



DTU International Energy Report 2016: The Energy-Water-Food Nexus - from local to global aspects

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Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):
Sønderberg Petersen, L., & Larsen, H. H. (Eds.) (2016). *DTU International Energy Report 2016: The Energy-Water-Food Nexus - from local to global aspects*. Technical University of Denmark.

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The Energy-Water-Food Nexus – from local to global aspects

Edited by **Leif Sønderberg Petersen** and **Hans Hvidtfeldt Larsen**



DTU International Energy Report 2016
The Energy-Water-Food Nexus
– from local to global aspects

December 2016

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Design
e-Types Daily

Print
GraphicCo

ISBN 978-87-550-3973-5

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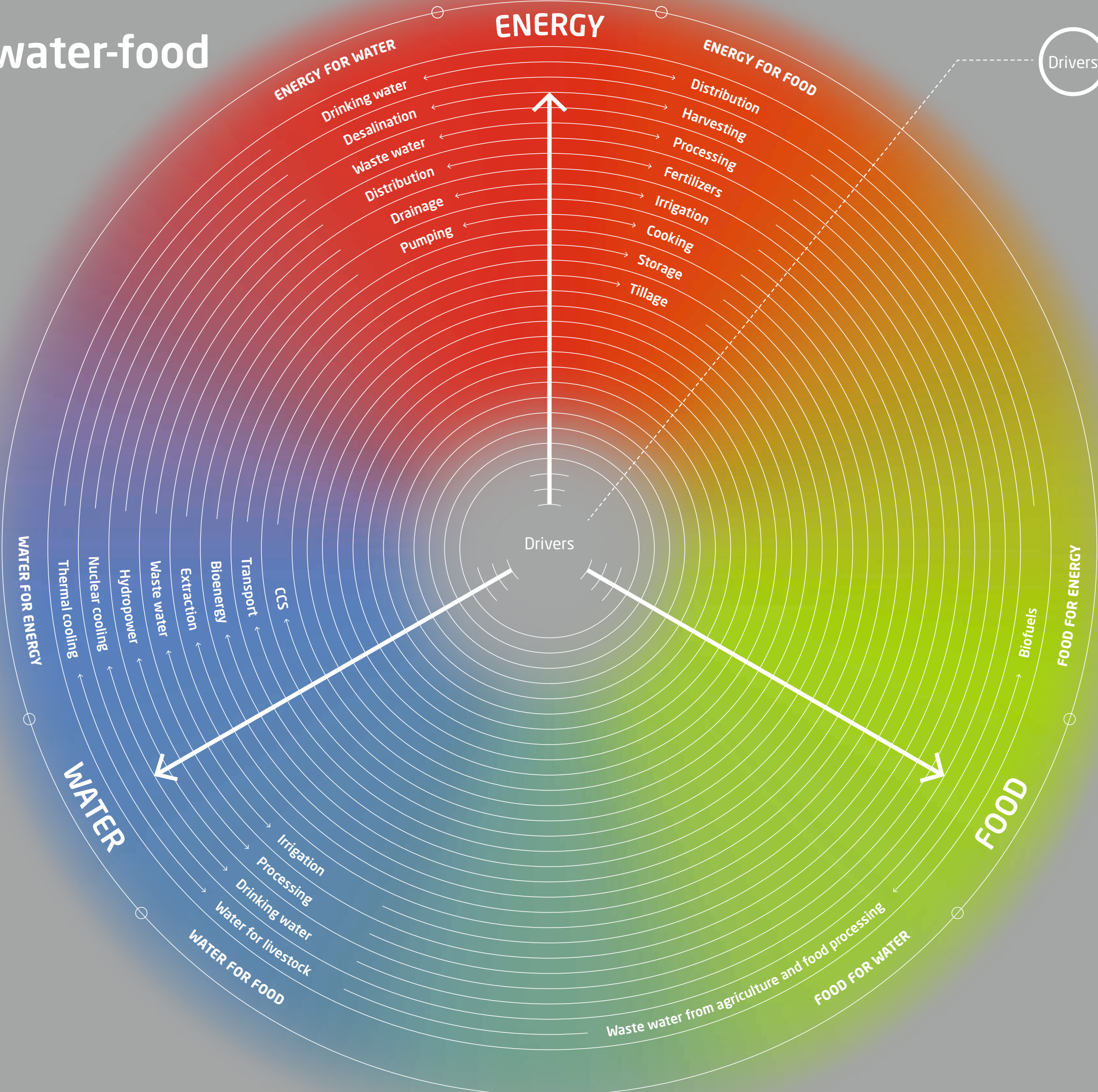
Energy, water, and food systems are closely interlinked

Water is of paramount importance for the energy sector. For example, thermal power plants require water for cooling. Conversely, energy is critical for the extraction of potable water and cleaning of waste water. Energy and water are indispensable for agriculture and livestock farming.

As demand for resources increase due to both economic and population growth, more competition, and, in some places, scarcity may affect the security of supply across the three sectors. Climate change is likely to compound this pressure.

The Energy-Water-Food Nexus concept is now seen as a key paradigm in sustainable development strategies. This approach will enhance the understanding of the complex and dynamic interrelationships between energy, water and food, and facilitate more sustainable management of these finite resources.

Energy-water-food Nexus



Drivers

Drivers that upset the Energy-Water-Food Nexus balance

- Global population
- Urbanisation
- Energy demand
- Water demand
- Food demand
- Climate change

Drivers for rebalancing the Energy-Water-Food Nexus balance

- Research & development
- Technology shifts
- Governance
- Market, regulations and economy

Drivers that upset the Energy-Water-Food Nexus balance

GLOBAL POPULATION

The world population will likely increase 33% from currently 7.3 billion to around 9.7 billion by 2050.

URBANISATION

Already now 54% of the world's population reside in urban areas. By 2050, the projections indicate that approx. 66% of the world's population will be urban.

ENERGY DEMAND

The world energy demand will continue to grow, unless current patterns are fundamentally changed, and by 2040 increase to more than 40% above current levels.

WATER DEMAND

The water demand is projected to increase by more than 50% globally between 2000 and 2050. The available water for irrigation is expected to decrease with impact on food production, especially in tropical countries.

FOOD DEMAND

In 2050, the global food production is expected to have a growth of 50% for cereals and 85% for meat, in relation to the corresponding figures for 2005.

CLIMATE CHANGE

Power plants across the world could be affected by changes in precipitation patterns, which are combining with increasing competition between water users to adversely affect the resilience of energy services.

Expanded food supply might be restricted by water scarcity.

Drivers for rebalancing the Energy-Water-Food Nexus

RESEARCH & DEVELOPMENT

There is a need for more definite and quantitative guidelines and recommendations on proper pathways towards more sustainable power generation sources.

It is important to develop local-to-regional assessments using site-specific weather- and climate data as well as associated variability and extremes, hydrology and energy modelling. Along with this, local policies and regulations should be implemented.

It is important to stimulate R&D in new sources of renewable energy based on energy conversion of food and water sector residues through thermo-chemical or biological processes.

Likewise, it is important to stimulate R&D in membrane-based water treatment technologies to pave the way for new sources of sustainable power.

There is a critical need to further develop, implement and evaluate systematic Energy-Water-Food Nexus modelling tools in order to facilitate efficient policy-making and develop strategies accommodating climate change and socio-demographic development.

Big data should be integrated in the Nexus modelling tools, where lack of access to quality data often is as a major constraint for the application of integrated methods.

Big data are also required in the study of how the different elements of the nexus relate to each other, as it is essential for confidence in the results of a nexus analysis (e.g. in terms of decision-support) to understand the data requirements and the specific difficulties of data collection across the interconnected nexus systems.

Nexus assessment tools should be based on standardised data collection routines since the cross-sectoral and multi-scale nature of the Nexus adds to the difficulty of collecting and compiling information.

An International Energy-Water-Food Nexus R&D centre should be established in Denmark, as the country has international outstanding competencies within research and industry in all three areas of the Nexus. The centre should develop tools for public sector consultancy and research-based knowledge dissemination to industry.

TECHNOLOGY SHIFTS

Renewables should be introduced more widely as wind, solar PV and oceanic based technologies have inconsiderable water consumption.

Alternative cooling technologies can significantly lower the freshwater consumption in thermal power production.

Carbon Capture and Storage or Utilisation (CCSU) is a double-edged sword: CCSU increase water consumption in power production substantially but lead to a higher degree of carbon neutrality.

Nitrogen fertiliser is the most energy-demanding aspect of conventional intensive crop production and should be replaced by the use of nitrogen fixing plants.

GOVERNANCE

The Energy-Water-Food Nexus concept should be an integrated part of future policy making and decisions in the energy, water and food sectors.

The Energy-Water-Food Nexus concept should be applied on all levels from local to global.

Appropriate legal Nexus instruments and frameworks for transboundary policy making and decisions needs to be developed.

Integrated solutions are highly location dependent and require collaboration at multi-national level, sharing data, technologies, ideas, etc., to make an impact globally.

The use of economic and legislative tools as well as social awareness campaigns can be implemented as tools for increased efficiency in the use of water and energy.

MARKET, REGULATIONS AND ECONOMY

Nexus effects related to the market, costs and international regulations, emissions trading and implementation of emerging technologies must be analysed and included in Nexus models.

A Nexus approach can provide an important additional risk assessment tool in financial analyses for investors in the energy, water and food sectors.

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Chapter 1

Preface

Energy, water, and food systems are closely inter-linked in the Energy-Water-Food Nexus.

Water is of paramount importance for the energy sector. Fossil fuels require water for extraction, transport and processing. Thermal power plants require water for cooling, whether they use nuclear, fossil or biofuels. Hydropower is based on water in rivers or reservoirs. Feedstock production for biofuels may depend on water for irrigation.

On the other hand, energy is necessary for pumping of ground- and surface water, for water treatment as well as for transport and distribution of water to end-users. The waste water is often returned to the environment after energy requiring waste water management.

Most modern crop production is inconceivable without external inputs of water. Agriculture and livestock farming consumes energy for land preparation and tillage, crop and pasture management, transportation, machinery, irrigation, and electricity supply. Add to this the use of energy-intensive products like fertilisers, pesticides, and animal feed. The strong dependence on energy inputs makes the current food supply system vulnerable to energy availability. Expected population growth and changing consumption patterns put pressure on our ability to produce ever more food.

The complexity in the Energy-Water-Food Nexus is not at least apparent in transboundary water systems. For example, the building of a new hydropower plant in an upstream country will have a number of consequences for the downstream countries in the competition for the same water resources for e.g. thermal power production and for agriculture as well as for fishing.

The demand for resources is increasing due to both economic and population growth, more competition and – in some places – scarcity which may affect the security of supply across the three sectors. Climate change is likely to compound this pressure.

Even so, today most of the policy and administrative decisions within each of the three sectors are made by separate institutions with no or little emphasis on local, national or regional Nexus coordination. In the future the sectors of energy, water, and food need to be assessed together in the Energy-Water-Food Nexus. A concept that now is seen as one of the headlines for the global research agenda and a new paradigm for sustainable development and future development strategies.

DTU International Energy Report 2016 brings up these issues and analyse challenges and opportunities for wider introduction of the Nexus concept from local to global scale in order to enhance the security and sustainability in the Energy-Water-Food Nexus.

The DTU International Energy Report series

DTU International Energy Reports deal with global, regional and national perspectives on current and future energy issues. Individual chapters of the reports are written by DTU researchers in cooperation with leading Danish and international experts. Each Energy Report is based on internationally recognised scientific material and is fully referenced. Furthermore, the reports are refereed by independent international experts before being edited, produced and published in accordance with the highest international quality standards.

The target readership is DTU colleagues, collaborating partners and customers, funding organisations, institutional investors, ministries and authorities, and international organisations such as the EU, IEA, World Bank, World Energy Council and the UN.

Chapter 2

Conclusions and recommendations

The current growth in the world population combined with an enhanced consumption of natural resources worldwide puts increasing pressures on the energy-, water- and food sectors, and will in many places be affected by climate change.

The world population will likely increase by 33 per cent from currently 7.3 billion to around 9.7 billion by 2050. The water demand is projected to increase by more than 50 per cent globally between 2000 and 2050, and the available water for irrigation is expected to decrease which is likely to have an impact on food production. The world energy demand will continue to grow unless current patterns are fundamentally changed and by 2040 increase to more than 40% above current levels. In 2050, the global food production is expected to increase by 50% for cereals and 85% for meat, in relation to 2005. Climate change will affect both the demand and supply of energy, water, and food resources worldwide and call for significant mitigation and adaptation actions, including the transition to new sustainable technologies.

Nexus solutions can secure sustainable energy, clean water, and high-quality food for all

The global trends will significantly affect the future demand and production opportunities for the energy, water, and food sectors. All three sectors however, are intricately linked together and mutually dependent on each other – they form a critical “nexus,” the Energy-Water-Food Nexus. This concept is now seen as one of the headlines for the global research agenda and a new key paradigm in many sustainable development strategies. Adopting a Nexus approach will enhance the understanding of the complex and dynamic interrelationships between energy, water,

and food, and facilitate more sustainable management of these resources.

Managing the Energy-Water-Food linkages requires careful examination of trade-off’s not only among users of the same resource, but also across users of the other resources. By anticipating potential trade-offs and synergies however, actions can be designed, appraised and prioritised so they are viable across the different sectors. Thus, it is critical for governments to ensure that their institutions are ready for such an integrated approach.

Energy-Water-Food Nexus assessments can be applied from local to global scales. At the local level, Nexus assessments might focus on integrated waste water management, energy production, or improved water and energy efficiency in agricultural production. This could save water, reduce emissions, boost recycling of nutrients, and increase energy, water, and food security. Within a region spanning more countries that are connected via a transboundary freshwater system, Nexus tools can be applied to identify incentives for strengthening collaboration between interested parties at all levels from the local to the supranational.

Systematic approaches are essential for understanding the coherence and competing demands of the Energy-Water-Food Nexus not only at different temporal and spatial scales but also across multiple sectors and local climate conditions. Such tools are urgently needed e.g. to facilitate policy measures as well as technical actions that will ensure sustainable and efficient use of energy, water resources and food production. The development of integrated system-scale approaches for managing energy, water, and food resource systems under climate change is one of today’s key challenges.

Drivers that upset the Energy-Water-Food Nexus balance

- GLOBAL POPULATION**
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URBANISATION
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ENERGY DEMAND
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CLIMATE CHANGE
Power plants across the world could be affected by changes in precipitation patterns, which are combining with increasing competition between water users to adversely affect the resilience of energy services.

Expanded food supply might be restricted by water scarcity.

Recommendations

The interdependencies of energy, water, and food systems pose a systemic risk which could negatively impact e.g. the robustness of the energy supply and demand over many years to come. In the future the sectors of energy, water, and food therefore need to be considered together in the Energy-Water-Food Nexus. This approach will enhance the understanding of the complex and dynamic interrelationships between energy, water, and food, and facilitate more sustainable management of these finite resources to ensure access for all.

A number of recommendations can be deduced from the present report in order to support further development of the understanding and managing of future demand and production opportunities for the energy, water, and food sectors in a sustainable way,

in order to secure sustainable energy, clean water and high-quality food for all.

Danish companies and researchers currently hold prominent positions internationally within all three sub-areas of the Nexus; however, coordinated research and development (R&D) efforts within the Nexus itself are limited. Thus, one of the key recommendations of this report is that an international Energy-Water-Food Nexus R&D centre should be established in Denmark to enhance both national R&D competencies as well as industrial competencies in this field by bringing together key actors from both the public and private sector in a joint effort to generate improved knowledge and new techniques, which could ultimately lead to new jobs and increased exports.

Drivers for rebalancing the Energy-Water-Food Nexus

RESEARCH & DEVELOPMENT

There is a need for more definite and quantitative guidelines and recommendations on proper pathways towards more sustainable power generation sources.

It is important to develop local-to-regional assessments using site-specific weather- and climate data as well as associated variability and extremes, hydrology and energy modelling. Along with this, local policies and regulations should be implemented.

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Chapter 3
Synthesis

By **Leif S nderberg Petersen**, DTU Office for Innovation and Sector Services (lepe@dtu.dk)



→ Energy, water, and food systems are closely interlinked.

Water is of paramount importance for the energy sector. For example fossil fuels require water for extraction and refining. Thermal power plants require water for cooling. Hydropower relies on water from rivers or reservoirs to drive electricity generation. Feedstock production for biofuels requires substantial amounts of water e.g. for irrigation.

Conversely, energy is critical for the extraction and treatment of water aimed at both private consumers and industrial users as well as for transport, collection and cleaning of waste water.

Energy and water are necessary for agriculture and livestock farming. Energy is consumed for land preparation and tillage, crop and pasture management, transportation and irrigation. Add to this the use of energy-intensive products like fertilisers, pesticides and animal feed. Finally, food processing, packaging and preparation are also highly energy intensive. Most modern crop production is inconceivable without external inputs of water.

As demand for resources increase due to both economic and population growth, more competition, and, in some places, scarcity may affect the security of supply across the three sectors and climate change is likely to compound this pressure.

Global status and trends

→ Some key global trends are especially important for the future demand and production opportunities in the energy, water, and food sectors. Population growth has a direct effect on future demand for energy, water, and food, although trends here are affected by

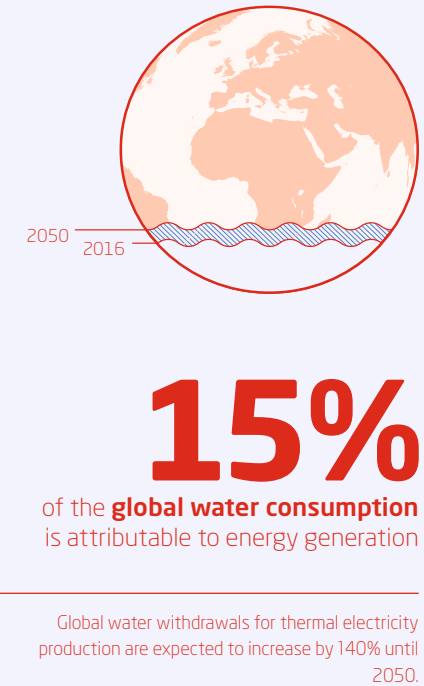
many modifying factors like efficiency improvements, changes in diet and consumer preferences, etc. The demographics of population growth patterns will similarly be important, e.g. where will the main growth be regionally, how many will live in urban settlements and so on. Finally the consequences of climate change will affect both demand and supply in all three areas, but the uncertainty about the local and regional impacts of climate change is still high in many areas.

World population will increase by 33%

The world population will likely increase by 33% from currently 7.3 billion to around 9.7 billion by 2050. It is expected that the fastest population growth will take place in sub-Saharan Africa. Increasing populations are clearly one of the key determinants for future energy, food and water demand, but a number of other factors need to be analysed to understand the intricate links between the different elements. Linking population with urbanisation trends indicate that most of the growth will happen in urban settings and this will be compounded by continued migration from rural areas to cities. Already now 54% of the world's population reside in urban areas. By 2050, the projections indicate that approx. 66% of the world's population will be urban. Sustainable development challenges will be increasingly concentrated in cities, particularly in the lower-middle-income countries where the pace of urbanisation is fastest. This will likely also be some of the areas where issues relating to the Energy-Water-Food Nexus will figure most prominently.

Water demand will increase by more than 50%

The water demand is expected to increase by more than 50% globally between 2000



and 2050. The increase in demand will come mainly from manufacturing and process industries, electricity generation, and domestic use. With these competing demands the available water for irrigation is expected to decrease with impact on food production, especially in tropical countries.

In Europe, efficiency improvements in water management and use in the energy sector and public water supply are important factors in the decreasing water abstraction over time. In this respect climate change is likely to impose new pressure on the available water resources in some parts of Europe, particularly in Southern Europe where drought is expected to pose a major future challenge. Also the risk concerning the future availability of water of the right quality e.g. for consumption as drinking water or industrial production is likely to be further exacerbated by climate change.

Energy demand will increase by more than 40%

The world energy demand in a scenario with no additional policy efforts undertaken would continue to grow and by 2040 increase to more than 40% above current levels.

Over the next decades on the other hand there will be some remarkable change in the way energy is produced. Coal and oil use will decline while renewables and gas will be playing larger roles. While this transition is driven by technological advances and climate policies, it will impact future water demand in the energy sector in a positive direction as water use for renewable power production is generally significantly lower than for thermal fossil power plants.

The energy demand development shows a number of similarities with the water demand development described above. The OECD countries at large will stabilise or likely reduce demand while the demand in developing countries will continue to grow.

The growing population will need 50% more cereals and 85% more meat

In 2050, the global need for cereal production is expected to reach around 3,000 million tonnes and the need for meat production around 460 million tonnes. This is a growth of 50% for cereals and 85% for meat – in relation to the corresponding figures for 2005/2007 (around 2,010 million tonnes and 250 million tonnes).

While there will be a need for significantly increased quantities of cereals and meat, the annual growth rate will decline.

A key question is if the expanded food supply can take place or will be restricted

by water scarcity. Estimates have shown that it could be possible under current global climate conditions, but how changes e.g. in rainfall patterns caused by climate change will impact local food production and correspondingly the global food market is not clear. Regional studies using climate models imply possibilities for significant changes in rainfall patterns and volume in many parts of the world, which is certain to affect local production system.

The Nexus concept is a new paradigm for sustainable development

→ The global trends discussed above and the interlinkages between energy, water, and food production will no doubt set the stage for future demand and production opportunities for the energy, water, and food sectors. Consequently, it is essential that future policies will anticipate potential trade-offs and synergies of the Energy-Water-Food Nexus in order to design, appraise and prioritise actions so they are viable across the different sectors. In this way the Nexus also constitutes a new paradigm for sustainable development and future development strategies. Hence the Nexus approach helps better to understand the complex and dynamic interrelationships between energy, water, and food, and facilitates more sustainable management of these finite resources.

Evidently, management of the Energy-Water-Food linkages will require the examination of the trade-off's not only among users of the same resource, but also across users of other related resources, which will ultimately call for highly integrated and trans-disciplinary approaches to be employed. Thus governments need

to ensure that their institutions are prepared to this new paradigm.

Harnessing the Nexus concept on different scales

→ The concept of the Energy-Water-Food Nexus can and should be applied from local to global scales. At the local level, Nexus considerations might focus on integrated waste water management, energy production, or improved water and energy efficiency in agricultural production. This could save water, reduce emissions, boost recycling of nutrients, and increase energy, water, and food security.

Within a region spanning more countries that are connected via a transboundary freshwater system, Nexus tools can be applied to identify incentives for strengthening the collaboration between



In 2050, the global need for cereal production is expected to reach around 3,000 million tonnes, and the need for meat production around 460 million tonnes. This is a growth of 50% for cereals and 85% for meat compared to the 2005 figures (around 2,010 million tonnes and 250 million tonnes, respectively).

interested parties at all levels from the local to the supranational. An example is bilaterally agreements between countries in flood protection and hydropower generation. On a regional level there may be treaties for trading power and food. On the global level it could be mitigating and adapting to climate change through the deployment of renewable energy sources.

A typical example of transboundary Nexus issues is a river traversing several countries in a catchment area. This creates management conflicts over issues such as water rights, usage and pricing of water in the countries that the river passes through. Upstream management of rivers affect the quality and quantity of water available for downstream countries. The linkages in the nexus are such that water, energy and land are needed to grow food in adjoining countries. Some food crops also serve as biofuel. Power plants need water for their operations. Energy intensive water schemes provide water for drinking and agriculture.

Characteristics of the Energy-Water Nexus

→ Fossil fuel production requires water for extraction and processing. Thermal power generation – whether based on nuclear, fossil fuels or concentrated solar power, needs cooling water. Approx. 90% of global power generation is water intensive and of these, hydropower and thermal power are responsible for roughly 80% of the global electricity production. Feedstock production for biofuels may also depend extensively on water for irrigation.

Energy generation accounts for 15% of the global water consumption and global water withdrawals are expected to increase by another 55% until 2050 with thermal electricity production

accounting for a 140% increase related mainly to developing countries experiencing higher demands for energy, food and other goods.

It is important to make a distinction between water withdrawal and water consumption connected with energy production. Water withdrawal includes all extracted and diverted water which has been affected during the process also including what is reinjected into the supply source. Water consumption includes evaporated and transpired water as well as water integrated in crops or otherwise removed. The consumption is therefore a subset of the withdrawal.

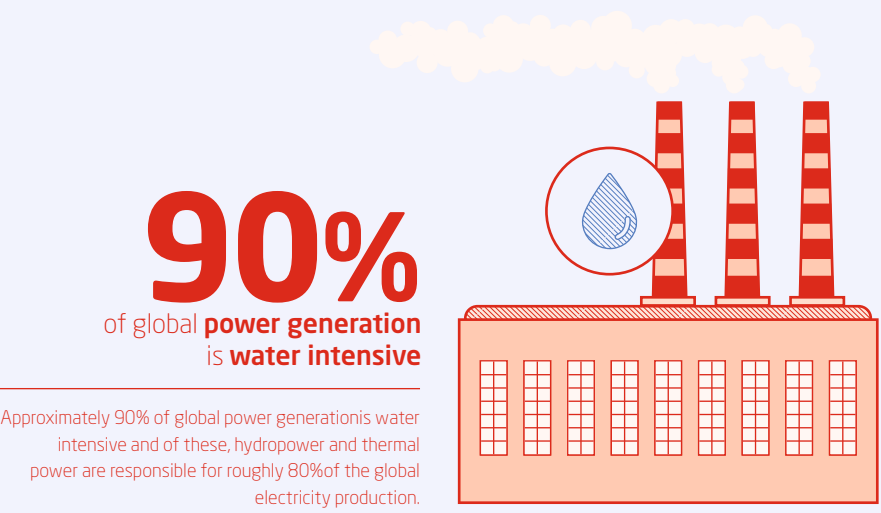
In conventional oil production, water consumption varies in relation to mainly geology, type of recovery and state of the reservoir. Oil production consumes far more water than conventional natural gas extraction where the water consumption is negligible. Typically the water demand for nonconventional oil extraction (including hydraulic fracturing of shale oil and tar sand oil) is significantly higher than the water demand from crude oil extraction. It should be emphasised that all kinds of fossil fuel extraction will

influence not only the water quantity but also the water quality.

Thermal power plants share many characteristics independent of their power source (nuclear, fossil fuels, or concentrated solar power), including the processes related to water usage. Cooling accounts for the main share of the total water use. The water withdrawal for thermal power plants varies with the applied cooling technology – from large amounts to zero for dry cooling plants. Switching to non-freshwater cooling and dry cooling reduces freshwater consumption – the latter, however, imposes penalties in terms of reduced output and increased costs depending on the local climate.

Carbon capture and storage (CCS) increase the plant's cooling demands significantly. Thus, increasing the degree of carbon neutrality by the use of CCS will intensify the water consumption.

Alternative cooling water sources can provide more sustainable water consumption (e.g. waste water, otherwise non-potable (brackish) groundwater, water from oil/gas production and in-plant water recycling).



Wider introduction of renewable energy will reduce water consumption

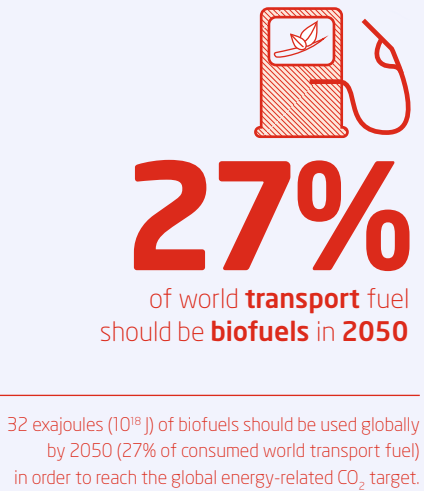
Renewable energy as wind, solar PV and ocean technologies generally consume minimal water making them well-suited for a more carbon- and water-constrained future. In water sparse areas, the future energy sources should therefore focus on technologies with a negligible freshwater consumption such as solar, wind and ocean technologies whereas regions with sufficient and sustainable water resources are more feasible to implement technologies which are water consuming, albeit still renewable.

Concentrated solar power production technologies involve significant water consumption for plants with wet cooling, whereas dry cooling plants consume much less.

Hydropower needs water from rivers or reservoirs. Some studies argue that water usage from hydropower plants can be somewhat neglected in a comparison study due to the societal purposes of the reservoir such as flood control, leisure, irrigation, and water supply storages. It should be emphasised that the water usage is highly dependent on the geographical conditions, including temperature and type of reservoir. Shallow reservoirs in a tropical climate will have dramatically higher water consumption than deep reservoirs in a temperate region.

For geothermal power plants, water consumption varies greatly with the type of power plant design.

In biofuel production, water is required for biomass cultivation. The water consumption varies greatly based on the type of crop and region. For example, 90 litre of water is used to produce one litre of ethanol in Brazil whereas 3,500 litres was used in India to produce the same amount.



The mutual interdependency of energy and water systems poses a systemic risk which could impact the robustness of the energy supply and demand over many years to come. Power plants across the world could be affected by changes in availability of water e.g. as compounded by changes in regional precipitation patterns, combined with increasing competition between water users to adversely affect the resilience of energy services.

The urban Energy-Water Nexus imply extraordinary challenges

→ Urban water infrastructure is growing increasingly complex, driven by a number of factors including decreasing freshwater availability, increased allocation for environmental water flows, and increasing water demand caused by population growth. In addition waste water management is met with increasingly strict demands for effluent water quality and requirements for resource recovery, which in turn leads to an intensification of waste water treatment. Climate change

affects water availability in many places, but also requires cities to adapt to new storm water regimes.

Most cities handle three major water flows and a myriad of minor flows in between compartments of the cities. The major flows are rainfall, water supply and industrial/household waste water. These vary dramatically between geographic locations.

Rainfall and waste water adequately cover for the water demand in many cities, but intermittency and poor quality have historically limited its use, although this is changing due to increased focus on decentralised rainwater harvesting and waste water reclamation. Besides the major urban water flows, cities also have access to water resources available as groundwater, surface water (rivers or lakes), and seawater.

In all cases, water often needs energy-intensive treatment before use or it needs to be conveyed from the resource to the point of use. Water may be converted from one quality to another to be used for drinking water, to sustain environmental flows, or protect recipients, e.g. when waste water is discharged to the sea.

Simple treatment can be used to remove organic pollutants, through microbial degradation in sand filters, stripping to air by aeration, or sorption to filter materials such as activated carbon. Usually, simple filtering is gravity driven and requires modest electricity consumption to operate. Membrane treatment allows utilities to convert poorer water qualities to drinking water quality when

Storm water is rain water collected from impervious areas, i.e., roofs, roads, parking areas etc. This rain water often becomes contaminated due to particles, dust, oil, micro-plastic, bird droppings, other organic material etc. All of this is carried with the water after contact with the surface.

clean water resources are not available. Oxidation and disinfection steps have low demands for electricity compared to membrane treatment.

Rainwater harvesting can substitute parts of the urban household water supply, e.g. for toilet flushing, clothes washing, and hot water demands. Rainwater harvesting has modest electricity consumption.

Often, the options for additional water resources stand as a choice between intensified treatment, increased production from a known resource, or increasing imports from resources available further away. Some of these water transports are heavy energy consumers, others come at a very low energy cost such as gravity-driven water transport.

In Copenhagen the average electricity values for operating water abstraction, drinking water treatment, and distribution corresponds to 3% of the total electricity consumption and 11% of the household electricity consumption. As such, the electricity use for urban water management is a marked contribution to the total energy use of urban households and related to heating the water. Thus, water and waste water services make an important contribution to the total electricity use in cities.

The drinking water composition, notably the water hardness, will affect the scaling in the plumbing system, appliances and heat exchangers. Even a slight reduction in hardness, will have a significant positive environmental impact for Copenhagen. With ambitious goals for Copenhagen to become carbon-neutral in the near future, the comparably high electricity consumption by desalination will have reduced influence on the systems environmental burden. Caused by this anticipated change in the energy mix and the relatively low hardness of desalinated seawater, the environmental

burden is expected to be lower for the desalination scenario than for the conventional groundwater based system already by 2020.

Energy demand for waste water treatment is largely dependent on local effluent water quality standards. In areas where legislation craves reduction of particles, organic compounds and nutrients before discharge waste water treatment require primary treatment with screens and settling tanks, before secondary and tertiary treatment remove organic compounds and nutrients. To this comes energy for transporting the waste water.

Some waste water utilities recover parts of their electricity use by sludge digestion. In Denmark, the waste water utility Vandcenter Syd is substituting 64% of its own electricity demand and together with 33 other waste water utilities with self-produced electricity, the production substitutes 28% of their total demand.

Storm water management is expected to have a low demand for electricity in the use phase. This is explained by the fact that after installation drainage systems are mainly passive when new paradigms within storm water control measures manages water at the surface and use less pipes and basins it may lead to a reduction in total energy impact and save energy at the waste water treatment plant.

Since water systems consist of infrastructure with long lifetimes in the range of 20-100 years, it is important to consider how new infrastructure investments will respond to future changes to power generation.

Characteristics of the Energy-Food Nexus

→ It is estimated that energy use in modern food production, including agricultural production, transportation, food processing, packaging and preparation amounts to about a fifth of all energy use. This corresponds to 2,000 litres of oil equivalents to support the diet of one person for one year.

The strong dependence on energy inputs makes the current food supply system vulnerable to energy availability. Expected population growth and changing consumption patterns put pressure on our ability to produce ever more food. Current trends go towards diets rich in meat, highly processed and vigorously transported products, and urbanisation. These trends are associated with increased consumption of luxury foodstuffs, many of which are energy intensive in production and distribution. Food production must increase by 70% between 2006 and 2050 to feed the growing human population with a continued

transition toward food demand from intensive, crop-based animal husbandry.

