urban water systems. Energy costs make up a substantial share of water utility expenditures, and, hence, tapping into locally available energy resources allows utilities to reduce costs and improve the reliability of water supply. In arid regions of the world where energy-intensive desalination will play an ever important role in meeting growing water demand, substantial focus is now being directed to develop renewable energy-based desalination solutions that can, together with renewable energy for electricity generation, provide an integrated solution to address the water and energy challenge.

Renewable energy when implemented in a sustainable manner can stimulate the food sector with new economic opportunities and bridge the modern energy deficit along the supply chain to reduce losses and enhance productivity. There is consensus, however, that the growth in renewable energy deployment has to be supported with adequate consideration of the broader impacts, both positive and negative, on other development sectors. Bioenergy, for instance, can play a transformative role in the transition towards a renewables-based energy system. It is a resource that is widely and locally available with tremendous synergies with rural agri-economies.

The development of this resource needs to consider impacts on water and land use, competition with food crops and broader sustainability issues. Such an assessment is particularly useful at an energy-system level wherein energy sector strategies can be vetted through standard frameworks, such as the FAO's Bioenergy and Food Security Approach, which allows for cross-sectoral assessment.

The chapter presented preliminary quantitative analysis for a set of five countries and the GCC region to demonstrate how preliminary assessments can be useful in identifying cross-sectoral impacts of energy sector scenarios. Such assessments provide important insights into where potential stresses (or trade-offs) could arise in the future, and help guide steps to address it. The next chapter will focus on nexus assessment tools that can support nexus-oriented decision making.

3

DECISION-MAKING TOOLS WITH A NEXUS PERSPECTIVE

Planning and decision making that consider the impacts of energy strategies on other sectors and that more broadly support an integrated approach to resource management require substantial qualitative and quantitative insights.

This chapter delves deeper into those insights and explores the tools available to policy makers for obtaining them. These tools are reviewed based on the main inputs they require, the outputs they provide (and hence the policy questions they address) and some of their analytical characteristics. On the basis of gaps identified in the review, the chapter also proposes a framework for a scenario-based nexus decision-support tool – with energy as the entry point – that makes it possible to quantify how an increased deployment of renewable energy in the national mix could affect the demand of water and land/food.

3.1 INSIGHTS FOR NEXUS-FRIENDLY DECISION MAKING: THE CASE FOR TOOLS

Policy making often tends to occur in *silo* mode, without sufficient co-ordination and without necessarily considering the influences that policy decisions in one sector could have on the others. Such lack of policy co-ordination could exist within one level of the administration (*e.g.*, the Ministry of Energy dealing with energy and the Ministry of Agriculture dealing with food), or between different administration levels (*e.g.*, energy decisions being made at the national level, while water decisions are made at the local level).

A silo approach to managing these resources has often led to unsustainable policy and development choices (Weitz, 2014). There is growing recognition of the need to better understand the linkages between water, energy and food, and to adopt an integrated approach to managing these sectors. Integrated resource management is not a new concept and has been a key feature of well-known development approaches, such as integrated water resources management (IWRM)[15] or watershed management (*e.g.*, in Brazil, India, Ethiopia). These and related methodologies have been proposed by various UN agencies, the World Bank (*e.g.*, in its Strategic Environmental Assessment) and other institutions.

Adopting a nexus approach to sector management involves analysing cross-sectoral interactions to facilitate integrated planning and decision making. Such an approach encompasses the use of a vast array of quantitative and qualitative decision-support tools and methodologies depending on the purpose of the analysis, access to data and availability of technical capacity (SEI, 2013).

The outcomes from such tools inform policy making by quantifying the extent to which a certain policy affects the different sectors. The need for such integrated decision-support frameworks is illustrated, for example, by the FAO's nexus assessment methodology (see box 3.1).

Methodologies to support nexus-friendly decision making can be qualitative, quantitative or combined. Although the main focus of this chapter is

---

[15] According to the Global Water Partnership's definition, IWRM is a "process which promotes the co-ordinated development and management of water, land and related resources, in order to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems".

BOX 3.1

THE FAO'S NEXUS ASSESSMENT METHODOLOGY

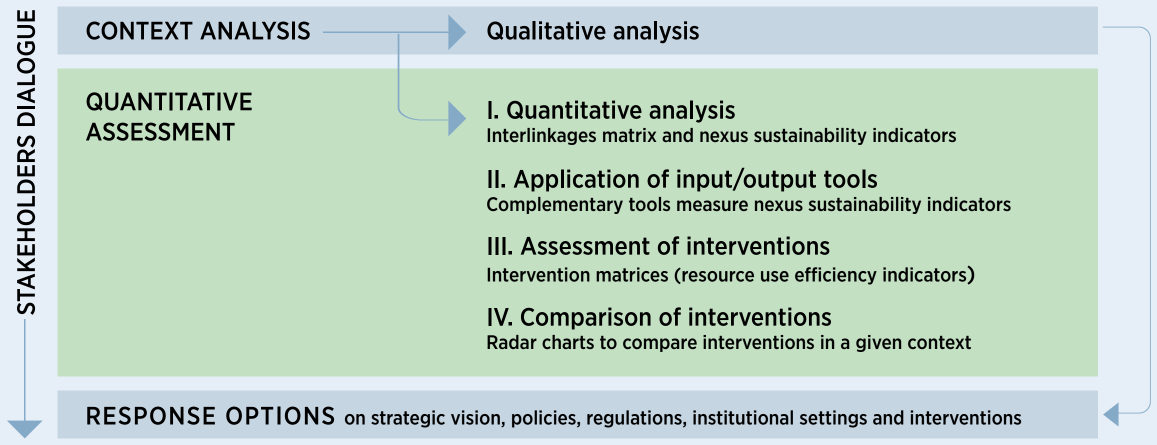
The FAO is co-leading, with German Federal Ministry for Economic Cooperation and Development (BMZ), the High-Impact Opportunity (HIO) on the Water–Energy–Food Nexus within the UN´s Sustainable Energy for All initiative (SE4ALL). The Water–Energy–Food Nexus HIO is a voluntary partnership of like-minded stakeholders that seeks to facilitate the development and deployment of sustainable nexus solutions to aid SE4ALL in reaching its goals. Current partners include the FAO, BMZ/GIZ, IRENA, OPEC Fund for International Development (OFID), REEEP, the World Bank, the European Commission and the U.S. Agency for International Development (USAID).

As part of its contribution to the Nexus HIO, the FAO has developed the WEF nexus assessment methodology (FAO, 2014b). The goal of this methodology is: 1) to have an idea of the sustainability of the reference system/territorial context (*e.g.*, a country or a region) and its bio-economic pressures, and 2) to assess the performance of specific policy- or project-level interventions in terms of natural and human resource-use efficiency. The assessment can be carried out at different levels and scales. Suggested indicator matrices and tools can be used for the following four main building blocks of the assessment (see also figure 3.1):

- Qualitative and/or quantitative assessment of the context where interventions take place. This first step can already, in some cases, provide insights on some of the response options.
- Quantitative assessment of specific interventions, with the aim of analysing how they perform from a nexus perspective. This step ideally should be carried out after the context analysis because an intervention could have the same nexus performance in two different contexts, but be acceptable in only one of them (hence the importance of assessing interventions against the nexus situation of the context). This stage also allows for the comparison of different interventions in the same context with regard to their nexus performance.
- Identification of response options needed to ensure the sustainability of the environment and livelihoods.
- Adequate stakeholder engagement at every relevant step. Stakeholders can develop their own indicators and benchmarking systems; however, if this is difficult or data are not available, as a starting point the FAO methodology proposes indicators for which information is available from international data sets, as well as a benchmarking system based on international references.

The FAO's proposed nexus assessment methodology reflects the international community's ongoing efforts to propose and adopt frameworks that support integrated and nexus-friendly decision making. The present chapter supports the need for these frameworks, and intends to add value in this field.

Figure 3.1 Main components of the FAO's nexus assessment methodology



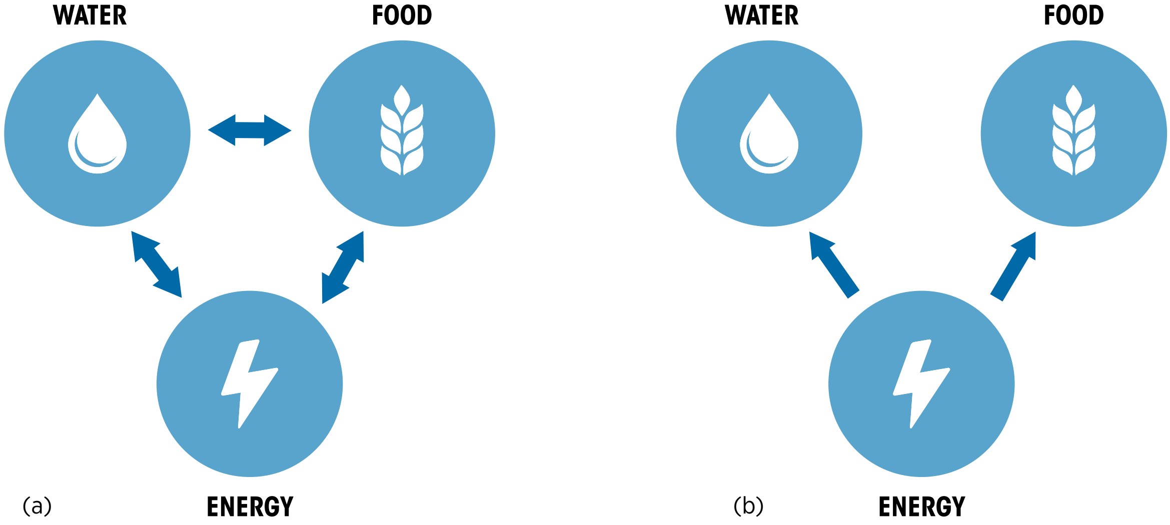
Source: Adapted from FAO, 2014b
For more details on the methodology, please refer to FAO (2014b).

on quantitative tools[16], qualitative methodologies also can bring important insights to decision-making processes. The FAO's Nexus Assessment methodology, for example, combines both types of approaches, whereas other methodologies are mainly qualitative in nature, such as that of the UN Economic Commission for Europe (UNECE) and Kungliga Tekniska Högskolan (KTH) (2014).

This report differentiates[17] two main approaches in quantitative nexus tools: a "fully integrated" approach and an "entry point" approach, as illustrated in figure 3.2. A fully integrated approach represents the relations between resources in all directions, whereas an "entry point" approach analyses the influence of one resource (*i.e.*, the "entry point") on the others. While some experts consider nexus tools as those that address interactions between elements in a bi-directional way (*e.g.*, water on energy and energy on water), this report also considers as nexus tools those that address interactions only in a uni-directional way (*e.g.*, energy on water). In the case of energy, assessing the implications of a specific energy policy on other sectors such as water and food (*i.e.*, using a uni-directional approach with energy as the entry point, illustrated in figure 3.2 (b)), can bring useful preliminary insights even in the absence of a fully integrated approach. For instance, assessing the water resource requirements of an energy strategy can provide useful initial information with regard to potential trade-offs with other water uses, even if a fully integrated planning of these sectors is more preferable. Some existing methodologies such as the FAO's nexus assessment (FAO, 2014b) or the Water, Energy, Food Nexus Tool 2.0 (Mohtar and Daher, 2013) use food as the entry point; others, such as the one in UNECE and KTH (2014), use water as the entry point; and still others, such as MARKAL/TIMES (Loulou et al., 2005), use energy as the entry point. In the remainder of the chapter, the discussion will be mainly from the energy perspective (*i.e.*, energy as the entry point).

Adopting a nexus perspective in energy policy making is becoming necessary, and quantitative tools could prove useful. Such tools could help gain insights into the nexus implications of energy policies, support informed renewable energy policy making and mitigate potential risks[18]. For example, solar pumping could be promoted to expand irrigation and to decouple water availability from the fossil fuel or grid

Figure 3.2 Fully integrated and bi-directional approach (a) and entry point uni-directional approach from the energy sector (b)



---

[16] In the remainder of the report, unless otherwise stated, the expressions "analytical frameworks", "quantitative frameworks", "analytical tools" and "quantitative tools" will be treated as synonyms.
[17] This differentiation has been found to be unclear in the literature.
[18] A thorough analysis of renewable energy policies from a nexus perspective is out of the scope of this report.

electricity supply. This intervention, favourable from the food and energy perspectives, could put unanticipated pressure on the water system (*e.g.*, in arid countries) by encouraging excessive water use due to more affordable pumping. To pre-meditate such risks, the need for wider use of analytical frameworks in the nexus context has been raised globally (FAO, 2014b; UNECE and KTH, 2014; Granit et al., 2013; Bazilian et al., 2011).

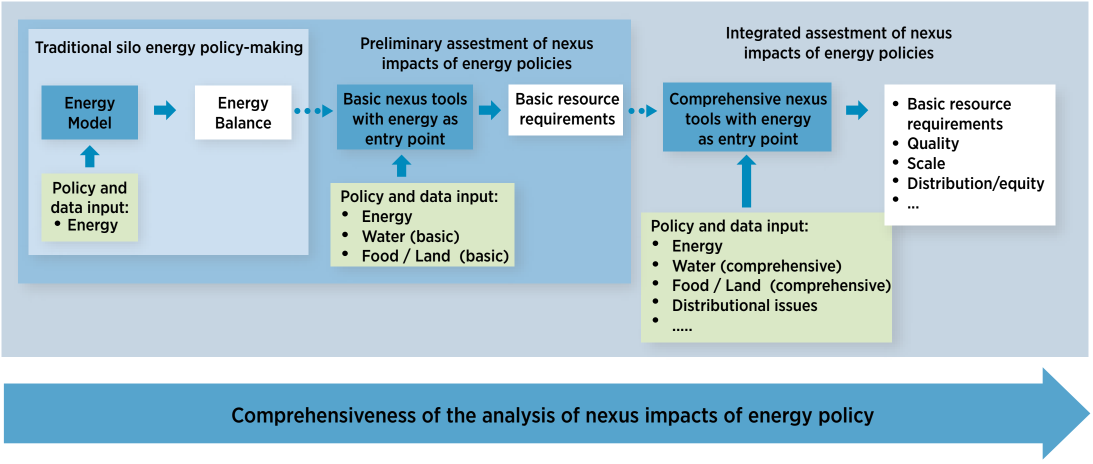
Quantitative tools for analysing the nexus impacts of energy policy can vary in terms of comprehensiveness, as illustrated in figure 3.3[19]. The left side of the figure represents the silo approach to energy policy, in which policy inputs and other data relevant to the energy sector are provided to an energy model, which in turn yields outputs representing the energy sector under such policies (*e.g.*, the resulting energy balance), disregarding the impacts on water and food/land. A more comprehensive approach (in the centre) consists of a basic nexus tool that receives policy and data inputs regarding the energy sector and also basic inputs relevant to water and food/land, and provides outputs about the basic resource requirements (*e.g.*, water and land) of the analysed energy policy.

A comprehensive nexus tool (right side of the figure) accepts detailed inputs of the three sectors and provides information on basic resource requirements (*e.g.*, total land needed), complemented with quality aspects (*e.g.*, types of land) or other issues related to scale, distribution/equity or governance, among others. In some cases (represented with dotted blue arrows), the outputs of one analysis could be inputs to a more comprehensive one.

The figure does not intend to represent a sequential process: some comprehensive nexus tools could directly perform the most advanced assessments without previously going through the other levels. Preliminary nexus tools, despite their limitations (*e.g.* limited scope of questions they can answer), can be useful in bridging the gap between a silo approach and a fully comprehensive nexus assessment, especially when the resources (*e.g.*, time, data, financial, human) are limited.

Some institutions are beginning to propose such preliminary tools, for instance the FAO's nexus assessment methodology presented in box 3.1 (FAO, 2014b). The next section reviews both simple and comprehensive nexus tools based on a set of criteria, and identifies existing gaps. Other relevant reviews of nexus tools and related frameworks (*e.g.*, integrated assessment models of climate change) can be found in FAO (2014b), World Bank (2013), Pollitt et al. (2010) and Tol (2006).