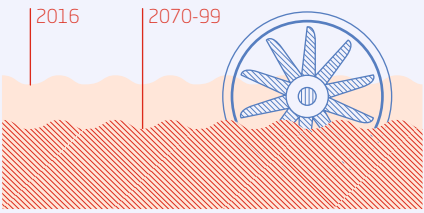
It has been shown that about four units of fossil energy are required to produce one nutritional unit of energy in food at the retailer in Denmark in 2007. In addition, this high energy use in Danish food production and processing is indicated by the sector's energy intensity calculated as energy consumption in kg oil equivalent per dollar of value generated. In 2014, this ratio for Denmark was the highest worldwide (0.43) whereas it was only 0.12 for the US. The world average was 0.04 which was a result of a steady decline over the last 15 years.

About half of the energy consumption of the modern food supply system occurs in food handling, comprising packaging, sales and preparation. The other half is considered to be close to evenly divided between agriculture, distribution and processing in some countries, in Denmark agriculture uses the most. This means that initiatives to reduce energy use in the food supply system should go beyond agricultural production practices. This opens up for an extended range of possible approaches to reduce the overall energy use of the food supply system.

The energy intensity of agricultural production varies across crop productions, livestock production, aquaculture and fisheries. Generally speaking, crops require the least energy input per ton produced. Farm animal products and aquaculture require similar energy inputs. Fishery products range from comparable to crops to much higher than farm animal products.

Nitrogen fertiliser is the most energy-demanding aspect of conventional intensive crop production, accounting for approx. 60% of cumulative energy demand. While nitrogen may be synthesised with electricity from renewable

36% less hydropower due to climate change



Hydropower systems might suffer from changes in the water balance. The projected general decrease in hydropower production rates in the Swiss Alps by 2070-2099 is 36%.

sources, this would continue to be an energy-intensive approach. The most apparent alternative is to biologically fixate nitrogen from the air by adding legumes to the crop rotation.

In predominantly rain-fed crop production, machinery use is typically the second-most important energy consumer with tillage and harvesting as the most energy-requiring activities.

Increased demand for convenience products is the explanation a large increase in food processing-related energy use in the last few decades. Retailing is the third-most energy intensive stage in the supply chain from agriculture to household. More than half of the energy use in retail is from refrigeration followed by lighting and space heating. Households constitute the single-largest energy consumer of the food supply system.

The transportation system built on access to relatively plentiful amounts of oil not only connects food producers with the global market, it also allows for extensive

transport within agricultural production, e.g. fodder for animal production. Energy used in refrigeration means that e.g. tropical fruits are available in supermarkets year round. Additionally, the durability of transported food requires sufficient packaging, particularly after or between processing steps. The production, transport and discard of packaging entail energy use. These considerations have popularised the concept of food miles and suggest that local production and use leads to higher energy efficiency.

Increased groundwater use for irrigation is a consequence of the availability of cheap energy and it is estimated that 70% of global water consumption by humans is caused by agriculture. Most modern crop production is inconceivable without external inputs of water.

In production systems that depend on irrigation, increased water use efficiency with low-tech interventions as drip irrigation may be a key to reduce energy inputs. Another type of approach is to reduce the dependence on irrigation. This may be achieved by improving the soil's water retention capacity or by reducing exposure to the sun when it is strongest.

The generation of food waste significantly affects energy use of our food supply. It is estimated that 30-50% of all food produced is wasted. Altogether, it appears that approaches to reduce food waste in the developing world should focus on changing production practices while developed world approaches should focus on changing consumption practices.

Bioenergy production has positive as well as negative effects in the food sector. An example is manure, which in most of Europe is typically stored and applied on-land without any treatment. Boosting production of bioenergy out of manure has the beneficial side-effect of reducing undesired emissions occurring during



Oil extraction consumes from 500 to 1,200 litres per MWh, corresponding to about 800 to 2,000 litres for one barrel. Coal extraction employs water consumption rates of 15 to 105 litres per MWh for mining and washing, and an additional consumption of 40 to 90 litres per MWh if transported by slurry pipeline.

storage and application of land of raw manure. On the other hand, using feed/food crops for bioenergy may increase the demand for conventional fodder and food, thereby adding pressure on the agricultural sector for production of grains and meat. Using agricultural residues like straw may contribute to soil carbon loss and more research is required to search for the right balance between increased energy demand, and the systematic carbon recycling and build up needed to counteract climate change.

Producing energy crops determines two distinct effects on land-use. In regions such as Denmark the land needed for their cultivation is likely to come at the expenses of other (feed/food) crops. Such effect is called direct land use change (dLUC). At an international level, this initial displacement increases the demand for conventional fodder, thereby adding pressure on the global agricultural sector for production of grains and meat. This, in turn, may induce expansion of arable land into nature (deforestation) and increased use of fertilisers. These effects are called indirect land use change (iLUC) impacts and are typically much more important, in terms of magnitude, than dLUC.

The Energy-Water-Food Nexus and potentials for renewable energy production

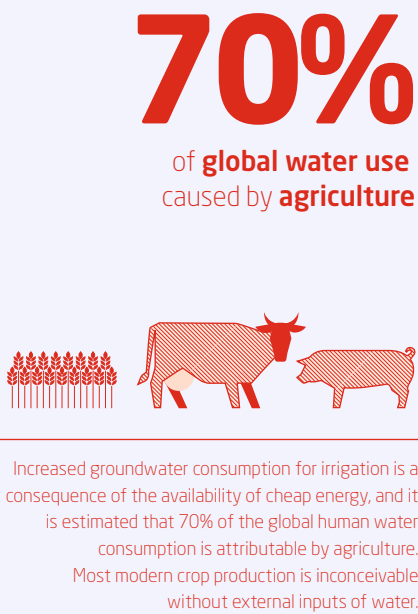
→ Currently, solar and wind power are regarded as the ultimate sources for sustainable power. Now, novel membrane-based water treatment technologies pave the way for a new source of sustainable power. An example is salinity-gradient power (SGP). These

techniques have high power density and energy recovery potential. The energy of mixing 1 m³ of seawater with 1 m³ of river water is 0.92 MJ or 0.256 kWh, and the global potential is 2.8 TW.

By the use of membrane bioreactors (MBR) the organic content of domestic waste water can be converted efficiently to methane gas. With 200 liters of waste water/(person day), a membrane bioreactor has a theoretical yield of 0,12 kWh/(person day) or 43 kWh/(person year). For comparison, this is about seven times larger than the annual Danish electricity consumption per person per year.

Conversion of food and water sector residues to energy represent an important opportunity to produce bioenergy and mitigate global warming effects. A long range of emerging technologies will allow for efficient and sustainable energy recovery from waste water and food waste. Thermal gasification is a promising technology for conversion and utilisation of agricultural residues or industrial and municipal sewage sludge, due to its flexible and robust heat and power generation and the possibility to produce various value-added products, such as storable high energy density fuels, chemicals and valuable fertiliser ashes. The gas produced during gasification can be converted directly into heat and power, stored as gaseous fuels in the existing gas infrastructure or synthesised into liquid fuels or chemicals.

Among the emerging sludge management options, thermochemical valorisation including pyrolysis and gasification, has been identified as some of the most promising alternatives due to high flexibility, efficiency and the ability to simultaneously address bio-ash valorisation and energy utilisation. This will facilitate an optimised energy recovery, reduced energy use and increased plant robustness at municipal waste water treatment plants.



Biomass derived from food industry and water sector can be used as influent feedstock in biogas plants. This include residues from food processing industry, slaughterhouses, edible oil industry, dairy products, inedible residues from food crops, dedicated energy crops, manure from livestock farming and sewage sludge from municipal waste water treatment plants. Even though anaerobic digestion of organic residues is a mature and widely applied technology, specific challenges need to be addressed so as to further optimise the process and maximise the energy output.

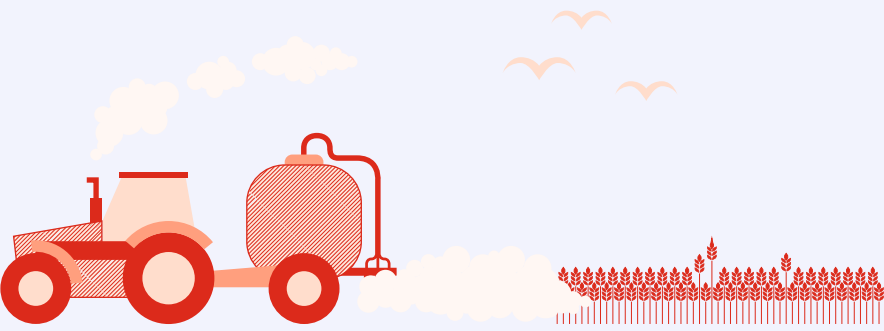
Modelling the Energy-Water-Food Nexus from local to global scale

→ Systematic approaches are essential for understanding the coherence and competing demands of the Energy-Water-Food Nexus, not only at different temporal and spatial scales but also across

multiple sectors and local climate conditions. Such tools are urgently needed e.g. to inform policy measures as well as technical actions that will ensure sustainable and efficient use of energy, water resources and food production. The development of integrated system-scale approaches for managing food, energy and water resource systems under climate change is one of today's key challenges.

A number of Nexus methods and tools have been developed during the recent years. They range from qualitative approaches like surveys and indicator-based analysis to more data-driven and quantitative modelling approaches that are suitable for analysing the complex interlinkages of the Energy-Water-Food Nexus from global to local scales. Such tools can support decision-making and implementation of sustainable management strategies along multiple value chains within the Nexus. Further, they can strengthen collaboration between stakeholders.

At the local level, Nexus assessments at the appropriate scales might focus on integrated waste water management, energy production, or improved water and energy efficiency in agricultural production, which – if applied – may pave the way for new innovations to save water, reduce emissions, recycle nutrients, and to increase energy and food security.



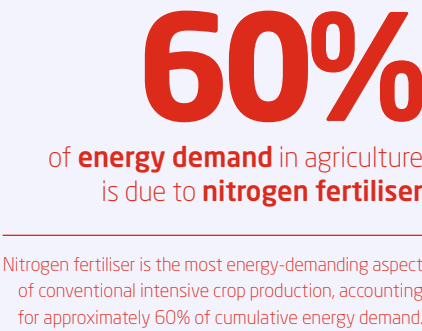
Nexus assessments can be used for integrating energy, water, and food systems in an urban context. As an example, fluctuating renewables like wind and solar PV can be shared in the best possible way with hydropower, as well as biomass under the constraint of energy and water security by intelligent real-time control of the energy demand, e.g., related to the use of water for industrial processes as well as water distribution and treatment.

Within a region or ‘macro-region’ spanning two or more regions (e.g. countries) that are connected via transboundary energy and/or freshwater systems, Nexus assessment tools can be used to identify incentives to strengthen collaboration between actors at all levels from the macro-regional to the local. This includes market-based transactions which can occur bilaterally between regions (e.g. flood protection and hydropower generation), at regional level (e.g. trade of power and food), or at global level (e.g. mitigating and adapting to climate change through the deployment of renewable energy sources).

On a wider transboundary scale, Nexus tools can be used for assessing key development opportunities in the Energy-Water-Food Nexus at a highly aggregated level, while taking into account qualitative assessments of water resource constraints. It can be used to explore benefits

to be generated and shared, and for stakeholders to identify drivers, barriers and preferred options, e.g., how to mitigate pressures or use limited water resources more efficiently and innovatively.

An important aspect of the Energy-Water-Food Nexus problem is the determination of “willingness-to-pay” for water (the value of water) in the energy, agricultural, and environmental sectors. Traditionally, water engineers have derived the sectoral willingness-to-pay for water from external prices of energy, of crops and from the valuation of ecosystem services. Hence at the system scale decisions in the water sector will affect prices for food and energy.



Chapter 4

The Energy-Water-Food Nexus in a global perspective

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→ Energy, water, and food systems are closely interlinked. Energy is necessary for the extraction and handling of water as well as for transport, distribution and treatment of waste water. Water is of paramount importance for the energy sector. Fossil fuels require water for extraction and refining. Thermal power plants require water for cooling. Hydropower needs water from rivers or reservoirs. Feedstock production for biofuels may depend on water for irrigation. Agriculture and livestock farming consume energy and water for land preparation and tillage, crop and pasture management, transportation and irrigation. In addition food production often requires the use of energy-intensive products like fertilisers, pesticides while animal feed and waste water is produced.

Demand for resources increases globally due to both economic and population growth, and this is likely to result in increased competition for all three resources and in some regions there may be direct scarcity affecting the security of supply. Climate change is likely to compound this pressure both short term due to increased variability on temperatures and precipitation and long term with increased global temperatures.

Population growth increases the need for energy, water, and food

Population growth has a direct effect on the future demand for food, water, and energy although trends are affected by many modifying factors like efficiency improvements, changes in diet, and consumer preferences, etc. The demographics of population growth patterns will similarly be important e.g. where will the main growth be regionally, how many will live in urban settlements and so on. Finally, the consequences of climate change will affect both demand and supply in all three areas, but the uncertainty about the local and regional consequences is still high in many areas.

The latest UN forecast for global population growth was presented by the UN last year (UN DESA, 2015) and it shows an expected increase from currently 7.3 billion people to around 9.7 billion by 2050, as illustrated in *Figure 1*. Projections are very sensitive to assumptions, and the numbers mentioned are median with a span of approx. +/- 300 million.

Increasing populations are clearly one of the key determinants for future energy, food and water

demand, but as mentioned above, a number of other factors need to be analysed to understand the intricate links between the different elements.

A basic challenge when looking at water, energy and food is the lack of “harmonised” data sources. Various sources present elements of the global picture, with different timing and approach. It is, however, not possible to find one single fully comprehensive overview. But even if the food and water projections presented in this section use earlier population data than the recent DESA report above, the overall trends are still quite robust.

Linking population with urbanisation trends indicate that most of the growth will happen in urban settlements and this will be compounded by continued migration from rural area to cities.

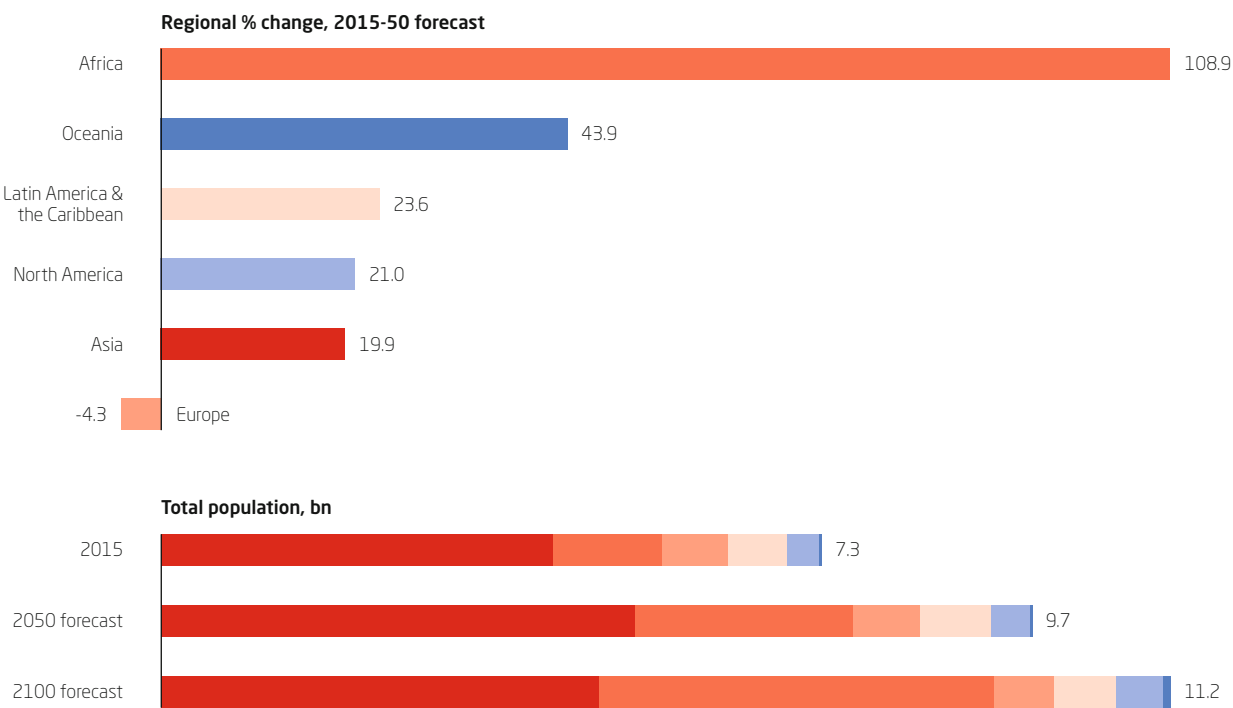
Already now, some 54% of the world’s population reside in urban areas (UN DESA, 2014). By 2050, the projections indicate that approx. 66% of the world’s population will be urban. All regions are expected to urbanise further over the coming decades, but those regions with the lowest urbanisation rates, in Africa and Asia, will be urbanising faster than the other regions and are projected to become 56% and 64% urban, respectively, by 2050. Sustainable development challenges will therefore be increasingly concentrated in cities, particularly in the lower-middle-income countries where the pace of urbanisation is fastest. This will likely also be some of the areas where issues relating to the water-energy-food nexus will figure most prominently, see also *Figure 1*.

Increasing demand for water, but large regional differences

An analysis by OECD (OECD, 2012) indicates that water demand is projected to increase in a “no new policy” scenario by more than 50% globally between 2000 and 2050. The analysis also shows that the increase in demand will come mainly from manufacturing, electricity and domestic use. With these competing demands the available water for irrigation is expected to decrease with impact on food production esp. in tropical countries.

The global numbers shown in *Figure 2* cover large regional differences. Through dedicated policies OECD countries are likely to have adequate and

Figure 1 - The World's population. (The Economist, 2015)



high quality water resources and many BRIIC (Brazil, Russia, India, Indonesia and China) countries will experience significant improvements, while the situation in the rest of the developing world will remain very problematic with 1 to 2 billion people in 2050 still lacking access to basic sanitation and safe drinking water. It should be noted that the new population numbers by the UN presented above were released after the OECD report referenced here and since the new population numbers are slightly higher than those used by OECD in 2012, the access numbers are likely to be at the low end reflecting that population growth especially will be happening in urban settings in Africa and South Asia.

The European Environmental Agency, EEA, has made an assessment of water availability, resource stress, and needs of the European economic sectors including agriculture, industry and other business, energy, navigation, recreation and households (European Environmental Agency, 2012 a).

Figure 3 provides an overview of the major water abstraction sectors in Europe in 1990 and 2007. Water abstraction has – as it can be seen from

Figure 3 – decreased for all subregions from 1990 to 2007 except in the case of Turkey. Irrigation is the major sector in Southern Europe and Turkey, while energy and public water supply are the most important sectors in Eastern and Western Europe.

Figure 2 - Global water demand, baseline scenario, 2000 and 2050. (OECD, 2012)

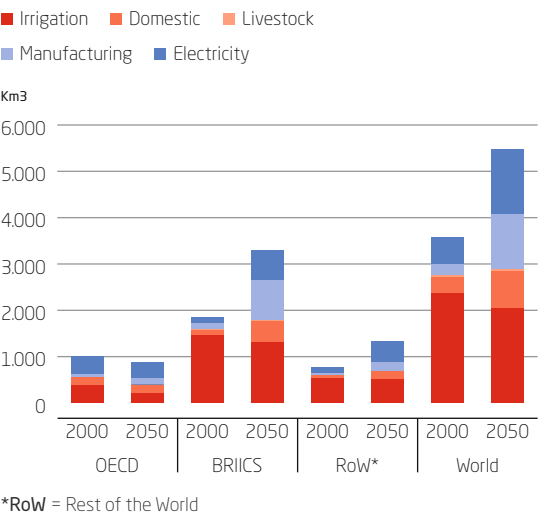
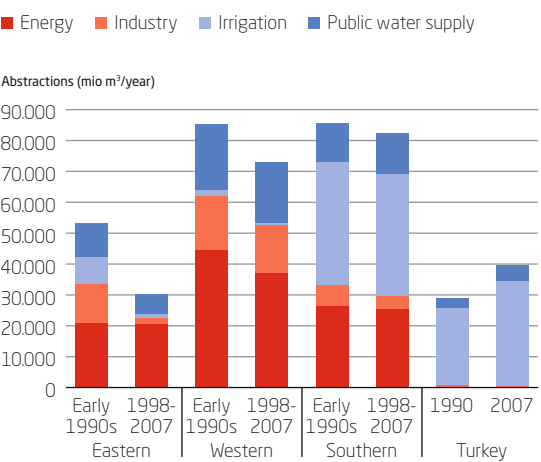


Figure 3 - Overview of the major water abstraction sectors in Europe in 1990 and 2007. Source: (European Environmental Agency, 2012 a).



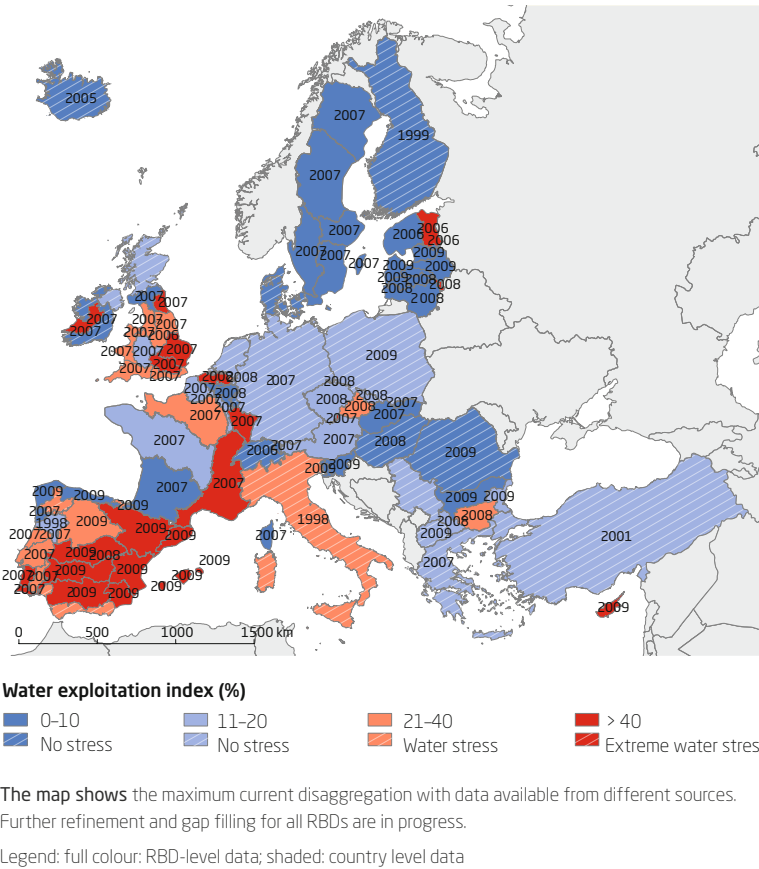
Efficiency improvements in water management and consumption in the energy sector and public water supply are important factors in the decreasing water abstraction over time.

The demand for water services in Europe will decrease in the future with economic development, but climate change could impose further pressure on the available water resources in particularly in Southern Europe, where drought is expected to be a major challenge. The water stress in different parts of Europe in 2010 is illustrated in the following map, and this stress is expected to be further exacerbated by climate change.

On this basis a special report of the European Environmental Agency on strategies towards efficient use of water resources in Europe (European Environmental Agency, 2012 b) concludes that several policies and technologies should be taken into consideration in efficiency improvements. They include technologies, cross-sectoral coordination, economic instruments, and consumer awareness raising.

40% higher energy demand in 2040
According to the analysis by the International Energy Agency (International Energy Agency, 2014) the world energy demand in a scenario with no additional policy efforts undertaken would continue to grow and by 2040 be more than 40% above current levels.

Figure 4 - Water exploitation index – towards a regionalised approach (European Environmental Agency, 2012 b).



With new climate-friendly policies under discussion or implementation, like those included in the Intended Nationally Determined Contributions (INDCs) submitted by all countries as a pledge for the Climate Summit – COP 21 in Paris and now

Figure 5 - Changing dynamics of global energy demand. Source: World Energy Outlook 2014

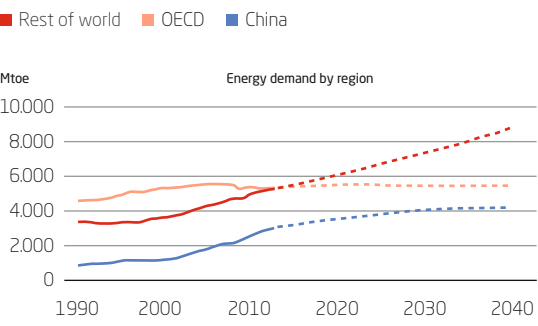
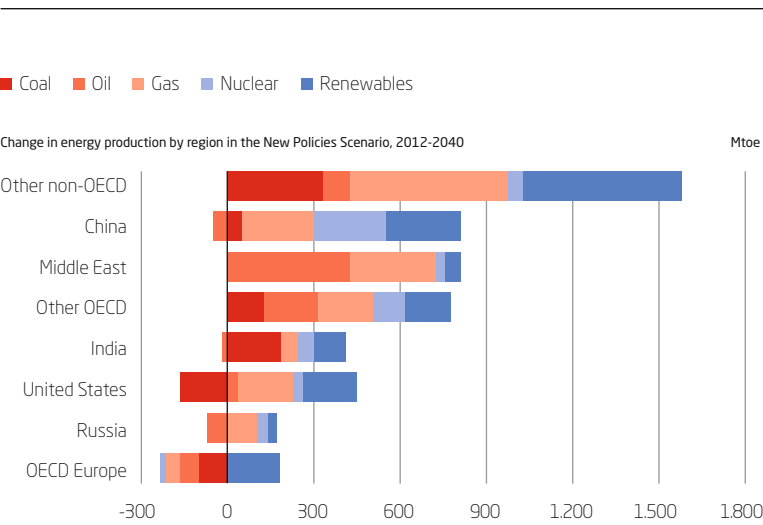


Figure 6 – Energy production by 2040.
Source: World Energy Outlook 2014.



forming the basis for the Paris Agreement; the increase in demand compared to the no-policy case is likely to be more than halved. This will reflect a significant shift from carbon-intensive fuels towards more low carbon or renewable energy sources. The energy demand development shows a number of

similarities with the water demand development described above. The OECD countries at large will stabilise or likely reduce their demand while developing countries will continue to grow. The main difference from water situation seems to be that BRIIC countries at least in the first decade will dominate more on energy and be responsible for the major part of growth and then stabilise while other developing countries will continue to grow in the following decades.

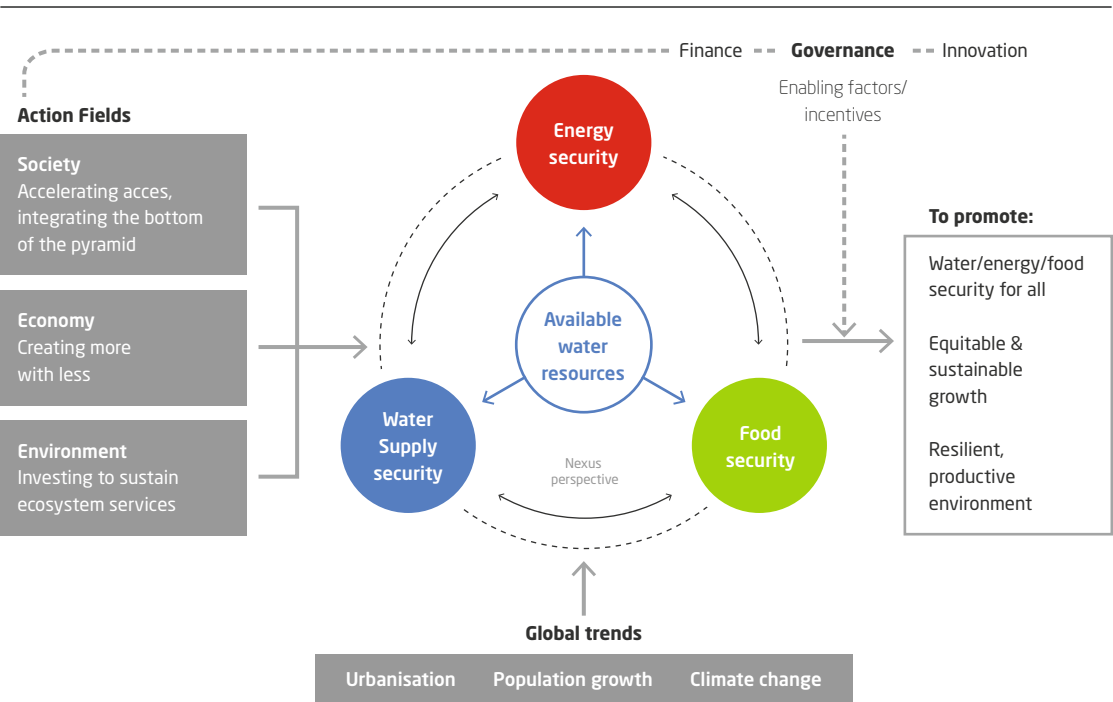
As mentioned, the IEA projects a major shift over the next decades in the way energy is produced. Coal and oil production will decline rapidly, while renewables and gas will be playing an increasing role. While this transition is driven by technological advances and climate policies, it will likely impact future water demand in the energy sector in a positive direction, as water use for renewable power production is generally significantly lower than for thermal fossil power plants. There may be a larger demand for land for RE installations, but it should be possible to accommodate that need without really impacting the available arable land. Noting also that there will likely be an increase in off-shore wind and possibly wave systems, solar may increasingly be building integrated, etc.

Table 1 – Increases in agricultural production.

Region	1961/1963	2005/2007	2050	Increase in percent, 1961/1963-2005/2007	Increase in percent, 2005/2007-2050
World (146 countries)					
Population ^a (million people)	3133	6372	8796	103	38
Cereals ^b (million tonnes)	843	2012	3009	139	49
Meat production (million tonnes)	94	249	461	165	85
Developing (93 countries)					
Population ^a (million people)	2139	5037	7433	135	48
Cereals ^b (million tonnes)	353	1113	1797	215	61
Meat production (million tonnes)	42	141	328	236	132
Developed (53 countries)					
Population ^a (million people)	994	1335	1362	34	2
Cereals ^b (million tonnes)	490	900	1212	84	35
Meat production (million tonnes)	52	108	133	108	23

(a) Population figures for 2005/2007 are population in 2005; for 2050 from the United Nations 2002 assessment; the 2050 projection from the United Nations 2008 assessment amounts to 9,056 million for the 146 countries covered. (b) Including rice in milled form. The latest country balance sheet (CBS) cereal data show a world cereal production of 2,138 million tonnes for 2006/2008, implying an increment to 2050 of less than 900 million tonnes if measured from the 2006/2008 average (FAO, 2009).

Figure 7 – The water, energy and food security nexus (Hoff, 2011).



Need for food increasing, but annual growth rate will decline
Projecting future food demand and supply faces a mix of challenges:

- Population increase (note that the FAO study uses 10 year old population data that compared with the numbers presented above are almost one billion lower, illustrating the difficulties with projections on all parameters).
- Increase in average per capita calorie intake related to both increased income and changes in diets.
- Changes in land and livestock productivity.

The data from FAO in *Table 1* (FAO, 2009) shows that while there will be a need for significantly increased quantities of both cereals and meat, the annual growth rate will continue to decline. Growth in crop production is expected to come through a combination of increased intensity in countries with already high percentage use of arable land and land expansion, especially in those developing countries where current use of arable land is limited.

Both the intensity of production and the land expansion will in many cases be based on increased demand for irrigation. A key question in the Food-Water Nexus is therefore if the expanded food supply can take place or will be restricted by water scarcity. The cited study by FAO (FAO, 2009) concludes that it is possible under current rainfall patterns. How changes caused by climate change will impact is not clear at global level while regional studies imply possibilities for significant changes in rainfall patterns and volume.

Three sectors united in a single Nexus
Figure 7 reflects how the abovementioned key global trends are important for future demand and production opportunities for all three sectors. In the future these sectors need to be assessed together in the so-called Energy-Water-Food Nexus, a way of thinking which took one of its first steps at United Nations University with the establishment of their Food-Energy Nexus Programme in 1983. The objective was to find methods to fill the research gap between the synergistic solutions to food and energy problems. In 1990 the university published a book that addressed the following issues:

- More efficient use of energy in the production, processing, and consumption of food.
- Food-energy systems in diverse ecosystems.
- Household economy in both rural and urban settings and the role of women and children in the provision of food, fuel, and water.

(Ignacy Sachs, D. S. 1990)

In 2002, the UN Secretary General Kofi Annan proposed the “WEHAB initiative,” with emphasis on water, energy, health, agriculture, and biodiversity. (United Nations, 2002). The initiative should divert the World’s collective efforts from commitments to action to ensure more sustainable livelihoods for all, including access to water and sanitation, energy, health, agriculture and biodiversity (WEHAB).

The Energy-Water-Food Nexus way of thinking gained real momentum at the World Economic Forum’s Annual Meeting in 2008 (World Economic Forum, 2008) with focus on the future risk for water scarcity. A range of important actions was listed, among others water for agricultural use, water for industry, and water for energy.