Figure 3.3 Different levels of comprehensiveness in analysis of the nexus impacts of energy policy



---

[19] *Since the discussion is focused on energy, energy is considered to be the entry point for all tools in figure 3.3, even for the most comprehensive ones placed on the right-hand side. In the figure, comprehensiveness does not necessarily mean complexity, since for instance some energy models (which would be placed on the left-hand side) can themselves be quite complex.*

3.2 REVIEWING EXISTING NEXUS TOOLS: SOME CURRENT GAPS

Several nexus tools exist with varying inputs, outputs or analytical characteristics. The inputs needed are used to characterise the systems under study and their context. Regarding the outputs, some tools focus on a single element of the nexus (*e.g.*, only water), other tools represent two or more elements, and others even add further components such as greenhouse gas emissions. Lastly, the underlying analytical characteristics of the tools can also differ, for instance in: 1) their level of accessibility to a wide number of users (*e.g.*, from free online tools to costly software packages), 2) their flexibility to be applied to different contexts (*e.g.*, to various countries), 3) the level at which the tools are defined (*e.g.*, while some tools are defined at a national level, others focus on the sub-national or even local levels, for instance considering a single watershed[20]) or 4) their comprehensiveness and degree of complexity. While the type of data required may vary between the different tools, most of them are highly data intensive, which, in light of the difficulty of obtaining quality data, represents a key constraint on their use.

The review includes only tools that comply with specific selection criteria, and does not intend to be exhaustive. The review criteria are grouped into three categories: inputs required, outputs provided (and, therefore, answered questions) and analytical characteristics (see table 3.1). This approach allows for a structured review of tools, providing insights on what the tool needs, what the tool provides and how the tool works. The tools analysed in this report are selected based on a selection criteria highlighted in table 3.1 and justified in box 3.2. The review does not delve into aspects of how the tools can be used for scenario characterisation and generation. A detailed discussion on the strengths and weaknesses of each tool is out of the scope of this report, but related efforts have been undertaken by the FAO in collaboration with other tool developers[21].

Table 3.1 List of the review and selection criteria

REVIEW CRITERIA		SELECTION CRITERIA
1. Input requirements		
1.a)	Main inputs	–
2. Outputs/ answered questions		
2.a)	The tool accounts for the energy system	At least two of the three
2.b)	The tool accounts for the water system	
2.c)	The tool accounts for the food system	
2.d)	The tool accounts for greenhouse gas emissions	–
2.e)	The tool produces economic indicators, notably the costs of the scenario	–
2.f)	The tool accounts for land requirements	–
3. Analytical characteristics		
3.a)	The tool is widely accessible, ready to be used or open access	Yes
3.b)	The tool allows for policy analysis at a national level	At least national
3.c)	The tool can be applied to different geographies (*i.e.*, to different countries)	–
3.d)	The tool is simple and provides valuable preliminary assessments, and it incorporates explicit context-specific input from decision makers	–

---

[20] According to the U.S. Environmental Protection Agency, "watershed is the area of land where all of the water that is under it or drains off of it goes into the same place".

[21] The FAO hosted the workshop "Moving ahead to implement the nexus approach: lessons learned and discussion of next steps regarding integrated assessment of water-energy-food needs in a climate change context", which aimed to identify key lessons learned and current strengths and weaknesses of existing nexus tools. The workshop took place in March 2013 in Rome, Italy.

BOX 3.2

JUSTIFICATION OF THE CRITERIA USED FOR THE SELECTION OF TOOLS

The tool is included in the review if it satisfies the following criteria:

- It covers at least two of the three elements of the water–food–energy nexus (*i.e.*, water and energy, food and energy or water and food).

To identify tools able to inform decision making from a nexus perspective, this review excludes tools that focus on just one particular element of the nexus. While the perspective adopted in this report is energy centric, tools that do not assess energy explicitly (but do address both water and food) can in some cases provide interesting methodological insights of application to energy.

- It allows for policy analysis at a national level.

Policy makers at different levels of the administration require insights at national, regional or local levels to guide their decisions. In this review, the primary focus is on tools providing information at the national level. For large countries, however, some flexibility is needed when dealing at times with very different circumstances with regard to the elements of the nexus within the country. In this context, the review also includes tools that provide the possibility of analysing the nexus elements at the sub-national and local levels.

- It is widely accessible and ready to be used or it has open access.

Ease of accessibility for potential end-users allows some tools to be applied more easily in decision-making processes. Moreover, some tools are freely available, which ensures even wider engagement opportunities, especially for users that may lack resources for expensive modelling software. In any case, it should be noted that accessibility does not always mean usefulness.

The specific review criteria are described as follows:

1. Inputs required: the review criteria within this group will allow the reader to understand the main data and other types of inputs that are required by the model.
    - » Main inputs

      These inputs represent the main information that the tool needs in order to perform the analysis, be it in terms of data or of any other quantitative or qualitative information. These inputs normally would be provided by the user of the tool. Some examples could be the quantities and type of the existing energy resources in the country under study, the availability of different types of water, the accessible land for food production, soil types or the costs of different energy or water technologies.
2. Outputs and questions answered: the review criteria within this group give information on the outputs that can be expected from the tool and, therefore, which questions can potentially be answered by using it.
    - » The tool accounts for the energy system

      Tools that account for the energy system can provide insights on aspects such as the energy mix, imports/exports of energy, or the installed capacity of each technology, which in turn can be used to answer questions of relevance to this sector.
    - » The tool accounts for the water system

      Tools that account for the water system can provide insights on aspects such as the use of renewable freshwater resources, how much water is consumed for different purposes or the amount of withdrawals from different sources of water.
    - » The tool accounts for the food system

      Tools that account for the food system can provide insights on aspects such as food production, processing, storage and distribution.
    - » The tool accounts for greenhouse gas emissions

      Policy making related to energy, water or food/land cannot be done in isolation from climate change because the repercussions are clear and bi-directional: all three sectors are substantial emitters of greenhouse gases, and will be affected by climate change. Although accounting for the effects of climate change on the elements of the nexus is outside the scope of this report, some of the reviewed tools account for the effects of the analysed policies or scenarios on greenhouse gas emissions. A comprehensive nexus tool could be able to analyse the trade-offs that may exist between carbon emissions and the elements of nexus (*e.g.*, nuclear power being carbon-free but a large water consumer).

» The tool produces economic indicators, notably the costs of the scenario

Since economic considerations are key to policy making, some tools are able to provide an appraisal of the economic implications of the analysed scenarios or policies, notably the incurred costs. The inclusion of non-economic costs (*i.e.*, externalities) can also be of relevance, for instance to account for the value of ecosystem services (*e.g.*, keeping forest land unused, which can capture some of the carbon emissions and therefore reduce the externality associated with them).

» The tool accounts for land requirements

While land is widely available in some countries, it represents an important resource constraint in others. An example is Qatar, where land could be the resource most affected by strategies pursuing enhanced food self-sufficiency (Mohtar and Daher, 2013). Some of the tools reviewed are able to provide insights into such issues, which are also described under this review criterion.

3. Analytical characteristics: the review criteria within this group describe some specific analytical characteristics that are considered relevant for this report.

» The tool is widely accessible, ready to be used or open access

Although accessibility does not guarantee usefulness, the present review criterion analyses how accessible a tool is. As explained in box 3.2, this report considers accessibility to be, in general, a desirable feature in order to allow for wide use of tools, which would in turn bring improved nexus-friendly decision making.

» The tool allows policy analysis at a national level

Policy makers at different levels of the administration require information at different levels, such as national, regional or local, to guide their decisions. This review criterion addresses the level of the analysis carried out by the tool. In this review, as explained in box 3.2, the primary focus is placed on tools providing information at the national level.

» The tool can be adapted to different contexts and geographies (*i.e.*, different countries)

The present review criterion assesses whether a tool is flexible enough to allow for application to different contexts/countries without fundamentally changing its structure. For such application, it should only require new, country-adapted, inputs and data.

» The tool is simple and provides valuable preliminary assessments, and it incorporates explicit context-specific input from decision makers

This review criterion considers some of the internal workings of the tool. Although analytical complexities may be needed for comprehensive nexus tools, this chapter focuses on simple tools. By definition, complexities should be avoided in simple tools, since they may provide results that are not easily understood, which in turn could lead to distrust in their implications. Furthermore, to maximise the engagement and interest from decision makers, the tool should incorporate context-specific policy preferences as explicit inputs to the analysis. This can be done, for instance, by introducing the desired level of energy independence, or a preference between two conflicting policy goals.

Based on the review criteria enumerated above, table 3.2 presents the review of tools, showcasing whether the different criteria are covered by the eight tools surveyed and highlighting current gaps. The table is designed to provide a visual indication of the existing gaps: if a criterion is not addressed by a specific tool, the corresponding cell within the table is white (indicating gaps); if it is addressed, the cell is shaded in blue and contains further information.

Table 3.2 Review of eight different nexus tools

TOOL AND REFERENCE	**REVIEW CRITERIA**			
	1. INPUTS REQUIRED	**2. OUTPUTS/ ANSWERED QUESTIONS**		
	1.a) Main inputs	**2.a) Energy**	**2.b) Water**	**2.c) Food**
Climate, Land-use, Energy, and Water (CLEW) (Alfstad, 2013)	• Extensive data requirements • Technical and economic parameters of power plants, farming machinery, water supply chain, desalination terminals, irrigation technologies, fertiliser production, etc.	• Energy balance, including power generation and refining • Energy for food • Foreign (virtual) energy	• Water balance • Water supply and desalination • Water pumping • Water for food • Water for energy (hydropower, power plant cooling, biofuel crops)	• Irrigation technologies • Use of fertilisers • Use of farming machinery
The Water, Energy, Food Nexus Tool 2.0 (Mohtar and Daher, 2013)	• Data and local characteristics of food, water and energy systems • Local production of food, water and energy (per type) • Context-specific policy inputs	• Implications of food production on energy trade • Energy for water (pumping, treatment, desalination) • Energy for food (tillage, fertiliser production, distribution, harvest)	• Implications of food production on local and virtual water	• Levels of local production of different types of food
MARKAL/TIMES (Loulou et al. 2005)	• Extensive data requirements • Techno-economic details of energy technologies • Characterisation of the reference energy system	• Energy planning with high technological detail • Energy balances • Effectiveness of energy policy	• Water use in energy sector	
WEAP-LEAP (SEI, 2013)	• Extensive data requirement • Techno-economic details of energy technologies	• Detailed analysis of energy demand, transformations and stocks • Energy balances	• Watershed hydrology and water planning • Physical and geographical simulation water demands and supplies • Groundwater, water quality and conservation, reservoirs and hydropower	
FAO's nexus assessment methodology (FAO, 2014)	• Indicators that are already available • Key classifications of the country under study to place it under country typologies	• Specific to each type of intervention, but a large choice (e.g., energy consumption and production)	• Specific to each type of intervention, but a large choice (e.g., water pumped, water for energy, etc.)	• Specific to each type of intervention, but a large choice (e.g., yields, harvested food, etc.)
WBCSD Nexus tool (WBCSD, 2014)	• Characterisation of the energy sector • GIS maps and information • Characterisation of water for food and for energy • Information on labour force and availability of machinery	• Energy for water • Energy for food (for irrigation, fertiliser production or machinery)	• Water for energy (for power generation or fuel production) • Water for food (e.g., green water, blue water)	• Food production
MuSIASEM –The Flow-Fund Model (FAO, 2013)	• Extensive data requirements • Socio-economic indicators, including work force evolution • Availability of land • Climate change impacts • Characterisation of all flows	• Energy flows in society (of fossil fuels and electricity)	• Water flows in society (e.g., for drinking, domestic use, irrigation, industrial processes, etc.)	• Food flows in society
Diagnostic, Financial, and Institutional Tool for Investment in Water for Agriculture (Salman, 2013)	• Full data sets needed to characterise local irrigation and hydropower projects	• Impact of hydropower projects in improving local livelihoods • Access to electricity	• Water management • Water for agriculture and energy (hydropower) • Water management	• Food security, agricultural production

			3. ANALYTICAL CHARACTERISTICS			
2.d) Greenhouse gas emissions	**2.e) Economic**	**2.f) Land**	**3.a) Accessibility**	**3.b) National geographic level**	**3.c) Different geographies**	**3.d) Simple but able to provide preliminary assessment, including explicit policy input**
• Local and foreign (virtual) • Cumulative emissions	• Selected economic indicators	• Biofuel crops • Types of land according to context	• Engagement with developers is possible	• National • Global	• Can be (and has been) applied to different geographies, but resource intensive	
• Implications of food production on emissions (local and virtual)	• Costs of food production	• Land for food	• Engagement with developers is possible	• National	• Can be applied to different geographies	• Simple accounting framework • Includes policy importance for sustainability index
• Emissions from energy sector	• Total discounted costs of energy sector, including its water supply		• Applicable to any country, proprietary graphical interface required	• National • Global • Regional • Local	• Can be (and has been) applied to different geographies, but resource intensive	
• Emissions from energy sector	• Includes a financial module		• Engagement with developers is possible; free for developing countries	• National • Global	• Can be applied to different geographies	
	• Specific to each type of intervention, but a large choice (e.g., costs, incomes, jobs, etc.)	• Specific to each type of intervention, but a large choice (e.g., areas needed, cultivated land, etc.)	• Largely described in (FAO, 2014); engagement with developers is possible	• National • Sub-national	• Can be applied easily to different geographies by using country typologies	• The nexus rapid appraisal is simple and relies on available indicators • The use of country typologies, and the proposal of indicators for each type of intervention, also eases the use
		• Land use	• Engagement with developers is possible, future graphical interface	• National • Global • Regional • Local	• Can be applied to different geographies	
• Implications of all flows on emissions	• Costs and value-added	• Land use	• Engagement with developers is possible, has been applied to different countries	• National	• Can be (and has been) applied to different geographies, but resource intensive	
• Impact of irrigation and hydropower on emissions	• Contribution of agriculture to GDP and income generation • Investment needs • Impact of irrigation projects in improving local livelihoods	• Cultivated land and crop yields	• Engagement with developers is possible, has been applied to different countries	• National	• Can be (and has been) applied to different geographies, but resource intensive	

An important conclusion that emerges from the review is that data is often a key difficulty. Extensive data inputs are needed for most of the tools, and in many cases, the required data are not available. Understanding the data requirements and the specific difficulties of data collection across the interconnected systems of the nexus is crucial. Examples of the type of data required may include:

- information about the different elements of the nexus separately – that is, energy, water or land (*e.g.*, recoverable energy resources and their production potential and costs, renewable water resource accessibility, the availability and quality of land resources and their current use, the different levels of food self-sufficiency); and
- data on how the elements of the nexus relate to each other (*e.g.*, energy consumption in water treatment processes, water usage in energy production, land requirements of power generation).

While obtaining data for the former (different elements of the nexus independently) is considerably difficult, the challenges mount when trying to obtain data linking two or more elements of the nexus. As discussed in box 3.3, the cross-sectoral and multi-scale nature of the nexus adds to the difficulty of collecting and compiling information. Indeed, many experts highlight the challenge of accessing data or insights needed to support nexus-friendly decision making, both from individual sectors and between sectors (IISD, 2013). Even in cases where data is available, comparability is a challenge since data collection methodologies and classifications may be different between the sectors. Hence, a sound nexus assessment benefits from standardised data gathering efforts.

The issue of scale in the data is also a difficulty. While it would be suitable to use national energy data, this is not necessarily the case for water, as many hydrological relationships are scale dependent and may be better characterised locally. In the case of land, its characteristics (*e.g.*, ownership, management, development) and suitability for different uses could require even more resolution (*e.g.*, of just a few metres), making geo-referenced data the ideal choice in this case.

In response to these data challenges, new initiatives seek to address these and related issues, including the lack of a sound, structured and widely accepted terminology understood by both water and energy experts. The World Water Council and Electricité de France (EDF), for instance, have launched the "Water for Energy Framework" initiative, which intends to address the differences in water accounting methodologies across different sectors. In particular, the initiative aims to "develop a common language and methodology through the energy sector to address the energy "impact" on water. The objective of the project is the development of a conceptual and analytical framework (and subsequent tool/s) for assessing and reporting the relations between any energy production activity and its water environment." (World Water Council and EDF, 2014).

Some of the review criteria are well covered by the eight tools surveyed, while there is a gap in simple tools. In particular:

- All reviewed tools provide outputs related to energy and water
- All reviewed tools are widely accessible, and they allow for policy making at a national level.
- All reviewed tools can be adapted to different contexts and geographies
- Seven of the eight tools provide economic indicators
- Six of the eight tools provide insights related to greenhouse gas emissions
- Six of the eight tools provide outputs regarding food or land
- Two of the eight tools are classified as simple tools

Most of the reviewed tools are designed as detailed frameworks for comprehensive nexus analyses, but not as simple, user-friendly tools for preliminary assessments. As such, these comprehensive tools generally have significant data needs and are resource intensive in terms of time, capacities and financing. Only two tools are considered to be simple, providing valuable preliminary assessments, and incorporating explicit context-specific input from decision makers. However, both

BOX 3.3

DATA CHALLENGES IN THE WATER–ENERGY NEXUS

While it is relatively straightforward to obtain national data for energy, water presents greater challenges, as reported by the UN World Water Development Report (UN Water, 2014b). Annual energy production, transformation and consumption data are available for most countries from sources such as the IEA, the UN, the World Bank or IRENA. Energy carriers such as coal, oil and natural gas are traded in markets, whether global, regional or even national (*e.g.*, gas hubs), which enhances data availability for prices or traded quantities, as compiled for example by the BP Statistical Review of World Energy.

Similar markets do not exist for water, partly as a consequence of its physical characteristics (*i.e.*, trans-boundary water flows, limited and costly trading of physical water), which makes it mainly a local resource. As a result, it becomes difficult to assign a correct value to water. While some data sets relating to water exist (e.g., those related to water consumption, withdrawals, renewable freshwater resources, water pollution or water productivity, published by sources such as UN Water, the FAO's AQUASTAT, the World Bank or the World Resources Institute), data availability for water is still relatively limited and important gaps remain.

Data availability on energy and water becomes even more challenging when looking at it from a water–energy nexus perspective. While, for instance, there could be adequate data available on water consumption (an area in which data availability is less limited) and on electricity generation, data on water consumption for electricity generation remain much more limited. Furthermore, lack of information on the cooling technologies used in power generation – which influence water use estimations as much as the generation technology itself (Halstead et al., 2014) – remains a key challenge. Hydropower and bioenergy are especially challenging because the relation of water use to energy production (instead of other services) is unclear. For example, water evaporation from hydro cannot be related entirely to power generation, but also can be attributed to other services provided by the dam, such as flood control or irrigation.

Other challenges include: 1) water requirements in other energy sectors beyond electricity (*e.g.*, oil extraction or refining) are even less understood, 2) it is often unclear whether water for energy data are expressed per unit of gross or net energy output (UN Water, 2014b), 3) the water consumption patterns of energy technologies vary considerably depending on the location (SEI, 2013) and 4) data gaps become even larger if the full life cycle of the technologies is considered.

As a consequence, there is a lack of indicators for water–energy nexus interactions, especially if consistent time series are needed. Additionally, when data are available, compatibility of data sets across different resources and contexts is often challenging. The UN has recently called for a co-ordination of approaches for data generation and harmonisation regarding water supply and use, and energy production. It also proposes a set of indicators and data sets, which could help support decision makers within the water–energy spectrum (UN Water, 2014b).

It should be noted, however, that some studies are slowly filling the data gap on the water–energy nexus. On the water for energy front, Spang et al., (2014) and the IEA (2012) present updated international comparisons of water use for both primary energy production and power generation. In the energy for water domain, although international evidence is more scattered (water supply is more locally specific), some sources provide partial data on desalination (Global Water Intelligence, 2010) or for specific countries such as the United States (Wang, 2013; Cooley and Wilkinson, 2012). Governments also are taking positive steps: in California, for example, a bill was unanimously approved that requires oil companies to report how much water they use in drilling operations and the source of water (California Legislative Information, 2014).

of them have food as the entry point, so there is a gap for simple tools with energy as the entry point.

The next section presents the conceptual framework for a tool that contributes to bridging this gap. This tool is conceptually inspired by the "Water, Energy, Food Nexus Tool 2.0" (Mohtar and Daher, 2013) which has food as its entry point and allows for preliminary assessments of nexus impacts and trade-offs. The tool presented in this report has energy as the entry point, which represents the main conceptual difference between them, in addition to their analytical approach. The tool presented would be able to provide valuable, even if approximate, snapshots of the impacts of renewable energy deployment on the nexus, and it would do so in a short period of time with limited use of resources (*e.g.* human or financial). Such snapshots could serve as a starting point for a broader, more comprehensive analysis using the tools discussed earlier.

3.3 CONCEPTUAL FRAMEWORK OF A PRELIMINARY NEXUS ASSESSMENT TOOL

This section proposes the conceptual framework for a tool that can conduct preliminary assessments of basic nexus impacts of energy policy. It is aimed at addressing some of the gaps identified in the previous section, and its main output would be the basic resource requirements (*e.g.*, water volumes and land areas) associated with a specific energy policy. This tool can integrate context-specific inputs from policy makers, present outputs in a practical and easily accessible format, and would be analytically simple while still providing preliminary insights. Currently, the tool is only a conceptual proposal and could be enhanced in future work.

The proposed conceptual framework is scenario based, where the country's energy balance is the main input for each scenario. It would allow the user to create different scenarios by modifying the energy balance associated with different policy choices (*e.g.*, a greater use of renewable energy), and to analyse the resulting nexus impacts. Even if the focus of this report is on renewable energy, the tool considers the complete energy balance because a greater deployment of renewables would normally influence the nexus elements not just as a result of such deployment, but also as a result of the substitution of the other types of energy that would have been needed otherwise.

To represent these substitutions, the complete energy balance needs to be considered. Most countries compile energy balances as part of their national energy statistics, and the IEA gathers this information in a standardised and widely accepted format on a regular basis (IEA, 2014c). This wide acceptance is a key advantage of using energy balance as the basis of the proposed conceptual framework. An example of such an energy balance is given in box 3.4.

The conceptual framework assumes the energy balance as an exogenous input, without questioning whether it is feasible from a technical perspective, as it is not an energy model. For instance, a 100% penetration of variable renewable power generation may not be technically viable for a specific country, but the tool would accept such an energy balance as an input. This implies that the proposed tool would normally be used after an energy model (*e.g.*, MARKAL/TIMES, which may also be data and resource intensive) has been run to develop energy sector scenarios and to identify feasible energy balances for the future (in a similar way as represented in the left-hand side of figure 3.3).

The first step in the use of the proposed tool is to provide a baseline energy balance that corresponds to a reference energy policy scenario. The baseline energy balance could represent the energy scenario at the time of the analysis (*e.g.*, 2013) or a reference case in the future (*e.g.*, 2030), based on a previous energy forecasting/modelling exercise.

The second step is to provide an alternative energy balance, which represents the energy policy scenario to be analysed from a nexus perspective (*e.g.*, putting stronger emphasis on renewable energy). It would also be based on an energy modelling exercise, normally carried out by the energy authorities of the country. Such an energy balance should reflect changes in the energy types that are modified by the analysed policy (*e.g.*, increased use of solar energy, if the policy

BOX 3.4

EXAMPLE OF AN ENERGY BALANCE

Energy balances, in the standardised format compiled and published by the IEA, provide a sound, concise and useful overview of the full energy sector of a country in a given year – specifically, how energy was produced, traded, transformed and consumed. The columns represent the different energy types (*e.g.*, coal, oil, natural gas, etc.), while the rows represent the different stages of the supply and consumption chain of each energy type (mainly primary energy production, imports, exports, energy transformation and final consumption).

Table 3.3 represents an energy balance for an imaginary country, excluding the details in the transformation sector and in final energy consumption. The balance is based on the IEA's methodology and is expressed in petajoules (PJ). The country's primary energy production mainly includes coal (111 PJ), bioenergy (12 PJ) and solar energy (4 PJ), accounting for a total of 130 PJ. The country also relies on importing energy, mainly crude oil (242 PJ), oil products (55 PJ) and natural gas, up to a total of 344 PJ. The country also exports energy, mainly in the form of refined oil products (69 PJ*) and crude oil, which amount to 82 PJ (exports are represented with minus signs because of their negative contribution towards energy use in the country). As a result, the main energy source in this country's total primary energy supply (TPES) is crude oil with 232 PJ, followed by coal, and the total TPES (including all energy types) is 392 PJ.

The next line of the energy balance represents the transformation sector (*e.g.*, electricity generation plants, oil refineries, etc.). Negative values mean that an energy type is an input to a transformation, and positive values mean that it is an output (*e.g.*, 231 PJ of crude oil were converted into 167 PJ of oil products and part of the 47 PJ of electricity generated from different sources). Total final consumption (TFC) of energy (*i.e.*, energy consumed by the different sectors of the economy) consists mainly of oil products (153 PJ), electricity and bioenergy, amounting to 234 PJ. The country does not use nuclear energy.

These energy balances, by definition, need to be balanced**: for each energy source (*i.e.*, column), the total primary energy supply needs to equal the amount of energy used for total final consumption and for transformations. The overall balance for all energy types (the "Total" column) also complies with this property.

Table 3.3 Example of a simplified energy balance, excluding details in transformation sector and final consumption

Energy balance (PJ)	Coal	Crude oil	Oil products	Natural gas	Nuclear	Hydro-power	Solar energy	Bioen-ergy	Elec-tricity	Total
Production	111	1				2	4	12		130
Imports	4	242	55	36				1	6	344
Exports		-11	-69					0	-2	-82
Total primary energy supply (TPES)	115	232	-14	36		2	4	13	4	392
Transformation sector	-109	-232	167	-27		-2	-2	0	47	-158
Total final consumption (TFC)	**6**	**0**	**153**	**9**		**0**	**2**	**13**	**51**	**234**

Source: Based on IEA energy balance methodology

* A country can both import and export the same energy type in a same year. For instance, the imports and exports could take place in different seasons, or in different geographic areas of the country. The energy balances show both exports and imports (instead of a net value) in order to capture this information.

** Except for statistical differences.

promotes renewables) and should be consistent with the baseline energy balance with respect to the energy policies that have not changed (*e.g.*, if energy efficiency remains the same, total final consumption of energy should be the same in both energy balances[22]). The proposed tool would then estimate the incremental energy balance, by simply subtracting the alternative and the baseline energy balances. The incremental energy balance would represent the changes in the energy situation due to the analysed policy.

As a next step, the proposed tool would estimate the water, land[23], emissions and cost[24] implications of the incremental energy balance; these provide insights about the basic resources, cost and emissions implications of the analysed energy policy. The tool would multiply the incremental energy balance by data matrices which represent, for each type of energy (columns of the energy balance) and for each stage of the energy supply chain (rows of the energy balance): the amount of water or land required per energy unit, the amount of emissions produced in each of those stages per energy unit, or the unitary cost incurred. This is illustrated in figure 3.4, where each of these data matrices are respectively called Water for Energy, Land for Energy, Emissions of Energy and Costs of Energy. These data matrices are exogenous inputs, and normally would be specific to the country or context under study. The result of this step would be the basic incremental[25] use of water or land resources (*e.g.* volume of water, area of land), the incremental costs[26] or the incremental emissions produced by the analysed energy policy, all else being equal.

It should be noted that this does not reflect any type of feedback or second-round effect (*e.g.*, if more water is needed for energy, less water could be available for human use, which could imply a higher need for desalination, which, in turn, would imply more energy). This is out of the scope of the proposed conceptual framework which, as explained above, is intended to be analytically simple. Since the tool analyses a proposed change in the energy balance for one year, it can be considered a static tool. The output obtained up to this point (*i.e.*, incremental use of resources) could be relevant for the policy maker, since it provides the implications of the analysed policy expressed in physical units (*e.g.*, additional cubic metres of water, reduced tonnes of CO_2 emissions).

The tool provides information about the nexus implications of the analysed policy[27], not about how the policy should be designed in order to minimise such nexus implications. For example, the tool can provide information on the land required for reaching a specific solar energy target, but does not consider how much land is actually available. Furthermore, as noted above, this approach only provides information about the basic resource requirements but does not provide information related to the quality, distribution, or conflicting uses of these resources. These represent an important next stage of analysis. For instance, solar PV may withdraw substantially less water than nuclear, but the type of water required may be different (*e.g.* freshwater or seawater), an effect that such a tool would not capture.

The last step of the proposed conceptual framework is to assess whether the incremental use of resources or emissions are acceptable. As introduced before, a policy could have the same nexus performance in two different contexts, but be acceptable in only one of them (FAO, 2014b). For instance, the same renewable energy policy (*e.g.,* promoting large-scale solar PV), applied to two different arid countries, could yield the same results in terms of water and land (*e.g.*, savings

---

[22] *This is just an illustrative example. It should be noted that energy efficiency is a fundamental pillar of any sustainable energy policy, alongside renewable energy.*

[23] *Even if, throughout the report, the focus has been on water, energy and food, the proposed tool will estimate the land impacts of the analysed policy, since this is considered here to be the actual resource. The proposed tool still complies with the criteria presented in previous sections, because it does include two* (i.e., *energy and water) out of the three water, energy and food nexus elements.*

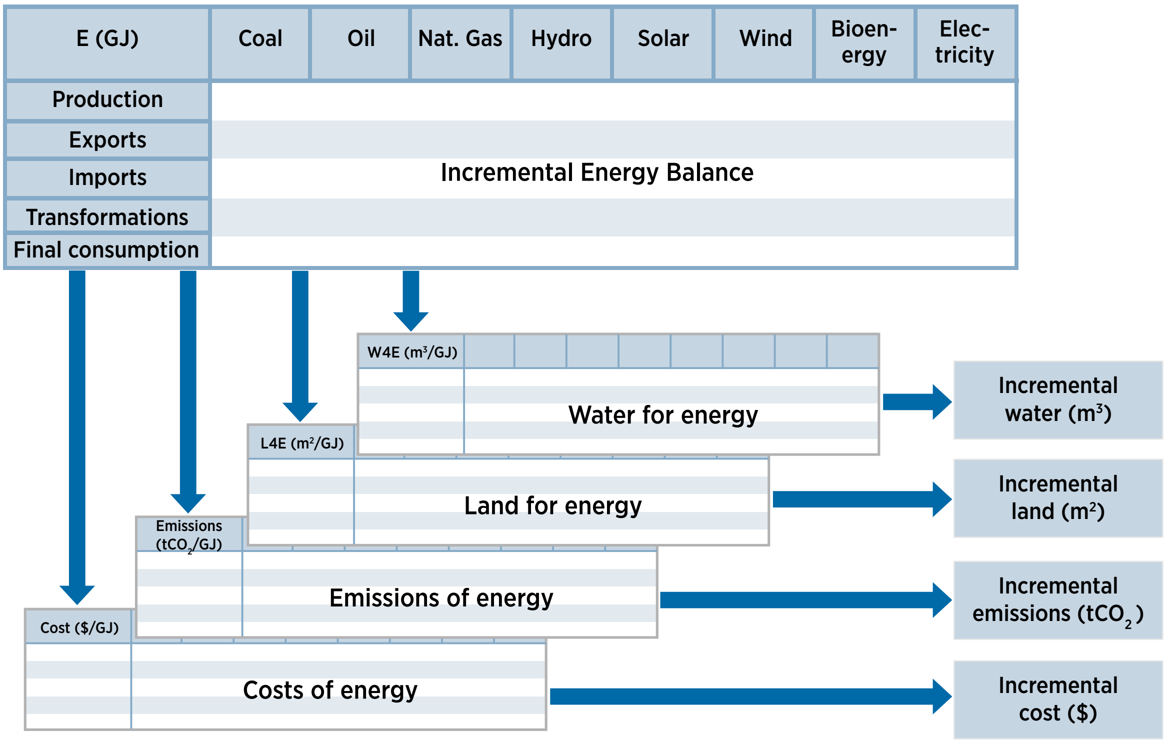
[24] *This refers to purely economic/monetary costs. External costs are out of the scope of this tool, even if certainly relevant. The monetary costs that would be accounted for would be an estimation of the total cost incurred to supply energy,* i.e., *including investment, operation and maintenance and any other costs. Since the tool is static, discounting* (e.g. *to calculate a Net Present Value) would only be necesary if the analysed year refers to the future. The tool does not minimise the cost, as an optimisation tool, such as MARKAL/TIMES, would.*

[25] *The word incremental in this context represents both positive and negative values,* i.e., *increases or reductions.*

[26] *The proposed tool could produce the increment/reduction in total energy supply cost that the alternative energy balance implies, but could not inform about how this is translated into changes in the energy prices paid by consumers. This would involve other aspects of energy markets that are out of the scope of this report, such as subsidies or competition.*

[27] *In a similar way as in "integrated energy planning".*

Figure 3.4 Estimation of the water, land, emissions and cost implications of the assessed energy policy



of cooling water for thermal generation and additional land needed). However, such results may not be acceptable in one of the two countries (*e.g.*, if a political decision has been made to prioritise land use for food production over other uses such as power generation[28]). This is the type of context-specific information that a policy maker would need the tool to incorporate in its results, and this is the main objective of the last step of the proposed framework.

In conducting such an analysis, policy makers would directly input the acceptable increments in water, land, emissions and costs. The definition of acceptability can be subjective, differing between countries but also between policy makers or other stakeholders within the same country, and can also change over time. Furthermore, the very use of nexus tools such as the one proposed here may initiate a political debate in which these levels of acceptability are evaluated (*i.e.*, the use of tools could, and sometimes should, trigger political debates around these issues). Going deeper into such aspects is out of the scope of this report, which considers these acceptable levels as a given input (*e.g.*, as defined by a policy maker).