This initiative was followed up at the World Economic Forum’s Annual Meeting in 2011 where the book “Water Security: The Water-Food-Energy-Climate Nexus” was launched (World Economic Forum, 2011). The book analyses how water security underpins and connects food, fibre, fuel, urbanisation, migration, climate change, and economic growth. Finally the attention is turned to what can be done, among others, that civil society and business leaders can play an important and constructive role in supporting governments in a comprehensive water-food-energy-climate reform process.

The same year, the German Federal Government organised the Bonn2011 Nexus Conference in order to contribute to the United Nations Conference on Sustainable Development (Rio+20). In the background paper for this conference (Hoff, H. 2011), the Energy-Water-Food Nexus was presented as a response to climate change, population growth, economic growth, globalisation, and urbanisation. The paper argues in favour of improved water, energy and

food security achieved through a Nexus approach that integrates management and governance across sectors and scales. Further, the paper argues for a Nexus approach can support the transition to a green economy.

The Bonn2011 Nexus Conference resulted, among others, in an online resource platform with documents, presentations, news, messages and other information. Its aim is to raise awareness that more systemic thinking is needed (The Federal Government of Germany, 2011).

In 2012, the Swedish professor Gustaf Olsson from Lund University published the book “Water and energy.” A second and extended edition of the book was published in 2015 (Olsson, G. 2015).

The International Energy Agency introduced for the first time the Nexus in 2012, in a special section on water and energy in its 2012 World Energy Outlook (International Energy Agency, 2012). It raises the question whether energy is becoming a ‘thirstier’ resource. Examples that are mentioned is that the availability of water could become an increasingly serious issue for power generation in parts of China and the United States, and India’s large fleet of water-dependent power plants. This will require deployment of better technology and greater integration of energy and water policies.

In 2013, IUCN (International Union for Conservation of Nature) and the IWA (International Water Association) launched the website ‘Nexus Dialogue on Water Infrastructure Solutions.’ The goal is to build partnerships for innovation in water, food, and energy security (IUCN and IWA, 2013).

At the Bonn conference in 2014 on Sustainability in the Energy-Water-Food Nexus, a call for action was issued to develop strategies that address a comprehensive nexus approach. The main conclusions from the conference are:

- Responsible governance of natural resources is the necessary first step for action on the Energy-Water-Food Nexus.
- The Nexus is calling for a broad involvement of stakeholders to collaboratively work toward sustainable development.

- It is essential to greatly expand financial, institutional, technical, and intellectual resources for Nexus research and applications.

(The Bonn Nexus conference, 2014)

In 2014, the World Bank launched their ‘Thirsty Energy’ initiative to help governments in developing countries tackle issues related to water resources and power services (World Bank, 2014). The aims were:

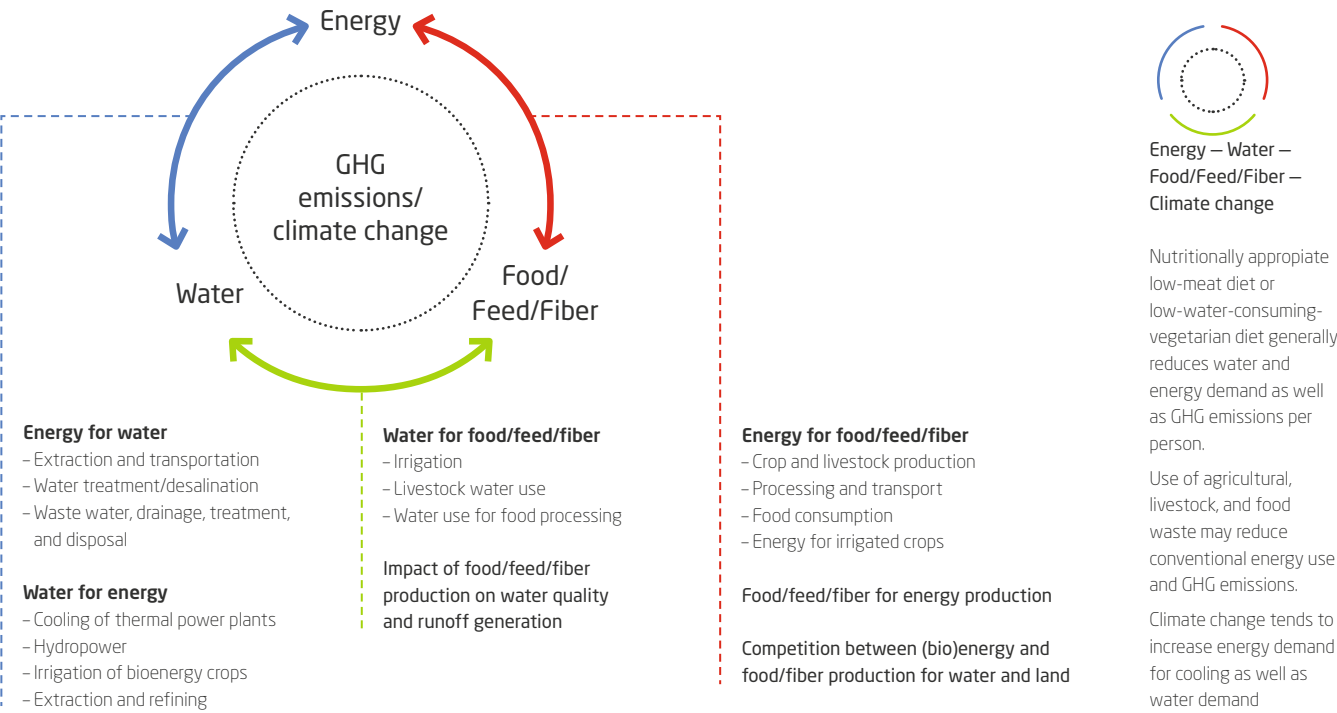
- First, to create increasing awareness regarding the water requirements of energy projects among political decision makers, the private sector and other stakeholders in order to reduce energy projects’ vulnerability to water constraints.
- Second, to enhance stakeholder capacity to plan and manage energy and water resources comprehensively, by improving the tools and technical solutions available to assess the economic, environmental and social implications of water constraints in energy and power expansion plans.

- And third, to foster interdisciplinary collaboration between the energy and water sectors and promoting knowledge exchange to help develop an integrated management framework and ensure its practical application.

FAO introduced in 2014 the Nexus as a new approach in support of food security and sustainable agriculture (FAO, 2014). FAO sees the Nexus approach as a mean to better understand the complex and dynamic interrelationships between water, energy and food. This understanding allows for managing resources sustainably, as the concept includes the analysis of the impacts of decisions made in one sector on the two other sectors. By analysing potential trade-offs and synergies, it will be easier to prioritise options that are viable across the three sectors.

In the technical summary to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change 2014, the Working Group II concludes that consideration of the interlinkages of energy, water, food, land use, and climate change have implications for:

Figure 8 – The water-energy-food nexus as related to climate change, with implications for both adaptation and mitigation strategies (Field et al., 2014)



- Security of supplies of energy, food, and water.
- Adaptation and mitigation pathways.
- Air pollution reduction.
- Health and economy.

The Working Group II sees the Nexus as critical to effective climate-resilient-pathway decision-making, although tools to support local- and regional-scale assessments and decision support remain very limited. (Field, 2014)

In 2015, in their global status report, REN21 find that the Energy-Water-Food Nexus has become a key to ensuring sustainability as well as security of supply. Not at least in a world with growing demand and constraints on resources it becomes more important to manage the interlinkages among systems. The growing demand is linked to population growth, economic development, and urbanisation. Meeting these growing demands will become progressively difficult as resource scarcity, the impacts of climate change, and conflicting needs within the Nexus intensify (REN21, 2015).

The EU Commission published in 2015 their strategic foresight report for preparation of the third strategic programme of Horison 2020, and here the commission among other things puts focus on future possible severe perturbations of the Energy-Water-Food Nexus, (European Commission, 2015) which could lead to rising migration and social unrest in the EU. The Commission introduced the Energy-Water-Food Nexus even before in the 2011/2012 European Report on Development,

‘Managing Water, Energy and Land for Inclusive and Sustainable Growth’ (European Commission, 2012). The report states that a drop of water, a piece of land, or a kilojoule of renewable energy cannot be seen through the single lens of water management, land management or energy policy respectively. The energy-water-food linkages require the examination and management of the trade-off’s not only among users of the same resource, but also across users of other related resources. Governments need to ensure that their institutions are ready for an integrated approach. The Nexus is already included in Horizon 2020, for example the project SIM4NEXUS – Sustainable Integrated Management for the Nexus of energy/water/food/land/climate for a resource-efficient Europe. (European Commission, Horizon 2020, 2015). Based on the fact that land, food, energy, water and climate are interconnected, the integrated management of the Nexus is critical to secure efficient and sustainable use of resources. Barriers to a resource-efficient Europe are policy inconsistencies and incoherence, knowledge gaps, especially regarding integration methodologies and tools for the Nexus, and knowledge and technology lock-ins. SIM4NEXUS is aimed at developing innovative methodologies to address these barriers.

In 2016, World Energy Council presented the early findings of a new Nexus report (World Energy Council, 2016). Prepared by a task force of over 140 experts from across the world, the report makes five recommendations:

1. Improve understanding of the water footprint of energy technologies in order to mitigate the risks of stranded assets.

The Ghana case - a clear-cut Nexus situation

Ghana, like many developing countries, needs more energy and more food, and for both the country depends on flows in the Volta River. Power production in the country is largely hydro based but in recent years, production has suffered from low water levels caused by droughts. Climate studies predict a high likelihood of increasing variability in rainfall and the key issue is if the Volta River can continue to provide for both energy and water needs while sustaining agricultural production in Ghana? The problems are compounded by the fact that increased rainfall variability inevitably risks to lead to further need for irrigation which again will increase demand for both energy and water. So this is a clear-cut Nexus situation which is emerging also in other hydropower based economies. Solutions are complex and need to be tailored to the specific national circumstances but likely start with alternative energy supply options in Ghana.

2. Account for the ‘price’ of water scarcity, particularly in areas of water stress.
3. Consider a wider range of financial and insurance instruments to hedge short term risks such as adverse weather incidents and electricity price volatility.
4. Give investors the confidence to invest by providing them with a risk assessment that includes different climate and hydrological scenarios in financial analyses.
5. Provide a reliable and transparent regulatory and legal framework that takes into account water issues and competing stakeholders’ interests.

According to the report, the Energy-Water-Food Nexus poses a systemic risk which could impact the robustness of the energy supply and demand over many years to come. Power plants across the world could be affected by changes in precipitation patterns, which are combining with increasing competition between water users to adversely affect the resilience of energy services. Co-ordination and integrated planning will be needed. Cross-border co-operation is vital due to the fact that 261 international transboundary basins that cover 45% of the earths land surface.

Harnessing the Energy-Water-Food Nexus on different scales

Energy-Water-Food Nexus assessments can be applied from local to global scales. At the local level, Nexus assessments might focus on integrated waste water management, energy production, or improved water and energy efficiency in agricultural production. This could save water, reduce emissions, boost recycling of nutrients, and increase energy, water, and food security.

Within a region spanning more countries that are connected via a transboundary freshwater system, Nexus tools can be applied to identify incentives for strengthening collaboration between stakeholders at all levels – from the local to the supranational. An example is bilaterally agreements between countries in flood protection and hydropower generation. At regional level it could be agreements for trading

Insights in a transboundary Energy-Water-Food Nexus: The Nile Basin

The Nile is one of the important rivers with a geopolitical significance in the world. At 6,671km (estimates differ), it is also the longest river in the world. The Nile Basin catchment area spans 11 countries: Uganda, Burundi, Rwanda, Tanzania, the Democratic Republic of Congo (DRC), Kenya, Ethiopia, Eritrea, South Sudan, Sudan and Egypt. It drains an area of approx. 3,349,000 square kilometres, i.e. about one tenth of the African continent. In the Nile basin, the downstream nation, Egypt, has the most powerful military, and fears that its upstream neighbours will reduce its water supply by constructing dams without its consultation.

In the Nile Basin, effective implementation of 2011 Framework of Cooperation (Hoff, H. 2011) in the situations of transboundary conflicts faces the following barriers:

- competing national interests
- security concerns
- and upstream-downstream trade-offs over the exploitation of the Nile Basin.

However, these barriers can be overcome through the Nexus approach, which recognises:

- that water resources management, at national and river basin level, is not only for water or environment sectors, but for energy and food sectors as well
- which need to be included on equal grounds and not as mere ‘water stakeholders’ to secure real engagement and create policy coherence across the nexus.

Similar situations prevail over the Mekong Delta in South East Asia as well the Middle East over the territories disputed in the Israeli and Palestinian (Holzwarth, F. 2014) and (Safi, A. M. 2016)

power and food. At the global level it could be mitigating and adapting to climate change through the deployment of renewable energy sources.

A typical example of transboundary nexus issues is a river traversing several countries in a catchment

area. This creates management conflicts over issues such as water rights, usage and pricing of water in the countries that the river passes through. Upstream management of rivers affect the quality and quantity of water available for downstream countries. The linkages in the nexus are such that water, energy and land are needed to grow food in adjoining countries. Some food crops also serve as biofuel. Power plants need water for their operations. Energy intensive water schemes provide water for drinking and agriculture.

Thus, it is clear that the infrastructure for water, energy, and food is essential for development across international boundaries. All in all when the basin hydrology is subjected to diversions, abstractions or interferences with the flow of a river regime at any point in its course – albeit to varying degrees – this inevitably affects the quality and volume of water received by river courses crossing international borders.

Therefore, there is a need to adopt new approaches to address transboundary conflicts in as far as they relate to the Energy-Water-Food nexus. There is also an obvious need for transboundary cooperation in shared river basins with the recognition that water, energy, and food security cannot be attained in a business-as-usual setup.

Conclusions and recommendations

The world population will increase from currently 7.3 billion to around 9.7 billion by 2050 which will increase the demand for energy, water, and food over the coming decades.

Therefore, the numerous interrelations between energy, water, and food have gained high priority in research, business and policy spheres all over the world. The Energy-Water-Food Nexus is now seen as one of the headlines for the global research agenda and a new paradigm for sustainable development.

The Nexus way of thinking breaks with the present practice where most of the policy decisions that affect the energy, water or food sectors respectively are made by different institutions with no or little emphasis on local, national or regional Nexus coordination.

The Energy-Water-Food linkages require the examination and management of the trade-off's not only

among users of the same resource, but also across users of other related resources. Governments need to ensure that their institutions are ready for an integrated approach.

Harnessing the Energy-Water-Food Nexus can take place on all scales from local to global. At local level, Nexus assessments might focus on integrated waste water management, energy production, or improved water and energy efficiency in agricultural production. At supranational level for solving issues such as water rights, usage and pricing of water in the countries that a transboundary river passes through.

Cross-border co-operation is vital due to the fact that 261 international transboundary basins cover 45% of the Earth's land surface.

Recommendations

- The Energy-Water-Food Nexus way of thinking should be incorporated in future policy making and decisions in the energy, water, and food sectors.
- The Energy-Water-Food Nexus should be applied at all levels – locally and globally.
- Appropriate legal Nexus instruments and frameworks for transboundary policy making and decisions need to be developed.
- A Nexus approach can provide an important additional risk assessment parameter in financial analyses for investors in the energy, water, and food sectors.
- A shift to renewable energy is underway, primarily for the sake of climate mitigation, but an important side effect is that it also will reduce the water demand in the energy sector, because water use for renewable power production generally is significantly lower than for thermal fossil power plants.

Chapter 5

Water consumption in the energy sector

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Introduction

This chapter addresses the water consumption used by key global energy technologies and the possibilities for a less water-intensive energy production through, e.g., an intensified use of renewable energy, reuse of waste water, energy efficiency, etc.

The chapter uses SI, or SI accepted, units primarily litre (L) and watt (W – or as here MWh).

Throughout the chapter the term ‘water’ is addressed. However, the term really refer to freshwater (consumption) – unless otherwise stated – as (unpolluted) freshwater is the resource required by subsectors in the global water-energy-food nexus.

The chapter is written in general terms with global perspectives, whereas there is an overweight of literature based on sources from developed countries, there among many from the USA. Therefore, quantitative examples bear an overweight of values from this part of the world.

Aspects of implementation costs, which can also be made up in a number of ways depending on focus and motivations, are largely outside the scope of the present chapter.

Water is paramount for the production, distribution, and use of energy. Water and energy are closely interlinked and interdependent. Choices made in one sector have direct and indirect consequences on other sectors. Fossil fuel production requires water for extraction and processing; thermal generation, whether it is based on nuclear, fossil fuels or concentrated solar power (CSP) needs cooling water; hydropower needs water from rivers or reservoirs; feedstock production for biofuels may depend on water for irrigation. Energy generation accounts for 15% of the global water consumption (WWAP, 2014) and global water withdrawals are expected to increase by another 55% until 2050 with thermal electricity production accounting for a 140% increase (OECD, 2012) related mainly to developing countries experiencing higher demands for energy, food and other goods. The increased water demand will further intensify the pressure on global water resources as well as other natural resources and ecosystems which are already considered to be under significant pressure (WWAP, 2014; Olsson, 2015). An estimated 18% of the global population experience scarcities or total lacks of electricity, an estimated 11-17% (depending on source and definition) (WWAP, 2006, WWAP, 2014) experience lack of access to a proper source of clean freshwater and at least 42% experience water scarcity at least one month per year (Hoekstra et al. 2012). Approx. 90% of global power generation is water intensive and of these, hydropower- and thermal power energy generation methods are responsible for roughly 80% of the global electricity production (WWAP, 2014). An estimated 52*109 m3 of fresh water is consumed for global energy production on a daily basis (Spang et al., 2014).

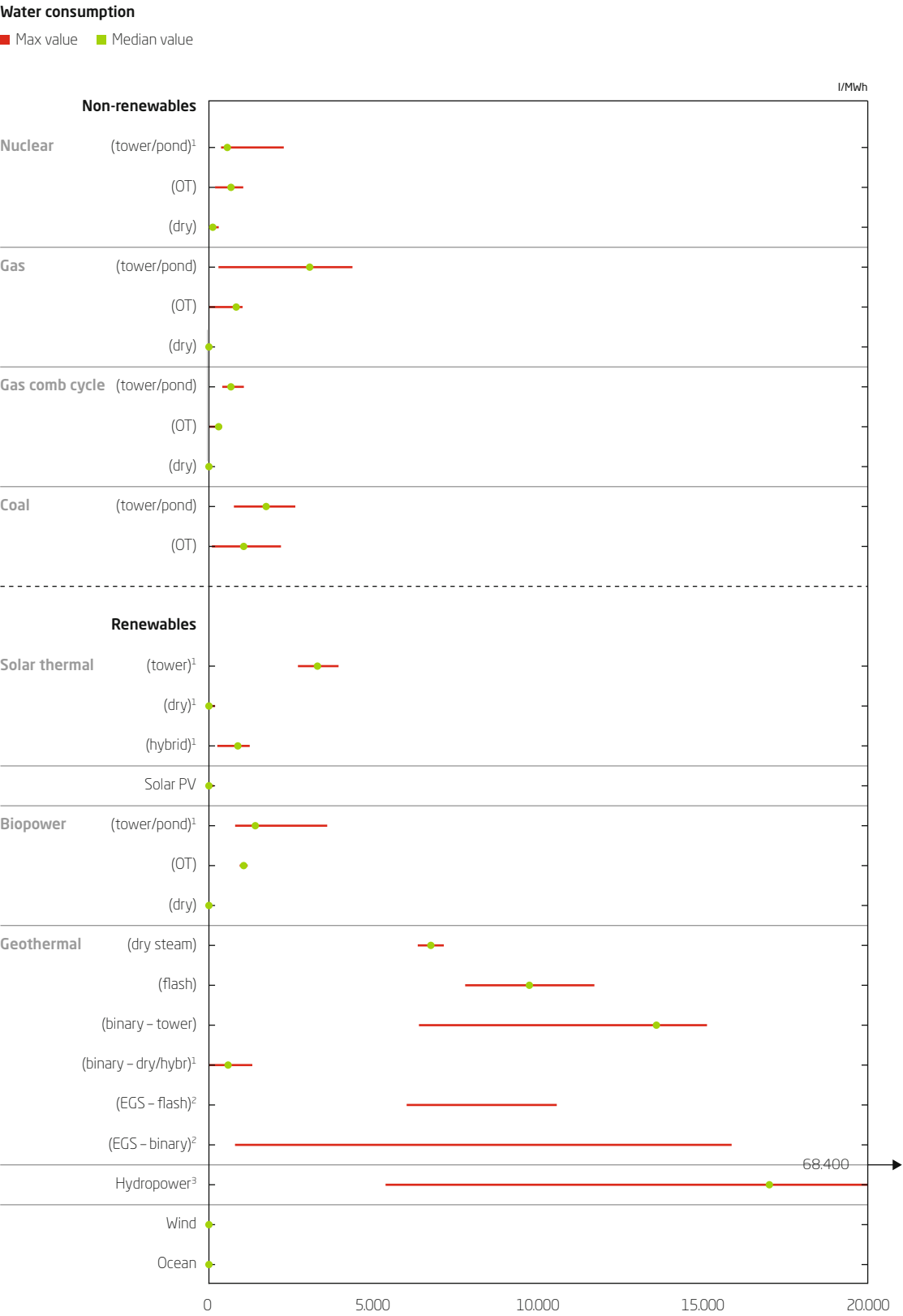
Due to the principal role of water availability in power generation, the location of new plants and implementation and distribution of new, and more renewable, technologies must strongly take this into account as well consider how water will be spatio-temporally distributed within the plant

life-cycle in a world of strong climate-, population and market changes. Decisions made for energy production might have significant impact on water availability and resources for other purposes, positive as well as negative, and also on both sub-yearly as well as longer-term temporal scales. Renewable technologies therefore might not be renewable in terms of water usage. Therefore, as a country’s or region’s energy mix evolves from fossil fuels to renewables, as is the trend now, so does the implications for water and its supporting ecosystem services and these issues must be taken into account. In water sparse areas, the future energy sources should therefore focus on technologies with a negligible (fresh-) water consumption such as solar (with no or dry cooling), wind and ocean (wave/tidal/pumped hydropower) technologies whereas regions with sufficient and sustainable water resources are more feasible to implement technologies which are water consuming, albeit still renewable. And in addition, water recycling, carbon capture and energy storage technologies, under current development, are likely to be further implemented in the future.

Water withdrawal vs water consumption

There is a distinction between water withdrawal and consumption. Water withdrawal includes all extracted and diverted water affected during the process also including what is reinjected into the supply source. Water consumption only includes evaporated and transpired water as well as water integrated in crops or otherwise removed (and therefore represents the net balance). The consumption is therefore a subset of the withdrawal. In the present report key aspects of both are addressed since there are a number of arguments for reducing both. Differences between withdrawal and consumption values can be immense with factors above 200 as is the case for nuclear once-through plant cooling (Figure 9 and Figure 10) and power plants in USA account for 3% of total consumed freshwater but 40-50% of water withdrawals (depending on source) returning the main share to its source (EPRI, 2008; WWAP, 2014). Also, the focus is on the production side of water consumption as opposed to including water use in the entire life cycle of energy facilities including establishment and dis-assembly. Some literature addresses human water use related to maintaining the plant (cleaning, drinking and sanitation) – these are not included since they make up only a fraction of the direct plant use.

Figure 9 – Operational water consumption ranges (median (where available), min and max) from recent sources of literature.

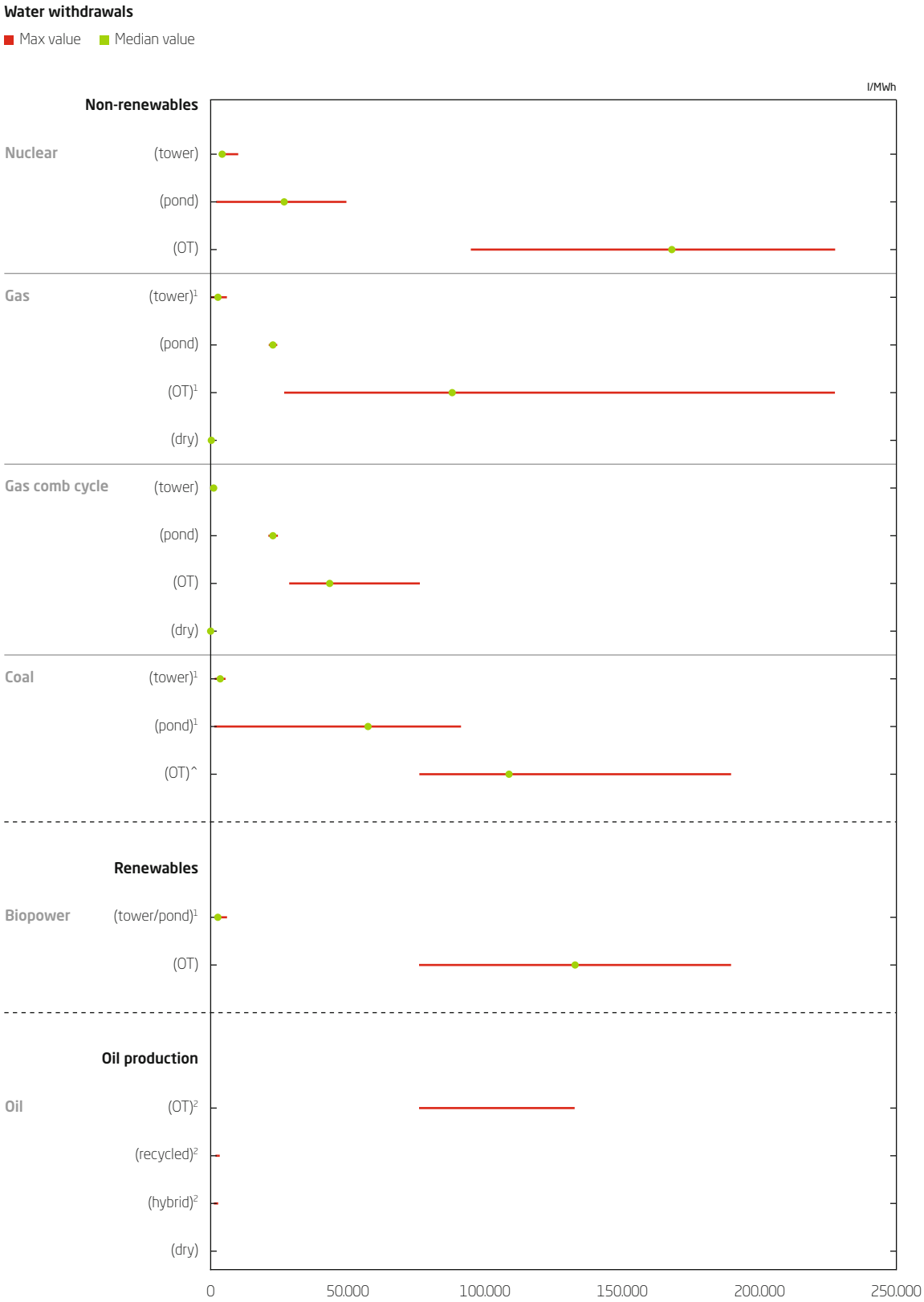


The numbers do not include extraction and processing. Some values have been estimated from figures. Cooling technologies are in brackets ‘()’ and ‘OT’ refers to once-through (i.e. no recycling). References: EPRI (2008), ANL (2010), Mielke et al. (2010), FAO (2011), NETL (2011), NREL (2011), IEA (2012), ANL (2014), Spang et al. (2014), WWAP (2014), Byers et al. (2015), Clark et al. (2015) and JISEA (2015).

- 1 Approximate median value due to aggregated view of technologies.
- 2 No median value available in literature.
- 3 The upper value for hydropower does not include extreme values exemplified by the Akosombo-Kpong dam in Ghana consuming an estimated 3*10⁶ l/MWh (Mekonnen and Hoekstra, 2011).

Figure 10 – Operational water withdrawal ranges (median (where available), min and max) from recent sources of literature.

Figure specifics correspond to those in Figure 9 on water consumption.



Water consumption by energy source in production, transmission, conversion, storage, and waste water treatment

With a few exceptions water is indispensable for the production, distribution, and use of energy. The exceptions are wind, solar PV and ocean technologies which generally consume minimal water making them well-suited for a more carbon- and water-constrained future. Between water consuming power plants the water requirement vary highly and is dependent on mainly power source, type of plant/technology and cooling technology. To some degree, the local climate also affects power plant water use.

Non-renewable energy sources

Cooling in thermal power plants

Thermal power plants, making up approx. 80% of the global electricity production (WWAP, 2014), share many characteristics independent of their power source (coal, nuclear and, for a part of the process, gas), including the processes related to water usage. In these plants cooling accounts for the, by far, main share of the total water use. In thermal power plants, in essence, water is continuously circulated in a closed loop where water is heated into high pressure steam to drive a turbine and create electricity followed by cooling down the water. In relative terms hardly any water is used in this closed loop process requiring only a small amount of make-up. It is the cooling of the closed loop water that requires, and consumes, the integral part of total thermal water use. This cooling can be divided into three overall categories namely:

1. Once-through cooling (abbreviated ‘OT’ in Figure 9 and Figure 10).
2. Recirculation/tower cooling (abbreviated ‘tower’ or ‘pond’ in Figure 9 and Figure 10).
3. Dry cooling (abbreviated ‘dry’ in Figure 9 and Figure 10).

The distribution and shares of these is of course closely related to the availability of water and water use legislations (which are also likely to be related to water availability also in their level of restrictions). The share between these cooling technologies in

the USA amounts to 43%, 56% (thereof 15% using cooling ponds) and 1% respectively (GAO, 2009). In less developed countries with cooling water scarcity once-through cooling is however more common (FAO, 2011).

Once-through cooling employs cooling water from adjacent sources such as rivers, groundwater, lakes or the sea and returns the water to its source, now in a warmer state. The water withdrawal for this type of plant is immense for all energy sources (25,000-225,000 L/MWh – Figure 10) whereas the respective water consumption is considerably lower (50-2,300 L/MWh – Figure 9). Despite high water withdrawal rates, consumption is typically lower than in recirculation systems since no evaporation from a cooling tower is involved. New(er) plants rarely use this cooling type. Concerns about aquatic life due to the heated return water and potential intake/trapping in inlet pipes have been raised.

Recirculation/tower cooling reuses the water in a loop where the temperature of the cooling water is lowered through evaporation in the cooling tower resulting in lowered water withdrawal rates for all energy sources combined (550-10,000 L/MWh – Figure 10). For pond based plants withdrawals are significantly higher (1,100-91,000 L/MWh – Figure 10) whereas corresponding consumption rates are within the same range as once-through cooling for all energy sources and towers/ponds combined (360-3,300 L/MWh – Figure 9). Another, less significant, share of the water usage in recirculation systems is the commutation of mineral compounds in cooling water which needs to be discharged (known as blowdown). Summarised, recirculation (tower/pond) plants have higher water consumption than once-through plants whereas water withdrawal rates are lower, although approaching once-through plant rates for pond-based recirculation plants.

Dry cooling plants, constituting a negligible share of current global power generation (although numbers are increasing with current possible or decided implementation examples from USA and South Africa), use no water for cooling purposes of the plant counterbalanced by lower efficiencies (2-5%) and higher costs (3-8%) depending on the local climate. Hybrid plants also exist utilising a combination of cooling technologies designed to have a water consumption

of 20-80% compared to that of recirculation plants (EPRI 2008). These plants are seen as a key available method to reduce power plant water consumption.

Water usage specifics for coal, gas and nuclear energy sources

Secondary water usages in thermal plants relate to secondary purposes such as pollution control equipment, cleaning, dust control and staff usage. Of these usages, *coal plants* have the largest secondary water requirement due to scrubbing, coal pulverisation and ash control (approx. 350 L/MWh) with nuclear and gas secondary usages approx. an order of magnitude lower (app. 10% and 1% of total consumption respectively) (EPRI 2008). Of these coal plant usages, scrubbing accounts for the main share (app. two-thirds). Coal-fired power plants have water consumption rates comparable to steam based coal plants (Mielke et al. 2010). *Gas plants* employing combined cycle gas turbines (CCGT) have considerably lower water consumption compared steam based turbine technologies as described above which is due to general higher plant efficiencies and therefore lower heat losses and cooling needs (Figure 9). *Nuclear plants* generally have lower cycle efficiencies resulting generally in the highest water consumption and withdrawal rates for thermal power plants. Due to the lower efficiency, cold cooling water is desirable. Nuclear plants tends to be more flexible in the choice of location than e.g. coal plants due to the higher energy density in the source material and can therefore more often use sea water cooling.

Oil and gas production

In conventional oil production the water consumption varies in relation to mainly geology, type of recovery and state of the reservoir and the main share consumed relates to primary and tertiary oil recovery techniques. For the former, water is injected to the subsurface to enhance the oil extraction rate and the level of depletion reached. For the latter, (typically referred to as enhanced oil recovery – EOR), various techniques are used to enhance extraction rates through reduced oil viscosities there among through steam injection requiring a cogeneration power plant. Secondary techniques (80% of USA oil production) consume 802 L/MWh whereas common tertiary techniques (almost the remaining 20% of USA oil production) consume 505-1215 L/

MWh (Mielke et al. 2010). For the mining of more shallow oil sands water consumption rates vary between an estimated 180-425 L/MWh averaging 375 L/MWh as used for both mining an upgrading (Mielke et al. 2010). Deeper deposits require on site upgrading with water consumption rates varying between 25-210 L/MWh depending on the output oil product and local geology. In conventional natural gas extraction the water consumption is negligible compared to other sources discussed here. Shale gas hydraulic fracturing has an average water use of 17 L/MWh (Mielke et al. 2010) and, although outside the scope of this report, is the subject of substantial environmental concerns related to among others water pollution. Although low compared to other extraction methods, the water consumption can be localised in both time and space and can therefore entail a massive impact on local water supplies. Coal extraction employs water consumption rates of 14-105 L/MWh for mining and washing and an additional consumption of 43-90 L/MWh if transported by slurry pipeline (Mielke et al. 2010).