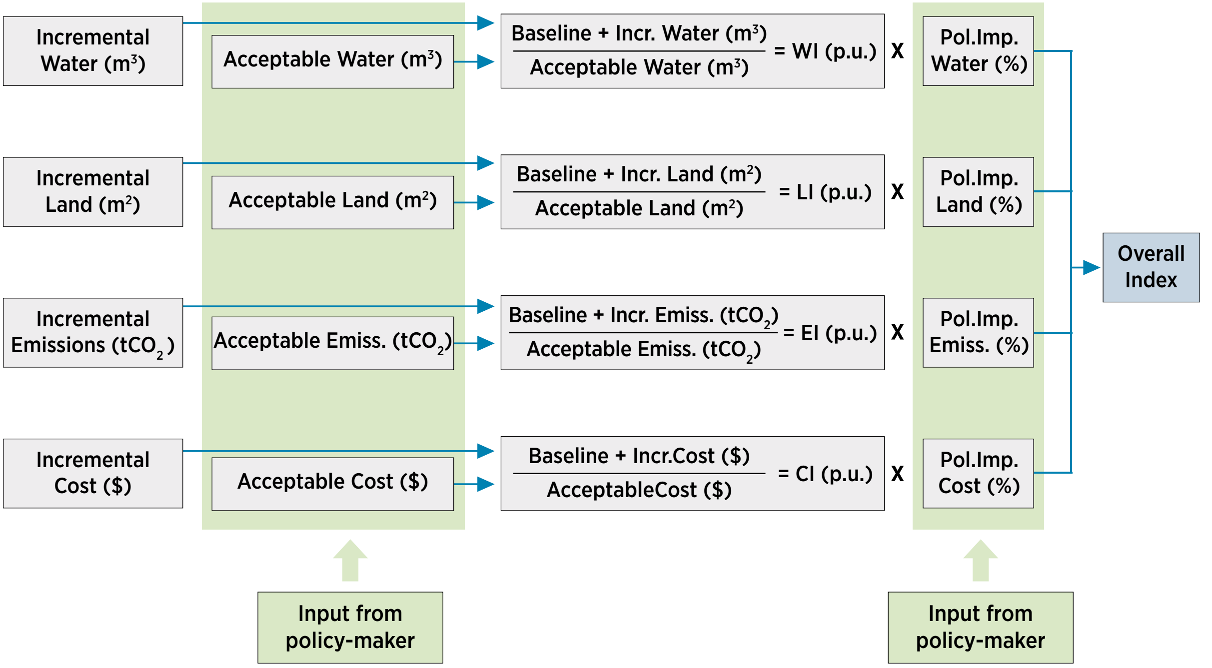
As illustrated in figure 3.5, comparing these acceptable levels with the ones in the case of the alternative energy balance (baseline + incremental) would produce four partial indexes (Water Index, Land Index, Cost Index and Emissions Index; WI, LI, CI and EI, respectively, in figure 3.5), all of which are expressed in per unit (p.u.) terms. An example is given in table 3.4, in which an imaginary wind energy deployment strategy would produce a reduction of water use of 50 million m^3, and an increment of land use of 63 km^2. Combined with their respective baseline levels and compared with the acceptable levels, the obtained Water Index is 0.63, and the obtained Land Index is 1.01.

If any of these indexes takes a value greater than one (as is the case with land in the example), it means that the acceptable limit has been exceeded, and the opposite occurs if the index is smaller than one[29]. Finally, the four partial indexes can be aggregated into an "overall index" according to the

[28] *If a policy maker already has made a decision regarding land allocation to different uses, it means that some type of integrated thinking/planning of resources (as opposed to silo) may already have been done. The proposed tool aims to further enhance the capabilities of policy makers to perform such integrated thinking/planning.*

[29] *Since the incremental values would in general be small or, at the most, relatively similar to the baseline values, the different indexes would in principle not take negative values. If they are similar to the baseline values, and negative, it would imply an almost complete shift away from that energy source.*

Figure 3.5 Use of policy inputs to estimate the water, land, emissions and cost implications of the analysed energy policies and to aggregate them into a context-specific overall index



policy importance ("Pol. Imp." in figure 3.5) that each of the four aspects has in the specific country, as indicated by the policy maker. In countries where a resource is deemed critical, the policy maker could decide to place a heavier importance to its corresponding index, increasing its influence on the final overall index. In the example, land could have a significant policy importance (for instance, if the priority is to use land for food production and not for energy), and therefore the corresponding parameter ("Pol. Imp. Land" in figure 3.5) would be larger than in a country where land is not a constrained resource. This means that an over-utilisation of land is importantly reflected in the final overall index.

The outputs derived from the proposed framework could serve as a building block for an in-depth qualitative and quantitative analysis. While certain qualitative aspects are addressed through the inputs provided by users at different steps of the proposed tool, a more detailed assessment could be required. For instance, once the incremental quantities of each resource are assessed, further analysis is required on context-specific quality aspects such as the types of different water or land resources. The proposed framework could also constitute a starting point for a more comprehensive and detailed quantitative nexus assessment, for instance through the tools discussed earlier in the chapter.

3.4 CONCLUSION

Today, most of the policy decisions with potential effects on the elements of the energy, water and food nexus are made by separate institutions (*e.g.*, different ministries, different levels of the administration), which often lack co-ordination. The challenges posed by the nexus are partly the consequence of such fragmented policy making applied to resources that are interrelated and increasingly scarce.

In this context, a fully integrated approach to resource planning, in line with the concept of integrated resource management, would be desirable for nexus-friendly policy making. Although such a fully integrated approach could be challenging, a useful starting point would be to analyse how the decisions taken for one specific resource affect the others (*i.e.*, an "entry point" approach). In particular, and from the perspective of energy policy making, this would imply understanding the water and food implications of

Table 3.4 Example of the calculation of water and land indexes associated with an imaginary wind energy deployment strategy

Incremental water use (million m³)	**Baseline water use (million m³)**	**Acceptable water use (million m³)**	**Water Index, WI (p.u.)**
-50	1 000	1 500	$\frac{1\,000 - 50}{1\,500} = 0.63$
Incremental land use (km²)	Baseline land use (km²)	Acceptable land use (km²)	Land Index, LI (p.u.)
63	493	550	$\frac{493 + 63}{550} = 1.01$

energy decisions. Analytical frameworks could be very useful for this purpose.

This chapter has reviewed some of the existing tools. Some of the key findings include:

» Data availability and accessibility is a key challenge. To undertake sound nexus assessments, data for respective sectors is necessary as well as those that can help quantify the interconnections and trade-offs (*e.g.*, data on water use *for* energy). Standardised data collection efforts could help overcome existing challenges associated with consistency, comparability, scale and the lack of time series data.

» Most tools available to policy makers today are detailed and sophisticated, designed to conduct thorough nexus analyses. Therefore, many have significant data and resource needs in terms of time, human and financial capacity.

» Accordingly, the review identifies the need for preliminary assessment tools that can provide valuable initial assessments. Such tools could serve as a starting point for assessing impacts of policy discussions on different sectors and possibly paving the way for the application of more sophisticated tools. The two preliminary assessment tools included in this review (*i.e.,* the FAO's nexus assessment methodology and the Water, Energy, Food Nexus Tool 2.0) have food as the entry point. None appears to have energy as an entry point.

The conceptual framework proposed in this chapter is meant to stimulate thinking on a preliminary tool with energy as an entry point and to provide a starting point for what could eventually support the integration of nexus thinking within energy sector decision making. The conceptual framework would be able to provide snapshot views of the impacts of renewable energy deployment (and other energy strategies) on the basic resource requirements of nexus elements (*e.g.*, volumes of water and areas of land).

The proposed tool is scenario based: each scenario represents a different set of energy policy decisions, summarised as energy balances, which become the main input for each scenario. The proposed tool would estimate the water, land, emissions and cost implications of each scenario to, finally, aggregate them into an overall index, which explicitly considers policy preferences specific to each context.

The outputs provided by the proposed tool could constitute a first stage towards a more comprehensive analysis of the impacts of renewable energy deployment on the water, energy and food nexus in different contexts. Although this is out of the scope of the present report, it could be a focus of future work by IRENA.

ANNEX

The electricity mix composition for the two cases – REmap 2030 and the Reference Case – are based on preliminary results from IRENA's ongoing REmap 2030 analysis as of June 2014, which could be updated as national plans are modified and further inputs are received from governments.The analysis presented here is preliminary and will be updated as more details become available on national plans, country-specific water factors, trends in cooling technology adoption and breakdown on type of water utilised within the power sector.

In this section, for each of the countries analysed, the discussion begins with a background on the electricity sector, definition of the REmap cases (REmap 2030 and Reference), illustration of the impacts on water consumption and withdrawal., and main assumptions used in the analysis.

UNITED KINGDOM

Background. The UK electricity sector comprises 90% thermoelectric generation capacity, based primarily on fossil fuels. In 2012, total generation included 11.4% renewable energy (IEA, 2014a). In England and Wales, the electricity sector constitutes about half of total water withdrawals, including 40% of all freshwater withdrawals. In 2010, 22% of the UK's thermoelectric cooling water withdrawals came from freshwater sources, 41% from tidal water sources, 19% from seawater and 18% of thermoelectric plants were air cooled (Byers et al., 2014). In England and Wales, 15% and 18%, respectively, of water catchments are over-licensed, and a further 35% have no water available for further licencing (Byers et al., 2014). Moreover, water withdrawals are regulated in the UK to reduce damage to marine environments as well as to better manage freshwater allocation.

Options. By 2030, the share of renewables is expected to reach 32% under Reference Case. In REmap 2030, the share of renewable energy in the UK electricity mix will increase further to 61%. In this case, coal power will nearly be phased out and will be replaced by renewables and combined-cycle natural gas power plants.

Impact on water consumption and withdrawal. In REmap 2030, the analysis found a 27% savings in total water consumption compared to the Reference Case, consuming 0.31 billion m^3 of water compared to 0.42 billion m^3 of water (see figure A.1). For total water withdrawals, REmap 2030 sees 52% savings compared to the Reference Case, with water withdrawals of 20.1 billion m^3 and 9.7 billion m^3, respectively.

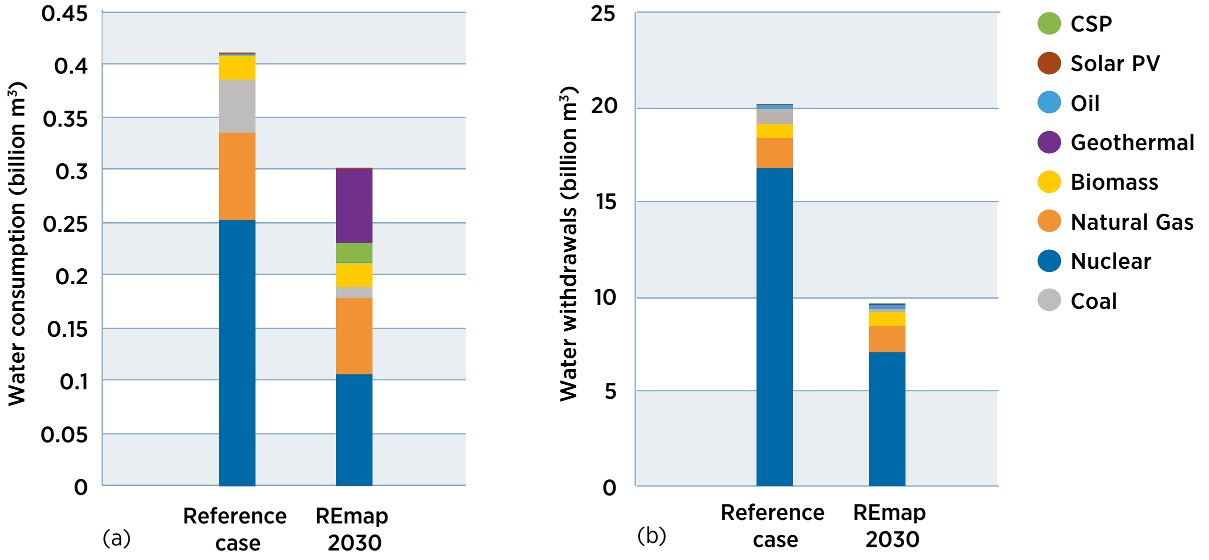
The reductions in water consumption and withdrawals for REmap 2030 are due largely to the significant scale-up of wind and solar PV energy. REmap 2030 will decrease shares of nuclear energy (with high tidal and seawater withdrawals) and coal thermal power plants (with higher water consumption rates than most natural gas power plants). These results are in line with a study by Byers et al. (2014) comparing water use under different decarbonisation pathways for the U.K.'s electricity sector. In scenarios with high levels of nuclear, withdrawals of tidewater and seawater increase significantly. Although volumes of sea level withdrawals can be inconsequential, the evidence examined indicated a lack of suitable sites for wide-scale nuclear power if negative environmental impacts are to be avoided.

Assumptions. Shares of cooling methods for thermal power plants are based primarily on figures in 2030 in Byers et al. (2014) using data from the Department of Energy and Climate Change (see table A.1). The analysis considers the conversion of all inland coal plants to closed-loop or dry cooling systems by 2030. In addition, all nuclear power plants are assumed to be located along the coast, utilising open-loop cooling systems that use tidal water and seawater as cooling sources. All natural gas power plants are assumed to be combined

Table A.1 Shares of cooling methods for UK thermal power plants by generation type in 2030

Generation Type	Wet Cooling		Air/Dry Cooling
	Once-through	Closed Loop	
Coal	20%	65%	15%
Natural Gas	20%	55%	25%
Oil	100%	0%	0%
Nuclear	100%	0%	0%
Biomass	10%	15%	75%
CSP	0%	50%	50%
Geothermal	0%	50%	50%

Figure A.1 Projected water (a) consumption and (b) withdrawals under Reference Case and REmap 2030 for the United Kingdom



cycle predominately based on closed-loop cooling. Biomass power plants are assumed to mostly use dry cooling methods. Due to lack of data on CSP and Geothermal, new capacity is assumed to use a mix of closed loop and dry cooling methods.

» UNITED STATES OF AMERICA

Background. The U.S. electricity mix is based primarily on thermal electric power production using fossil fuels. In 2013, coal and natural gas constituted 39% and 26%, respectively, of electricity generation sources, with renewable energy comprising 13% of total generation (EIA, 2014). Thermal electric power plants make up 41% of all freshwater withdrawals and 3% of all freshwater consumption annually in the country. Currently, of the 1 655 cooling systems in the United States, 53% use closed-loop cooling, 43% use once-through cooling, and the remaining use dry or hybrid systems (National Energy Technology Laboratory (NETL), 2010). Under U.S. Environmental Protection Agency guidelines, regulations are in place on water intake rates and encourage replacement of once-through cooling systems with closed-loop cooling towers or dry cooling (EPA, 2014b).

Options. By 2030, the share of renewables is expected to reach 16% under the Reference Case, with modest increases in wind, solar and biomass. In REmap 2030, the share of renewable energy electricity mix will further increase to 48%. In this case, wind, solar, biomass and hydropower are expected to see a scale-up in deployment relative to 2010.

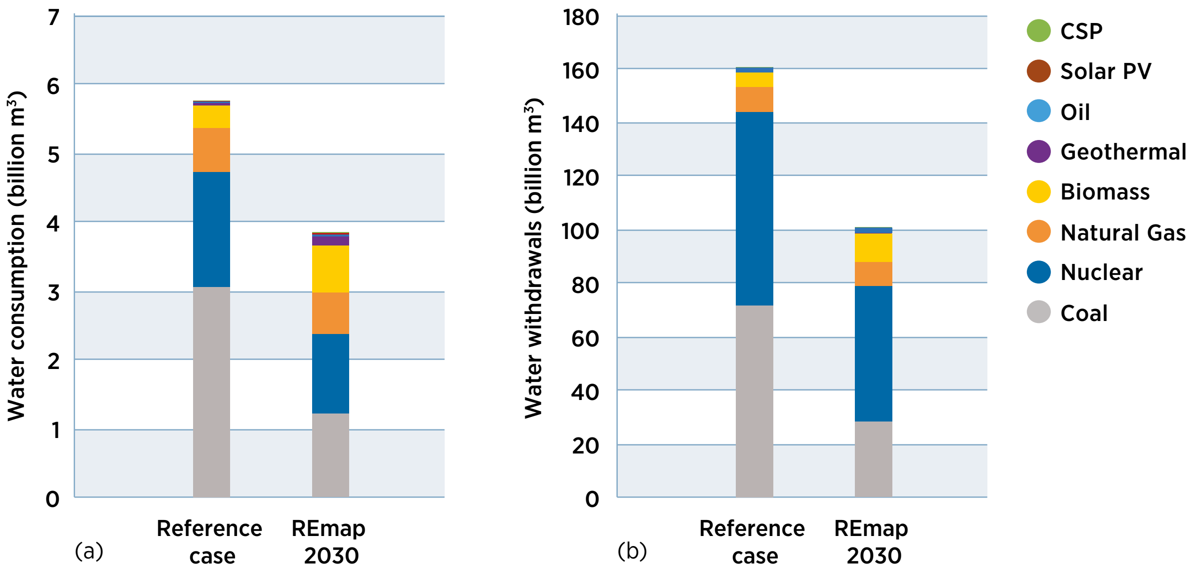
Impact on water consumption and withdrawal. In REmap 2030, electricity generation consumes 3.9 billion m^3 of water, compared to 5.8 billion m^3 in the Reference Case – a 33.1% reduction. The majority of this reduction comes from the high deployment level of wind and solar PV energy replacing existing coal plants. Withdrawals are 37% lower in REmap 2030 compared to the Reference Case, with 162 billion m^3 and 102 billion m^3 of withdrawals, respectively (see figure A.2). Coal and nuclear withdrawal requirements make up the bulk of water use. The reductions in coal and nuclear in REmap 2030 compared to the Reference Case account for the majority of water withdrawal savings.