Renewable sources

Biofuels

Biomass use for liquid transportation fuels and energy products, as a part of the renewable energy sources, is considered one of the key renewable energy sources to enable a reduction in the use of fossil energy sources. For the case of biofuels, 32 exajoules (10¹⁸ J) of biofuels should be used globally by 2050 (27% of consumed world transport fuel) in order to reach the global energy-related CO₂ target according to the International Energy Agency which is 50% below current levels (IEA, 2011).

Biofuels are advantageous since they are low-carbon, non-petroleum fuels, which require minimal changes to the current distribution infrastructure and vehicles (IEA, 2011). Moreover, the CO₂ streams from biofuel production (fermentation, gasification) are relatively pure, making its capture less laborious than carbon capture storage (CCS) of fuel gasses from fossil fuel power plants. The characteristics of biorefinery products (chemicals, fuels, energy, etc.) differ from those of traditional chemical processes or crude oil refineries. In biofuel production, a substantial amount of water is required in cultivation

of biomass which varies greatly based on the type of crop and region. For example, 90 L of water is used to produce one litre of ethanol from sugarcane in Brazil whereas a corresponding 3.500 L was used in India (de Fraiture et al., 2008). In energy units an estimated 1075-49.000 L/MWh was used for the USA depending on region as influenced mainly by irrigation demand where the majority is lost to evapotranspiration (Mielke et al. 2010). Some regions in the USA might even require a much higher water usage up to 375.000 L/MWh. While the water requirement for biofuel production can be considered small compared to the amount of water used for the cultivation of biomass, caution should be taken in order to ensure that the production of biofuel is efficient and sustainable. Water consumption and waste water generation from biofuel production varies significantly depending on the selection of processing technology and process configuration. Recent developments have been seen towards implementing second generation biofuels which utilise biomass not suited for food or feed or biomass from (chemically upgraded) residues and/or waste and thereby not competing with potentially scarce food supplies now and in the future. In the use of second generation biofuels, the water consumption is therefore decreased by diminishing the need for crop irrigation (grasses in some regions could still require irrigation) and by focusing on implementing water/waste water minimisation strategies through recycling and treatment.

Geothermal

Water consumption varies greatly within geothermal power plant facility types. On an overall basis, three types of geothermal power plant designs exist where steam and/or hot water is available from the subsurface at well depths which are typically closer to the surface (in the range of 60-3000 m) than enhanced geothermal systems (EGS) (in estimated, and exploitable, depths of 3-10 km).

Dry steam power plants operate on the basis of hydrothermal fluids primarily in the form of steam directly driving a turbine and omitting only excess steam from the plant. Flash steam power plants operate by ejecting hot (above 180°C) and high pressure steam into a turbine, sometimes followed by a second lower pressure turbine for the remaining liquid. This type of plant is the most common and also

the type consuming the largest amounts of water. Due to the non-potable mineral compound composition in exploited water for flash steam power generation, and overall typical water abundance in these regions, it can be argued if water consumption for flash steam plants can be compared one-to-one with other power generation technologies. A newer type of geothermal power plants, referred to as binary cycle plants, operate by letting lower temperature water (below 200°C) pass through a heat exchanger holding a secondary fluid (with a much lower boiling point) driving the turbine. The geothermal water is reinjected, thus resulting in much lower water consumption.

A fourth type of geothermal energy source, referred to as enhanced geothermal systems (EGS), is capable of exploiting the energy in regions where hot water does not reach the ground. EGS works by pumping hot water to great depths returning to the surface as steam powering turbines of either flash or binary type. For flash EGS, cooling water consumption is comparable to other flash usages closer to the ground. For binary EGS, the water resource temperature directly affects the water consumption (belowground) as lower temperatures require higher flow rates (Clark et al. 2015). The large span in water consumption for binary EGS (Figure 9) is therefore a function of the water resource temperature. For higher temperatures, binary EGS is therefore able to maintain low water consumption compared to EGS flash cooling. Risks of seismic activity have been reported in relation to EGS.

Other types of thermal exploitation include co-produced power generation (or direct heating indirectly saving energy usage) from oil and gas wells as well as lower temperature thermal energy. For these technologies, the use of binary technology will contribute to low water consumption rates. Heat pumps also represent a low water usage geothermal technology (excluding open loop systems where consumed water is returned to the surface thereby draining aquifers). A potential unwanted effect of geothermal energy includes enlarged concentrations of unwanted mineral compounds such as arsenic, mercury, lithium and boron in fluids used in geothermal energy production due to the bedrock contact in a hot environment with the risk of damaging ecosystems and restraining reuse.

Hydropower

The variation in water usage of hydropower plants is immense and highly dependent on the local climate as the consumption is related to evaporation (and potentially net seepage) as opposed to direct turbine usage (5.400-68.000 L/MWh – *Figure 9*) and hydropower plants differ from other energy production sources due to the water reservoir storage. The higher end of this consumption range firmly constitutes the highest levels for all energy production technologies. Some studies however argues that water usage from hydropower plants can be somewhat neglected in a comparison study due to the societal purposes of the reservoir such as flood control, leisure, irrigation and water supply storages (Spang et al. 2014) and some argue that the quantification of evaporative losses in relation to generated energy is too uncertain (ANL, 2010). Regardless, the establishment of new hydropower plants entails significant alterations to the existing environment and infrastructure (IEA, 2011)

Wind, ocean, solar PV and concentrating solar power (CSP)

Wind, ocean and solar PV technologies have little or no water consumption rates related to their direct use and therefore constitute a negligible fraction of the water use compared to other energy sources. This holds especially true for wind energy and ocean based technologies (e.g. tidal, wave and Ocean Thermal Energy Conversion (OTEC)). Even for OTEC, although in a relatively non-implemented state, sea water as opposed to freshwater is used. All ocean based energy production technologies amounted to 0.05% of renewable energy sources in the EU by 2013 (Eurostat, 2016). Solar energy production not using cooling (PV as opposed to CSP) use a certain amount for the cleaning of surfaces and panels (0-125 L/MWh – *Figure 9*). Opposing these technologies, current CSP energy production technologies involve a significant water consumption for plants with wet cooling (2800-4000 L/MWh) whereas dry cooling plants consume much less (100-300 L/MWh – *Figure 9*). Hybrid CSP plants fall here in between. For water cooled plants a disagreement between high incoming solar radiation levels (desert locations are typical) and water availability is seen. Other than CSP cooling demands, water is used for reflection mirror cleaning (75-150 L/MWh – JISEA (2015)).

CO₂ capture, storage and utilisation

Global warming has been attributed to the increasing concentration of greenhouse gases (GHG), including carbon dioxide (CO₂), carbon monoxide (CO) and methane (CH₄) and CO₂ represents more than 75% of greenhouse gas emissions (IPCC, 2014). A reduction in the emissions of GHGs is therefore high on the political agenda. Main sources of CO₂ emissions are electricity and heat generation, agriculture, industry and transportation (IPCC, 2014). For the purpose of climate change mitigation, two main methods have been adopted to extract CO₂ emissions from electricity generation, chemical industry and other industries: Carbon capture and storage (CCS) and carbon capture and utilisation (CCU) or in combined terms simply CCUS. The capture involves extracting waste CO₂ from e.g. fuel production or electricity generation plants, storage involves the deposition of the CO₂ in compartments (underground or in tanks) where it will not re-enter the atmosphere and utilisation involves the conversion of waste CO₂ into readily usable products like fuels and chemicals thereby pushing non-renewable energy utilisations in a more renewable direction. CSS disadvantages include high costs (currently unprofitable), the lack of storage possibilities in some regions and undocumented leakage rates and, likewise, CCU can cause environmental impacts and faces vast development to be readily applicable (Cuéllar-Franca and Azapagic, 2015). In terms of water consumption, CCUS must be viewed as a family of processes and technologies where the capture share (as opposed to the storage and utilisation) accounts for approx. 80% of the total CCUS water consumption (Li et al. 2016). CCS has been shown to cause increased cooling demands of app. 25-140% per plant (Byers et al. 2015) further highlighting the need to assess future water resource availabilities when proposing new plant locations and the technologies they will employ. CCUS is a unique opportunity for sustainable emission reduction because it produces a value added product and thereby improves the sustainability of the process in terms of emissions, energy, mineral- and general resource recycling and water consumption. With further research on associated technologies the benefits of CCUS are likely to increase, also in the near future.

Water recycling and waste water treatment

Reusing treated waste water into purposes of e.g. irrigation, industry, sanitation and groundwater

recharge can offer savings of water resource extractions and financial savings. That is, groundwater aquifers are exploited less heavily (in the case of groundwater extraction) and the cost of pumping and distributing water is reduced. In general, the additional energy required to reuse waste water is much less compared to the additional energy related to extracting the same amount of water from other sources (EPA, 2012). The degree and nature of the treatment can depend on the proposed use of the treated water to further save processing costs: As an example, irrigation water could require lower mineral and biochemical standards than drinking water. Examples of water recycling include power generation cooling, irrigation (agriculture and landscape), processing water in the industry, toilet flushing, construction, etc. Greywater (household waste water except from toilets) is often mentioned as a potentially beneficial specific water reuse source applicable for purposes of irrigation, indoor applications (toilet flushing) and heat reclamation through local household heat exchangers and requires less energy for recycling using a desalination plant. Quantitatively, savings are very site- and application specific but some estimates predict energy savings of 0.8-1.3 kWh per m³ of water savings in California and water savings of 220,000 m³ annually per plant (soft drink production in North America and Europe) after installing recycling loops (EPA, 2012).

Increased water demands combined with increased exploitations and population growth will further put incentives on increased use of water recycling, the development of new technologies within this field as well as legislation to e.g. enforce recycling systems in residential dwellings, industry and agriculture. Specific guidelines and concentration thresholds exist for water recycling due to the risks for public health as well as environmental-ecosystem pollution concerns mainly related to various types of microbial and chemical contaminations (EPA, 2012).

Emerging power generation technologies and storage solutions

Small modular (nuclear) reactors (SMRs) represent an emerging technology of smaller scale nuclear power plants (below 300 MWe as opposed to current plants of 1.000 MWe and up) capable of being transported by either air, sea or land to more remote locations. Without further addressing overall

disadvantages and risks of nuclear power production and even lead cooling (LFR technology), SMRs are reported to provide a higher degree of total-system flexibility and, in terms of water consumption, benefit from the newest cooling technologies and scale-dependent deployment in relation to locally available water resources.

Projected advances in long-term and large-scale energy storage technologies include 1) chemical energy storage, 2) compressed air energy storage (CAES), 3) pumped hydropower and 4) thermal storage. Chemical energy includes the storage of hydrogen and methane produced by excess wind and solar energy production and can lead to the production of fuels, district heating and electricity. Advances in chemical energy storages will contribute to reduced water consumption rates simply due to a more efficient use of non-water consuming power generation technologies such as wind and solar PV. Energy conversions along these linkages, such as electricity production however add to the water usage. Projected CAES systems include air storage produced by excess energy grid energy in salt caverns (sealing cracks and fissures under pressure) to produce turbine generated energy in periods of energy demand. As for chemical energy storage, CAES adds to the flexibility and efficiency of electricity systems where non-water consuming technologies can be used and water usage is related mainly to turbine cooling. CAES plants for dry regions with sparse access to cooling water have also been proposed (Najjar and Zaamout 1998). Pumped hydropower involves the pumping of water to a higher altitude reservoir using (excess) wind and solar energy permitting the backwards release through turbines on demand. The technology is reported efficient and capable of being implemented at large scales, at least, where renewable solar and wind power generation sources are abundant (Blakers et al. 2010). Water consumption includes mainly reservoir evapotranspiration. Pumped hydropower plants exist based on saline sea water making the fresh water use negligible. Thermal energy storage (TES) technology potentials face mostly barriers related to costs and material properties and potentials vary highly depending application and region and (IEA-ETSAP and IRENA, 2013). Implementation in CSP plants through molten salt and industrial waste heat are expected to be key future thermal storage applications. Large scale

energy system implementation of energy storage in batteries is at present at a very premature state but could potentially add flexibility to energy systems with low water consumption in the running stages (albeit with potential battery production and disposal usages).

Tidal power generation poses a fully renewable and largely water consumption-neutral energy source which has been only scarcely implemented at this point. Recent advances in construction types (i.e. DTP (Dynamic tidal power) dams) extending far into the sea and tidal lagoons both generating substantial water head gradients) and new turbines technologies have however seen the spur of recently planned and projected tidal constructions. While renewable and water neutral, drawbacks include effects on marine life, transformations of natural systems due to the extensive spatial footprint and short-lived lifecycles due to corrosion and effects from the growth of biological organisms.

Micro-algae biofuels, while capable of delivering low emission rates or even emission neutrality have a high water use requiring an estimated total of 1100x10⁹ m³/year for USA alone (Farooq et al., 2014) as well as high energy requirements. Water recycling within the production chain can however reduce both water and energy consumption.

Water related climate risks to the energy sector

The dependence on water availability in the energy sector, not just in quantitative terms but also in terms of an appropriate quality and temperature, imply that meteorological events might pose a risk to the energy supply and that longer term climate change patterns need to be taken into account when assessing future energy systems. The high supply from thermal power plants, dependent on cooling, is a natural cause for the vulnerability to meteorological events there among droughts. Recently, cooling water scarcity has led to reductions in energy production and even total plant shutdowns in Europe and USA (WWAP, 2014; Byers et al., 2015). Other sectors such as agriculture (with increased irrigation demands during droughts in some regions) and industry lead to an increased competition for water. Increased ambient water temperatures, despite adequate availability, also poses a risk since

plant efficiency goes down, and during some hot spells increased cooling water temperatures have led to complete plant shutdowns. Overexploitation in some regions is also causing major impacts on the available water resources with inevitable impacts on future supply and possible extraction rates (Li et al. 2016). Hydropower systems might also suffer from changes in the water balance as low storage systems will suffer decreased production in single seasons and regions of future general reductions in the net precipitation (evapotranspiration subtracted) too will experience lower production capacities or even lack of economic viability. An example includes projected general decreases in hydropower production rates in the Swiss Alps by 2070-2099 by 36% (Schaeffli et al., 2007). Several reports conclude that water availability could be a constraint for the expansion of the power sector in many emerging economies, especially in Asia. And finally, increasingly scarce water supplies are projected near population centres due to climate change giving rise to longer transportation distances, pumping from greater depths and the necessity for additional treatment (IEA, 2012).

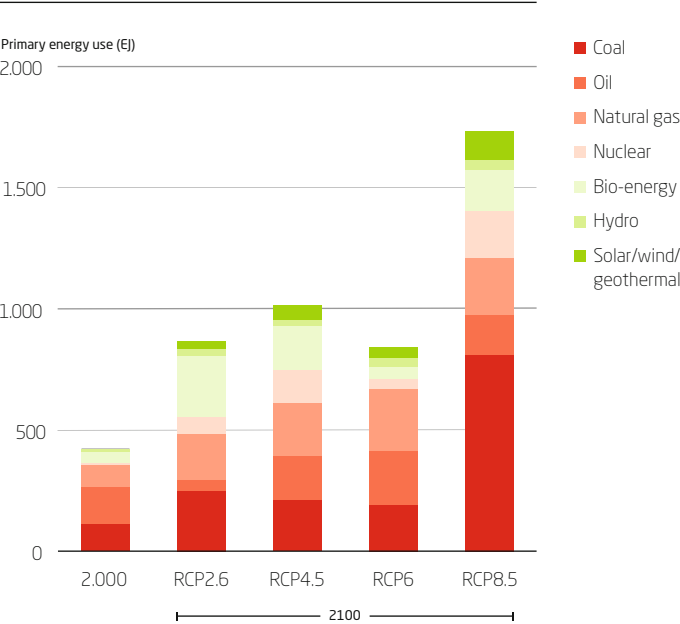
Conclusions and recommendations

The chapter has presented a review on water usage issues for key energy sources as well as for other affairs such as production, storage, capture, future perspectives, climate related risks and so forth. This, despite variations in methods and definitions in the literature used also holding an inclination towards sources from more developed countries. Further, most subchapters have addressed future perspectives in terms of implementing energy technologies with a sustainable water use. *Figure 11* presents the primary energy consumption in the year of 2000 and the corresponding proposed levels by 2100 in relation to the RCP scenarios (van Vuuren et al., 2011). The future energy projections are naturally strongly tied to the water availability along the water-energy-nexus as also dictated by the total availability and the consumption in other sectors. In general, there is no obvious single clear pathway towards reaching a sustainable, viable and renewable energy supply in the (near) future: Various technologies have differing advantages and flaws and the ever-changing market (also in space) and the development of new technologies will continue to change the picture. Despite this broad focus (and some omitted aspects), the inherent vast differences between the water consumption for

different power generation sources and technologies enable the provision of some general conclusions and recommendations.

- **Renewables** are integral in not only the mitigation of climate change but also in the climate change adaptation and continued research and development efforts can bring about improved viabilities for further implementing wind, solar PV and sea-based technologies having the lowest water usage rates.
- **Cooling technologies** in energy production, and changes in these, can significantly alter the freshwater consumption: Switching to non-freshwater cooling and dry cooling reduces water consumption. Hybrid cooling decreases water consumption rates and improves plant efficiencies. Alternative cooling water sources can provide more sustainable water consumption (waste water, non-potable/brackish groundwater, water from oil/gas production and water recycling). Water availability influences the viability of cooling technology (once-through or recycling) and proposed changes between these cooling types are also dependent on plant locations (i.e. coastal or inland).
- **CCS/CCSU and CSP** implementation to obtain a higher degree of carbon neutrality will increase water consumption.
- **The projected future climate** and the related water availability, temperature increase and seasonality – also in relation to timing of power plant peak production (summer/winter) – must be taken into account. Hereof related, dry cooling and non-fresh water cooling reduce these impacts of droughts.
- **Policy and planning** must be highly integrated and are also dependent on water availability. Jurisdiction and the use of economic and legislative tools as well as social awareness campaigns can be implemented as tools for increased efficiency in the use of water and energy.
- In essence, an **integrated approach** – including energy (multi-source renewable as well as non-renewable), CO₂ matters (capture and

Figure 11 – Primary energy consumption in 2000 and by 2100 according to the different RCP scenarios (reworked from van Vuuren et al., 2011).



utilisation), water (waste, freshwater demand, reuse) and food – is needed in a combined nexus approach to properly assess sustainability goals while still aiming improved living standards for underdeveloped regions and countries. Further, integrated solutions are highly location dependent requiring collaboration at multi-national level, sharing data, technologies, ideas, etc., to make an impact globally. This goes for GHG as well as water and treatment and extraction/generation; they all require a lot of energy causing increased emissions. In this context technology development and subsequent export and implementation at an international level is essential.

The Water-Energy Nexus is made up of an exhaustingly vast number of facets. For more definite and quantitative guidelines and recommendations on proper pathways towards more sustainable and renewable pathways to future power generations sources local-to-regional assessments using site-specific climate data (projections) as well as associated variability and extremes, hydrology and energy modelling (integrated study) and local policies and regulations are essential (e.g. Spang et al. 2014). As an example, a region prone to increased future

Acknowledgements
The work on the present chapter was supported by the REEEM project (grant agreement no. 691739) funded by the Horizon 2020 (LCE) EU research programme.

droughts and summer peak demands (due to cooling) will have significantly different characteristics compared to a more temperate region with winter peak demand (due to heating). To properly depict potential guidelines for each of these instances a study could, or should, include, from the geophysical side alone, e.g.:1) Climate variability (return period of occurrences posing a threat to electricity security), 2) spatio-temporal water availability (and variability again) in the water balance components where the water is to be extracted (groundwater/surface water) and 3) solar hours (for potential solar power implementation) and so forth. On top of this, geophysical factors pose a threat to potential plant installations such as future wave heights, flooding (pluvial and fluvial), hail, strong winds. The local-to-regional scale studies are vice-versa affected by global scale forcings related to mainly the market, costs and international regulations and emissions trading. On top of this there are emerging technologies which must be analysed and included.

Chapter 6

Energy footprints in the urban water cycle

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➔ **Urban water flows**

Urban water infrastructure is growing increasingly complex driven by a number of factors including decreasing freshwater availability, increased allocation for environmental water flows, and increasing water demand caused by population growth (Rygaard et al., 2011). Waste water management is met with increasingly strict demands for effluent water quality (Eggen et al., 2014; Luo et al., 2014) and requirements for resource recovery (Fang et al., 2015), and the development leads to an intensification of waste water treatment. Climate change affects water availability, but also requires cities to adapt to new storm water regimes (Sørup et al., 2016) with big changes to the urban infrastructure to follow (Wong et al., 2012; City of Copenhagen, 2015a). The increasing complexity, intensification of water treatment, and changes to the infrastructure all influence the energy use of urban water management. This chapter first provides an overview of the urban water cycle and its energy use. Then follows examples of new developments in water treatment that are likely to influence water management and associated energy demands in the future.

Most cities handle three major water flows and a myriad of minor flows in between compartments of the cities. The major flows are:

1. Rainfall.
2. Water supply.
3. Industrial and household waste water.

These vary dramatically between geographic locations (*Table 1*). Although rainfall dominates the urban flows in many cities, it is often only a fraction that is handled by the drainage system, e.g. 30 and 37% in densely populated Copenhagen and Sydney. The minor flows create links between water compartments, e.g. leakage from sewers and harvested rainwater that supplement the water supply.

Water treatment for water supply

Rainfall and waste water are plenty for the water demands in many cities, but intermittency and poor quality have historically limited its use, although this is changing due to increased focus on decentralised rainwater harvesting and waste water reclamation. Besides the major urban water flows, cities also have access to water resources available as groundwater, surface water (rivers or lakes), and seawater. In all cases water often needs treatment before its use or it needs to be conveyed from the resource to the point of use. In the following, we give an overview of the energy requirements related to the transport or conversion of water quality in the urban water system. Water may be converted from one quality to another to be used for drinking water, to sustain environmental flows, or protect recipients, e.g. when waste water is discharged to the sea. Water treatment options can be divided into three categories:

1. Simple treatment (e.g. settling, aeration, flocculation, sand filters, activated carbon filtration).
2. Membranes (e.g. microfiltration, ultrafiltration and reverse osmosis).
3. Oxidation, chemical treatment, and disinfection (e.g. ozonation, UV radiation and chlorination).

Simple treatment can be used to remove organic pollutants through microbial degradation in sand filters, stripping to air by aeration, or sorption to filter materials such as activated carbon. Usually, simple filtering is gravity driven and requires modest electricity consumption to operate. Aeration requires air blowers. In Denmark, most water supplies are based on aeration followed by sandfiltration. The energy use is typically 0.2-0.7 kWh/m³ treated water, including transport from groundwater to the waterworks. When clean water resources such as the

Danish groundwater or pristine surface water are not available, membranes allow utilities to convert poorer water qualities to drinking water quality. Membranes are operated at pressures reflecting their ability to reject pollutants (DOW, 2005; Singh, 2011). Micro and ultrafiltration removes particles and macromolecules in the range of 0.001-1 µm, e.g. proteins, virus, bacteria and typically require operating pressures between 1 and 5 bar. Nano filtration and reverse osmosis membranes will reject dissolved salts and most organic molecules. Reverse osmosis operates at pressures up to more than 70 bar. The pressure requirements are the main contribution to membrane filtration's energy use and micro and ultrafiltration have been observed using 0.03 to 0.2 kWh/m³ while typical seawater desalination using reverse osmosis requires energy of 3.5-4.5 kWh/m³ (Kirkegaard & Rygaard 2014; Plappally & Lienhard,2012). Reverse osmosis filtration of fresh water resources such as surface water or treated waste water requires just 0.3 to 0.5 kWh/m³ to pass the membrane, which reflects how the energy requirement is largely dependent on the salt concentration (Singh, 2011).

Operating oxidation and disinfection steps have low demands for electricity compared to membrane treatment. Disinfection by chlorine typically uses <0.01 kWh/m³, while UV disinfection requires <0.05 kWh/m³. Ozone will oxidise micropollutants as well as disinfect water, and for disinfection purposes the expected electricity demand for on-site production of ozone is <0.2 kWh/m³.

It is relevant to mention that rainwater harvesting can substitute parts of the urban household water supply, e.g. for toilet flushing, clothes washing and

hot water demands (Rygaard et al., 2009). In the literature, rainwater harvesting has been associated with a modest electricity consumption (median value 0.2 kWh/m³) based on theoretical assumptions (Vieira et al., 2014). However, Vieira et al. also found that theoretically based electricity demands are markedly lower than measured consumption reveals (median value 1.4 kWh/m³). The difference is explained by a large contribution from pump standby power and start-up power that have been neglected in most theoretical studies.

Water imports

Often, the option for additional water resources is a choice between intensified treatment, increased production from a known resource, or increasing imports from resources available further away. China, Spain and the USA are places where large scale water transports are essential parts of their water infrastructure (*Table 3*). Some of these water transports are heavy energy consumers e.g. the Metropolitan Water District imports at 2.1 kWh/m³, which contributes to the State Water Project that is the single largest user of electricity in California (Sanders, 2016). Other come at a very low energy cost such as the gravity driven LA Aqueduct, although water stress, droughts and nature conservation are important constraints to its continued use (Sanders, 2016). It is noteworthy that these large water transports in some cases represent energy costs up to 4 kWh/m³ which is comparable to the requirements of seawater desalination and water reuse mentioned above.

Waste water transport and treatment

Energy demands for waste water treatment are largely dependent on local effluent water quality standards.

Table 2 – Typical annual water flows in Copenhagen and Aarhus (Denmark), and Sydney (Australia). Data from (S. Kenway et al., 2011; Sørup et al., 2012).

	Copenhagen	Aarhus	Sydney
Area (km ²)	75	468	1420
Population (million people)	0.58	0.33	4.2
Rainfall (Mm ³ *)	62	351	1352
– of which handled	37%	4%	30%
Water supply (Mm ³ *)	33	19	526
Waste water incl. storm water (Mm ³ *)	60	30	854

* Mm³ = million m³

Table 3 – Energy requirements for large water imports.

Location	Annual volume Mm ³ *	Length km	Electricity use		Reference
			Wh/m ³ /km	kWh/m ³	
China Middle route SNWDP	2260	1432	0.04	0.05	(Li et al. 2016)
California, USA**					
LA Aqueduct	325	–	0	0	(Plappally & Lienharrrd, 2012;
Metropolitan Water District imports	246	–	4-5	2.1	Sanders, 2016)
Spain					(Plappally & Lienharrrd, 2012)
Tortosa to Aguadulce	–	744	5	4.1	

* Mm³ = million m³

**Covering several aqueducts in combination. LA Aqueduct is gravity driven.

In areas where legislation demands reduction of particles, organic compounds and nutrients before discharge, waste water treatment require primary treatment with screens and settling tanks, before secondary and tertiary treatment remove organic compounds and nutrients. The most common processes for secondary and tertiary treatment are biological treatment, e.g. activated sludge and chemical treatment, e.g. coagulants. With tertiary treatment, energy consumption was around 0.5 kWh/m³ in the US (Plappally & Lienhard, 2012). For the simpler secondary treatment option, where nitrogen is only partially removed, average values for are reported between 0.2 and 0.4 in Australia, China, Japan, USA, and Sweden. Danish waste water regulation requires settling, and bio-chemical removal of nutrients and the major utilities report an electricity consumption from 0.7 to 2 kWh/m³ with an average of 1.1 kWh/m³ (DANVA, 2016). A survey of 13 large waste water treatment plants in the UK found similarly an average electricity consumption of 0.5 kWh/m³, varying between 0.3 and 0.9 kWh/m³ (Singh et al., 2016).

Some waste water utilities recover parts of their electricity use by sludge digestion. In Denmark, the waste water utility Vandcenter Syd is substituting 64% of its own electricity demand. Vandcenter Syd together with 33 other waste water utilities with self-produced electricity, substitute 28% of their total demand (DANVA, 2016).

Before treatment, waste water is transported to the waste water treatment plant in sewers. In Denmark, transport of sewage and storm water have been reported to demand between 0.04 and 1.6 kWh/m³, with an average of 0.3 kWh/m³. For Denmark, the combined waste water transport and treatment costs 1.4 kWh/m³ not considering any self-production (DANVA, 2016).

Waste water reclamation

In more and more places, cities are relying on waste water reuse for potable use. In such cases, the conventional waste water treatment is expanded with several barriers against pathogens and unwanted micro-pollutants such as pharmaceuticals to ensure drinking water quality (Gerrity et al. , 2013). Treating waste water to a quality equivalent to drinking water is now established in Singapore at 0.95 kWh/m³, in Windhoek, Namibia, at 1.3 kWh/m³, and in Orange

County, California, at 0.8 kWh/m³ (Kirkegaard & Rygaard, 2014; Vincent et al., 2014). These are large-scale plants treating well above 5 million m³ per year and it shows how potable reuse in terms of energy use has become comparable to conventional waste water treatment and may compete with other options such as water imports and desalination.

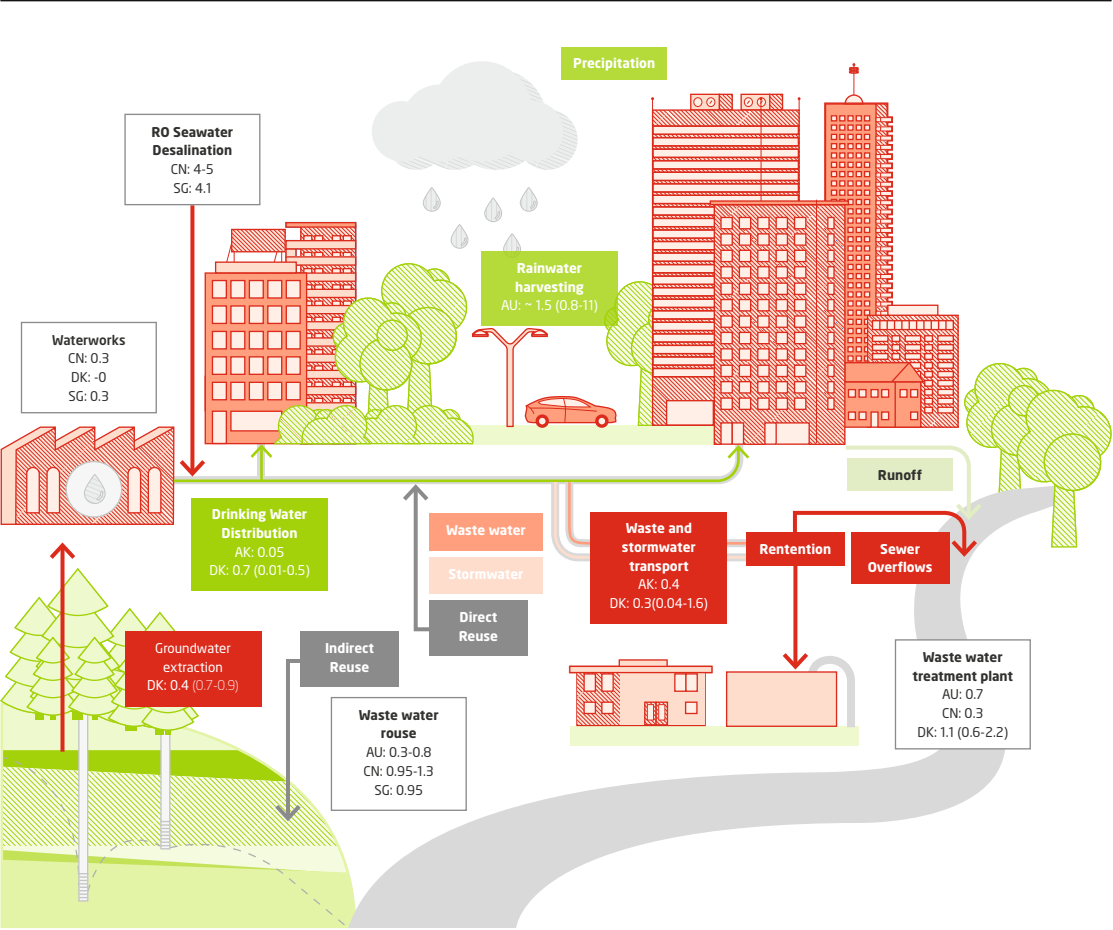
Electricity footprints in urban water flows

Figure 12 summarises the typical energy use in urban water systems as presented in previous sections. In Copenhagen 2014, the average electricity values for operating water abstraction, drinking water treatment, and distribution is 0.25 kWh/m³, while storm and waste water collection and waste water treatment uses 1.05 kWh/m³. Based on the typical urban water flows this totals to 71 GWh per year or approx. 122 kWh/person per year. This corresponds to 3% of the total electricity consumption in Copenhagen (2332 GWh) and 11% of the household electricity consumption (662 GWh) in 2014 (City of Copenhagen, 2015b). As such, the electricity use for urban water management is a marked contribution to the total energy use of urban households. Similar results were found in an Australian study that estimated water services to demand an average of 176 kWh/person/year for a typical large Australian city (Kenway et al., 2011). They also estimated that the average indirect electricity consumption related to water use, e.g. water heating and cooling in households was 1,161 kWh/person/year, which corresponded to 13% of the average total electricity use by an Australian citizen. The Australian/Californian case hides a somewhat lower energy requirement for water utility services compared to Danish conditions offset by a relatively larger water consumption per person. In summary, water and waste water services accounts for a minor, but important contribution to the total electricity use in Danish and Australian cities. Results from one Australian study, showed that indirect electricity consumption related to water’s use phase e.g. heating and cooling of water in households, may have a 7-fold larger electricity demand than the water and waste water service alone (Kenway and Lam 2016).