The trends of this analysis draw similar conclusions to a study by Macknick et al. (2012b) simulating water consumption and withdrawal requirements for U.S. energy pathways to 2050. In Macknick et al. (2012b), scenarios with water withdrawal reductions were attributed to the retirement of once-through cooled thermal generation and replacement with new coal thermal power plants using closed-loop cooling technologies. In addition, scenarios of high shares of renewable technologies

Table A.2 Shares of cooling methods for US thermal power plants by generation type in 2030

Generation Type	Wet Cooling		Air/Dry Cooling
	Once-through	Closed Loop	
Coal	25%	60%	15%
Natural Gas	15%	55%	30%
Oil	75%	25%	0%
Nuclear	45%	55%	0%
Biomass	15%	60%	25%
CSP	0%	25%	75%
Geothermal	0%	25%	75%

Figure A.2 Projected water (a) consumption and (b) withdrawals under Reference Case and REmap 2030 for the United States



lead to the most significant reductions in water consumption and withdrawals.

Assumptions. The percentage of once-through, closed loop, and dry cooling technology for each generation source is based on data for cooling technology mix from NETL (2010). The data has been adapted to account for an expected shift towards closed loop and dry cooling methods in 2030 (See table A.2). Accordingly, this analysis assumes that all new thermal generation (natural gas, biomass, coal, nuclear, CSP, and geothermal) employs closed-loop or dry cooling methods to comply with EPA guidelines on water withdrawals (EPA, 2014b). For CSP in particular, 75% of capacity is assumed to use dry cooling based on current trends in cooling methods and environmental regulation seen regions with proposed projects, such as California. The mix of cooling methods for geothermal is based on water demand scenarios for geothermal in 2035 conducted by Harto et al. (2013).

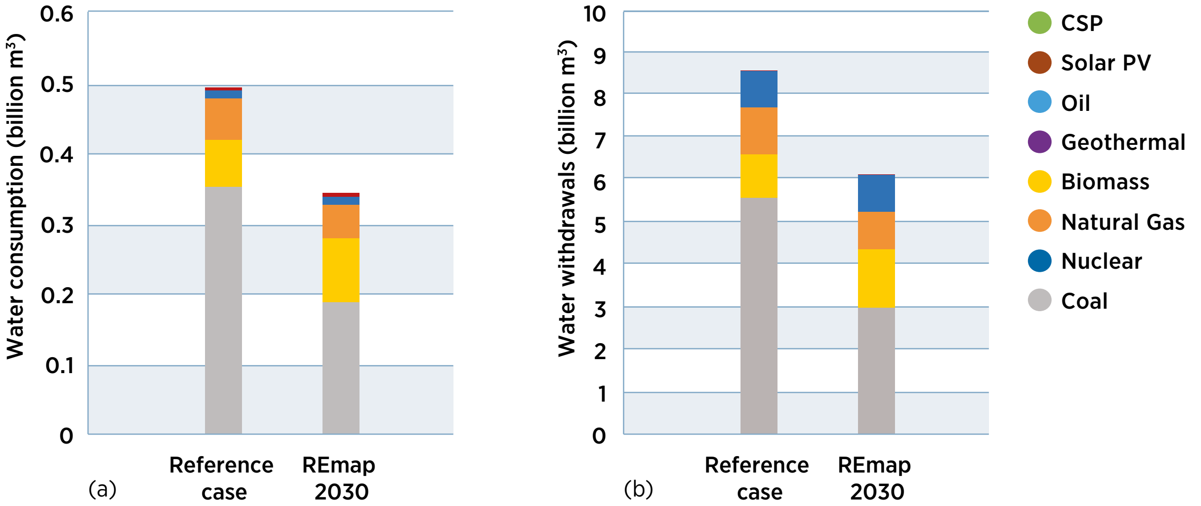
» GERMANY

Background. Germany's electricity generation in 2013 was based primarily on coal (45%) and nuclear (15%), with expanding shares of renewable energy (24%) and natural gas (11%) (Federal Statistical Office of Germany, 2014). In 2011, the German government decided to phase out all nuclear energy by 2022. Thermal power plants have the largest water withdrawal demands of any sector in Germany, requiring 20.7 billion m^3 of water annually almost exclusively from surface waters as cooling water for energy production (Kirschbaum and Richter, 2014). The electricity sector as a whole consumed an estimated 0.7 billion m^3 of freshwater in 2008 (Spang et al., 2014).

Table A.3 Shares of cooling methods for German thermal power plants by generation type in 2030

Generation Type	Wet Cooling		Air/Dry Cooling
	Once-through	Closed Loop	
Coal	20%	65%	15%
Natural Gas	20%	55%	25%
Oil	75%	25%	0%
Biomass	15%	60%	25%
Geothermal	0%	50%	50%

Figure A.3 Projected water (a) consumption and (b) withdrawals under Reference Case and REmap 2030 for Germany



Options. Under REmap 2030, the share of renewables will grow to 64% of electricity generation, with a total phase-out of nuclear energy and a reduction in coal. This features a large boost in wind, solar and biomass generating capacity, and a modest growth in natural gas power production. In the Reference Case, renewables reach 40% of power generation.

Impact on water consumption and withdrawal. The analysis shows 26.5% less annual water consumption in REmap 2030 compared to the Reference Case, with 0.37 billion m^3 and 0.50 billion m^3 of water consumed, respectively (see figure A.3). This can be attributed to a larger share of wind energy in REmap 2030 with a negligible water footprint, and a reduction in the share of coal thermal power plants, which make up the bulk of water consumption.

Similarly, total water withdrawals are significantly lower in REmap 2030 compared to the Reference Case. Both cases show a total decrease in withdrawals in 2030 compared to government statistics for water withdrawals in 2010 (20.7 billion m^3) due to replacement of large shares of coal and nuclear energy with solar PV and wind energy. REmap 2030 and the Reference Case result in 6.2 billion m^3 and 8.7 billion m^3 of water withdrawals, respectively – a 28 % reduction under the REmap 2030 case compared with the Reference Case. Water withdrawals for coal power comprise the majority of total withdrawals, with the modest share of plants with once-through cooling systems having the greatest withdrawal amounts.

Assumptions. Due to lack of national data for Germany, shares of cooling methods for thermal power plants are adapted from Byers et al. (2014) predictions for the UK based on expected trends in the German energy sector (see table A.3). As well, visual inspection of thermal power plant locations in Germany was used to estimate cooling method shares (Enipedia, 2010a). The analysis considers the conversion of all inland coal plants to closed-loop or dry cooling systems by 2030. All new natural gas power plants are assumed to be combined cycle based on closed-loop and dry cooling. Biomass power plants are assumed to mostly use closed loop cooling methods. Due to lack of data on geothermal, new capacity is assumed to use a mix of closed loop and dry cooling methods.

» AUSTRALIA

Background. Australia's electricity mix is composed primarily of thermoelectric power plants. In 2012, coal and natural gas thermal power plants generated 69% and 20% of total electricity, respectively. Hydropower produced 6% of generation, while wind and solar cumulatively contribute 3% (IEA, 2014). Around 65% of generating capacity in the national electricity market depends on freshwater for thermal power plant cooling (Smart and Aspinall, 2009). Hot and dry recent years have put pressure on Australia's freshwater resources, and government and power plants have played a proactive role in reducing water use for power plants, with a high share of coal power plants adopting closed-loop cooling technologies.

Options. In REmap 2030, renewables comprise 53% of electricity generation, with increases in solar PV and wind energy. In the Reference Case, renewables reach 35% of the total electricity mix.

Impact on water consumption and withdrawal. REmap 2030 consumes 24% less water than the Reference Case, with each case consuming 0.21 billion m^3 and 0.27 billion m^3, respectively (see figure A.4). The decrease is caused by the larger shares of wind and solar PV and the reduction in coal thermal power plants in REmap 2030. Water withdrawals totalled 2.1 billion m^3 in REmap 2030 and 3.0 billion m^3 in the Reference Case. The compared water savings are 32%. This can also be attributed to lower shares of electricity generated by coal and higher shares from solar PV and wind in REmap 2030 compared to the Reference Case.

Assumptions. Shares of cooling methods for thermal power plants are adapted from 2009 data compiled in Smart & Aspinall (2009). The analysis assumes that closed loop cooling technologies will remain the most common form of cooling in 2030, followed by dry cooling, given trends in cooling methods for the arid conditions (see table A.4). As well, visual inspection of thermal power plant locations in Australia was used to estimate cooling method shares (Enipedia, 2010b). All natural gas

Table A.4 Shares of cooling methods for Australian thermal power plants by generation type in 2030

Generation Type	**Wet Cooling**		**Air/Dry Cooling**
	Once-through	**Closed Loop**	
Coal	10%	65%	25%
Natural Gas	10%	55%	35%
Oil	50%	50%	0%
Biomass	10%	40%	50%
Geothermal	0%	50%	50%

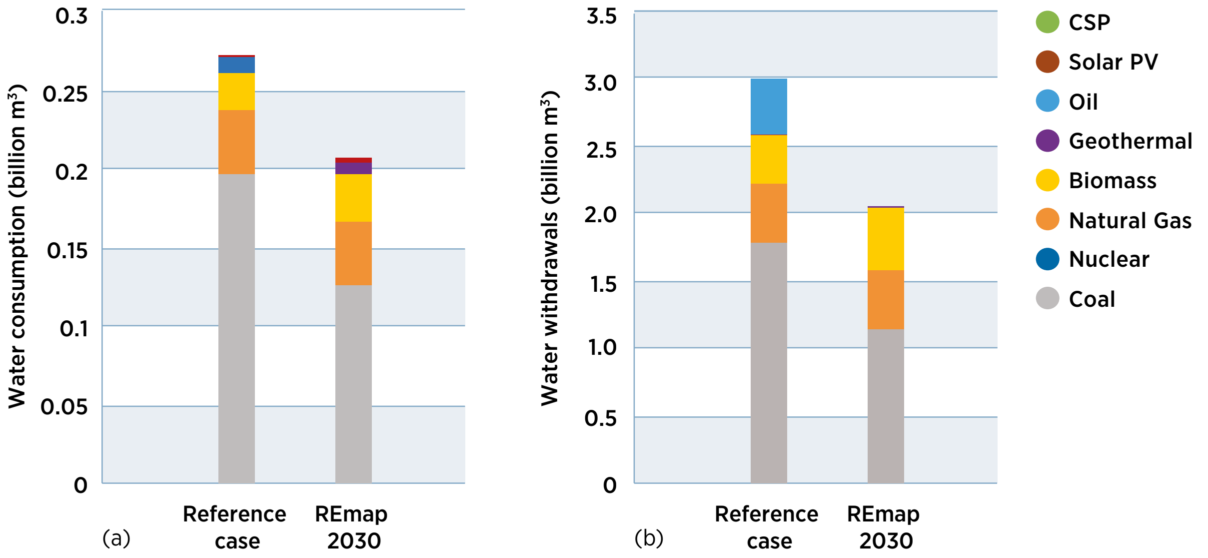


Figure A.4 Projected water (a) consumption and (b) withdrawals under Reference Case and REmap 2030 for Australia

power plants are assumed to be combined cycle predominately based on closed-loop cooling. Biomass power plants are assumed to mostly use dry and closed loop cooling methods. Due to lack of data on geothermal, new capacity is assumed to use a mix of closed loop and dry cooling methods.

» INDIA

Background. The electricity mix in India is dominated by coal-based power plants, followed by hydropower and natural gas (IEA, 2014). In 2012, renewables made up 16% of electricity generated, primarily from hydropower. India is a relatively water-scarce nation, with only 4% of the world's freshwater resources. The Ministry of Water Resources predicts that the national demand for water in energy production will increase 16-fold by 2050 (Institute for Global Environmental Strategies (IGES), 2012). This increase poses a particular threat for future energy supply considering 79% of new energy capacity will be built in areas that already face water scarcity or water stress (WRI, 2010).

Options. In REmap 2030, renewables will reach 39% of total generation. In a near tripling of energy generation compared to 2013, this option features a large scale-up of solar, wind, biomass and nuclear generation. In the Reference Case, renewables are estimated to account for 23% of the electricity generation.

Impact on water consumption and withdrawal. In REmap 2030, water consumption is reduced by 14% compared to the Reference Case, with each option consuming 2.8 billion m^3 and 3.2 billion m^3, respectively (see figure A.5). This can be attributed to the higher shares of solar PV and wind with minimal water footprints replacing coal. Biomass thermal power has a similar water footprint to coal and thus does not contribute to reductions in water in the generation phase.

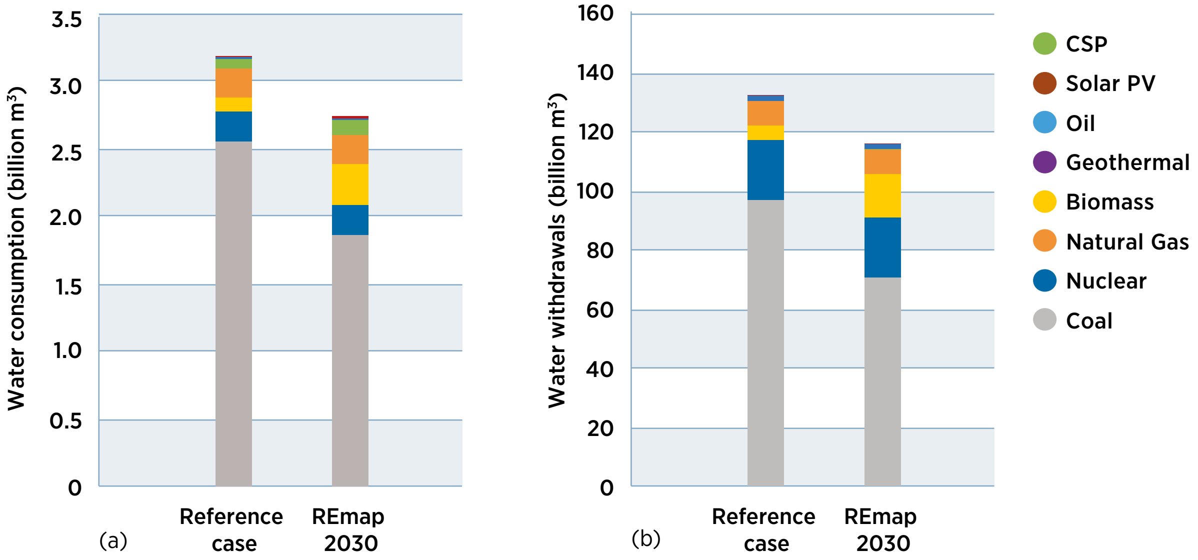
For water withdrawals, REmap 2030 results in 117 billion m3 of water withdrawn, while the Reference Case results in 134 billion m3 of water withdrawn. This 12% reduction in water withdrawals would avoid 17 billion m3 of water use annually. Reductions ware due to a lower share of coal and higher share of wind and solar PV, with high withdrawal rates from the majority of coal plants using open-loop cooling technology.

Assumptions. This study assumes that all inland thermal power plants use closed-loop cooling to adhere to Ministry of Environment and Forests regulations (IGES, 2013), while coastal thermal power plants use once-through cooling (see table A.5). The share of generation sources using once-through, closed loop, and dry cooling is based on predicted trends (UNEP FI, 2010) and visual data of current and planned power plant capacity (Enipedia, 2010; Maps of India, 2010). Nuclear energy capacity is assumed to be located primarily on the coast using once-through cooling systems. Biomass capacity is assumed to use a mix of once-through and closed loop cooling systems. CSP is assumed to use mostly closed-loop cooling methods.

Table A.5 Shares of cooling methods for Indian thermal power plants by generation type in 2030

Generation Type	**Wet Cooling**		**Air/Dry Cooling**
	Once-through	**Closed Loop**	
Coal	47%	50%	3%
Natural gas	47%	50%	3%
Oil	100%	0%	0%
Nuclear	75%	25%	0%
Biomass	47%	50%	3%
CSP	0%	97%	3%

Figure A.5 Projected water (a) consumption and (b) withdrawals under Reference Case and REmap 2030 for India



REFERENCES

2030 Water Resources Group (WRG) (2009), "Charting Our Water Future: Economic Frameworks to Inform Decision-Making", 2030 WRG, Washington, *www.mckinsey.com/App_Media/Reports/Water/Charting_Our_Water_Future_Exec%20Summary_001.pdf*.

Africa-EU (European Union) Partnership (n.d.), "Access to Drinking Water in the Sahel region - Harnessing the Power of the Sun", *www.africa-eu-partnership.org/success-stories/access-drinking-water-sahel-region-harnessing-power-sun*.

Alexandratos, N., and J. Bruinsma, (2012), "World Agriculture Towards 2030/2050: The 2012 revision", ESA (Agricultural Development Economics) Working Paper No. 12-03, *www.fao.org/fileadmin/templates/esa/Global_persepctives/world_ag_2030_50_2012_rev.pdf.*

Allan, J. (1997), "'Virtual water': A Long-Term Solution for Water Short Middle Eastern Economies?", School of Oriental and African Studies (SOAS), University of London, *www.soas.ac.uk/water/publications/papers/file38347.pdf.*

Al-Karaghouli, A., D. Renne and L. Kazmerski (2009), "Solar and Wind Opportunities for Water Desalination in the Arab Regions", *Renewable and Sustainable Energy Reviews*, Vol. 13. pp. 2397-2407.

Andrews, C.J., *et al.* (2010), "Alternative Energy Sources and Land Use". Climate Change and Land Policies, *www.lincolninst.edu/pubs/dl/2036_1358_LP2010-ch05-Alternative-Enegry-Sources-and-Land-Use.pdf.*

Anghileri, D., *et al.* (2013), "Optimizing Watershed Management by Coordinated Operation of Storing Facilities", *Journal of Water Resources Planning and Management*, ASCE, *www.researchgate.net/publication/258795463_JWRPCoordination/file/9c960528f4f0299f94.pdf*.

Atkinson, W. (n.d.), "Balance of Power: Water Utilities Find Ways to Reduce Energy Costs through Demand Response", Water World, *www.waterworld.com/articles/print/volume-29/issue-10/editorial-features/balance-of-power-water-utilities-find-ways-to-reduce-energy-costs-through-demand-response.html*.

Aulakh R. (2014), "China Wakes up to its Water Crisis", *www.thestar.com/news/world/2014/05/12/china_wakes_up_to_its_water_crisis.html*.

Aulakh, J., and A. Regmi (2014), "Post-Harvest Food Losses Estimation - Development of Consistent Methodology", *www.fao.org/fileadmin/templates/ess/documents/meetings_and_workshops/GS_SAC_2013/Improving_methods_for_estimating_post_harvest_losses/Final_PHLs_Estimation_6-13-13.pdf.*

AWEA (American Wind Energy Association) (2013), "Wind Energy Conserving Water", *www.awea.org/windandwater*.

Barefoot College (n.d.), "Solar Powered Desalination Plant and Reverse Osmosis", *www.barefootcollege.org/solutions/water-solutions/solar-powered-reverse-osmosis-ro-water-desalination-plants/.*

Barrett, K. (2014), "The Water-Energy-Food Nexus: Interlinked Solutions for Interlinked Challenges", *www.ecosystemmarketplace.com/pages/dynamic/article.page.php?page_id=10399&section=water_market&eod=1.*

Bazilian, M., *et al*. (2011), "Considering the Energy, Water and Food Nexus: Towards an Integrated Modelling Approach", *Energy Policy*, Vol. 39 No. 12, pp. 7896–7906, doi:10.1016/j.enpol.2011.09.039.

BMU (German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety) (2012), “Bonn 2011 Conference: The Water, Energy and Food Security Nexus – Solutions for a Green Economy”, *www.water-energy-food.org/documents/bonn2011_policyrecommendations.pdf.*

Bossio, D., *et al*. (2012), “Water Implications of Foreign Direct Investment in Ethiopia’s Agricultural Sector”, *www.water-alternatives.org/index.php/volume5/v5issue2/167-a5-2-3/file.*

BRE (Building Research Establishment) (2014), “Agricultural Good Practice Guidebook for Solar Farms”, *www.bre.co.uk/filelibrary/nsc/Documents%20Library/NSC%20Publications/NSC_-Guid_Agricultural-good-practice-for-SFs_0914.pdf.*

Breslin, M. (n.d.), “New Solar System to Power High Service Water Pumps”, WaterWorld, *www.waterworld.com/articles/print/volume-24/issue-2/editorial-feature/new-solar-system-to-power-high-service-water-pumps.html.*

Burkhardt, J.J., G.A. Heath, and C.S. Turchi (2011), “Life Cycle Assessment of a Parabolic Trough Concentrating Solar Power Plant and the Impacts of Key Design Alternatives”, *Environmental Science and Technology,* Vol. 45, pp. 2457-2464.

Buzan, B., O. Wæver and J. De Wilde (1998), *Security: a new framework for analysis*, Lynne Rienner Publishers.

Byers E.A., J.W. Hall and J.M. Amezaga (2014), “Electricity Generation and Cooling Water Use: UK pathways to 2050”, *Global Enviornmental Change*, Vol. 25, pp. 16-30, Elsevier, www.sciencedirect.com/science/article/pii/S0959378014000089.

California Legislative Information (2014), “SB-1281 Oil and Gas Production, Water Use, Reporting”, *http://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201320140SB1281.*

Cardoso 1st.2nd. initial? (2013), “Brazil Residential Demand Drives Market”, *http://solarthermalworld.org/content/brazil-residential-demand-drives-market.*

Casey, A. (2013), “Reforming Energy Subsidies Could Curb India’s Water Stress”, *www.worldwatch.org/reforming-energy-subsidies-could-curb-indias-water-stress-0.*

CDP (Carbon Disclosure Project) (2013), “Global Water Report 2013 - Moving Beyond Business as Usual: A Need for a Step Change in Water Risk Management”, *www.cdp.net/CDPResults/CDP-Global-Water-Report-2013.pdf,*

CEA (Central Electricity Authority) (2011), “Electrical Energy Generation during the Month of February’ 11 and During the Period April’ 10 - February’ 11”, *www.cea.nic.in/reports/monthly/elec_review/feb11.pdf.*

CEA (2013), “Growth of Electricity Sector in India from 1947-2013”, *www.cea.nic.in/reports/planning/dmlf/growth.pdf.*

CEEW (Council on Energy, Environment and Water) (2013), “Renewables Beyond Electricity”, *http://ceew.in/pdf/CEEW-WWF-RE+Renewables-Beyond-Electricity-Dec13.pdf.*

CEEW and NRDC (Natural Resources Defense Council) (2012), “Concentrated Solar Power: Heating up India’s Solar Thermal Market under the National Solar Mission”, Report (Addendum to Laying the Foundation for a Bright Future: Assessing Progress under Phase I of India’s National Solar Mission), September, pp 1-23, *http://ceew.in/pdf/CEEW-NRDC-Concentrated%20Solar%20Power_Sep12.pdf.*

Chatham House (2013), “Global Food Insecurity and Implications for Saudi Arabia”, *www.chathamhouse.org/sites/files/chathamhouse/public/Research/Energy, Environment and Development/290413summary.pdf.*

Chaturvedi, V., *et al.* (2013), “Climate Mitigation Policy Implications for Global Irrigation Water Demand”, *Mitigation and Adaptation Strategies for Global Change*, Springer, DOI10.1007/s11027-013-9497-4.

Chapagain, A., and D. Tickner (2012), “Water Footprint: Help or Hindrance?”, *Water Alternatives*, Vol. 5, No. 3, pp. 563 – 581, www.waterfootprint.org/Reports/Chapagain%20and%20Dave%202012-Waterfootprint.pdf.

Cho, R. (2011), “How China is Dealing With Its Water Crisis”, *http://blogs.ei.columbia.edu/2011/05/05/how-china-is-dealing-with-its-water-crisis.*

Clark, C., *et al*. (2011), “Water Use in the Development and Operation of Geothermal Power Plants”, ANL/EVS/R-10/5, Argonne National Laboratory, Argonne.

Climate Central (2014), “Blackout: Extreme weather, climate change and power outages”, *http://assets.climatecentral.org/pdfs/PowerOutages.pdf.*

Cooley, H. and R. Wilkinson (2012), “Implications of Future Water Supply and Sources for Energy Demands”, WaterReuse Foundation, Alexandria, *www.pacinst.org/wp-content/uploads/2013/02/report19.pdf*.

Davies, K., *et al.* (2013), “An Integrated Assessment of Global and Regional Water Demands for Electricity Generation to 2095”, Advances in Water Resources, *http://climatemodeling.science.energy.gov/sites/default/files/publications/Davies-Kyle-1-s2.0-S0309170812003028-AWR-Jan2013.pdf.*

DLR (German Aerospace Center) (2011), “MENA Regional Water Outlook Desalination Using Renewable Energy”, Overview of DLR work within the MENA Regional Water Outlook study, Muscat, *http://elib.dlr.de/72591/1/Workshop_Oman_Final_DLR.pdf.*

DOE (Department of Energy) (2013), “U.S. Energy Sector Vulnerabilities to Climate Change and Extreme Weather”, *http://energy.gov/sites/prod/files/2013/07/f2/20130710-Energy-Sector-Vulnerabilities-Report.pdf.*

Ecker, O., and C. Breisinger (2012), “The Food Security System: a new conceptual framework”, IFPRI (International Food Policy Research Institute), Washington D.C., *www.ifpri.org/publication/food-security-system,* accessed 27 March 2014.

EIA (Energy Information Administration) (2014), “Monthly Energy Review”, *http://www.eia.gov/totalenergy/data/monthly/index.cfm#electricity.*

Enipedia (2010a), “Germany Power Plants”, *http://enipedia.tudelft.nl/wiki/Germany/Powerplants*.

Enipedia (2010b), “Australia Power Plants”, *http://enipedia.tudelft.nl/wiki/Australia/Powerplants.*

Enipedia (2010c), “India Power Plants”, *http://enipedia.tudelft.nl/wiki/India/Powerplants.*

Environment America (2013), “Fracking by the Numbers”, *www.environmentamerica.org/sites/environment/files/reports/EA_FrackingNumbers_scrn.pdf*

EPA (Environmental Protection Agency) (n.d.), “Cutting Energy Usage and Costs”, *http://water.epa.gov/infrastructure/sustain/cut_energy.cfm.*

Epp, B. (2011), "Cyprus: Solar Thermal Industry Off to New Frontiers", *http://solarthermalworld.org/content/cyprus-solar-thermal-industry-new-frontiers.*

Eskom (2011), "Solar Water Heating Rebate Programme", *www.eskom.co.za/AboutElectricity/FactsFigures/Documents/The_Solar_Water_Heating_SWH_Programme.pdf.*

ESMAP (Energy Sector Management Assistance Program) (2012), "A Primer on Energy Efficiency for Municipal Water and Wastewater Utilities", *www.esmap.org/node/1355*

European Commission (2011), "Causes of the 2007-2008 Global Food Crisis Identified", *Science for Environment Policy,* European Commission DG Environment News Alert Service, SCU (Science Communication Unit) (Ed.), The University of the West of England, Bristol, *http://ec.europa.eu/environment/integration/research/newsalert/pdf/225na1.pdf.*

EverGreen Agriculture (2014), "Creating EverGreen Food-Energy Systems for Rural Electrification in Africa", *http://evergreenagriculture.net/*, (draft).

EWEA (European Wind Energy Association) (2014), "Saving Water with Wind Energy", *www.ewea.org/fileadmin/files/library/publications/reports/Saving_water_with_wind_energy.pdf.*

Farid, A., and W. Lubega (2013), "Powering and Watering Agriculture: Application of Energy-Water Nexus Planning", in GHTC (Global Humanitarian Technology Conference) 2013 IEEE, Silicon Valley, CA, pp. 1–6.

FAO (Food and Agriculture Organisation of the United Nations) (n.d. a), "Introduction to Agricultural Water Pollution", Chapter 1 from Control of Water Pollution from Agriculture, *www.fao.org/docrep/w2598e/w2598e04.htm.*

FAO (n.d. b), "Key Findings - SAVE FOOD: Global Initiative on Food Loss and Waste Reduction", *www.fao.org/save-food/resources/keyfindings/en/.*

FAO (n.d. c), "Food Security", *www.fao.org/energy/81345/en/.*

FAO (n.d. d), "Evergreen Agriculture: The use of Fertilizer Tees in Maize Production in Malawi", *http://teca.fao.org/read/7847#sthash.sK3bc3H3.8LKQfyFA.dpuf.*

FAO (2008a), "Climate Change and Food Security: A Framework Document", *www.fao.org/forestry/15538-079b31d45081fe9c3dbc6ff34de4807e4.pdf.*

FAO (2008b), "Agriculture and Water Quality Interactions: a Global Overview", *www.fao.org/fileadmin/templates/solaw/files/thematic_reports/TR_08.pdf.*

FAO (2009), "Global agriculture towards 2050", High Level Expert Forum - How to Feed the World in 2050", *www.fao.org/fileadmin/templates/wsfs/docs/Issues_papers/HLEF2050_Global_Agriculture.pdf.*

FAO (2010a), "Resource-seeking Foreign Direct Investment in African Agriculture: A review of Country Case Studies", FAO Commodity and Trade Policy Research Working Paper no. 31, *www.fao.org/fileadmin/templates/est/PUBLICATIONS/Comm_Working_Papers/EST-WP31.pdf.*

FAO (2010b), "Bioenergy and Food Security: The BEFS Analytical Framework", *www.fao.org/docrep/013/i1968e/i1968e.pdf.*

FAO (2011a), "Global Food Losses and Food Waste", *www.fao.org/docrep/014/mb060e/mb060e.pdf.*

FAO (2011b), "Energy-Smart Food for People and Climate". FAO, Rome, *www.fao.org/docrep/014/i2454e/i2454e00.pdf*.

FAO (2011c), "Investment in Agricultural Mechanization in Africa: Conclusions and Recommendations of a Round Table Meeting of Experts", *www.fao.org/docrep/014/i2130e/i2130e00.pdf.*

FAO (2012a), "Energy-Smart Food at FAO: An Overview", *www.fao.org/docrep/015/an913e/an913e.pdf.*

FAO (2012b), "Impacts of Bioenergy on Food Security: Guidance for Assessment and Response at National and Project Levels", *www.fao.org/docrep/015/i2599e/i2599e00.pdf.*

FAO (2013a), "Food Wastage Footprint: impacts on natural resources", FAO, Rome, *www.fao.org/docrep/018/i3347e/i3347e.pdf*.

FAO (2013b), "Biofuels and the sustainability challenge: A global assessment of sustainability issues, trends and policies for biofuels and related feedstocks", *www.fao.org/docrep/017/i3126e/i3126e.pdf.*

FAO (2013c), Climate-Smart Agriculture Sourcebook, *www.fao.org/docrep/018/i3325e/i3325e.pdf.*

FAO (2014a), "FAOSTAT Database", FAO, Rome. *faostat.fao.org/site/342/default.aspx*.

FAO (2014b), "Walking the Nexus Talk: Assessing the Water-Energy-Food Nexus in the Context of the Sustainable Energy for All Initiative", *www.fao.org/3/a-i3959e.pdf*.

FAO (2014c), "FAO and the post-2015 development agenda issue papers: Theme Energy", *www.fao.org/fileadmin/user_upload/post-2015/14_themes_Issue_Papers/EN/14_themes__ december_2014_/Energy-8.pdf.*

FAO (2014d), "Evidence-based assessment of the sustainability and replicability of integrated food-energy systems", *www.fao.org/docrep/019/i3669e/i3669e.pdf.*

Faeth, P. and B., Sovacool (2014), "Capturing Synergies Between Water Conservation and Carbon Dioxide Emissions in the Power Sector", *www.cna.org/research/2014/water-conservation-carbon-dioxide#sthash.szL3ZRxU.dpuf*

Federal Statistical Office of Germany, (2014), "Energy", *https://www.destatis.de/EN/FactsFigures/EconomicSectors/Energy/Energy.html.*

Frontier Economics (2008), "The Concept of 'Virtual Water' — a Critical Review", *www.depi.vic.gov.au/__data/assets/pdf_file/0006/233529/Virtual-Water-The-Concept-of-Virtual-Water.pdf.*

Fthenakis, V., and H.C. Kim (2009), "Land Use and Electricity Generation: a Life-cycle Analysis", *Renewable and Sustainable Energy Reviews 2009*, Vol. 13, pp. 649-668.