Energy demands related to water use and the importance of power mix

As stated in previous section, the electricity consumption associated with water use is a significant contribution to the total energy use in households.

Figure 12 – Typical electricity footprints in kWh/m³ treated or conveyed water in the urban water cycle (lowest-highest reported value in brackets).



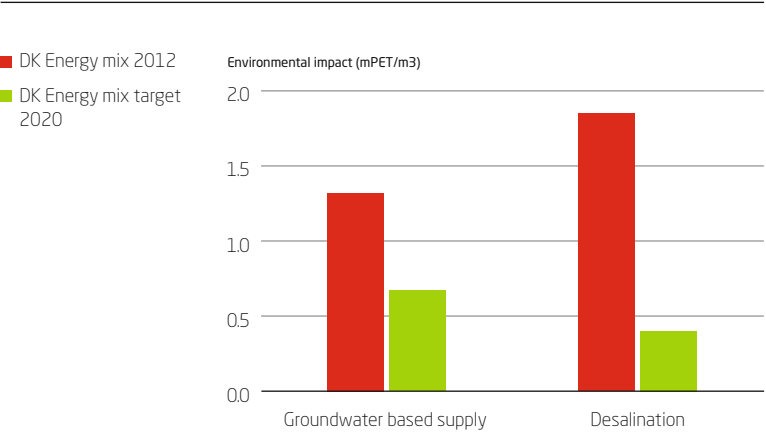
Data from Australia (AU) (Lane et al., 2015; Vieira et al., 2014) China (CN) (Li et al., 2016), Denmark (DK) (DANVA, 2016), and Singapore (SG) (Vincent et al., 2014).

This is also concluded in an analysis of environmental impacts related to changing the drinking water quality (Rygaard et al. 2011). The drinking water composition, notably the water hardness, will affect the calcium carbonate precipitation potential (scaling) in the plumbing system, appliances and heat exchangers. Another Danish study found that even a slight reduction in hardness, will have a significant positive environmental impact for Copenhagen (Godskesen et al., 2012). The researchers found the same importance of water quality in another study comparing water supply options for a new development in Copenhagen. In a direct comparison of total environmental impacts, desalination was a poor choice over the conventional groundwater-based supply in Copenhagen under the power mix of 2012, largely based on fossil fuel combustion. However, with ambitious goals for Copenhagen to become

carbon-neutral in the near future, the comparably high electricity consumption by desalination will have reduced influence on the systems environmental burden. Caused by this anticipated change in the energy mix and the relatively low hardness of desalinated seawater, the environmental burden is expected to be lower for the desalination scenario than for the conventional groundwater-based system already by 2020 (Figure 13).

These examples show how changing power generation regimes may have important implications for the environmental feasibility of water treatment options in the future. Since water systems consist of infrastructure with long lifetimes in the range of 20-100 years (Langeveld, 2015), it is important to consider how new infrastructure investments will respond to future changes to power generation.

Figure 13 – Comparison of total environmental impacts from two water supply options in Copenhagen under different power generation regimes.



Also, the example is a consequence of the fact that water end use dominates the energy use in the urban water cycle. Studies have shown that 15-50% of total energy consumption in Australian households was water-related and around 90% of energy use in the urban water cycle was related to water end use (Kenway and Lam 2016).

Energy inputs to storm water climate adaptation

This chapter has focused on electricity use in the operating phase of urban water infrastructure. Storm water management is expected to have a low demand for electricity in the use phase, but a larger energy consumption embodied in the materials and construction of the systems (Risch et al. 2015). This is explained by the fact that after installation drainage systems are mainly passive. A study of

Table 4 – Life-cycle CO₂-eq emissions from two alternative solutions to increased frequency of cloudbursts in a Copenhagen sub-catchment (Brudler et al. 2016).

	Surface [t CO ₂ eq.]	Sub-surface [t CO ₂ eq.]
Background processes (materials etc.)	11856	33255
Waste water treatment	0	8570
Fuel for channel or road cleaning	17	17
Fuel for pipe maintenance	134	103
Maintenance green areas (mowing etc.)	96	0

the Cloudburst Management Plan for a 2.6 km² sub-catchment of Copenhagen, reveals a 100-year CO₂-eq emission of 12 million kg CO₂-eq for a new surface-based alternative and 42 million kg CO₂-eq for a conventional pipe-based system (Table 4). In the same period, the area’s 79,000 inhabitants will emit 280 t CO₂-eq/person if maintaining the city-wide emission of 2014 (City of Copenhagen 2015b). Based on these numbers, the Cloudburst Management Plan will contribute less than 0.2% of the total emissions. The contribution is very low and may be underestimated because of reduced CO₂-eq emissions in the future (Brudler et al. 2016).

For the Cloudburst Management Plan, most energy related emissions are caused by background processes, i.e. built into materials such as concrete (Table 3). Another important lesson from this example is that when new paradigms within storm water control measures manages water at the surface and use less pipes and basins it may lead to a reduction in total energy impact and save energy at the waste water treatment plant.

Novel membrane-based water treatment technologies

Currently, solar and wind power are regarded as the ultimate sources for sustainable power. Recent developments in membrane technology have spurred interest in exploiting salinity-gradient power (SGP) thereby harvesting the Gibb’s free energy of mixing.

Of the existing mechanisms for directly harvesting SGP, reverse electro-dialysis (RED) and pressure retarded osmosis (PRO) are the most studied membrane-based technologies. Both techniques have high power density and energy recovery potential. RED seems best suited in sea and river water mixing whereas PRO seems to be more attractive for power generation using fresh water or reclaimed water mixing with hypersaline brines.

In addition, indirect energy recovery forward osmosis (FO) membranes have been investigated in conventional aerobic membrane bioreactor (MBR) technology for water purification. Recent progress in anaerobic MBR technology is opening for the possibility of replacing energy consuming aerobic digestion in water treatment with energy producing water treatment based on FO and anaerobic digestion.

Energy production with reverse electrodialysis (RED)

RED utilises the Nernst potential between waters of different salinity. Two kinds of membranes are used: one only permeable for cations and another only permeable for anions. By electro-diffusion, an ionic current is generated which is converted into an electron current at the electrodes by redox reactions. The energy of mixing 1 m³ seawater (~0.6M NaCl) with 1 m³ river water (~0.015M NaCl) is 0.92 MJ or 0.256 kWh and the global potential is 2.8 TW. For RED energy production the ion exchange membrane literature indicates that the presence of multivalent ions has a lowering effect on RED stack voltage and thus on power density. Unfortunately standard ion exchange membranes have low valence selectivity. Thus there is a need for selective membranes capable of separating monovalent ions from solutions (e.g. seawater and river water), containing both monovalent and multivalent ions. The state-of-the art approach to obtain relative permselectivity is to establish a very thin layer on the surface of conventional membranes that allows passage of only monovalent ions (e.g. Na⁺ and Cl⁻) while restricting the passage of divalent ions (e.g. Mg²⁺ and SO₄²⁻). This has been done with some success. However, recent advances in biomimetic membrane technology and membrane protein production present a radically new way to obtain superior permselectivity: namely using biological bacterial cation and anion selective channels.

In November 2014 the world’s first RED power generating pilot plant facility *Blue Energy* opened in the Netherlands. *Blue Energy* is a joint development of Redstack, FujiFilm and water technology knowledge institute Wetsus. The plant is located on the closure dam Afsluitdijk which is a fundamental part of the larger t, damming off the Zuiderzee, a salt water inlet of the North Sea, and turning it into the fresh water lake of the IJsselmeer. Thus *Blue Energy* can be seen as a testbed for the RED process and components paving the way for future international development of the technology (<http://www.redstack.nl/>).

Energy production with pressure retarded osmosis (PRO)

PRO was invented in 1973 and in 2009 the first PRO plant prototype facility operated by the state-owned company Statkraft in Norway opened since followed up in Japan and Korea. In PRO water is permeating a

semi-permeable membrane from a low concentration feed solution to a high concentration draw solution. Energy is generated by depressurising the volumetric increase on the draw side via permeated flow through a hydro-turbine. For PRO, the major challenge is to have robust membranes with low fouling propensity, high water flux, and high solute rejection. Current polymeric membrane designs builds on having a thin (~200 nm) active layer performing separation of water and solutes in the feed stream and an underlying (~300 µm) support layer. In PRO the energy density is proportional to the water flux across the membrane and for economic viability, membrane energy densities need to be >5W/m² and table as the draw solution side to be pressurised to half of the osmotic pressure difference. However, in addition to fouling three mass transfer phenomena can seriously impede water flux in PRO and FO: 1) external concentration polarisation as the water permeates across the active layer into the draw solution side and dilutes the solute concentration; 2) internal concentration polarisation (ICP) as retained solutes accumulate within the support layer; and 3) reverse solute permeation, which is caused by the reverse diffusion of solutes from the draw solution into the feed solution. All three phenomena need to be addressed in order to improve PRO membrane performance. For river water mixing with the sea, a classic PRO scenario, the maximum extractable energy under counter-current and constant pressure conditions is 0.192 kWh/m³ of mixed total solutions. This number can be higher if hypersaline gradients such as industrial brines are used.

Besides the Statkraft-led activities in Norway PRO has also gained interest in Japan. Here Kyowakiden Industry Co., Ltd, has conducted fundamental and operational research with the cooperation of Kyushu University, Nagasaki University and Tokyo Institute of Technology since 2002 and a PRO bench scale plant was constructed near the seawater reverse osmosis (SWRO) plant at Fukuoka. From 2007 to 2009, PRO possibilities were investigated and the first prototype plant of PRO using commercial type membrane module was constructed under the support of NEDO, New Energy and Industrial Technology Development Organization. In 2010, the prototype PRO plant joined the “Megaton Water System” project. PRO activities in Japan has further intensified after the Fukushima nuclear power plant disaster in 2011 (Kurihara et al. 2016).

Energy/water production: anaerobic membrane bioreactors (MBRs)

The use of domestic waste water as an energy source through conversion of organic content into energy in the form of methane (CH₄) gas has a long history. However, conventional aerobic waste water treatment combined with anaerobic sludge digestion in many cases consumes more energy than is gained. Microbial fuel cells converting organic bound energy to electricity have been studied extensively, but these systems are still far from being cost-effective. In principle, complete anaerobic digestion can convert waste water Chemical Oxygen demand (COD) to biogas, remove bacteria and most viruses, allow for N removal via anaerobic ammonium oxidation, and produce high-quality effluent with low COD and suspended solids (SS). However, the efficiency is inherently limited by the slow microorganism growth rate, which necessitates large reactor volumes. One way of improving the efficiency is to integrate anaerobic treatment with membrane filtration in a membrane bioreactor (MBR) where the membrane effectively decouples the hydraulic retention time (HRT) from the solids retention time (SRT). Using this concept HRTs as low as 3h has been obtained even at temperatures as low as 5°C in anaerobic digestion.

MBRs are typically operated as vacuum-driven process using ultrafiltration (UF) or microfiltration (MF) membranes. Most commercial UF/MF membranes are made from hydrophobic polymers due to the high chemical & thermal stability. But with high feed SS, and the applied vacuum, membranes foul easily which severely deteriorate water flux. This can be circumvented by using low-fouling hydrophilic FO membranes with high flux and low solute rejection (mediated by aquaporins) for so-called anaerobic submerged MBRs (SMBRs) where water diffuses from the bioreactor, across an FO membrane submerged in the MBR and high concentration draw solution by osmosis. The diluted draw solution can either be discharged (e.g. as brackish water with seawater as draw solution) or regenerated so high-quality product water.

Full anaerobic MBR treatment can produce net 0.6 kWh/m³ (with 0.4 kWh/m³ energy used) whereas the balance for aerobic digestion is negative (- 0.1 kWh/m³). With 200 litres of waste water/(person day), anaerobic digestion has a theoretical yield of

0.12 kWh/(person day) or 43 kWh/(person year). Even with significant energy conversion losses in the processes and other limitations, anaerobic SMBR have a huge potential in combined energy production and water treatment.

Internationally FO-MBR technology is being researched and developed at several locations. In terms of small-scale pilot systems, the FO-MBR has been tested at the Colorado School of Mines in the US. Also a pilot-scale FO system has been tested in Quyang Municipal Waste water Treatment Plant, Shanghai, China, which is used for concentrating real municipal waste water. The Dutch company BLUE-tec is currently commercialising FO-MBR systems for treatment of industrial waste water, waste water from the waste processing industry, domestic waste water, and waste water on board of ships and off shore locations.

Membrane bioreactor-based hospital waste water treatment

Waste water from hospitals generally contains medicinal and biological waste that requires advanced treatment to prevent contamination of waterways and health risks to people and wildlife. Traditionally hospitals pipe waste water into public sewer systems for treatment at a municipal treatment plant. However, municipal facilities are not equipped to effectively and efficiently treat the volume of hazardous waste generated by hospitals.

This was a concern for Herlev Hospital in Copenhagen. As the city’s largest hospital, with an expanding workforce of 6,000 employees and over 82,000 patients per year, the hospital needed a solution to provide the most effective waste water treatment while being cost and energy efficient.

In addition to concerns about the risk of harmful pathogens and antibiotic resistant bacteria due to insufficient waste water treatment, there is also the concern about the limited capacity of Copenhagen’s water infrastructure as the city’s growth put strain on municipal water and sewage systems.

To tackle these issues, Grundfos BioBooster and project partners worked with Herlev Hospital to develop an on-site, decentralised waste water treatment facility using the very latest advanced treatment

Table 5 – Energy consumption break down for the waste water treatment at Herlev Hospital (Nielsen, 2016).

Functional area of the plant	kWh/m³
MBR treatment including advanced nutrient removal	1.13
Sludge drying	0.23
Post treatment (O3, GAC, UV)	0.37
Advanced air treatment to avoid odour issues	0.57
Total	2.30

methods. The compact, tailor-made facility, designed by Grundfos BioBooster, treats waste water at the source of the pollution rather than piping it through the municipal sewer system for treatment at the central plant.

Designed based on a Membrane Biological Reactor (MBR), the treatment system consists of biological process tanks followed by an ultra-filtration membrane for the retention of biomass. The resultant particle and bacteria-free water provides optimal conditions for the next post-treatment step and makes it possible to adjust the biological treatment capacity to match the hospital’s future requirements.

All biological processes take place within the combined buffer and process tanks. These tanks can operate with or without full removal of Nitrogen (using intermittent aeration) and Phosphorous (through Bio-P and/or chemical precipitation) to meet any future requirements for the discharge of the effluent. A state-of-the-art fine-bubble aeration system allows for low energy consumption that contributes to lower operating costs.

The energy consumption of the decentralised solution is stated in *Table 5*.

Not only is the process more effective in removing hazardous medicinal and biological components from waste water, it is also 15 to 20 times less expensive than using the municipal treatment plant as it uses less energy for advanced treatment. This means a lower cost to taxpayers.

Water treated in the BioBooster is pure enough to re-enter the city’s waterways and for reuse in the

hospital. Herlev Hospital plans to pump treated water back into the nearby Kags stream to increase the water flow and improve the local aquatic environment: particularly during dry periods when plants and wildlife need it most. The hospital also plans to reuse the treated water as technical water, thereby reducing overall water intake, treatment and distribution. This reduces cost, energy consumption, and the strain on the municipal sewer infrastructure.

Installing a decentralised waste water treatment facility is an effective, sustainable solution for hospitals and municipalities around the world. These systems offer clean, safe water at a lower cost than traditional treatment methods and reduce the impact on the local environment.

Chapter 7

Energy consumption in the food supply system

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Setting the scene

Common sustainability principles as formalised by The Natural Step (www.thenaturalstep.org) provide a framework for long-term development of our food supply system including all phases from production to consumption. The development of a sustainable food supply system according to such principles implies:

1. Reducing dependence on the use of non-renewable resources.
2. Reducing emission of substances that are not naturally present in the environment.
3. Maintaining the physical characteristics of the landscape.
4. Providing enough output to sustain people's basic needs.

Currently, Denmark's official objective is to become fossil-free in 2050 and thus use only renewable energy in the food supply system. To outline the spectrum of possibilities, we provide two images of a food supply system that is independent from fossil fuel inputs.

Imagine a system that is built on labour efficiency, productivity, specialisation, economy of scale and centralisation, utilising robot and drone farming technology, diversity through trade, multiple-storey greenhouses, artificially produced proteins, global cycling of nutrients, and designed to satisfy global market demand. Such a system may demand more in the form of external energy and material inputs, but less in the form of area and farm labour compared to the current situation. Contrarily, imagine a food supply system that is built on resource efficiency, sufficiency, decentralisation, diversity by design, internal loops, small machines and structures, local cycling of nutrients and other resources, and where demand is adapted to local supply. Such a system may require little in the form of external energy and material inputs but may, on the other hand, require more in the form of area and farm labour compared to the current situation.

The first image may be characterised as having focus on efficiency (often implying **high input – high**

output) and being associated with a strategy that substitutes renewable energy for our current dependence on fossil energy. The second has focus on sufficiency (often implying **medium input – medium output**) and is associated with a strategy that reduces energy demand as well as substitutes fossil energy with renewable energy. Both images are relevant to have in mind, since we are likely to end up with a development that includes elements from both. *Figure 14* demonstrates how energy and material flows could take place when integrating food and energy production in the future.

The approaches we can take to reduce fossil energy use can be categorised as based on, respectively, substitution and dematerialisation.

Substitution implies using energy carriers (power, heat and liquid fuels) from non-fossil energy sources. Fossil energy substitution by integration of food and energy production may take place in all parts of the food supply chain and, in general, substitution in the food supply chain would be similar to substitution in other sectors of the society. Part of this would include integration of processes based on biomass. On the farm, co-products like straw from crop production and manure from meat production may be used in farm/community biological (e.g. biogas) or thermal (e.g. incineration) plants and the energy may be used on the farm and/or delivered to the surrounding society. In the processing sector, we see a development, which tends to integrate processes and use biomass for products as well as for energy production either used within the same facility or in industrial symbiosis. Other kinds of substitution may focus on the interaction between the food sector and the part of the energy sector that provides intermittent energy carriers. This would especially be relevant for food processing industries with storage possibility or ability to adjust production in response to fluctuating electricity production.

Dematerialisation implies the general reduction of both direct and indirect energy consumption. As an example of the difference between direct and indirect energy use, we can consider vegetable cultivation: direct energy inputs are diesel for tractors and electricity for lighting and heating greenhouses and indirect energy is energy required for provision of the greenhouses and the tractors. Indirect energy

inputs often exceed direct energy inputs (Woods et al., 2010). Energy consumption may be reduced in the agricultural phase, the transport, processing and retailing phase, and the food consumption phase. Reducing energy consumption is often described as increasing the energy efficiency of production and processing. However, it is important to notice that increasing efficiency does not necessarily result in less consumption since it often leads to lower price and thus larger demand. This is a general consequence of increasing efficiency, which has been designated Jevons's paradox or the rebound effect.

In the following, we examine how a modern food supply system currently uses energy. We identify the largest contributions to energy use and suggest approaches for how to reduce these. We focus on dematerialisation and, in addition, indicate the need for changing the lifestyle of people. The chapter concludes by providing a number of specific recommendations for the development of a less energy intensive food supply system.

Present energy consumption and approaches for reduction

Energy use and other environmental impacts of food production have been studied increasingly during the last few decades by means of Life Cycle Assessment (LCA), Net Energy Analysis (NEA), and Emergy Assessment (EmA). Publications in the field of food LCA has increased more than ten

times during the last 15 years (Nemecek et al., 2016). NEA in the form of energy return on energy investment (EROI) has been used to demonstrate the energy expenditures in food production relative to the energy content of the food (Markussen and Østergård, 2013). Energy efficiency indicators that emphasise the use of non-renewable energy have been calculated by distinguishing between renewable and non-renewable energy inputs (Alonso and Guzmán, 2010; Kamp and Østergård, 2016), the latter analysis using EmA.

It is estimated that energy use in modern food production, including agricultural production, transportation, food processing, packaging and preparation amounts to about a fifth of all energy use, and this energy is predominantly from fossil fuels (Pimentel et al., 2008). This corresponds to 2000 L of oil equivalents to support the diet of one person for one year and presents modern food production as a major driver of the depletion of non-renewable energy sources. Markussen and Østergård (2013) estimate that Danish agriculture, food processing and distribution depend on energy inputs in the order of 220-240 PJ/year ($PJ=10^{15}J$). Such a strong dependence on energy inputs makes the current food supply system vulnerable to reduced energy availability and restrictive policies on fossil energy use. Further, it has been shown that about 4 units of fossil energy are required to produce 1 nutritional unit of energy in food at the retailer in Denmark in

2007 (Markussen and Østergård, 2013) as well as in the US in 1995 (Heller and Keoleian, 2003). Another indication of the high energy use in Danish food production and processing is captured in the sector's energy intensity calculated as energy consumption in kg oil equivalent per dollar of value generated (<https://www.wec-indicators.enerdata.eu/agriculture-energy-intensity.html>). In 2014, this ratio for Denmark was the highest worldwide (0.43) whereas it was only 0.12 for the US. The world average was 0.04, which was a result of a steady decline over the last 15 years. The energy use in Denmark and the US rose slightly during this same period.

Surprisingly, about half of the energy consumption of the modern food supply system occurs in food handling, comprising packaging, sales and preparation. The other half is considered to be close to evenly distributed between agriculture, distribution and processing (Cuéllar and Webber, 2010). Markussen and Østergård (2013) find that for Danish food production specifically, this allocation is around 50%, 22% and 28%, respectively. This means that initiatives to reduce energy use in the food supply system should go beyond agricultural production practices. This opens up for an extended range of possible approaches to reduce the overall energy use of the food supply system.

Agricultural production

The importance of energy use in agricultural production and the associated energy intensities depends on the type of product and the production mode. Generally speaking, crops require the least energy input per ton produced. Farm animal products and aquaculture require similar energy inputs but they are higher than for crops. Fishery products range from comparable to crops to much higher than farm animal products (Cuéllar and Webber, 2010).

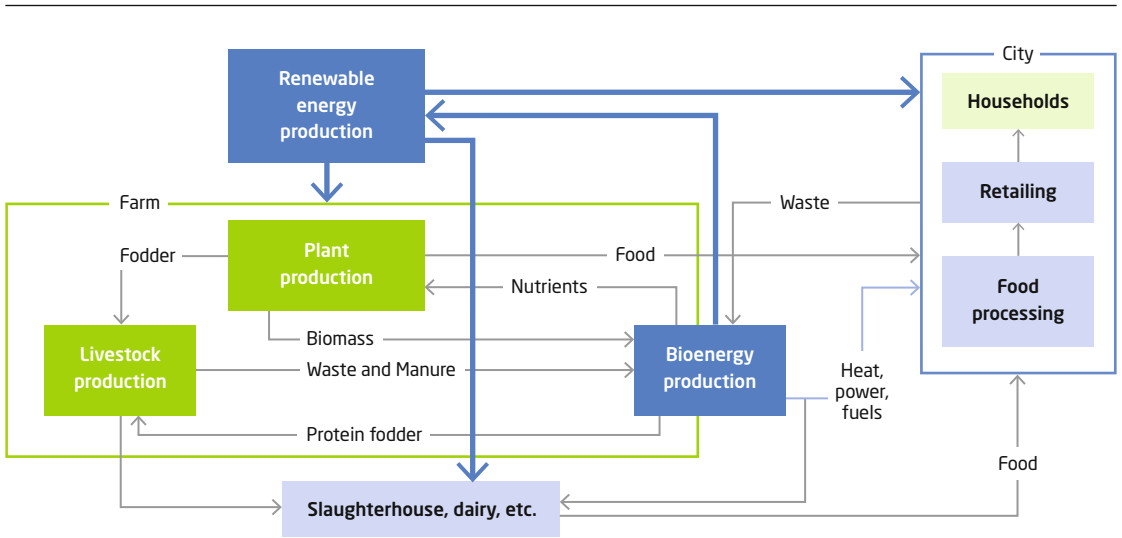
Several studies describe organic practices as less dependent on non-renewable energy inputs in the production of crops in Spain, U.S.A., Canada and Switzerland, with some exceptions (Pelletier et al., 2008; Alonso and Guzmán, 2010; Nemecek et al., 2011; Pimentel and Burgess, 2014). In all studies, the difference was primarily attributable to the use of biological nitrogen fixation instead of synthetic fertiliser (see review by Pelletier et al., 2011).

Some studies point to greater productivity and resource efficiency for smaller farms, but not necessarily with respect to energy use (see Pelletier et al., 2011). In developing countries, small farmers may accomplish more per energy input than larger farmers who can afford tractors and fertiliser. In an industrial context, however, the benefits of scale seem apparent, since mechanised equipment may be used more fully on larger farms. Large-scale production of e.g. lamb and fruit in New Zealand appear to be less energy intensive than smaller-scale production in the countries to where the products are imported. The comparison, however, is affected by differences in climate and land availability, making it difficult to isolate scale as a decisive factor. As a consequence, it was not concluded whether small- or large-scale production is more energy efficient.

With respect to production in greenhouses the following examples were found (see Pelletier et al., 2011). Production of grapes in Turkish greenhouses was shown to be more energy intensive than open-field production. Another study showed that the energy requirement for Swedish tomato production in greenhouses was higher than that for tomatoes imported to Sweden from Southern Europe. There are indications that food produced in smaller greenhouses are more energy efficient than food from larger greenhouses.

Diversified agro-ecological systems, such as intercropping, agro-forestry, permaculture, and polyculture with fish production, are designed with the aim of facilitating natural synergies that reduce dependence on external inputs, conserve soil and support variation (IPES-FOOD, 2016). Specifically, agro-biodiversity in time is achieved through crop rotations, which includes the use of cover crops to reduce weeds, pests and soil-borne diseases, enhance nutrient use efficiency and improve soil quality (Altieri, 1999). Agro-biodiversity in space may be implemented by annual or perennial grass-legumes mixtures, within species varietal mixtures, annual or perennial grain intercrops, agro-forestry and field spatial design. These cropping systems may contribute to enhancing crop yield without enhanced energy consumption or other negative environmental effects. Examples of yield increase in intercropping systems of legumes and cereals are shown in Table 6 and Figure 15.

Figure 14 - Integrated food and energy systems.



Some diversified agro-ecological systems, like Asian rice-fish production systems, are reported to require little exogenous energy (see Pelletier et al., 2011). Further, small farms applying agro-ecological techniques may be two to four times more energy efficient than large conventional farms (Chappell and LaValle, 2011). Perennial grains may be up to 35 times as nitrogen efficient as annual grains (Glover et al., 2010).

Generally, the documentation of the energy requirements of diversified agro-ecological systems is scarce. Nevertheless, it is agreed that future agricultural systems require enhanced internal efficiency of the farming system to activate the inherent self-regulating capacity and ecosystem services of plant-soil systems (Jensen et al., 2012) with increased focus on, e.g. plant nutrition through biological nitrogen fixation or mineralised nutrients from soil organic matter, disease suppressive soil microorganisms, or soil loosening through deep-rooting catch crops, rather than a dependence on scarce external resources that can be associated with environmental risks (Altieri, 1999). Examples of such cropping systems are Conservation agriculture (CA) and Organic farming (OF). Defined as an approach to managing agro-ecosystems for improved and sustained productivity, increased profits and food security, CA focuses on three linked principles, namely:

- 1. Minimum mechanical soil disturbance,
- 2. Permanent organic soil cover,

- 3. Diversification of crop species grown in sequences and/or associations.

Widespread CA implementation in especially North and South America and Australia suggests significant farmer profitability achieved (Brouder and Gomez-Macpherson, 2014). However, comprehensive documentation of agronomic productivity and reduced input costs in other continents are largely missing from the literature.

Another strategy much more common in Europe is OF defined through the four principles of:

- 1. Health,
- 2. Ecology,
- 3. Fairness,
- 4. Care.

OF has strong emphasis towards biodiversity and cycles adapted to local conditions, rather than the use of external inputs. However, there has been only little attention within the OF research and advice on a better understanding of how OF management can reduce energy use originating from e.g. the need for intensive soil cultivation to manage weeds, and greenhouse gas emissions from e.g. the nitrous oxide emissions associated with incorporation of nitrogen rich green manure crops and cover crops (Olesen and Bindi, 2002).

Table 6 – Dry matter (DM) yields in intercropping experiments with sole cropping (sole) and intercropping (+) of faba bean (Faba), pea and oat.

	Straw			Grain			Total		
	Mean ± SE		LER	Mean ± SE		LER	Mean ± SE		LER
	g DM m ⁻²			g DM m ⁻²			g DM m ⁻²		
Faba sole	657 ± 34a		–	389 ± 29b		–	1046 ± 32ab		–
Pea sole	357 ± 24c		–	490 ± 17ab		–	847 ± 21b		–
Oat sole	465 ± 57bc		–	472 ± 38ab		–	937 ± 48ab		–
Faba + Oat	455 ± 25bc	0.91		516 ± 29a	1.11		971 ± 27ab	1.02	
Pea + Oat	475 ± 38bc	1.10		519 ± 40a	1.09		994 ± 39ab	1.09	
Faba + Pea	550 ± 53ab	1.17		535 ± 48a	1.20		1085 ± 51a	1.17	

Different letters indicate significant differences between treatments. LER =Land equivalent ratio calculated as the sum of the intercrop yield divided by the sole-crop yield of each of the component crops in the specific intercropping systems. Small letter indicate significantly different groups. Values are the mean (n=8) ± standard error (SE). From (Lachouani, 2013)

Soil nutrients and carbon

Agricultural productivity is closely associated with soil quality and nutrient availability. High output systems tend to drain soils of carbon and nutrients. In modern farming this is currently compensated by increasing external inputs. The considerably improved agricultural yields of the green revolution were achieved largely through the application of synthetic fertilisers and other agrochemicals, irrigation water and extensive use of machinery in e.g. tillage. All of these are underpinned by flows of industrially mediated energy, i.e., based on fossil fuels and typically channelled through a petroleum-based industrial system (Pelletier et al., 2011).

The production of ammonia fertiliser, synthesised from atmospheric nitrogen (Haber-Bosch process), is perhaps the most striking technological achievement in agricultural development and it is estimated to ensure food for about half the global population (Erisman et al., 2008). However, due to the industrial process, nitrogen fertilisers constitute the most energy-demanding aspect of conventional intensive crop production, accounting for approx. 60% of cumulative energy demand (Pelletier et al., 2008). It is estimated that Danish agriculture relies on more than 200,000 t of synthetic N-fertiliser yearly and only 37,000 t of N fixated by legumes (Markussen and Østergård, 2013). Before the advent of N fertilisers, it was typical to maintain 25-50% of a farm in a legume-rich pasture or cover crop. This prioritisation provided relatively few commodities, but played the necessary role of regenerating soil fertility through biological fixation of atmospheric dinitrogen (N₂) by biological legume-rhizobial symbioses with a build-up of slowly weathered nutrients in plant biomass (Crews and Peoples, 2004). A steady increase in synthetic fertiliser use has reduced the global area of legume-based systems.

The absence of nutrient cycling is comparable to mining the land of non-renewable resources that are necessary for plant growth. While N may be synthesised with electricity from renewable sources, this would continue to be an energy-intensive approach. The most apparent alternative is to biologically fixate nitrogen from the air by adding legumes to the crop rotation. A comprehensive comparison of the use of energy by field pea or barley production (annual), and in production of grass-clover mixtures

Figure 15 – Field plots of different cereal-legume intercropping strategies and wind turbine test facilities at DTU Risø Campus (Lachouani, 2013)



or pure grass (perennial) in Denmark shows that energy consumption was 55% and 81% lower in the legume cropping and forage systems, respectively (Peoples et al., 2009). The most energy-expensive input was nitrogen fertiliser accounting for 51% of the total fossil energy use for barley production and 81% of the fossil energy use for the grass forage crop production. In the review paper of Jensen et al. (2012) it was shown that fossil fuel energy use was on average 12-30% lower per year when legumes were included in the crop rotation. In a recent study from Denmark it was shown how crop rotation productivity in low nitrogen input pasture systems including

legumes can reach satisfactory yield levels compared to comparable high nitrogen input systems including fertilised grasses. This was achieved by using leguminous atmospheric nitrogen fixation and catch cropping to avoid leaching (Hauggaard-Nielsen et al., 2016).

Another very important nutrient for all biological processes is phosphorus (P) and thus, food security requires a phosphorus-secured future. Historically, nature's balance of P in the soil regulated crop productivity, later on, addition of locally available organic substance like guano (bird excrement deposited over previous millennia), animal and human faeces were applied to increase yields (Cordell et al., 2011). As the population grew rapidly over the 20th century, demand for food naturally followed suit and locally available organic substances were replaced with primarily rock phosphate (Cordell et al., 2011). Phosphorus is a non-renewable resource with no biological or technological substitute or replacement (Childers et al., 2011) and meeting the long-term phosphorus demands will require adopting a high rate of P recovery from various waste streams including human and animal excreta. Urbanisation is challenging the potential for phosphorus recycling because of increased distance between production and consumption. Furthermore, organic contaminants accumulating in sewage sludge from waste water treatment plants carry risks of micro-plastics and harmful chemicals returning to fields – depending on urban area characteristics like type of industries. Again, by linking food and energy system to a higher extent, risks of unwanted organic compounds in the sewage sludge can be eliminated when integrated with e.g. a local thermal conversion technology without reducing phosphorus plant availability in the returned ash-fertiliser (Müller-Stöver et al., 2012).