Garthwaite, J. (2014), "California Drought Dries Up Hydro, But Power Stays On", National Geographic, *http://news.nationalgeographic.com/news/energy/2014/03/140311-california-drought-dries-up-hydro-but-power-stays-on/*.

Gelting, R., and M. Baloch (2012), "The Food-Water Nexus: Irrigation Water Quality, Risks to Food Safety, and the Need for a Systems-Based Preventive Approach", *www.cdc.gov/nceh/ehs/Docs/JEH/2012/Oct_Food_Water_Nexus.pdf.*

Gerdes, K., and C. Nichols (2009), *Water Requirements for Existing and Emerging Thermoelectric Plant Technologies,* U.S. Department of Energy National Energy Technology Laboratory Report 402/080108, Morgantown.

GIZ (German Federal Enterprise for International Cooperation) (2013), "The Ecological Footprint of Cassava and Maize Post-Harvest-Losses in Nigeria: A Life Cycle Assessment", *www.giz.de/fachexpertise/downloads/giz2013-en-report-food-loss-of-maize-and-cassava.pdf.*

GIZ and ICLEI (2014), Operationalizing the Urban NEXUS: towards resource efficient and integrated cities and metropolitan regions, GIZ Eschborn.

Gleick, P.H., (1994), "Water and Energy" *Annual Reviews of Energy and the Environment*, Vol. 19, pp. 267-299.

GlobalData (2014), "GlobalData Power database [Internet]", *http://power.globaldata.com/,* accessed 5 May 2014, registration required.

Global Water Intelligence (2010), *Desalination Markets 2010*, Media Analytics Limited.

Goldernberg, S. (2014), "Farming Practices and Climate Change at Root of Toledo Water Pollution", *www.theguardian.com/world/2014/aug/03/toledo-water-pollution-farming-practices-lake-erie-phosphorus.*

Granit, J., *et al.* (2013), "Unpacking the Water-Energy-Food Nexus: Tools for Assessment and Cooperation Along a Continuum", in A. Jägerskog, *et al.* (eds.) *Cooperation for a Water Wise World – Partnerships for Sustainable Development*, Report No. 32, Stockholm International Water Institute, Stockholm, pp. 45–50.

Greenpeace (2012), "Water Hungry Coal: Burning South Africa's Water to Produce Electricity", *www.greenpeace.org/africa/Global/africa/publications/coal/WaterHungryCoal.pdf.*

Greenpeace (2014), "Coal Impacts on Water", *www.greenpeace.org/international/en/campaigns/climate-change/coal/Water-impacts/.*

Groenewald, Y. (2012), "Coal's Hidden Water Cost to South Africa", *www.greenpeace.org/africa/Global/africa/publications/coal/CoalsHiddenWaterCost.pdf.*

Gulf News (2011), "Dewa to Introduce Fuel Surcharge", *http://gulfnews.com/business/general/dewa-to-introduce-fuel-surcharge-1.838387.*

IGES (Institute for Global Environmental Strategies) (2012), "Long Term Electricity Scenario and Water Use: A case study on India", *http://pub.iges.or.jp/modules/envirolib/view.php?docid=4089.*

Koschikowski, J. (2011), "Water Desalination: When and Where Will it Make Sense?", Presentation at the 2011 Annual Meeting of the American Association for the Advancement of Science, Fraunhofer ISE (Institute for Solar Energy Systems), *http:// ec.europa.eu/dgs/jrc/downloads/jrc_aaas2011_energy_water_ koschikowski.pdf.*

Hadi, M. (2014), "Trace of Pollution Caused by Coal Mining Tracked in Kalimantan" *http://en.tempo.co/read/news/2014/03/31/206566584/Trace-of-Pollution-Caused-by-Coal-Mining-Tracked-In-Kalimantan.*

Halstead, M.I., T. Kober, and B. van der Zwaan (2014), "Understanding the Energy-Water Nexus", ECN-E--14-046, *http://ftp.ecn.nl/pub/www/library/report/2014/e14046.pdf.*

Harto, C., *et al.* (2013), "Geothermal Energy: The Energy-Water Nexus", *http://www.geothermal-energy.org/pdf/IGAstandard/SGW/2013/Harto.pdf.*

Hazell, P., and R. Pachauri (2006), "Bioenergy and Agriculture: Promises and Challenges", *www.ifpri.org/sites/default/files/publications/focus14.pdf.*

Herndon, A. (2013), "Energy Makes Up Half of Desalination Plant Costs", *www.bloomberg.com/news/2013-05-01/energy-makes-up-half-of-desalination-plant-costs-study.html.*

Hoekstra, A. (2010), "The Relation between International Trade and Freshwater Scarcity", *www.waterfootprint.org/Reports/Hoekstra-2010-InternationalTrade-FreshwaterScarcity.pdf*.

Hoff, H. (2011), "Understanding the Nexus", SEI (Stockholm Environment Institute), Stockholm, *www.water-energy- food.org/documents/understanding_the_nexus.pdf*.

Hsu, S. (2014), "China's Water Pollution Mire", *http://thediplomat.com/2014/05/chinas-water-pollution-mire/*.

IEA (International Energy Agency) (2010), "Sustainable Production of Second-generation Biofuels: Potential and Perspectives in Major Economies and Developing Countries", *www.iea.org/publications/freepublications/publication/biofuels_exec_summary.pdf.*

IEA (2012), "World Energy Outlook 2012", OECD (Organisation for Economic Co-operation and Development), Paris, *www.worldenergyoutlook.org/publications/weo-2012/.*

IEA (2013a), "Outlook for Biofuels". Speech by Maria van der Hoeven, Executive Director IEA, World Biofuel Markets 2013, Rotterdam, *https://www.iea.org/newsroomandevents/speeches/EDWorldBiofuelsMarketsROTTERDAMOutlookforBiofuels08_03_13withnotepages4.pdf*.

IEA (2013b), "Bio-energy in Family Farming: A New Sustainable Perspective for the Rural Sector in Brazil", *www.iea-biogas.net/case-studies.html?file=files/daten-redaktion/download/case-studies/brazil_web_Final.pdf.*

IEA (2014a), World Energy Statistics and Balances, *http://data.iea.org/ieastore/statslisting.asp.*

IEA (2014b), "Heating without Global Warming", *www.iea.org/publications/freepublications/publication/FeaturedInsight_HeatingWithoutGlobalWarming_FINAL.pdf.*

IEA (2014c), "Energy Balances of non-OECD Countries", IEA/OECD, Paris, pp. 554, ISBN 978-92-64-21708-9

IEA (n.d.), "Energy Security (Definition)", *www.iea.org/topics/energysecurity/.*

IEA SHC (2013), "Solar Heat Worldwide", *www.iea-shc.org/data/sites/1/publications/Solar-Heat-Worldwide-2013.pdf.*

IEA SHC (2014), "Solar Heat Worldwide", *www.iea-shc.org/data/sites/1/publications/Solar-Heat-Worldwide-2014.pdf.*

IFC (International Finance Corporation) (2014), "Scaling up Opportunities for Solar-Powered Irrigation Pumps", World Water Week 2014, *http://programme.worldwaterweek.org/sites/default/files/colback_stockholm_presentation.pd*f.

IGEP (Indo-German Energy Programme) (2013), "Solar Water Pumping for Irrigation", *http://igen-re.in/files/giz__2013__report_solar_water_pumping_for_irrigation_in_bihar.pdf.*

IISD (International Institute for Sustainable Development) (2013), “The Water–Energy–Food Security Nexus: Towards a Practical Planning and Decision-support Framework for Landscape Investment and Risk Management”, IISD, Winnipeg, *www.iisd.org/pdf/2013/wef_nexus_2013.pdf*.

Indian Ministry of New and Renewable Energy (MNRE) (2014), “Solar Energy Based Dual Pump Piped Water Supply Scheme”, h*ttp://mnre.gov.in/file-manager/UserFiles/solar-energy-based-dual-pump-piped-water-supply-scheme.pdf*.

Institute for Global Environmental Strategies (2012), “Long Term Electricity Scenario and Water Use – a Case Study on India”, *http://pub.iges.or.jp/modules/envirolib/upload/4089/attach/PB_20_E_final.pdf.*

IPCC (Intergovernmental Panel on Climate Change) (2011), “Renewable Energy Sources and Climate Change Mitigation: Summary for Policy Makers and Technical Summary”, *www.ipcc.ch/pdf/special-reports/srren/SRREN_FD_SPM_final.pdf.*

IPCC (2014), “The Synthesis Report of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change”, *www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_LONGERREPORT.pdf.*

IPCC (2007), “Projected Climate Change and its Impacts”, Climate Change 2007, Synthesis Report, *www.ipcc.ch/publications_and_data/ar4/syr/en/spms3.html.*

IPCC (2008), “Technical Paper on Climate Change and Water”,
http://ipcc.ch/pdf/technical-papers/climate-change-water-en.pdf.

IRENA (International Renewable Energy Agency) (2014a), “REthinking Energy: Towards a New Power System”, *www.irena.org/rethinking/Rethinking_FullReport_web_view.pdf.*

IRENA (2014b), “REmap 2030: A Renewable Energy Roadmap”,
www.irena.org/remap/REmap_Report_June_2014.pdf.

IRENA (2014c), “IRENA - Cyprus Event on Renewable Energy Applications for Island Tourism”, *www.irena.org/DocumentDownloads/events/2014/June/Agenda.pdf.*

IRENA (2014d), “Global Bioenergy Supply and Demand Projections”,
www.irena.org/remap/IRENA_REmap_2030_Biomass_paper_2014.pdf.

IRENA (2013), “Programmatic Discussion IV: Emerging Opportunities in Renewable Energy Applications”, *www.irena.org/documents/uploadDocuments/5thCouncil/C_5_CRP_4_IV%20Emerging%20opportunities.pdf.*

IRENA (2012a), “International Off-grid Renewable Energy Conference 2012: Key Findings and Recommendations”, *www.irena.org/DocumentDownloads/Publications/IOREC_Key%20Findings%20and%20Recommendations.pdf.*

IRENA (2012b), “Renewable Energy Policy in Cities: Selected Case Studies”,
www.irena.org/menu/index.aspx?mnu=Subcat&PriMenuID=36&CatID=141&SubcatID=286.

IRENA (2012c), “Renewable Energy Jobs and Access”,
www.irena.org/documentdownloads/publications/renewable_energy_jobs_and_access.pdf.

IRENA and IEA-ETSAP (-Energy Technology Systems Analysis Program) (2013), “Production of Liquid Biofuels: Technology Brief”, *www.irena.org/DocumentDownloads/Publications/IRENA-ETSAP%20Tech%20Brief%20P10%20Production_of_Liquid%20Biofuels.pdf.*

IRENA and IEA-ETSAP (2012), "Water Desalination Using Renewable Energy: Technology Brief", *www.irena.org/DocumentDownloads/Publications/IRENA-ETSAP%20Tech%20Brief%20I12%20Water-Desalination.pdf.*

ISIS (Institute of Science in Society) (2013), "Japanese Farmers Producing Crops and Solar Energy Simultaneously", *www.i-sis.org.uk/Japanese_Farmers_Producing_Crops_and_Solar_Energy.php.*

IWD (Idyllwild Water District) (n.d.), "Solar Project", *www.idyllwildwater.net/facilities/solar-project*.

IWMI (International Water Management Institute) (2002), "Wastewater Use in Agriculture: Review of Impacts and Methodological Issues in Valuing Impacts", Working Paper 37, *www.iwmi.cgiar.org/Publications/Working_Papers/working/WOR37.pdf.*

KACST (2014), "The 2nd Saudi International Water Technology Conference 2014", The 2nd International Conference and Workshops on Water Technologies, http://kacstwatertech.org/2014/En/images/Brochure/EN-Brochure.pdf.

Kaye, L. (2014), "Can Solar Thermal Desalination Make Sustainable Agriculture Possible?", *http://cleantechnica.com/2014/12/05/can-solar-thermal-desalination-make-sustainable-agriculture-possible/.*

Kiger, P. (2013), "Fukushima's Radioactive Water Leak: What You Should Know", *http://news.nationalgeographic.com/news/energy/2013/08/130807-fukushima-radioactive-water-leak/.*

King, M., and J. Gulledge (2014), "Climate Change and Energy Security: an Analysis of Policy Research", *Climatic Change*, Vol. 123, No. 1, pp. 57-68. www.researchgate.net/publication/257924798_Climate_change_and_energy_security_an_analysis_of_policy_research/file/504635262a2aa57484.pdf.

Koellner, T., and R. Scholz (2008), "Assessment of Land Use Impacts on the Natural Environment. Part 2: Generic Characterization Factors for Local Species Diversity in Central Europe.", The International Journal of Life Cycle Assessment, Vol. 13, pp. 32-48.

Kramer, A. (2010), "Russia, Crippled by Drought, Bans Grain Exports", *www.nytimes.com/2010/08/06/world/europe/06russia.html?_r=0*.

Kovalyova, S. (2011), "U.N. food body FAO warns against food export curbs", *http://in.reuters.com/article/2011/01/26/idINIndia-54418520110126*.

Lane, J. (2014), "Biofuels Mandates Around the World: 2014", Biofuels Digest, *www.biofuelsdigest.com/bdigest/2013/12/31/biofuels-mandates-around-the-world-2014/.*

Lavelle, M. and T. Grose (2013), "Water Demand for Energy to Double by 2035" *http://news.nationalgeographic.com/news/energy/2013/01/130130-water-demand-for-energy-to-double-by-2035/*.

Leonardo Energy (2012), "Solar Water Heating in the World: Strong Diffusion Due to the Large Impact of Incentives", *www.leonardo-energy.org/solar-water-heating-world-strong-diffusion-due-large-impact-incentives.*

Liqreina A., and L. Qoaider (2014), "Dry Cooling of Concentrating Solar Power (CSP) Plants, an Economic Competitive Option for the Desert Regions of the MENA region", *Solar Energy*, Vol. 103, pp. 417-424, www.sciencedirect.com/science/article/pii/S0038092X14001273.

Loulou, R., *et al.* (2005), "Documentation for the TIMES Model. Part I: General Description of the TIMES Paradigm", ETSAP, *www.iea-etsap.org/web/Docs/TIMESDoc-Intro.pdf.*

Macknick, J., *et al.* (2012a), "Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies: a Review of Existing Literature", *http://iopscience.iop.org/1748-9326/7/4/045802/pdf/1748-9326_7_4_045802.pdf.*

Macknick, J., *et al.* (2012b), "The Water Implications of Generating Electricity: Water Use Across the United States Based on Different Electricity Pathways through 2050", Environmental Research Letters 7 045803, doi:10.1088/1748-9326/7/4/045803

Maps of India (2012), "Nuclear Power Plants in India", *http://www.mapsofindia.com/maps/india/nuclearpowerplants.htm.*

Masudi, F. (2014), "Greenhouses Key to Water and Food Security in UAE, Expert says", Gulf News, *www.zawya.com/story/Greenhouses_key_to_water_and_food_security_in_UAE_expert_says-GN_19062014_200646/.*

McDonald, R.I., *et al.* (2009), "Energy Sprawl or Energy Efficiency: Climate Policy Impacts on Natural Habitat for the United States of America", PLoS One, *www.plosone.org/article/info:doi/10.1371/journal.pone.0006802.*

Mekonnen, M., and A. Hoekstra, (2011), "National Water Footprint Accounts: The Green, Blue and Grey Water Footprint of Production and Consumption", Volume 1: Main Report, Value of Water Research Report series no. 50, *www.waterfootprint.org/Reports/Report50-NationalWaterFootprints-Vol1.pdf.*

Meldrum, J., *et al.* (2013), "Life Cycle Water Use for Electricity Generation: a Review and Harmonization of Literature Estimates", *http://iopscience.iop.org/1748-9326/8/1/015031/pdf/1748-9326_8_1_015031.pdf.*

Mielke, E., L.D. Anadon, and V. Narayanamurti (2011), "Water Consumption of Energy Resource Extraction, Processing and Conversion", *http://belfercenter.ksg.harvard.edu/files/ETIP-DP-2010-15-final-4.pdf.*

Mitra, B. (2013), "Resources sustainability in Myanmar: Lessons from integrated assessment of water-energy nexus in neighbouring countries", Presented at the Third Green Economy Green Growth Forum, Institute for Global Environmental Strategies, *http://www.iges.or.jp/files/research/climate-energy/mm/PDF/20131120/2_Mitra.pdf.*

MNRE (Ministry of New and Renewable Energy) (2014), "Physical Progress (Achievements) as on 30 September 2014", *http://mnre.gov.in/mission-and-vision-2/achievements/.*

Mohtar, R., and B. Daher (2013), "Water-Energy-Food Nexus. A Basis for Strategic Resource Planning", Presented at a Workshop on Moving Ahead to Implement the Nexus approach: Lessons Learnt and Discussion of Next Steps Regarding Integrated Assessment of Water-Energy-Food Needs in a Climate Change Context, FAO, Rome, QEERI (Qatar Energy and Environment Research Institute), *www.fao.org/energy/36625-0d50b82e2b4b8f56f7516b0a0fd657432.pdf.*

Mohtar, R. and B. Daher (2012), "Water, Energy, and Food: The Ultimate Nexus", in Encyclopedia of Agricultural, Food, and Biological Engineering, Second Edition, *http://d3aqnc497nf4cb.cloudfront.net/app/media/242*.

MoFA, IRENA, and REN21 (2013), "MENA Renewables Status Report 2013", http://www.ren21.net/Portals/0/documents/activities/Regional%20Reports/MENA_2013_lowres.pdf.

MSPA (Mauritius Sugar Producers' Association) (n.d.), "Bagasse/Coal Power Plants", *www.mspa.mu/index.php?rubrique=17.*

NL (Netherlands) Agency (2013), "Combining Bioenergy Production and Food Security", *www.globalbioenergy.org/uploads/media/1305_NL_Agency_-__Combining_biomass_production_and_food_security.pdf.*

NREL (National Renewable Energy Laboratory) (2013a), "Land-use Requirements for Solar Power Plants in the United States", *www.nrel.gov/docs/fy13osti/56290.pdf.*

NREL (2011), "A Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies", *www.nrel.gov/docs/fy11osti/50900.pdf.*

NREL (2009), "Land-use Requirements of Modern Wind Power Plants in the United States", *www.nrel.gov/docs/fy09osti/45834.pdf.*

NREL (2008), "20% Wind Energy by 2030: Increasing Wind Energy's Contribution to U.S. Electricity Supply", *www.nrel.gov/docs/fy08osti/41869.pdf.*

OECD-FAO (2012), "OECD FAO Agricultural Outlook 2013-2022", OECD, Paris, *www.oecd.org/site/oecd-faoagriculturaloutlook/highlights-2013-EN.pdf.*

Ogburn, S., and ClimateWire (2014), "Indian Monsoons Are Becoming More Extreme", *www.scientificamerican.com/article/indian-monsoons-are-becoming-more-extreme/.*

Plappaly, A., and V.J. Lienhard (2012), "Energy Requirements for Water Production, Treatment, End Use, Reclamation, and Disposal", *Renewable and Sustainable Energy Reviews*, Vol. 16, No. 7, pp. 4818-4848, *http://dx.doi.org/10.1016/j.rser.2012.05.022.*

Pollit, H., *et al*. (2010), "A scoping Study on the Macroeconomic View of Sustainability", Final report for the European Commission, DG Enviornment, SERI (Sustainable Europe Research Institute), Cambridge Econometrics, *http://seri.at/wp-content/uploads/2009/12/SERICE-2010_Macroeconomic-view-of-sustainability.pdf*.

Practical Action (2012), "Poor People's Energy Outlook 2012", *http://cdn1.practicalaction.org/p/p/4f1ea5d5-024c-42a1-b88d-026b0ae4f5bb.pdf.*

ProDes (2010), "Roadmap for the Development of Desalinaiton Powered by Renewable Energy", *www.prodes-project.org/fileadmin/Files/ProDes_Road_map_on_line_version.pdf.*

REEEP (Renewable Energy and Energy Efficiency Partnership) (2014), "Making the Case: How Agrifood Firms are Building New Business Cases in the Water-Energy-Food Nexus", *www.reeep.org/sites/default/files/REEEP_Making_The_Case.pdf.*

REEEP (2010), "Solar Water Heating Guide for Brazil ", *www.reeep.org/news/solar-water-heating-guide-brazil.*

Regions202020 (2011), "Paving the way for Sustainable Energy in Europe", ENNEREG Good Practice in Renewable Energy, *www.regions202020.eu/cms/assets/Uploads/Resources/130227-GP-CRES-RE-Milos.pdf.*

REN21 (Renewable Energy Policy Network for 21st Century) (2014), "Renewables 2014: Global Status Report", *www.ren21.net/Portals/0/documents/Resources/GSR/2014/GSR2014_full%20report_low%20res.pdf.*

REN21 (2013), "Renewables 2013: Global Status Report", *www.ren21.net/Portals/0/documents/Resources/GSR/2013/GSR2013_lowres.pdf.*

Reuters (2014), "China must Import Food to Divert Water Supply to Energy Production, says Environment official", *www.dnaindia.com/world/report-china-must-import-food-to-divert-water-supply-to-energy-production-says-environment-official-2005911.*

River Network (2009), "The Carbon Footprint of Water", *www.rivernetwork.org/sites/default/files/The%20 Carbon%20Footprint%20of%20Water-River%20Network-2009.pdf.*

Rockström, J., *et al*. (2013), "Sustainable Development and Planetary Boundaries", Background Research Paper, *www.post2015hlp.org/wp-content/uploads/2013/06/Rockstroem-Sachs-Oehman-Schmidt-Traub_Sustainable-Development-and-Planetary-Boundaries.pdf.*

Rulli, M., *et al.* (2013), "Global Land and Water Grabbing", *www.pnas.org/content/110/3/892.full.*

Sanders, K., and M. Webber (2013), "The Energy-Water Nexus: Managing Water in an Energy-Constrained World", *www.earthmagazine.org/article/energy-water-nexus-managing-water-energy-constrained-world.*

Saumweber, P. (2013), "Farming Sustainability Series Part III: Sundrop Farms- Growing with Seawater and Sunlight", *www.futuredirections.org.au/publications/food-and-water-crises/1337-sundrop-farms-growing-with-seawater-and-sunlight-2.html.*

Schneider, K. (2011), "Choke Point: China – Confronting Water Scarcity and Energy Demand in the World's Largest Country", *www.circleofblue.org/waternews/2011/world/choke-point-chinaconfronting-water-scarcity-and-energy-demand-in-the-worlds-largest-country/.*

Shankleman J. (2013), "Are Hot Rocks the Answer to Global Food Shortages?", *www.businessgreen.com/bg/feature/2253007/are-hot-rocks-the-answer-to-global-food-shortages.*

Shatat, M., M. Worall and S. Riffat (2013), "Economic Study for an Affordable Small Scale Solar Water Desalination System in Remote and Semi-arid Region", *Renewable and Sustainable Energy Reviews*, Vol. 25, pp. 543-551.

Smart, A., and Aspinall, A. (2009), "Water and the electricity generation sector: Implications of use", *http://archive.nwc.gov.au/__data/assets/pdf_file/0010/10432/Waterlines_electricity_generation_industry_replace_final_280709.pdf*

Steger, C. (2011), "Oversimplifying a Complex Topic- Measuring the "Sustainability" of Renewable Energy", the energy collective, *http://theenergycollective.com/caisteger/59154/oversimplifying-complex-topic-measuring-sustainability-renewable-energy.*

SEI (2013), "Launching a New Analytical Platform to Explore the Water Energy Nexus", presented at a Workshop on *Moving ahead to implement the nexus approach: lessons learned and discussion of next steps regarding integrated assessment of water-energy-food needs in a climate change context*, FAO, Rome.

Spang, E.S., *et al.* (2014), "The Water Consumption of Energy Production: an International Comparison", Environmental Research Letters, Vol. 9, No. 10, 105002, doi:10.1088/1748-9326/9/10/105002.

TAMU (Texas A&M University) (2003), "Irrigation Water Quality Standards and Salinity Management Strategies", *http://soiltesting.tamu.edu/publications/B-1667.pdf.*

Tan, D. (2012), "China: No Water, No Power", *http://chinawaterrisk.org/resources/analysis-reviews/china-no-water-no-power/.*

Taylor, M., and E. dela Cruz (2014), “Asia Readies Food Security Defences Against El Nino Threat”, *http://in.reuters.com/article/2014/05/26/asia-elnino-idINL3N0O828W20140526.*

The Guardian (2011), “Fracking May be Causing Groundwater Pollution, says EPA Report”, The Guardian, London, *www.theguardian.com/world/2011/dec/09/epa-reports-fracking-groundwater-pollution*.

Tol, R.S.J. (2006), “Integrated Assessment Modelling”, FNU-102, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg.

Tweed, K. (2014), “India Plans to Install 26 million Solar-powered Water Pumps”, *http://spectrum.ieee.org/energywise/green-tech/solar/india-plans-for-26-million-solar-water-pumps.*

UNDESA (United Nations Department of Economic and Social Affairs) (n.d.), “Water scarcity”, *www.un.org/waterforlifedecade/scarcity.shtml.*

UNECE (United Nations Economic Commission for Europe) and KTH (Kungliga Tekniska Högskolan) (2014), “Water-Food-Energy-Ecosystems Nexus: Reconciling Different Uses in Transboundary River Basins”. Presented at the UNECE Water Convention, *www.unece.org/fileadmin/DAM/env/documents/2014/WAT/09Sept_8-9_Geneva/Methodology_1Sept2014_clean_forWeb.pdf.*

UNEP (United Nations Environment Programme) (2011), “The Bioenergy and water nexus”, *www.unep.org/greeneconomy/Portals/88/documents/ger/Water_Bioenergy_FINAL_WEB_VERSION.pdf.*

UNEP Finance Initiative (2009), “Chief Liquidity Series: Power Sector”, *http://www.unepfi.org/fileadmin/documents/chief_liquidity2_01.pdf.*

UNESCO-WWAP (United Nations Educational, Scientific and Cultural Organization - World Water Assessment Programme) (2012), “Facts and Figures: Managing Water under Uncertainty and Risk”, *http://unesdoc.unesco.org/images/0021/002154/215492e.pdf.*

UNESCO (n.d.), “The UN World Water Development Report Facts and Figures: Water and industry”, *http://webworld.unesco.org/water/wwap/facts_figures/water_industry.shtml.*

UNESCAP (United Nations Economic and Social Commission for Asia and the Pacific) (2013), “The Status of the Water-Food-Energy Security Nexus in Asia and the Pacific region”, Position paper, *www.unescap.org/sites/default/files/Status-of-the-Water-Energy-Food-Nexus-15%2520March.pdf.*

Union of Concerned Scientists (2013), “Water-Smart Power: Strengthening the U.S. Electricity System in a Warming World”, *www.ucsusa.org/clean_energy/our-energy-choices/energy-and-water-use/water-smart-power.html#.VICs21fF9Ko*

UN Water (United Nations Water) (2012), “Status Report on The Application of Integrated Approaches to Water Resources Management”, *www.un.org/waterforlifedecade/pdf/un_water_status_report_2012.pdf*.

UN Water (2013), “Proceedings of the UN-Water project on the Safe Use of Wastewater in Agriculture”, *www.ais.unwater.org/ais/pluginfile.php/62/course/section/29/proceedings-no-11_WEB.pdf.*

UN Water (2014a), “World Water Day 2014: Water and Energy”, UN Water, New York, *www.unwater.org/worldwaterday/about-world-water-day/world-water-day-2014-water-and-energy/en/*.

UN Water (2014b), “The United Nations World Water Development Report 2014”, UN Water, New York, *unesdoc.unesco.org/images/0022/002257/225741E.pdf*.

UN Water (2014c), "Statistics", *www.unwater.org/statistics/statistics-detail/pt/c/211827/.*

US EPA (United States Environment Protection Agency) (2014a), AgSTAR Accomplishments, *www.epa.gov/agstar/about-us/accomplish.html.*

US EPA (2014b), "Final Regulations to Establish Requirements for Cooling Water Intake Structures at Existing Facilities", *http://water.epa.gov/lawsregs/lawsguidance/cwa/316b/upload/Final-Regulations-to-Establish-Requirements-for-Cooling-Water-Intake-Structures-at-Existing-Facilities.pdf*

UNU (United Nations University) (2013), "UN: Rising Reuse of Wastewater in Forecast but World Lacks Data on 'Massive Potential Resource'", *http://inweh.unu.edu/wp-content/uploads/2013/09/Rising-reuse-of-wastewater-Press-Release.pdf*.

Urbanchuk, J. (2012), "Contribution of Biofuels to the Global Economy", *http://globalrfa.org/file_download/2/GRFA_Commissioned_Report_on_the_Global_Economic_Impact_of_Biofuels.pdf.*

Uyttendaele, M., and L. Jaxcsens (2009), "The Significance of Water in Food Production, Processing and Preparation", Ghent University, Ghent, *www.foodprotection.org/events/european-symposia/09Berlin/Uyttendaele.pdf.*

Varadi, P. (2014), "Sun Above the Horizon: Meteoric Rise of the Solar Industry", CRC Press, *http://books.google.co.in/books?id=8c2uAwAAQBAJ&pg=PA202&lpg=PA202&dq=sahel+water+solar&source=bl&ots=PLcRA_nNy9&sig=9sgNaoJ-q1xJJ8K2AvMsuKFiFIM&hl=en&sa=X&ei=WVwdVJy6GoSrOryIgKgG&ved=0CFYQ6AEwCw#v=onepage&q=sahel%20water%20solar&f=false.*

Wang, R. (2013), "Water-Energy Nexus: A Critical Review Paper", Yale School of Forestry and Environmental Studies.

Water in the West (2013), "Water and Energy Nexus: A Literature Review", *http://waterinthewest.stanford.edu/sites/default/files/Water-Energy_Lit_Review.pdf.*

WEF (World Economic Forum) (2011), "Global Risks 2011, Sixth Edition: An Initiative of the Risk Response Network", *http://reports.weforum.org/global-risks-2011/.*

Weitz, N. (2014), "Cross-sectoral Integration in the Sustainable Development Goals: a Nexus Approach", Stockholm Environment Institute, Stockholm.

WERF (Water Environment Research Foundation) (2011), "Energy Production and Efficiency Research – The Roadmap to Net-Zero Energy", *www.werf.org/c/RFP/2013/ENERc13/ENER1_Fact_Sheet.aspx.*

WISIONS (2007), "Renewable Energy in the Food Supply Chain", *www.wisions.net/files/uploads/PREP_09_Food_Supply.pdf.*

World Bank (2010a), "Rising Global Interest in Farmland: Can it Yield Sustainable and Equitable Benefits?", *http://siteresources.worldbank.org/DEC/Resources/Rising-Global-Interest-in-Farmland.pdf.*

World Bank (2010b), "Improving Wastewater Use in Agriculture: An Emerging Priority" *http://siteresources.worldbank.org/INTWAT/Resources/ESWWastewaterAg.pdf.*

World Bank (2012), "Renewable Energy Desalination: An Emerging Solution to Close the Water Gap in the Middle East and North Africa", World Bank, Washington, D.C.

World Bank (2013), “Thirsty Energy: Securing Energy in a Water-Constrained World”, World Bank, Washington, D.C., *www.worldbank.org/en/topic/sustainabledevelopment/brief/water-energy-nexus*.

World Water Council and EDF (2014), “Water for Energy Framework: Understanding the relations between energy activities and water”, *www.eip-water.eu/sites/default/files/W4EF%20detailled%20leaflet.pdf.*

WRI (World Resources Institute) (2010), “Over Heating: Financial Risks from Water Constraints on Power Generation in Asia”, *www.wri.org/sites/default/files/pdf/over_heating_asia.pdf.*

WRI (2013), “Majority of China’s Proposed Coal-Fired Power Plants Located in Water-Stressed Regions”. WRI: Washington, D.C., *www.wri.org/blog/majority-china’s-proposed-coal-fired-power-plants-located-water-stressed-regions*.

WRI (2014), “Global Shale Gas Development: Water Availability and Business Risks”, *www.wri.org/sites/default/files/wri14_report_shalegas.pdf*

WSP (Water and Sanitation Programme) (2009), “Water Utilities in Africa: Case Studies of Transformation and Market Access”, *www.wsp.org/sites/wsp.org/files/publications/Water_Utilities_Africa.pdf.*

Wu, M., *et al.* (2009), “Water Consumption in the Production of Ethanol and Petroleum Gasoline”, Environmental Management, Vol. 44, No. 5, pp. 981-997.

WWF (World Wide Fund for Nature) (2014), “Developing an Understanding of the Energy Implications of Wasted Food and Waste Disposal”, *www.health.uct.ac.za/sites/default/files/image_tool/images/91/2__a16245_developing_an_understanding_of_the_energy_implications_of_wasted_food_lores.pdf.*

WWF and CEEW (2014), “Renewables Beyond Electricity: Solar Air Conditioning and Deaslination in India”, *http://awsassets.wwfindia.org/downloads/solar_air_conditioning___desalination_in_india.pdf.*

IRENA

International Renewable Energy Agency

www.irena.org