Increasing food demands are changing global farming systems away from traditional management practices and grasslands and forests and toward annual food and feed croplands. This land use change contributes to anthropogenic climate change because grasslands and forests typically absorb high levels of CO₂. Thus, soil carbon loss, also from tillage and removal of plant parts (e.g. straw for bioenergy) is of great concern decreasing the soil organic matter pool and soil quality. More research is required to search

for the right balance between increased energy use per unit of food output, and the systematic carbon recycling and build up needed to counteract climate change. The often more recalcitrant residual carbon fractions from bioenergy conversion technologies like anaerobic digestion (Albuquerque et al. 2012), thermal gasification (Müller-Stöver et al., 2012) and incineration (Kelessidis and Stasinakis, 2012) may contribute to maintain or even increase soil organic carbon stocks if returned and incorporated into the soil.

Much effort has been directed at estimating the energy use associated with fertilisation but only a few estimates of energy use are available for non-fertiliser agrochemicals, irrigation and machinery use. Pelletier et al. (2008) estimate in a specific study from the UK that pesticides account for approx. a sixth of the energy use required for synthetic fertiliser for a selection of crops.

Irrigation

Increased groundwater use for irrigation is a consequence of the availability of cheap energy and it is estimated that 70% of global water use by humans is caused by agriculture (The Crop Site in (Nemecek et al., 2016)). Most modern crop production is inconceivable without external inputs of water. As aquifers and other storages are depleted by over-usage, and climate change involves altered precipitation patterns, the energy requirement for irrigation may be expected to increase.

In production systems that depend on irrigation, increased water use efficiency with low-tech interventions such as drip irrigation may be a key to reduce energy inputs (see Pelletier et al., 2011). Another type of approach is to reduce the dependence on irrigation. This may be achieved by improving the soil's water retention capacity or by reducing exposure to the sun when it is strongest. The increase in water holding capacity associated with focus on soil organic matter production in e.g. no-till agriculture indirectly reduces demand for energy inputs related to irrigation. Regarding exposure to the sun, agroforestry systems may be designed to provide shade to crops in certain periods of the growing season and, thereby, maintain a microclimate between and under the trees that loses less moisture.

Machinery

In predominantly rain-fed crop production, machinery use is typically the second most important energy consumer with tillage and harvesting as the most energy requiring activities (Pelletier et al., 2011). As a side-effect of fertiliser availability, the share of arable land that is worked regularly (ploughed or tilled) has strongly increased, generally under systems of annual crop rotations more or less diversified (see Kleijn et al., 2009).

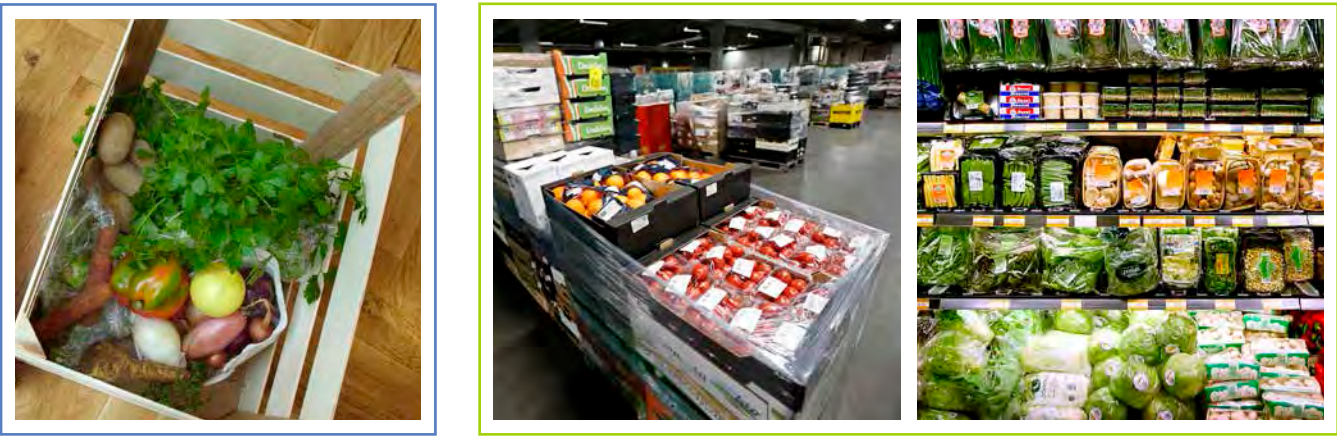
Mechanisation significantly reduces farm labour but does not it in itself produce larger yields. The energy expenditure, however, rises accordingly. A further issue of machinery use is soil compaction, which is related to energy use through the reduction in the soil's biological activity, air and water holding abilities, and thereby soil productivity. Approaches to reduce machinery usage include combining work processes to reduce the amount of field operations, e.g. by simultaneous harrowing and rolling; sharing machinery among farmers to reduce the indirect energy inputs in machinery production; improving machinery e.g. by focusing on multi-functionality. As mentioned before, no-till practices are shown to have lower energy intensity since tilling is among the most energy intensive field operations (see Pelletier et al., 2011). No-till cultivation is a characteristic component of conservation agriculture (Kirkegaard et al. 2014). Further, it may signal a general de-mechanisation strategy that attempts to readjust the balance between machinery and non-machinery inputs, including human labour. Bardi et al. (2013) point to less

and smaller machinery as a necessary part of restructuring our food supply and Pimentel et al. (2008) add that increased human and, in some places, animal labour will be part of this reorganisation.

Transport, processing and retailing

A transportation system built on access to relatively plentiful amounts of oil not only connects food producers with the global market, it also allows for extensive transport within agricultural production, e.g. fodder for animal production. Energy used in refrigeration means that e.g. tropical fruits are available in supermarkets year round. Additionally, the durability of transported food requires sufficient packaging, particularly after or between processing steps. The production, transport and discard of packaging entails energy use. These considerations have popularised the concept of food miles and suggest that local production and use leads to higher energy efficiency. Markussen et al. (2014) studied a local box-scheme distribution system compared to a domestic supermarket distribution system for UK vegetables (*Figure 16*) and found that the box-scheme system was three times as resource efficient as the supermarket distribution system. However, even if local or domestic products do tend to reduce transports, this advantage may be lost if the impacts of the food production are substantially increased. Additionally, the relative importance of distribution compared to agricultural production, processing, etc. varies widely among products. It is however, well understood that the mode of transport plays an important role with impacts per tonne-kilometre of

Figure 16 - The box-scheme products versus the similar products in the supermarket after a centralised distribution system.



freight ship < rail < road << air freight (Pelletier et al., 2011). The consequences for energy consumption of future extended e-commerce, e.g. online shopping where products are delivered directly from the retailer to the consumers' home, has yet to be evaluated in details.

An operational strategy may be to re-localise the supply of energy, nutrients, feed and food (Markussen and Østergård, 2013). This might have indirect effects that go beyond energy reduction, e.g. in terms of cultural value, food security, support for regional and domestic economies, and what may be termed intergenerational transfer of locally adaptive subsistence food production skills (Satterthwaite et al., 2010). Directing settlement patterns toward less distance between food production and consumption may be a long-term approach for gradual reduction of energy use in food distribution. More production by the consumer, e.g. with urban gardens, community gardens or through involvement in community supported food production schemes, may reduce the need for distribution of food products.

The US Department of Agriculture assessed energy inputs in processing, retailing and households (Canning, 2010). Increased demand for convenience products were suggested to explain a large increase in food processing energy use in the last few decades. In the use of pre-processed food products, households and food service establishments attempt to outsource food preparation and clean-up. Retailing constituted the third-most energy intensive stage in the supply chain from agriculture to household. More than half of the energy use in retail is from refrigeration followed by lighting and space heating, and the energy use is more than double the average for commercial buildings when measured per m² (Davies and Konisky, 2000). It follows that increased energy efficiency in processing and retailing and/or reduced need for processing and retailing could reduce the overall energy use of the food sector. Improved refrigeration, lighting and heating are candidates for technical innovation while reducing the need for processing and retailing is more closely associated with cultural change, e.g. using relatively more time to prepare food at home, based on un-processed ingredients. As expressed by Pimentel et al. (2008): 'The most effective method for decreasing energy inputs in processing and

packaging is to dramatically reduce consumer demand for products that require large energy inputs in their production.'

Food consumption

Expected population growth and changing consumption patterns put pressure on our ability to produce ever more food. Current trends are toward diets rich in meat, highly processed and vigorously transported products, and urbanisation. These trends are associated with increased consumption of luxury foodstuffs, many of which are energy intensive in production and distribution (De Haen et al., 2003). It is estimated that food production must increase by 70% between 2006 and 2050 to feed the growing human population with a continued transition toward food demand from intensive, crop-based animal husbandry (Pelletier et al., 2011). This demonstrates an expected huge food gap to cover.

When the use of food in households is included as part of the analysis, it constitutes the single-largest energy consumer of the food supply system (Canning, 2010; Pelletier et al., 2011). The storage and preparation of food products relies on a range of energy intensive appliances. As in other modern homes, a typical Danish household requires extensive energy inputs to run its refrigerator, coffee machine, microwave oven, dishwasher, freezer, and various kitchen power tools.

Allowing for variation in production methods, there is evidence to suggest that diets containing less meat, exotic (imported) foods, highly processed foods and foods with low nutritional value are representative of food systems with lower energy uses (Pelletier et al., 2011; Perryman and Schramski, 2015).

The generation of food waste significantly affects energy use of our food supply. It is estimated that 30-50% of all food produced is wasted (Pelletier et al., 2011). In the developing world, much waste occurs before food reaches the user, so there, approaches should focus on reducing damage by pests, weeds and diseases and on improving storage and transport infrastructure. In the developed world, food waste primarily occurs closer to the user, and efforts should be directed towards e.g. balancing food purchases with food uses, making better use of meal leftovers, and changing consumers' high expectations

of food cosmetic standards. Altogether, it appears that approaches to reduce food waste in the developing world should focus on changing production practices while developed world approaches should focus on changing consumption practices.

As a final note concerning choices of food production and consumption it is clear that more research can cast light on possibilities for reducing energy use. For example, we have not found sufficient information regarding energy usage in insect and seaweed production, synthetic meat production, food production with genetically modified organisms and other food types that are regarded by some as foods of the future, and that may have a role to play in the development of a less energy intensive food supply.

Recommendations for energy use in the food supply system

Historically, productivity gains have been possible by the application of energy intensive technologies. In the future, new technologies and practices based on energy from renewable resources are central for the development of our food supply system and they will contribute in two different ways. As the energy sector increasingly bases energy supply on renewable sources, the energy requirements of the food sector will automatically substitute renewable energy for non-renewable energy in all stages of food supply. In principle, the food sector does not need to change if renewable energy is sufficient and available as the energy carriers that we are used to today. We may think of this as passive adaptation. A passive adaptation strategy may support a development towards the image 'high input – high output.'

The food sector, however, may also actively adapt to a future without fossil fuels and change production methods, distribution systems etc. to depend on fewer external energy inputs and make better use of the energy and other resources provided by natural processes. Active adaptation may be a characteristic component of a strategy for the image 'medium input – medium output.'

We expect that the increasing world population and the increasing demand for resource intensive food and life style will require a strategy for the future food supply system centred on energy reduction.

We recommend approaching an active adaptation along the following lines:

- Remove subsidies on energy use in the entire food sector;
- Internalise costs by taxing products with high indirect energy use;
- Encourage the consumption of local, in-season products;
- Develop alternatives to industrialised food production;
- Reduce consumption of meat and other energy intensive food products;
- Campaign to reduce food waste in every stage of the food supply chain, particularly in households;
- Incentivise the use of nitrogen fixing plants to reduce the use of synthetic fertiliser;
- Promote no-till farming, perennial crops and other agro-ecological techniques to manage soil fertility;
- Downscale current machinery, reduce its usage and replace part of it with human labour;
- Counteract that expensive labour inputs drive increase in energy use.

Our recommendations regarding energy use in the food supply system support the conclusions reached in a recent report about future food production and food security by World Resources Institute, which recommends three kinds of approaches:

1. To close the food gap by reducing growth in food consumption;
2. To close the food gap by increasing food production on the same agricultural land area;
3. To reduce the environmental impact of food production without directly closing the food gap.

(World Resources Institute, 2013).

Chapter 8

Energy recovery from water and food sector residual resources

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Introduction

Residual resources from the food and water sector encompass all waste, residues, and by-products generated within the food and water life-cycle, i.e. during production, processing, consumption, and final disposal. For example, producing one kg of wheat also generates approx. 0.5 kg of straw; within industrial processing, producing one litre of beer also generates approx. 0.1 kg of residual brewer's grains; at a consumption level, an average EU citizen generates about 123 kg of edible food waste per year. In Denmark the level is even higher, being estimated to 137 kg per person per year.

Food sector residues may be utilised as fodder for animal feeding, as substrate for bioenergy and biomaterial production, or as organic fertilisers. For example, industrial food-processing residues have traditionally been used as complementary feedstuff in animal diets due to their high nutritional value. This is indeed the case in EU for the majority of the residues from beer, sugar, starch, cheese, oil, fish and (partly) animal meat processing industries. In many EU countries municipal food waste used to be landfilled prior to the implementation of the EU directive limiting landfilling of organic waste (CEC, 1999). This shifted the management towards composting, anaerobic digestion, or thermal treatment of the waste. Manure is typically stored and applied on-land without treatment, although anaerobic digestion is increasingly implemented to minimise emissions (De Vries et al., 2012a, 2012b; Hamelin et al., 2014, 2011).

With respect to the water sector, the main residual resource is represented by sewage sludge, i.e. the residual concentrated biomass after treatment of the municipal waste water. Sewage sludge may be used as substrate for bioenergy and biomaterial production, or as organic fertilisers. The main environmental aspects associated with sewage sludge management are related to emissions to air, soil, and water occurring during storage, treatment, and final disposal of the sludge (Yoshida, 2014).

Overall, the management and utilisation of these residual resources may follow different pathways; with each pathway being characterised by different effects on the environment. The overall sustainability of these pathways or alternative uses of biomass

resources require a detailed understanding of the resource potential, the relevant conversion processes involved, and the diverse characteristics of environmental impacts. A holistic evaluation of the environmental performance of individual technology pathways is therefore necessary in order to avoid unintended environmental consequences.

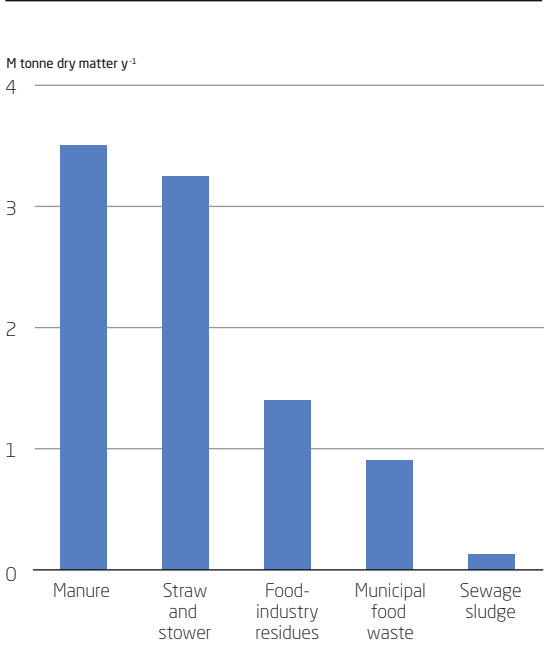
This chapter provides an introduction to the availability of residual resources from the water and food sector, and then followed by a discussion of thermal and biological conversion of selected resources into energy. Finally, utilisation of the resources is addressed from an environmental perspective with focus on the energy conversion itself as well as indirect environmental impacts associated with land-use.

Resource availability and potential for energy production

In Denmark, residual resources generated within the food and water sector (agricultural waste such as straw/stover and manure, sewage sludge, municipal food waste, and food-industry residues) amount to about 9.2 Mt of dry matter annually, representing an equivalent potential energy of around 100 PJ (10^{15} J) (Mathiesen et al., 2011; Tonini and Astrup, 2012). For the purpose of comparison, this potentially represents about 14% of the primary energy supply of Denmark in 2013 (719 PJ; DEA, 2015). Currently, the actual use of these substrates for energy purposes is much lower than the total potential, as alternative utilisations exist such as feeding, bedding, fertilisation/soil amelioration, or material production. For instance, only about 5% of the manure is used for energy, and most of the food-industry residues are used in the feed sector, while ca. 90% of the household food waste is used for energy recovery (incinerated). Sewage sludge is also mainly digested and/or incinerated. At a European level, these residues amount to about 4450 PJ (EU27; Panoutsou et al., 2009). This potentially represents about 6-7% of the primary energy supply (ca. 69 EJ (10^{18} J) in 2013; Eurostat, 2013).

It should be realised that the values mentioned above do not include the food waste generated during agricultural production, for lack of information. In context, estimates for the United States indicate that as much as 40% of the food produced in US may be wasted during agricultural production (e.g. left

Figure 17 – Availability potential of residues from food and water sector, dry basis (Denmark).



on-field, not collected, or only partly collected due to market prices, market standards and acceptance criteria, etc.). Thus, also for EU and Denmark generation of food waste and agricultural residues may be higher than indicated above.

As illustrated in Figure 17, the most abundant residual resource from the Danish food and water sector is represented by crop-residues (straw and stover; ca. 4.6 Mt dry matter) followed by manure (ca. 3.5 Mt dry matter). Industrial food-processing residues and municipal food waste are estimated to ca. 1.4 and 0.9 Mtonne dry matter, respectively. In the water sector, sewage sludge amounts to 0.14 Mtonne dry matter, corresponding to a potential energy (measured on a dry basis) of ca. 2 PJ. The value for Denmark resembles the rest of EU, where the largest potential is found in crop residues followed by manure, food-industry residues and municipal food waste, while sewage sludge constitutes ca. 2% of the total potential from the food-water sector (Panoutsou et al., 2009).

These biomass resources can be converted to a number of different energy carriers, e.g. bioethanol, biomethane, biohydrogen, bioelectricity, bioheat, etc. Among these, the conversion to biogas

and bioethanol may offer an important alternative to conventional fossil fuels in the transport sector.

Table 7 illustrates how much gasoline could be displaced when converting selected substrates into biofuel (Tonini et al., 2016a). Besides the potential for biofuel production, some of these residues also have a high nutritional value in terms of energy-feed and (for some of them, e.g. whey or brewer’s grain) proteins. When used for animal feeding, the residues become important alternatives to conventional fodder, thus basically avoiding production and use of grains and meals (Tonini et al., 2016a).

Table 7 also illustrates how much corn and soymeal (as an example) can be substituted by using typical food-processing residues available in Europe. For example, using 1000 kg of whey for feeding could displace about 59 kg of corn and 16 kg of soymeal, corresponding to savings of about 250 m² of arable land, while using the same whey for biomethane production could displace about 18 kg of gasoline (760 MJ) (Tonini et al., 2016a).

Thermal conversion of residues

Thermal gasification is a promising technology for conversion and utilisation of agricultural residues or industrial and municipal sewage sludge, due to its flexible and robust heat and power generation and the possibility to produce various value-added products, such as storable high energy density fuels, chemicals and valuable fertiliser ashes. The gas produced during gasification can be converted directly into heat and power, stored as gaseous fuels in the existing gas infrastructure or synthesised into liquid fuels or chemicals.

One of the areas where gasification is showing an immense potential is within conversion and valorisation of sewage sludge. Sewage sludge carries a substantial energy potential, and has a high content of valuable micro- and macro nutrients including the essential element phosphorous that is rapidly becoming an increasingly scarce resource (DEPA, 2013). However, sludge also contains traces of numerous harmful substances including heavy metals, phthalates, pharmaceuticals, flame retardants, micro plastics and many more. While there is still no optimal solution to manage sewage sludge, the global production increases year by year along with the

global middle-class and improving global sanitation levels. Currently, the most widely used sludge management options are incineration, landfilling and application on land as agricultural fertiliser (Reed et al., 2005). Direct application of sludge on agricultural land is the most used management option in Denmark where as much as 75% of the collected municipal sewage sludge is spread in near-by agricultural systems. However, in many EU countries (e.g. Germany) strong opposition exists for direct use of sludge as a fertiliser due to concerns for environmental and health related consequences. The use of sludge disposal in landfills in EU is also becoming problematic due to changes in recent legislation and increased gate costs (Manara and Zabaniotou, 2012).

Among the emerging sludge management options, thermochemical valorisation including pyrolysis and gasification, has been identified as some of the most promising alternatives due to high flexibility, efficiency and the ability to simultaneously address bio-ash valorisation and energy utilisation (Manara and Zabaniotou, 2012). This will facilitate an optimised energy recovery, reduced energy use and increased plant robustness at municipal waste water treatment plants (WWTPs). During thermochemical gasification, sludge volatiles and char carbon are converted into combustible gases while the solid residual is reduced in volume and cleaned of pathogens and organic xenobiotics. The total content of P, K and micronutrients is preserved while the amount of certain heavy metals is decreased (Tyagi and Lo, 2013). Compared to incineration, the gasification process presents some unique advantages e.g. production of P-rich bio-ashes, a flexible energy and chemical product portfolio (Malkow, 2004; DEPA, 2013), high energetic efficiency and potential reductions in NOx emissions (Malkow, 2004; Manara and Zabaniotou, 2012). Successful integration of a gasifier with a gas engine as a new system component into already operating WWTPs in Denmark would result in co-production of electricity, heat and a phosphorus rich soil fertiliser from dry sewage sludge. The future sludge product from WWTPs will then be a high quality bio-ash that provides the agricultural sector with a new alternative to the non-renewable and limited rock-P based fertilisers at a lower cost.

The underlying principle of the suggested gasification concept is based on the TwoStage Gasifier

(“Viking gasifier”) (Henriksen et al., 2006). In this process, the pyrolysis and gasification take place separately, linked by a partial oxidation zone. The system has a very fine temperature control and a very low final gas tar content owing both to the partial oxidation and a subsequent thermal decomposition in the fixed char bed. By passing several heat exchangers, delivering heat for the process and district heating, the produced gas is cooled and the soot particles are finally removed in a simple bag house filter. The cooled gas is fuelled to a gas engine coupled to a generator, producing power and district heating. Figure 18 provides an overview of such a gasification concept integrated into a Danish WWTP.

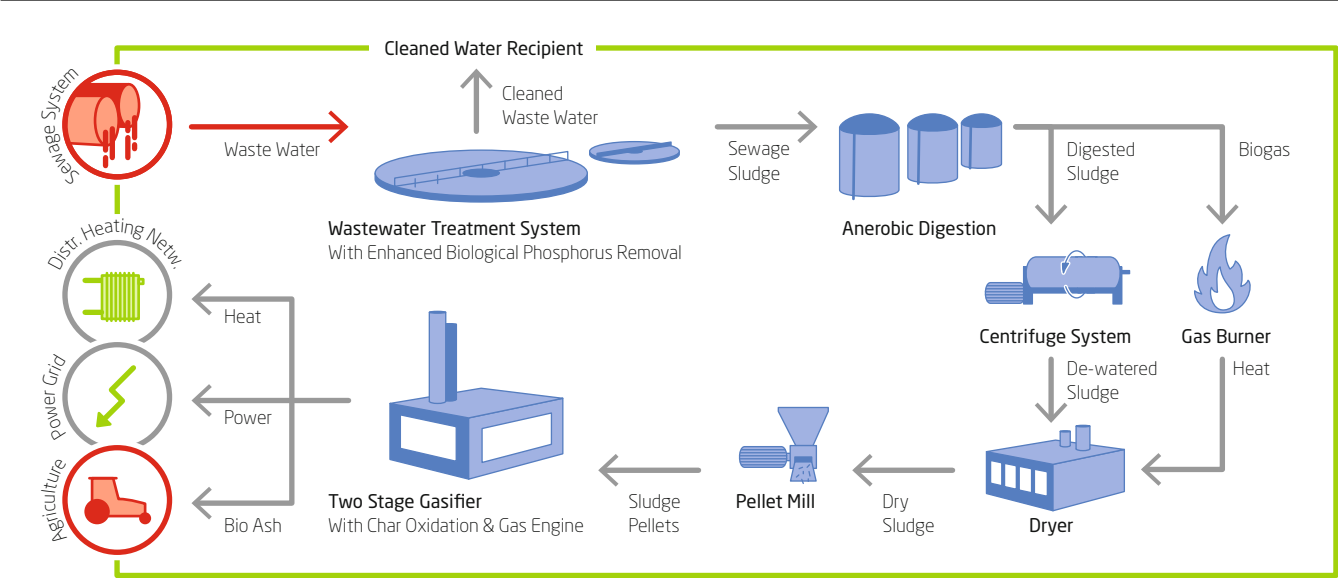
Including a gasification unit in a waste water treatment plant for sewage sludge conversion bears several advantages:

- Valorisation of sludge by polygeneration of a wide portfolio of products including electricity, heat and bio-ash (fertiliser) (even liquid and gaseous fuels and chemicals).
- The WWTP can become energy self-sufficient.
- Production of bio-ash that is concentrated, easy to handle, odour-free and high in P content.
- Reduction of the environmental impact and toxicity of bio-ash compared to sewage sludge.

Table 7 – Nutritional value of selected residues (1000 kg) from the food-processing industry in terms of maize and soy meal equivalent. For comparison, the energy value when converted to biofuel (biomethane) is also presented (Tonini et al., 2016a).

	Use as feed		Use as biofuel
	Maize-eq. kg ww (m²)	Soy meal-eq. kg ww (m²)	Gasoline-eq. kg (MJ)
1000 kg wet substrate:			
Whey	59 (190)	16 (60)	18 (760)
Brewer's grain	60 (180)	120 (520)	62 (2680)
Beet molasses	510 (1600)	226 (940)	188 (8100)
Beet pulp	170 (530)	49 (200)	60 (2600)
Beet tops	96 (300)	87 (360)	49 (2100)
Potato pulp	122 (380)	20 (80)	36 (1560)

Figure 18 - Overview of a TwoStage gasification unit integrated into a Danish waste water treatment plant.



- Efficient, cheap and simple gas cleaning in the TwoStage gasifier design.
- Dry sludge pellets can provide storable energy.

Proof of concept operation conducted by DTU Chemical Engineering as well as first draft system modelling with energy analysis conducted by DTU Mechanical Engineering and LCA studies conducted by DTU Chemical Engineering and DTU Management Engineering have provided the first very promising results, and indicate that TwoStage sludge gasification has the potential to initiate a new direction for WWTP optimisation with very positive perspectives both nationally and globally.

Biological conversion to biogas

By applying anaerobic digestion, a biologically mediated process, the organic fraction of the residues (i.e. lipids, carbohydrates, and proteins) is degraded and biogas is produced. The types of biomass derived from food industry and water sector that can be used as influent feedstock in biogas plants include:

- Manure from livestock farming.
- Sewage sludge from municipal waste water treatment plants.

- Residues from food processing industry.
- Residues from slaughterhouses.
- Residues from edible oil industry.
- Residues from dairy products.
- Inedible residues from food crops (e.g. meadow grass, vegetable wastes such as carrot leaves, banana peels, lemon pressing).
- Dedicated energy crops (e.g. maize, wheat, beets).

Biogas is a gas mixture typically containing methane (40-75%), CO₂ (25-60%) and trace gases such as H₂S and N₂. Specifically in Denmark, biogas is envisioned as one of the main renewable energy pillars (together with wind energy). The expansion of biogas plants will be further supported by an additional Danish goal, which is the exploitation of up to 50% of the annual manure generation for bioenergy production (Danish Government, 2009). Co-digestion of manure with several of the other substrates mentioned above is a common practice applied in the Danish centralised biogas plants for more than two decades (Angelidaki and Ellegaard, 2003). Table 8 shows the methane potential of several residues derived from the food and water sector.

Currently, biogas produced in Danish centralised biogas plants is energetically valorised to generate electricity and heat using “combined heat and power” (CHP) installation units. The efficiency of such units is 35-40% electrical and 45-50% thermal. Recent ongoing studies are focussing on integrating multiple renewable energy sources in order to increase the calorific value of biogas so as to be directly injected into the natural gas grid or used as transport fuel (Luo et al., 2012; Bailera et al., 2015). For example, by applying biological biogas upgrading, the excess amount of wind energy produced during the wind peak loads can be exploited for water hydrolysis generating H₂ which can be coupled with CO₂ contained in biogas so as to produce biomethane (Bassani et al., 2015).

Even though anaerobic digestion of organic residues is a mature and widely applied technology, specific challenges need to be addressed so as to further optimise the process and maximise the energy output. These challenges include: a) better design of digesters, b) extension of existing mathematical models to be able to predict more accurately the biogas production rates, c) development of pretreatment technologies in order to minimise the retention times and increase the degradation efficiency d) optimise upgrading technologies for more novel applications like vehicle fuel and fuel cells (Appels et al., 2011), e) development of simple time effective methods for methane potential determination, f) elucidation of the microbial community populating biogas reactors and g) better instrumentation for more efficient monitoring of the process based on biochemical parameters (e.g. Volatile Fatty Acids).

Direct environmental impacts: plant-scale greenhouse gas emissions

While energy conversion of residual resources from the water and food sector may displace fossil fuels in the energy system, the conversion itself may contribute with local greenhouse gas emissions, e.g. methane and nitrous oxide. Both gases are potent greenhouse gases with global warming potentials of 28 and 265 times that of carbon dioxide (Stocker et al., 2013) and thus relative small emissions can have a significant environmental impact. Emissions can occur from different point releases at the facilities (e.g. open ponds, storage areas or storage tanks, reactors, etc.) as well as when applying residual organic

material (e.g. digestate from anaerobic digestion) on agricultural land. The extent of these emissions is poorly understood, partly because the emissions are diffusive and dynamic, and partly due to a lack of suitable measurement methods.

DTU Environment has established a mobile analytical platform and developed and tested a tracer gas based methodology for quantification of gas emissions. The tracer dispersion method is a ground-based optical remote sensing method combining a controlled release of tracer gas with concentration measurements downwind of the facility using high resolution analytical equipment (Mønster et al., 2014). The method measures the total emission from full scale facilities or sources. During the last 10 years the method has been used to quantify the methane emissions from more than 40 landfills (Mønster et al., 2015). Moreover, within the last five years the tracer dispersion method has been applied at a number of Scandinavian waste water treatment plants as well as at biogas plants treating manure, organic household waste and industrial waste (Yoshida et al., 2014, Reinelt et al., 2016).

At waste water treatment plants, the main methane-emitting sources include the sludge treatment and energy production lines, while N₂O is principally released from the main waste water treatment reactor and reject water treatment unit (Reinelt et

Table 8 - Biogas potential of organic residues from food and water sector.

Organic residue	Methane yield (m³/kg VS)	Reference
Pig manure	0.21	Kougias et al., 2014
Cattle manure	0.32	Tsapekos et al., 2015
Chicken manure	0.43	Tsapekos et al., 2015
Mink manure	0.23	Tsapekos et al., 2015
Rye straw	0.36	Angelidaki & Ellegaard, 2003
Barley straw	0.20	Angelidaki & Ellegaard, 2003
Meadow grass	0.29	Tsapekos et al., 2015
Wheat straw	0.15	Angelidaki & Ellegaard, 2003
Fish Oil	0.60-0.80	Angelidaki & Ellegaard, 2003
Molasse	0.31	Angelidaki & Ellegaard, 2003
Vinasse	0.15	Angelidaki & Ellegaard, 2003
Meat and bone flour	0.57	Angelidaki & Ellegaard, 2003

al., 2016). Important CH₄ emission sources included anaerobic digester tanks, dewatering units, digestate tanks, and gas upgrading systems, etc. At some plants methane emissions were also seen from the water treatment line including the mechanical treatment units, primary settlement tanks, and activated sludge reactors. Overall methane emission rates from the plant were between 1 and 18 kg CH₄ h⁻¹, whereas nitrous oxide emission rates between up to 6 kg N₂O h⁻¹ were detected (Delre et al., 2016). Emissions were highly dynamic and during periods with sub-optimal plant operation higher emissions were observed. As an example venting of biogas reactors during foaming situations resulted in methane emissions of more than 90 kg CH₄ h⁻¹ (Yoshida et al., 2014).

Methane emissions from biogas plants have been found to vary between 5 and 25 kg CH₄ h⁻¹ (Delre et al., 2016). The biogas plants studied included plants treating mainly manure as well as plants treating a mix of organic household waste, industrial waste and agricultural waste (Reinelt et al., 2016). Significant variations in methane emissions were seen between plants as well as over time within individual plants. In general, the total methane loss was dominated by sources like pre-storage tanks, mixing tanks, open after-storage tanks, and biogas upgrading units. Also methane leakages from the biogas-bearing plant components were seen (e.g. digesters, biogas storages, biogas piping, biomethane compressor stations, etc.) (Reinelt et al., 2016).

Application of digestate on agricultural land will result in emissions to the environment as the carbon and nitrogen applied with the digestate mineralises over time. The majority of organic carbon applied on land will be converted to carbon dioxide and emitted into the air, while a smaller part will be emitted as methane (Bruun et al., 2016). The part of the organic carbon, which is resistant to degradation will remain in the soil after 100 years and is thus considered to be sequestered. Nitrogen goes through complex transformations in soil. A part of the nitrogen will be taken up by plants but the remaining part will be emitted into the environment as reactive nitrogen (NH₃, N₂O, NH₄⁺, NO₃⁻). The specific emission rate depends on the stabilisation of the digestate, the soil type, climate factors, current fertiliser status of the soil, crop rotation, and soil management practices. Emission factors for long term consequences

of organic residues application on land (including digested sludge) are available in Yoshida et al. (2015, 2016) and in Bruun et al. (2016).

Indirect environmental impacts: alternative use of the residual resources

The common understanding is that energy production from biomass is beneficial for the climate, i.e. mitigation of global warming effects from the displacement of conventional fossil fuel. Yet, more bioenergy does not necessarily always mean net reductions of GHG emissions and mitigation of global warming. While introducing more bioenergy certainly displaces corresponding fossil resources, bioenergy may also cause other indirect effects outside the energy sector itself. These effects may be beneficial or detrimental depending upon the alternative management of the biomass. In Denmark and most of Europe, manure is predominantly stored and applied on-land without any treatment. Thus, increasing bioenergy from manure, in addition to displacing more conventional energy sources, has also the beneficial side-effect of reducing undesired emissions (methane, nitrous oxide, ammonia, etc.) occurring during storage and application on land of raw manure in the agricultural sector. Using feed and food crops (e.g. wheat, maize, ryegrass, etc.) or substrates with high nutritional value for bioenergy may increase the demand for conventional fodder, thereby adding pressure on the agricultural sector for production of more grains and meals.

Both of the above examples highlight that a holistic perspective is imperative in relation to environmental assessment of biofuels; in order to account for all the environmental consequences, even beyond the energy sector. In this respect, life cycle assessment (LCA) is a useful tool for accounting of all environmental savings and impacts throughout the life cycle of energy products, such as biofuels. DTU Environment has developed a dedicated LCA-model for quantification of environmental impacts of any bioenergy/biomass system: EASETECH (Clavreul et al., 2014).

Focusing on global warming mitigation, Tonini et al. (2016b) calculated the GHG emission factors for twenty-four Northern European biomass types in EASETECH. The results highlighted that only bioenergy produced from residues, currently not

used as animal feed, is truly beneficial from a climate perspective. This applies to substrates such as manure, sewage sludge, straw/stover, municipal food waste, and wild grass (Figure 19). In contrast to this, diverting annual crops (such as grains) and substrates with high nutritional value (such as whey, brewer's grains, beet and starch processing residues, etc.) from the feed/food sector to the energy sector should be discouraged. In other words, the environmental performance of these residues when used in the feed sector is better (Figure 19).

It should also be kept in mind that the environmental performance of bioenergy, for instance in terms of GHG emission reduction, is highly dependent upon the type of energy source displaced. For example, displacing natural gas-based electricity provides about half of the GHG savings of displacing coal-electricity, as indicated in Figure 19. Accordingly, in future electricity systems with high shares of wind power, the environmental savings induced by bioenergy may be limited or even nil. In this context, production of transport fuel, feed, biomaterials may likely be preferable to power and heat generation (Tonini et al., 2016b).

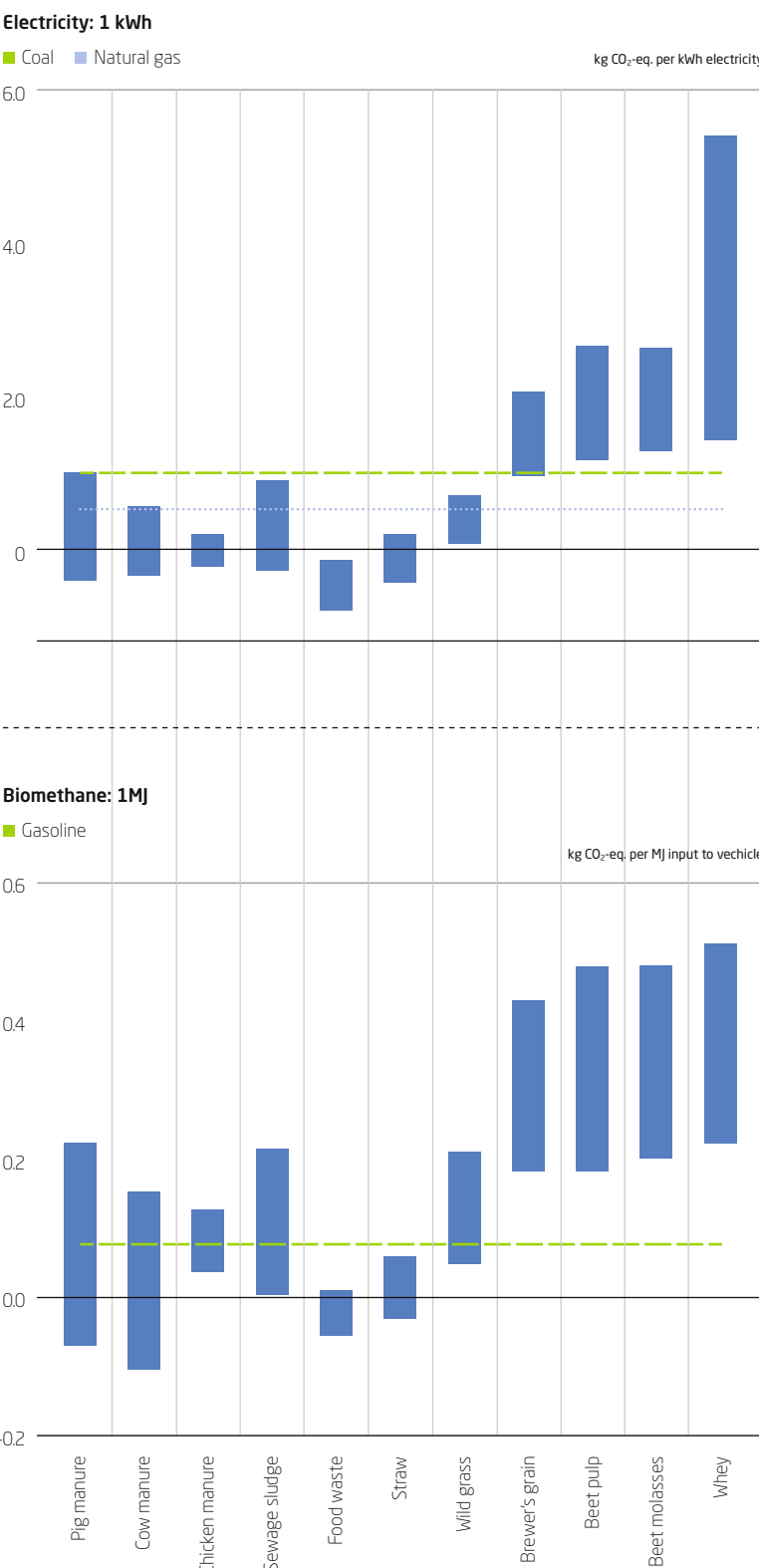
Indirect environmental impacts: changes in land use

Producing energy crops has two distinct effects on land-use. In regions, such as Denmark, where agriculture covers ca. 63% of the available land, the land needed for cultivation is likely to come at the expenses of other feed or food crops. This effect is called direct land use change (dLUC).

Further, at an international level, this initial displacement increases the demand for conventional fodder, thereby adding pressure on the global agricultural sector for production of grains and meals. This, in turn, may induce expansion of arable land into nature (deforestation) and increased use of fertilisers (intensification of production). These effects are called indirect land use changes (iLUC) and are typically much more important, in terms of magnitude, than dLUC (Tonini et al., 2012).

LUCs also represent sources of GHG emissions that may eventually counterbalance or exceed the GHG savings obtained from displacement of fossil fuels within the energy sector (Hamelin et al., 2014;

Figure 19 – GHG emission factor for the production of electricity and transport fuel for selected biomasses from the Danish food and water sector (Tonini et al., 2016b).



Searchinger et al., 2008; Tonini et al., 2016a). This logic also applies to emissions and effects other than GHGs and climate, for example N-emissions, P-depletion, or water stress impacts.

With respect to iLUC impacts, DTU Environment (Tonini et al., 2016a) quantified that demanding one hectare of arable land during one year corresponds to emissions of about 4100 kg CO₂-eq. For example, diverting one tonne (dry basis) of wheat to biogas induces the need for ca. 1600 m² of arable land corresponding to an emission of 660 kg CO₂-eq.

Outlook

Energy conversion of food and water sector residues through thermochemical or biological processes represents an important opportunity to produce bioenergy and mitigate climate change. Biogas and syngas production, because of their storability and versatility (i.e. they can be used directly for heat and power or be upgraded to transport fuels and chemicals) can provide the required flexibility of

future energy systems with high penetration of fluctuating sources (e.g. wind). Yet, the environmental benefits of bioenergy technologies highly depend upon the alternative management of the input-biomass as well as the surrounding energy system. Diverting substrates, even residual substrates, from the feed sector to the energy market may induce larger GHG emissions than the GHG savings obtained through displacement of fossil fuels, when LUC impacts are considered. Energy conversion of residues not competing with the feed sector is therefore recommended. In systems where wind is the main competitor for power generation, conversion to transport fuels, feed, and biomaterials is preferred over electricity and heat. In the Danish and European context, the largest potential for bioenergy production is found in manure, crop residues, and municipal food waste. DTU Environment has developed a user-friendly LCA tool, namely EASETECH, to perform the environmental assessment of any bioenergy and biomass systems.

Chapter 9

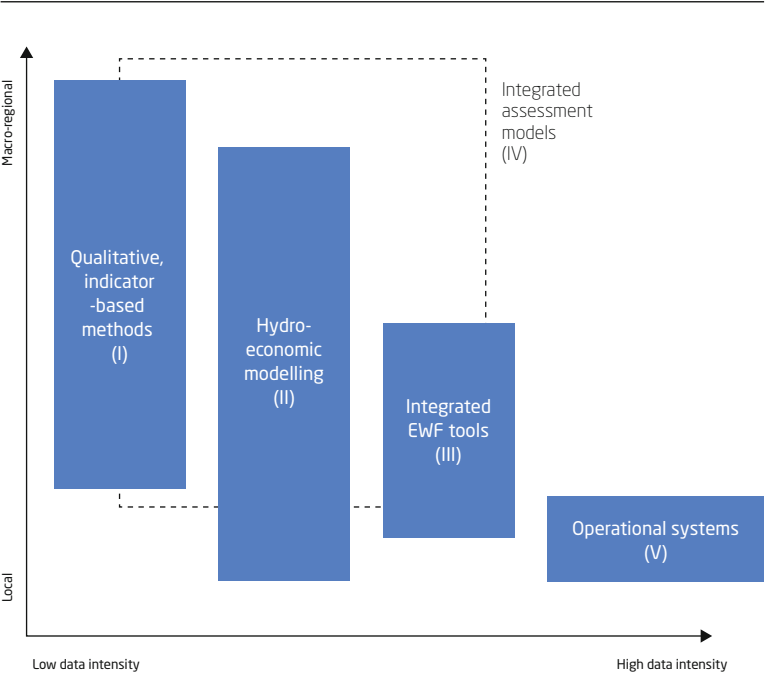
Methodologies for managing the Energy-Water-Food nexus at different scales

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Introduction

Systematic approaches are essential for understanding the coherence and competing demands of the Energy-Water-Food (EWF) Nexus not only at different temporal and spatial scales but also across multiple sectors and local climate conditions. Such tools are urgently needed e.g. to inform policy measures as well as technical actions that will ensure sustainable and efficient use of water resources, energy, and food production. In this chapter we highlight a collection of state-of-the-art methods and tools ranging from qualitative approaches like surveys and indicator-based analysis to more data-driven and quantitative modelling approaches that are suitable for analysing the complex interlinkages of the EWF nexus from global to local scales; to support decision-making and implementation of sustainable management strategies along multiple value chains within the nexus; and to strengthen collaboration between stakeholders. Finally, we present two examples on how to utilise the flexibility of water and food systems intelligently to increase the share of renewables and conversely how renewable energy can help to address the world’s pressing water, energy and food challenges.

Figure 20 – Overview of assessment tools and methodologies used for analysing aspects of the EWF nexus at different scales and with different levels of data intensity (adapted from Granit et al., 2013).



At the local level, nexus assessments at the appropriate scales might focus on integrated waste water management, energy production, or improved water and energy efficiency in agricultural production, which – if applied – may pave the way for new innovations to save water, reduce emissions, recycle nutrients, and to increase energy and food security. Similarly, within a region or ‘macro-region’ spanning two or more regions (e.g. countries) that are connected via transboundary energy and/or freshwater systems, sound assessment tools are needed to identify incentives to strengthen collaboration between actors at all levels from the macro-regional to the local. This includes market-based transactions, which can occur bilaterally between regions (e.g. flood protection and hydropower generation), at the regional level (e.g. trade of power and food), or at the global level (e.g. mitigating and adapting to climate change through the deployment of renewable energy sources).

Assessment tools and methodologies for integrated approaches

Decision-makers generally lack tools for understanding the interdependencies and trade-offs between water, energy and food systems that are integrative and multi-scale (e.g. Daher and Mohtar, 2015). Instead most existing tools and methodologies for resolving the energy-water-food nexus span a continuum, from almost purely qualitative approaches via mixed approaches to more data-driven and quantitative modelling (Granit et al., 2013). Likewise, the spatial and temporal scales span the whole range from the local (time scales down to hours or beyond for operational applications) to the regional or national (multi-decadal, climate change) scales. *Figure 20* summarises some of the common methodologies that are currently used by policy-makers at different levels e.g. as foundations for debate, discussion and action. As indicated in this schematic it is a range of different factors like access to data and models, which will generally decide what methodology is more applicable to a specific case, including the analysis objectives, capacity (and trust) of competing stakeholders and sectoral integration (Granit et al., 2013). As exemplified in *Table 9* (based on IRENA, 2015) each approach offers important advances in terms of analysing separate aspects of the EWF nexus and uses different methods for looking at distinct flows between the separate nexus systems.

Table 9 – Examples of tools and methodologies for assessing the EWF nexus at different scales.

Tool and reference	Type*	Description
Transboundary Waters Opportunity Analysis (Phillips et al., 2008)	I	Qualitative approach for assessing the EWF nexus at a highly aggregated level
FAO’s Nexus Assessment Methodology (Flammini et al., 2014)	I	Qualitative approach for assessing the EWF nexus based on indicators that are already available, including country typologies
MuSIASEM (FAO, 2013)	I	Characterizes the flows of water, energy and food systems in society; employs a range of socio-economic indicators, including availability of land and climate change impacts
Hydro-economic modelling (Harou et al., 2009; Booker et al., 2012)	II	EWF policies maximizing the system-wide welfare are identified by hydro-economic optimisation using methodologies from operations analysis
CLEWS (Climate, Land-use, Energy and Water Strategies) (Howells et al., 2013)	III	Integrates the LEAP energy model, WEAP water model and AEZ land-use model with climate change scenarios. Module-based approach where data are passed between sectoral models in an iterative fashion to establish e.g. water requirements in the land-use and energy systems; energy needs for water supply and land-use; and land requirements for energy and water infrastructure
Water, Energy, Food Nexus Tool 2.0 (Daher and Mohtar, 2015)	III	Scenario-based framework and a set of methodologies that define the linkages between the interconnected resources of water, energy and food, and enable explicit corresponding quantifications
PRIMA (Platform for Regional Integrated Modelling and Analysis) (Kraucunas et al.,2014)	IV	Integrated approach which explicitly combines a regional climate model/impact models with a modular integrated assessment model; PRIMA can virtually address all scales
TRBNA (Transboundary River Basin Nexus Approach) (de Strasser et al., 2016)	I-III	Combines elements of hydro-economic modelling, WEAP-LEAP models and FAO’s Nexus Assessment Methodology with a novel approach to assess the governance aspects of the EWF nexus

See also IRENA (2015).
* The Roman numerals refer to Figure 21.

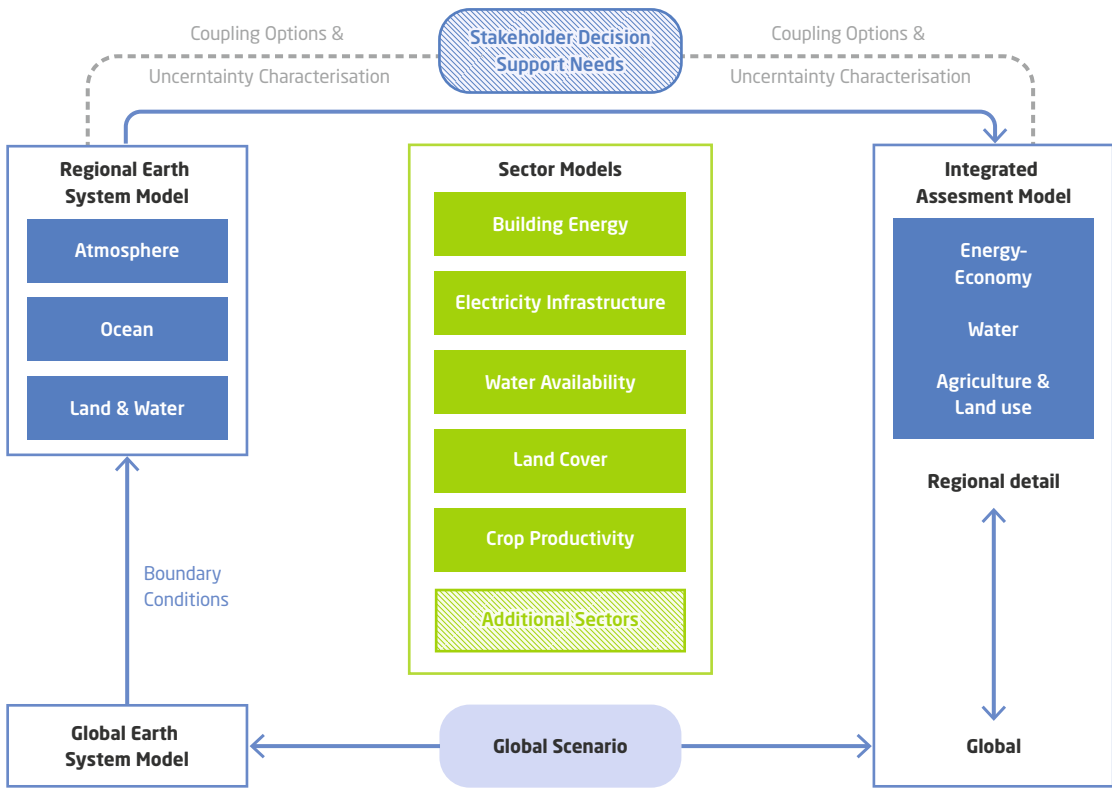
The **Transboundary Waters Opportunity Analysis** proposed by Phillips et al. (2008) is an example of a qualitative approach to assess key development opportunities in the EWF nexus at a highly aggregated level, while taking into account qualitative assessments of water resource constraints. It is used to explore benefits to be generated and shared, and for stakeholders to identify drivers, barriers and as well as preferred options e.g. how to mitigate pressures or use limited water resources more efficiently and innovatively. This approach can also represent an initial step towards more quantitative analyses, as well as for assessments of institutional and policy options. Correspondingly, an index building approach addresses the macro-regional scale using a core set of indicators for key sectors based on stakeholder surveys and relevant datasets that are publicly available. Based on this foundation an initial analysis is carried out i.e. to identify important issues for stakeholders at the macro-regional level to consider.

Hydro-economic modelling (e.g. Harou et al., 2009; Booker et al., 2012), also called hydro-economic

optimisation, is a quantitative and more data intensive approach to nexus assessments, which is well suited for regional applications but which can be applied at virtually any scale e.g. from macro-regional (e.g. European-scale) applications down to modelling a single pump-and-storage plant. The hydro-economic approach has emerged as a privileged tool for both informing and operationalising integrated water resources management (IWRM; Global Water Partnership); however, the use of (optimising) economic objectives is well-known in pretty much any context within the field of operations analysis. It addresses the hydrologic, engineering, environmental and economic aspects of water resources systems within a coherent framework, where economic concepts for water valuation and allocation are operationalised by bringing them into the core of water resource management models.

Integrated EWF tools like for example the Water Evaluation and Planning (WEAP) and Long Range Energy Alternatives System Planning (LEAP) models developed by the Stockholm Environment Institute

Figure 21 – The Platform for Regional Integrated Modelling and Analysis (PRIMA).
Source: Kraucunas et al. (2014).

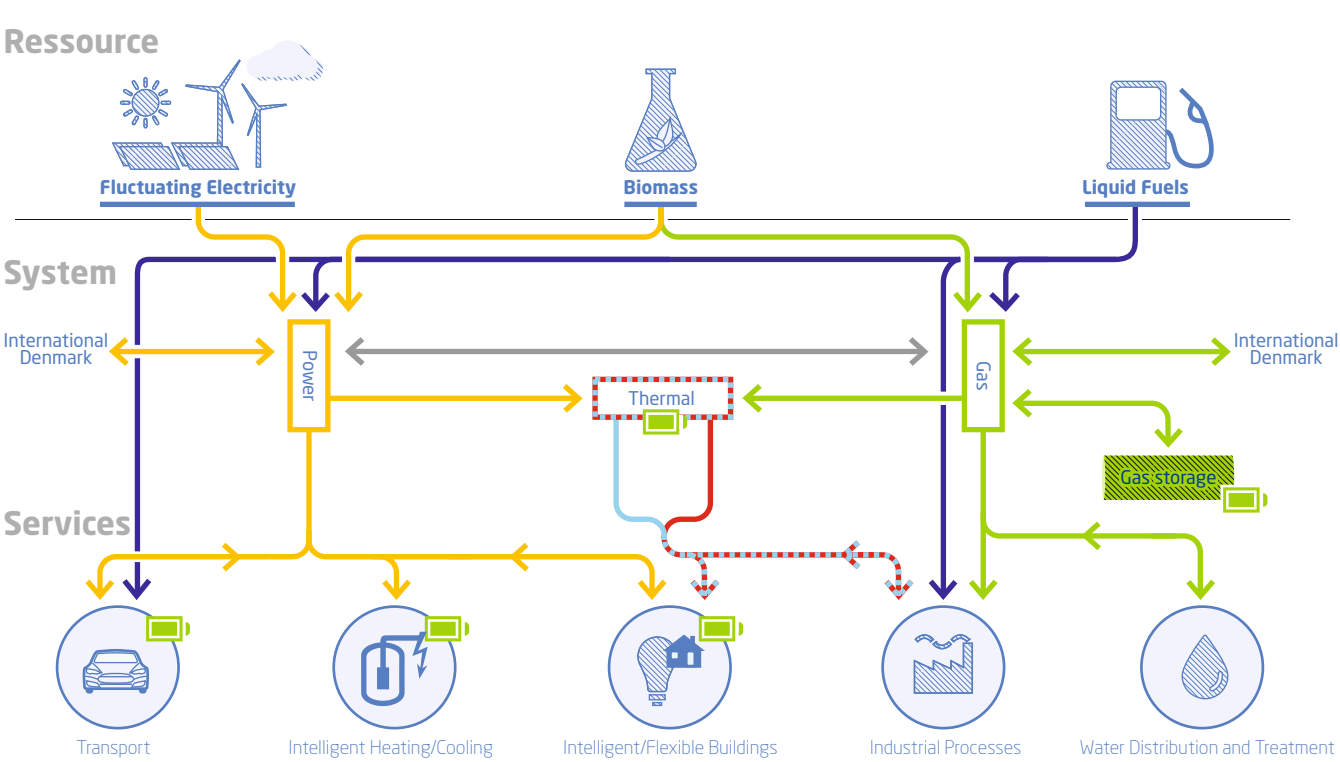


(Howells et al., 2013; Welsch et al., 2014; Dale et al., 2015) are sector-specific and data-intensive modelling approaches, which can often be linked explicitly to e.g. land use through Graphical Information Systems. Tools like the integrated CLEWS framework (Howells et al., 2013), which combines the WEAP/LEAP models with the Agro-Ecological Zoning (AEZ) land use model are – if combined with deep stakeholder involvement – well suited to support national and local planning at regional to macro-regional levels; moreover they can be used to assess conflicting nexus needs between water, land and energy for e.g. agricultural intensification and food, biofuels and hydropower production in relation to dedicated sectors, such as tourism and water for industry and domestic use. In the same manner **integrated assessment models** e.g. GCAM (Edmonds et al., 1997), or extended energy system models e.g. OSeMOSYS (Howells et al., 2011) can offer valuable insight into the Energy-Water-Food Nexus at aggregated scales. Current trends within the

field of integrated assessment models tend to favour higher resolutions and higher complexities in order to provide seamless and decision-relevant information at all relevant spatial and temporal scales, considering both present conditions and future scenarios. One of the most ambitious of these initiatives is the Platform for Regional Integrated Modelling and Analysis (PRIMA), shown in *Figure 21*, which was recently developed by the Pacific Northwest National Laboratory (Kraucunas et al., 2014). PRIMA is designed to simulate the complex interactions among climate, energy, water, and land use using a flexible modular approach. Thus, the PRIMA framework uniquely combines the capabilities of state-of-the-art global/regional climate and integrated assessment models with a plethora of sector models covering e.g. energy demands, energy infrastructure, water, land cover and food production at different scales.

At the end of the continuum (*Figure 20*) are **operational tools** for managing the Energy-Water-Food

Figure 22 – Conceptual approach for integrating energy, water, and food systems in an urban context.
Figure provided by the Centre for IT-Intelligent Energy System in Cities, <http://smart-cities-centre.org>.



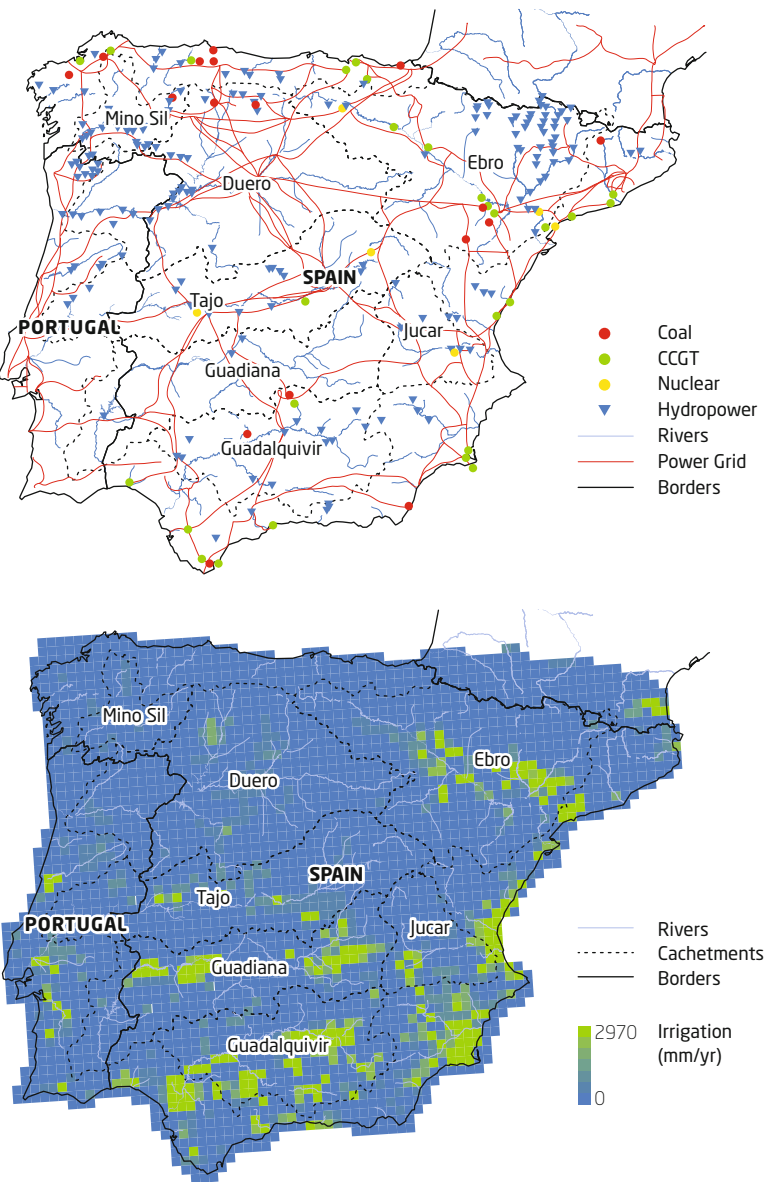
Nexus at the local scale. These tools include ICT-intelligent systems for real-time model predictive control and optimisation, which are extremely data intensive and highly localised. To exemplify *Figure 22* shows a conceptual approach for integrating energy, water, and food systems in an urban context. In this methodological example fluctuating renewables like wind and solar PV and can be shared in the best possible way with hydropower and biomass under the constraint of energy and water security by intelligent real-time control of the energy demand e.g. related to the use of water for industrial processes as well as water distribution and treatment.

A potential criticism which would seem to apply to all of the abovementioned methodologies is that while they collectively span all scales, they are not formally linked. For this aim the methodology of a Transboundary River Basin Nexus Approach (TRBNA) was recently proposed by de Strasser et al. (2016). The idea behind the TRBNA approach is

"to increase the integration and coordination in management and governance across sectors and scales, particularly in water and land resources planning" (de Strasser et al., 2016). Hence the methodology synthesises elements from all the different approaches, notably a quantitative basin approach similar to hydro-economic modelling and closely related to the IWRM approach; the climate, land use, energy and water strategies framework underpinned by the WEAP/LEAP models (Howell et al. 2011); the (qualitative) nexus approach developed in the Food and Agriculture Organisation of the United Nations (e.g. Flammini et al. 2014); and finally a novel approach to assess the governance aspects of the Energy-Water-Food Nexus (de Strasser et al. 2016).

In the following we will exemplify and further discuss two of the abovementioned methodologies based on ongoing work at Technical University of Denmark i.e. a hydro-economic method for exploiting the synergies of both renewable and non-renewable energy

Figure 23 - The Iberian Peninsula: Water and power systems (upper) and irrigation agriculture (lower).



sources, water and food services in the Iberian Peninsula; and an approach based on model-predictive control for optimal management of urban drainage and waste water systems in Kolding, Denmark, which maximises the usage of wind energy.

Cross-sectorial opportunities for coordinating energy, water, and food services and to exploit the benefits of synergies

As mentioned above developing integrated system-scale approaches for managing food, energy and water resource systems under climate change is one of today’s key challenges. In this case study we use a hydro-economic approach to quantify the trade-offs between “water for food,” “water for energy” and “water for ecosystems” at high temporal and coarse-to-intermediate spatial resolution under a range of climate change scenarios. Such information is essential for supporting scheduling and planning decisions in the water, energy and agricultural sectors. Also, the hydro-economic approach provides a consistent framework to evaluate infrastructure investments (e.g. upgrades of the power grid, new hydraulic infrastructure) from an integrated system-scale perspective. In the following the specific focus is on economic trade-offs in the use of “blue” water, which here refers to conventional liquid fresh-water resources drawn from aquifers, rivers, lakes, and dams; as opposed to “green” water e.g. moisture in the soils and the vapour flows back to the atmosphere (Falkenmark and Rockström, 2006).

The hydro-economic modelling is a well-established methodology at the interface between water resources engineering and economics (Harou et al., 2009; Booker et al., 2012). By hydro-economic optimisation we aim to determine the water allocation policy that maximises system-wide welfare over a given planning period, taking into account the stakeholders’ willingness-to-pay for water at all use locations as well as the river basin connectivity and available water storage facilities. Since future water availability is uncertain, allocation becomes a stochastic dynamic optimisation problem. Different strategies for solving such problems have been developed, including stochastic dynamic programming (SDP), stochastic dual dynamic programming (SDDP) and evolutionary algorithms (e.g. Labadie, 2004; Nicklow et al., 2010).

At the heart of the EWF nexus problem is the determination of ‘willingness-to-pay’ for water (the value of water) in the energy, agricultural and environmental sectors. Traditionally, water engineers have derived the sectoral willingness-to-pay for water from external prices of energy, of crops and from the valuation of ecosystem services (Booker et al., 2012; Young, 2005). At the system scale, decisions in the water sector will thus affect prices for food and energy. Recent work at the Department of Environmental Engineering (DTU Environment) has addressed this problem by coupling basin-scale water models to a simple merit-order representation of the energy market, where energy prices are internal variables determined by the equilibrium of supply and demand (Pereira-Cardenal et al., 2016, 2015, 2014). Figure 23 shows the configuration of the water, energy (power) and agricultural systems on the Iberian Peninsula. The Iberian Peninsula has 7 major river basins, which are equipped with significant hydropower facilities for renewable power generation; hydropower contributes approx. 15% of the Iberian power mix. The rivers provide water to a large number of thermal and nuclear power stations as well as to important aquatic ecosystems. Up to 80% of the consumptive water use is used for irrigation (Garrido et al., 2010) and contributes significantly to the agricultural output in the area.

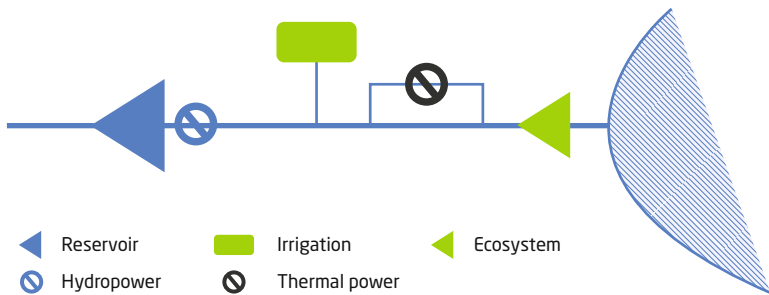
In the present optimisation approach, each individual river basin is conceptualised as illustrated in Figure 24. The basin system for the Iberian Peninsula consists of water storage facilities, hydropower stations, irrigation districts, thermal power stations (which have cooling water requirements) and riverine ecosystems. Surface water availability is estimated using a regional-scale rainfall-runoff model and constraints on groundwater abstraction are enforced. The objective function at basin level is to maximise basin-scale welfare subject to constraints related to water availability, water use by different infrastructure, cooling water requirements and ecological flow constraints. Individual basins are linked by market clearing conditions for energy and/or agricultural products.

We implement our hydro-economic model using the simple merit-order approach described in Pereira-Cardenal et al. (2014). The stochastic inter-temporal allocation problem is solved using stochastic

dynamic programming (Stedinger et al., 1984) at the aggregate level and stochastic dual dynamic programming (Pereira and Pinto, 1991) at higher spatial resolution. A semi-discrete variant of stochastic dynamic programming known as the ‘water value’ method (Stage and Larsson, 1961) has previously been used to solve both pure water allocation problems (Davidsen et al., 2014) and coupled water-energy problems (Pereira-Cardenal et al., 2014). This stochastic dynamic programming variant is found to be particularly well suited for adaptive optimisation, since it does not only provide a single optimal solution but also provides optimal decision rules from any given state of the system at any given point in time. Thus, decisions can easily be adapted to the latest input on the states of crop and vegetation e.g. as obtained from near real-time remote sensing data.

Fixed exogenous energy prices have traditionally been used in studies of water resources optimisation. Such approaches are appropriate when modelling relatively small hydropower plants, which can be safely considered as “price takers.” However, when optimising water and power at systemic scales, hydropower becomes a “price maker” and power prices have to be endogenously determined in the modelling system. This is particularly important for systems with large shares of hydropower and other renewable energy sources. Due to the high intermittency of solar and wind power production, hydropower has a key role in balancing the energy system. Pereira-Cardenal et al. (2015) demonstrate that reasonable hydropower operation rules can only be obtained if the price feedbacks from the energy system are taken into account. On the other hand, hydropower scheduling needs to take into

Figure 24 - Conceptual river basin model.



account water demands from the agricultural, domestic and industrial sectors as well as environmental flow requirements in order to avoid excessive curtailment costs for those users. In the optimisation approach presented here, willingness-to-pay for water is therefore compared across space, time and use sectors in order to minimise total cost to society (or maximise welfare).

A further challenge for joint water-energy-food optimisation models is spatial and temporal aggregation. Due to limits in data availability and computational resource systems both have to be represented at a highly aggregated level when working at regional to continental scale. Pereira-Cardenal et al. (2016) present results for the Iberian Peninsula obtained at two different levels of spatial aggregation: peninsular scale and river basin scale. When resolving the river basin scale, different operation strategies are revealed for different river basins. While some river basins “specialise” in irrigation agriculture, others are managed primarily to benefit the energy system. This leads to heterogeneous water allocation and power production patterns, which are averaged out when modelling at regional scale. Temporal aggregation causes similar issues, because time scales in the water and energy systems are significantly different. Most modern power markets operate at hourly or shorter time scales, while hydrologic processes and the hydraulic infrastructure have inherent time scales of days and longer.

Lastly, a key question is how trade-offs between water for food, water for energy and water for ecosystems are going to change under the future climate. A number of effects are important in this context: Climate change will change water availability, water demands (especially in irrigation agriculture) and energy demand (due to changes in heating/cooling requirements). Also, cooling constraints on thermal power production may be significantly affected as outlined in Chapter 5. Pereira-Cardenal et al. (2014) compare optimal policies as well as costs for a baseline period (1961-1990) and a scenario period (2036-2065). Under a climate change scenario causing lower precipitation and higher temperatures and consequently reduced water availability and increased irrigation demand on the IP, the authors find an estimated reduction in hydro-power production of 24% (from 11.5% to 8.7% of

mean annual generation), and an increase in thermal power generation by 6.7% (from 40.5% to 43.3%). These changes to the energy mix increases annual CO₂ emissions from the Iberian energy sector from 71.9 to 76.9 million tons. Similarly, higher expected temperatures modify the seasonal energy demand by reducing the winter demand and increasing the summer demand.

Optimal management of urban drainage and waste water systems for maximising wind energy usage

Management of waste water treatment is undergoing an important paradigm shift: from a source of environmental impacts, where pollutants need to be removed before discharge to the environment, waste water has become a valuable resource, with nutrients and other materials (e.g. bioplastics) being increasingly recovered from the water fluxes for reuse in e.g. agriculture (Gao et al., 2014; Olsson et al., 2014; Mo & Zhang, 2013). The transition from the “traditional” Waste water Treatment Plant (WWTP) to a Water Resource Recovery Facility (WRRF) implies new management objectives, which also include energy optimisation (Sweetapple et al., 2015). This objective embraces both reduction of energy costs and utilisation of electricity sources with lower CO₂ impact, creating a new link between the water and the energy sectors at the urban scale as well as connections with food production.

The principal condition to achieve an optimal operation of a WRRF is the availability of a storage capacity where waste water can be stored and subsequently treated when operating conditions are favourable, e.g. when wind-power is predominant and thus operating prices are lower. When looking at the existing urban water infrastructures, current WRRFs do not in general have the necessary capacity to store the large volumes which are necessary to obtain significant benefits. The urban drainage network, on the other hand, is designed to cope with large volumes of storm water during rain events, resulting in a storage capacity that is not fully exploited during dry weather periods. By implementing an integrated control system, it is possible to store the waste water in the drainage network and then pump it to the WRRF when needed. A first example of this integrated control can be found in Kolding, Denmark, where the WRRF characteristics allow

for a storing waste water in the drainage network for several hours (Bjerg et al., 2015).

An optimal control strategy has to consider to multiple objectives: the WRRF needs to comply with effluent quality criteria (in Denmark those are reinforced by taxation on pollution discharge), while maximising resource recovery and minimising energy costs. The drainage network, at the same time, must be able to fulfil its original purpose, i.e. managing waste water and storm water without causing health and flood risks in urban areas. This requires merging different information and forecasts regarding plant operations, future evolution of energy prices, and expected weather characteristics. In the Kolding case, a model predictive control (Halvgaard et al., 2015) developed at the Department of Mathematics and Computer Science (DTU Compute) regulates the inflow to the WRRF by taking into account the expected variations in electricity prices (which have an hourly resolution and are available on a daily basis) and the most energy demanding process in the WRRF, namely ammonia removal (which requires updated set points every 2 minutes). Well-established models for simulating biological nutrient removal processes was simplified and adapted to operate in on-line conditions. Also, waste water represents a harsh environment for the sensors providing the data necessary for plant operations: malfunctioning and erroneous measurements are an inherent part of controlling a WRRF. Therefore, a stochastic approach was adopted to cope with sensor malfunctioning and other uncertainties affecting the available measurements.

To distinguish between dry weather (when the drainage network cooperates with the WRRF to optimise energy usage) and wet weather (when the system switches back to its original storm water conveyance purpose), a PhD project is currently carried out at DTU Environment to investigate the use of forecasts generated by Numerical Weather Prediction models (Courdent et al., 2016). These forecasts (generated every 6 hours by the Danish Meteorological Institute) predict the future evolution of the weather over 48 hours, but they are affected by uncertainty. Hence the overall control procedure must be able to merge data and model simulations seamlessly though characterised by different temporal resolutions, levels of detail, and levels of uncertainty. The results are

promising and suggest that this new integrated control is able to fully exploit the existing infrastructures, optimising the performance of the WRRF also with respect to energy consumption, while at the same time maximising the usage of wind power.

Conclusions and recommendations

As outlined in previous chapters the EWF nexus approach endorsed by e.g. the United Nations Food and Agricultural Organization (FAO), the World Bank etc. largely breaks with traditional policy-making practices, where various supply chains that deliver essential services to society are often managed in ‘silos,’ i.e. where the silos can represent different sectors but also different institutional actors. Conversely, research has clearly demonstrated the advantages of integrated resources management (Howells and Rogner, 2014). In this chapter we discuss different examples of quantitative, qualitative, and mixed assessment methodologies ranging from purely qualitative to highly data-intensive and data-driven approaches suitable for underpinning the EWF nexus approach; we demonstrate and argue the potential for such methods to increase our understanding not only of the interdependencies but also of the constraints of water, energy and food systems both at different scales and across multiple sectors. Arguably, there is a critical need to further develop, implement and evaluate such systematic approaches in order to facilitate efficient policy-making and develop strategies accommodating climate change and socio-demographic development; strengthen the collaboration with stakeholders; identify measures for cooperative governance and management that support outcomes along multiple value chains within the nexus; and ultimately to achieve the Sustainable Development Goals (Granit et al., 2013). It is the aim and a principal, recommendation of this chapter to inspire further work within this area.

Another important conclusion from our discussion of different tools and examples is that lack of access to quality data often serves as a major constraint for the application of integrated methods (a detailed discussion is provided in e.g. IRENA, 2015). Hence many of the reviewed tools require extensive data input, and often the required data sets are unavailable. This may include separate information about the different elements of the EWF nexus like renewable and non-renewable energy resources,

their production potential, and costs, accessibility of water resources, the availability and quality of land resources, different levels of food self-sufficiency, climate change impacts, etc. Similarly, detailed data are required on how the different elements of the nexus relate to each other like energy consumption in water treatment processes, water usage by energy production, and land-use requirements for power generation. Needless to say, it is essential for confidence in the results of a nexus analysis, e.g. in terms of decision-support, to understand the data requirements and the specific difficulties of data collection across the interconnected nexus systems. Here the cross-sectoral and multi-scale nature of the EWF nexus adds to the difficulty of collecting and compiling information. Finally, even in cases where data is available, comparability may be a significant challenge since methodologies for data collection and classifications tend to vary between sectors. As a result the use of nexus assessment tools benefits greatly from standardised data collection routines.

Chapter 10

Abbreviations

AEZ	Agro-Ecological Zoning land use model	OF	Organic farming
BTu	British thermal unit, a measure of energy	OSeMOSYS	Extended energy system model
CA	Conservation agriculture	OT	Once-through cooling
CAES	Compressed air energy storage	OTEC	Ocean Thermal Energy Conversion
CCGT	Combined cycle gas turbines	P	Phosphor
CCS	Carbon capture and storage	PJ	Petajoule
CCSU	Combination of carbon capture storage and carbon capture and utilisation	PRIMA	Regional Integrated Modelling and Analysis
		PRO	Pressure retarded osmosis
CCU	Carbon capture and utilisation	PV	Photovoltaics
CH ₄	Methane	RED	Reverse electro-dialysis
CLEWS	Combines the WEAP/LEAP models with the Agro-Ecological Zoning (AEZ) land use model	SDDP	Stochastic dual dynamic programming
		SDP	Stochastic dynamic programming
CO ₂	Carbon Dioxide	SGP	Salinity-gradient power
COD	Chemical Oxygen Demand	SMRs	Small modular (nuclear) reactors
CSP	Concentrated Solar Power	SRT	Solids retention time
dLUC	Direct land use change	SS	Suspended solids
EGS	Enhanced geothermal systems	SWRO	Seawater reverse osmosis
EmA	Emergy Assessment	TRBNA	Transboundary River Basin Nexus Approach Model
EWf	Energy-Water-Food Nexus	UF	Ultrafiltration
FO	Indirect energy recovery forward osmosis	WEAP	Water Evaluation and Planning Model
GCAM	Integrated assessment model	WRRF	Water Resource Recovery Facility
GHG	Greenhouse gasses	WWTP	Waste water treatment plant
H ₂ S	Hydrogen sulphide		
HRT	Hydraulic retention time		
iLUC	Indirect land use changes		
IS	International System of Units		
LCA	Life Cycle Assessment		
LEAP	Long Range Energy Alternatives System Planning Model		
MBR	Aerobic membrane bioreactor		
MF	Microfiltration		
MMBTu	One million Btu		
N	Nitrogen		
N ₂ O	Nitrous oxide		
NEA	Net Energy Analysis		
NH ₃	Ammonia		
NH ⁴⁺	Ammonium		
NO ³⁻	Nitrate		
NO _x	Mono-nitrogen oxides		

Chapter 11

References

Chapter 4

B

Bach, et al. (2014). Cooperation for Water, Energy and Food Security in Transboundary Basins under Changing Climate. Retrieved 08 01, 2016, from Mekong River Commission, Lao PDR: <http://www.mrcmekong.org/assets/Publications/conference/MRC-intl-conf-publ-2014.pdf>

E

European Commission (2012). The 2011/2012 European Report on Development, Confronting Scarcity: Managing Water, Energy and Land for Inclusive and Sustainable Growth.

European Commission (2015). Strategic Foresight: Towards th 3rd Strategic Programme of Horizon 2020.

European Commission, Horizon 2020 (2015). SIM4NEXUS – Sustainable Integrated Management FOR the NEXUS of water-land-food-energy-climate for a resource-efficient Europe. Project reference: 689150.

European Environmental Agency (2012 a). European waters — current status and future challenges EEA Report No 9/2012.

European Environmental Agency (2012 b). Towards efficient use of water resources in Europe EEA Report No 1/2012.

F

FAO (2009). Looking ahead in world food and agriculture: Perspectives to 2050. Edited by Piero Conforti. Data and graphics from Chp 6: The resources outlook: by how much do land, water and crop yields need to increase by 2050? by Jelle Bruinsma.

FAO (2014). The Water-Energy-Food Nexus: A new approach in support of food security and sustainable agriculture. FAO.

Field, et al. (2014). Technical summary. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change.

H

Hoff, H. (2011). Understanding the Nexus. Background Paper for the Bonn2011 Conference: The Water, Energy and Food Security Nexus. Stockholm Environment Institute.

Holzwarth, F. (2014). Cooperation for Water, Energy and Food Security in the Transboundary Basin under Changing Climate, Ho Chi Minh City, Vietnam.

I

Ignacy Sachs, D. S. (1990). United Nations University website (old version). Retrieved 03 15, 2016, from Food and Energy – Strategies for Sustainable Development: <http://archive.unu.edu/unupress/unupbooks/80757e/80757E00.htm#Contents>

International Energy Agency (2012). World Energy Outlook 2012. International Energy Agency.

International Energy Agency (2014). World Energy Outlook 2014, Paris 2014. Paris: International Energy Agency.

IUCN and IWA (2013). Nexus Dialogue on Water Infrastructure Solutions: <http://www.waternexusolutions.org>

O

OECD (2012). Environmental Outlook to 2050: The Consequences of Inaction.

Olsson, G. (2015). Water and energy – Threats and opportunities 2nd edition. London: IWA Publishing.

R

REN21 (2015). RENEWABLES 2015 – GLOBAL STATUS REPORT. REN21.

S

Safi, A.M. (2016). Water in the Gaza Strip: An Evolution of Protracted Crisis and Persistent Adaptation.

T

The Bonn Nexus conference (2014). Sustainability in the Water-Energy-Food Nexus: Call to Action. Bonn.

The Economist (2015, August 4). Daily chart: Growth areas, Global population forecasts. Retrieved 10 3, 2016, from Graphic detail: <http://www.economist.com/blogs/graphicdetail/2015/08/daily-chart-growth-areas>

The Federal Government of Germany, The Water, Energy & Food Security Nexus Resource Platform: <http://www.water-energy-food.org>

U

UN DESA (2014). World Population Prospects: the 2014 Revision. United Nations, Department of Economic and Social Affairs (DESA), Population Division.

UN DESA (2015). World Population Prospects: the 2015 Revision. United Nations, Department of Economic and Social Affairs (DESA), Population division.

United Nations (2002). Report of the World Summit on Sustainable Development. Johannesburg: United Nations.

W

World Bank (2014). Securing energy in a water-constrained world. World Bank.

World Economic Forum (2008). Managing our Future Water Needs for Agriculture, Industry, Human Health and the Environment – Discussion Document for the World Economic Forum Annual Meeting 2008. World Economic Forum.

World Economic Forum (2011). Water Security, The Water-Food-Energy-Climate Nexus, The World Economic Forum Water Initiative.

World Energy Council (2016). The Road to Resilience – Managing The Risks of The Energy-Water-Food Nexus. World Energy Council.

Chapter 5

A

ANL (Argonne National Laboratory) (2010). Water use in the Development and Operation of Geothermal Power Plants, Report ANL/EVS-10/5. Available at: http://www1.eere.energy.gov/geothermal/pdfs/geothermal_water_use_draft.pdf (latest access 1 Aug.2016)

DTU International Energy Report 2016

DTU International Energy Report 2016

ANL (Argonne National Laboratory) (2014). Geothermal Water Use: Life Cycle Water Consumption, Water Resource Assessment and Water Policy Framework, Report ANL/EVS-14/2. Available at <http://www.evs.anl.gov/downloads/ANL-EVS-14-2.pdf> (latest access 1 Aug. 2016)

B **Blakers, A., Pittcock, J., Talent, M., and Markham, F. (2010).** Pumped hydro for large scale storage of solar generated electricity in Australia. Solar 2010, 48th Annual Conference of the Australian Solar Energy Society (AuSES).

Byers, E. A., Qadrdan, M., Kilsby, C. G., Tran, M., Alderson, D., Leathard, A., Chaudry, M., Amezaga, J. M., and Hall, J. W. (2015). Cooling water for Britain's future electricity supply. Proceedings of the Institution of Civil Engineers – Energy 168 (3) , pp. 188-204. 10.1680/ener.14.00028

C **Clark, C. E., Harto, C. B., Schroeder, J. N., and Anderson, A. (2015).** The Geothermal Energy–Water Nexus. World Geothermal congress, Melbourne, Australia, 19-25 April, 2015.

Cuéllar-Franca, R. M., and Azapagic, A. (2015). Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life cycle environmental impacts. Journal of CO2 Utilization, Volume 9, March 2015, Pages 82-102, doi:10.1016/j.jcou.2014.

D **de Fraiture, C., Giordano, M., and Liao, Y. (2008).** Biofuels and implications for agricultural water use: blue impacts of green energy. Water Policy 10 Supplement 1, 67-81.

E **EPA (United States Environmental Protection Agency) (2012).** Guidelines for Water Reuse. EPA/600/R-12/618, September 2012. Available at <http://nepis.epa.gov/Adobe/PDF/P100FS7K.pdf> (latest access 1 Aug. 2016).

EPRI (2008). Water Use for Electric Power Generation, Palo Alto, CA: 1014026. Full report available at <http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=0000000000001014026> (latest access 1 Aug. 2016)

Eurostat (2016). Primary production of renewable energy by type (Tide, Wave and Ocean). Database accessed on 28/5-2016 (<http://ec.europa.eu/eurostat/data/database>)

F **FAO (2011).** Cooling water for energy generation and its impact on national-level water statistics, FAO AQUASTAT Report, by Kohli, A., and Frenken, K. Available at <http://www.fao.org/3/a-bc822e.pdf> (latest access 1 Aug. 2016)

Farooq, W., Suh, W. I., Park, M. S., and Yang, J.-W. (2014). Water use and its recycling in microalgae cultivation for biofuel application. Bioresource Technology, Volume 184, May 2015, Pages 73-81, doi:10.1016/j.biortech.2014.10.140

G **GAO (2009).** Energy-Water Nexus – Improve-ments to Federal Water Use Data Would Increase Understanding of Trends in Power Plant Water Use. US Government Accountability Office, Report no. GAO-10-23. Available at <http://www.gao.gov/products/GAO-10-23> (latest access 1 Aug. 2016).

H **Hoekstra, A. Y., Mekonnen, M. M., Chapagain, A. K., Mathews, R. E., and Richter, B. D. (2012).** **Global Monthly Water Scarcity:** Blue Water Footprints versus Blue Water Availability. PLoS ONE 7(2): e32688. doi:10.1371/journal.pone.0032688

I **IEA (International Energy Agency) (2011).** World Energy Outlook 2011. Outlook (Vol. 23). Full report available at https://www.iea.org/publications/freepublications/publication/WEO2011_WEB.pdf (latest access 1 Aug. 2016).

IEA (International Energy Agency) (2012). Water for Energy – Is energy becoming a thirstier resource? Excerpt from the World Energy Outlook 2012. Available at <http://www.worldenergyoutlook.org/weo2012/> (latest access 1 Aug. 2016)

IEA-ETSAP and IRENA (2013). Thermal Energy Storage – technology brief. Available at <https://www.irena.org/DocumentDownloads/Publications/IRENA-ETSAP%20Tech%20Brief%20E17%20Thermal%20Energy%20Storage.pdf> (latest access 1 Aug. 2016).

IPCC (2014). Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. Available at https://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_full.pdf (latest access 1 Aug. 2016)

J **JISEA (Joint Institute for Strategic Energy Analysis) (2015).** Concentrating Solar Power and Water Issues in the U.S. Southwest, Technical Report, NREL/TP-6A50-61376. Available at <http://www.nrel.gov/docs/fy15osti/61376.pdf> (latest access 1 Aug. 2016)

L **Li, Q., Wei, Y.-N., and Chen, Z.-A. (2016).** Water-CCUS nexus: challenges and opportunities of China's coal chemical industry, Clean Techn Environ Policy, 18:775-786, DOI 10.1007/s10098-015-1049-z.

M **Mekonnen, M. M., and Hoekstra, A. Y. (2011).** The water footprint of electricity from hydropower, Value of Water Research Report Series No. 51, UNESCO-IHE, Delft, the Netherlands.

Mielke, E., Anadon, L. D., and Narayanamurti, V. (2010). Water Consumption of Energy Resource Extraction, Processing and Conversion, Discussion Paper #2010-15, Energy Technology Innovation Policy, Discussion Paper Series, Harvard Kennedy School. Available at <http://belfercenter.ksg.harvard.edu/files/ETIP-DP-2010-15-final-4.pdf> (latest access 1 Aug. 2016)

N **Najjar, Y. S. H., and Zaamout, M. S. (1998).** Performance analysis of compressed air energy storage (CAES) plant for dry regions. Energy Conversion and Management, Volume 39, Issue 15, October 1998, Pages 1503-1511, doi:10.1016/S0196-8904(98)00034-X.

NETL (National Energy Technology Laboratory) (2011). Estimating Freshwater Needs to Meet Future Thermal Generation Requirements, DOE/NETL-2011/1523. Available at https://www.netl.doe.gov/energy-analyses/temp/FY12_EstimatingFreshwaterNeedsToMeetFutureThermoelectricGenReqs2011Update_100111.pdf (latest access 1 Aug. 2016).

NREL (National Renewable Energy Laboratory) (2011). A Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies, Technical Report NREL/TP-6A20-50900. Available at: <http://www.nrel.gov/docs/fy11osti/50900.pdf> (latest access 1 Aug. 2016)

O **OECD (2012).** **OECD Environmental Outlook to 2050:** The Consequences of Inaction, OECD Publishing, Paris. DOI: doi.org/10.1787/9789264122246-en. Available at <http://www.oecd.org/env/indicators-modelling-outlooks/oecdenvironmentaloutlookto2050theconsequencesofinaction.htm> (latest access 1 Aug. 2016)

Olsson, G. (2015). Water and energy- Threats and opportunities 2nd edition, IWA Publishing, London.

S **Schaeffli, B., Hingray, B., and Musy, A. (2007).** Climate change and hydropower production in the Swiss Alps: quantification of potential impacts and related modelling uncertainties. Hydrol. Earth Syst. Sci., 11, 1191-1205, doi:10.5194/hess-11-1191-2007

Spang, E. S., Moomaw, W. R., Gallagher, K. S., Kirshen, P. H., and Marks, D. H. (2014). The water consumption of energy production: an international comparison. Environ. Res. Lett. 9 (2014) 105002 (14pp)

V **Van Vuuren, D. P. et al. (2011).** The representative concentration pathways: an overview. Climatic Change (2011) 109:5-31, doi:10.1007/s10584-011-0148-z

W **WwAP (2006).** United Nations World Water Assessment Programme, Water – A shared responsibility, The United Nations World Water Development Report No 2. Executive summary p43. Full report available at <http://unesdoc.unesco.org/images/0014/001454/145405E.pdf> (latest access 1 Aug. 2016)

WwAP (2014). United Nations World Water Assessment Programme. Water and Energy. The United Nations World Water Development Report. Paris, UNESCO. Available at <http://unesdoc.unesco.org/images/0022/002257/225741E.pdf> (latest access 1 Aug. 2016)

Chapter 6

B **Brudler, S., Arnbjerg-Nielsen, K., Hauschild, M. Z., and Rygaard, M. (2016).** Life cycle assessment of stormwater management in the context of climate change adaptation. Water Research, 106, 394-404. doi: 10.1016/j.watres.2016.10.024

C **City of Copenhagen (2015a).** Climate Change Adaptation and Investment Statement. Copenhagen, Denmark.

City of Copenhagen (2015b). Copenhagen Green Accounts Climate and Energy (København's Miljøregnskab. Tema Om Klima Og Energi, in Danish). The City of Copenhagen. www.kk.dk/miljoeregnskab.

D **DANVA (2016).** Water in Figures. Skanderborg. <http://www.e-pages.dk/danva/100/>.

DOW (2005). FILMTEC Reverse Osmosis Membranes. Technical Manual. Dow Liquid Separations. http://dowac.custhelp.com/app/answers/detail/a_id/3428/~/filmtec-membranes---filmtecs-technical-manual.

E **Eggen, R. I. L., Hollender, J., Joss, A., Schaerer, M., and Stamm, C. (2014).** "Reducing the Discharge of Micropollutants in the Aquatic Environment: The Benefits of Upgrading Waste water Treatment Plants." Environmental Science & Technology, June. doi:10.1021/es500907n.

F **Fang, L. L., Valverde-Pérez, B., Damgaard, A., Plósz, B. G., and Rygaard, M. (2015).** "Life Cycle Assessment as Development and Decision Support Tool for Waste water Resource Recovery Technology." Water Research, October. doi:10.1016/j.watres.2015.10.016.

G **Gerrity, D., Pecson, B., Trussell, R. S., and Trussell, R. R. (2013).** "Potable Reuse Treatment Trains throughout the World." Journal of Water Supply: Research and Technology—AQUA 62 (6): 321. doi:10.2166/aqua.2013.041.

Godskesen, B., Hauschild, M., Rygaard, M., Zambrano, K., and Albrechtsen, H.-J. (2012). "Life Cycle Assessment of Central Softening of Very Hard Drinking Water." Journal of Environmental Management 105 (August). Elsevier Ltd: 83-89. doi:10.1016/j.jenvman.2012.03.030.

K **Kenway, S. J., Lant, P., and Priestley, T. (2011).** "Quantifying Water-Energy Links and Related Carbon Emissions in Cities." Journal of Water and Climate Change 2 (4): 247-59. doi:10.2166/wcc.2011.005.

Kenway, S. J., and Lam, K. L. (2016). "Quantifying and Managing Urban Water-Related Energy Use Systemically: Case Study Lessons from Australia." International Journal of Water Resources Development 32 (3): 379-97. doi: 10.1080/07900627.2015.1132195.

Kirkegaard, P., and Rygaard, M. (2014). Renset Spildevand Som Drikkevandsressource. DTU Environment, Technical University of Denmark.

Kurihara, M., Sakai, H., Tanioka, A., and Tomioka, H. (2016). "Role of Pressure-Retarded Osmosis (PRO) in the Mega-Ton Water Project." Desalination and Water Treatment, April. Taylor & Francis, 1-11. doi:10.1080/19443994.2016.1168582.

L **Lane, J. L., de Haas, D. W., and Lant, P. A. (2015).** "The Diverse Environmental Burden of City-Scale Urban Water Systems." Water Research 81. Elsevier Ltd: 398-415. doi:10.1016/j.watres.2015.03.005.

Langeveld, J. (2015). "Comment on 'Life Cycle Assessment of Urban Waste water Systems: Quantifying the Relative Contribution of Sewer Systems.'" Water Research 84. Elsevier Ltd: 375-77. doi:10.1016/j.watres.2015.06.020.

Li, Y., Xiong, W., Zhang, W., Wang, C., and Wang, P. (2016). "Life Cycle Assessment of Water Supply Alternatives in Water-Receiving Areas of the South-to-North Water Diversion Project in China." Water Research 89 (February): 9-19. doi:10.1016/j.watres.2015.11.030.

Luo, Y., Guo, W., Ngo, H. H., Nghiem, L. D., Hai, F. I., Zhang, J., Liang, S., and Wang, X. C. (2014). "A Review on the Occurrence of Micropollutants in the Aquatic Environment and Their Fate and Removal during Waste water Treatment." Science of The Total Environment 473: 619-41. doi:10.1016/j.scitotenv.2013.12.065.

N **Nielsen, U. (2016).** Full Scale Advanced Waste water Treatment at Herlev Hospital. Treatment Performance and Evaluation.

P **Plappally, A. K., and Lienhard V., J. H. (2012).** "Energy Requirements for Water Production, Treatment, End Use, Reclamation, and Disposal." Renewable and Sustainable Energy Reviews 16 (7): 4818-48. doi:10.1016/j.rser.2012.05.022.

Plappally, A. K., and J. H. Lienhard V. (2012). "Energy Requirements for Water Production, Treatment, End Use, Reclamation, and Disposal." Renewable and Sustainable Energy Reviews 16 (7). Elsevier: 4818-48. doi:10.1016/j.rser.2012.05.022.

R **Risch, E., Gutierrez, O., Roux, P., Boutin, C., and Corominas, L. (2015).** "Life Cycle Assessment of Urban Waste water Systems: Quantifying the Relative Contribution of Sewer Systems." Water Research 77 (June): 35-48. doi:10.1016/j.watres.2015.03.006.

Rygaard, M., Arvin, E., Bath, A., and Binning, P. J. (2011). "Designing Water Supplies: Optimizing Drinking Water Composition for Maximum Economic Benefit." Water Research 45 (12). Elsevier Ltd: 3712-22. <http://www.ncbi.nlm.nih.gov/pubmed/21565384>.

Rygaard, M., Godskesen, B., Jørgensen, C., and Hoffmann, B. (2014). "Holistic Assessment of a Secondary Water Supply for a New Development in Copenhagen, Denmark." The Science of the Total Environment 497-498C (August). Elsevier B.V.: 430-39. doi:10.1016/j.scitotenv.2014.07.078.

Rygaard, M., Albrechtsen, H. J., and Binning, P. J. (2009). Alternative Water Management and Self-Sufficient Water Supplies. London, United Kingdom: IWA Publishing. <http://books.google.com/books?id=aSj2A5IEiv8C&pgis=1>.

Rygaard, M., Albrechtsen, H. J., and Binning, P. J. (2011). "Increasing Urban Water Self-Sufficiency: New Era, New Challenges." Journal of Environmental Management 92 (September): 185-94. doi:10.1016/j.jenvman.2010.09.009.

S Sanders, K. T. (2016). "The Energy Trade-Offs of Adapting to a Water- Scarce Future: Case Study of Los Angeles Case Study of Los Angeles" 0627 (June). doi:10.1080/07900627.2015. 1095079.

Singh, P., Kansal, A., and Carliell-Marquet, C. (2016). "Energy and Carbon Footprints of Sewage Treatment Methods." Journal of Environmental Management 165 (January). Academic Press: 22-30. doi:10.1016/j.jenvman.2015.09.017.

Singh, R. (2011). "Analysis of Energy Usage at Membrane Water Treatment Plants." Desalination and Water Treatment 29 (1-3): 63-72. doi:10.5004/dwt.2011.2988.

Sørup, H. J. D., Lerer, S. M., Arnbjerg-Nielsen, K., Mikkelsen, P. S., and Rygaard, M. (2016). "Efficiency of Storm water Control Measures for Combined Sewer Retrofitting under Varying Rain Conditions: Quantifying the Three Points Approach (3PA)." Environmental Science & Policy 63. Elsevier Ltd: 19-26. doi:10.1016/j.envsci.2016.05.010.

V Vieira, A. S., Beal, C. D., Ghisi, E., and Stewart, R. A. (2014). "Energy Intensity of Rainwater Harvesting Systems: A Review." Renewable and Sustainable Energy Reviews 34 (June). Elsevier: 225-42. doi:10.1016/j.rser.2014.03.012.

Lenouvel, V., Lafforgue, M., Chevauché, C., and Rhétoré, P. (2014). "The Energy Cost of Water Independence: The Case of Singapore." Water Science and Technology: A Journal of the International Association on Water Pollution Research 70 (5). IWA Publishing: 787-94. doi:10.2166/wst.2014.290.

W Wong, T. H. F., Allen, R., Beringer, J., Brown, R. R., Deletic, A., Fletcher, T. D., Gangadharan, L., et al. (2012). Storm water Management in a Water Sensitive City. Clayton, VIC, Australia.

Chapter 7

A Albuquerque, J. A., de la Fuente, C., and Bernal, M. P. (2012). Chemical properties of anaerobic digestates affecting C and N dynamics in amended soils. Agric Ecosyst Environ 160:15-22. doi: 10.1016/j.agee.2011.03.007

Alonso, A. M., and Guzmán, G. J. (2010). Comparison of the Efficiency and Use of Energy in Organic and Conventional Farming in Spanish Agricultural Systems. J Sustain Agric 34:312-338. doi: 10.1080/10440041003613362

Altieri, M. A. (1999). The ecological role of biodiversity in agroecosystems. Agric Ecosyst Environ 74:19-31. doi: 10.1016/S0167-8809(99)00028-6

B Bardi, U., El Asmar, T., and Lavacchi, A. (2013). Turning electricity into food: The role of renewable energy in the future of agriculture. J Clean Prod 53:224-231. doi: 10.1016/j.jclepro.2013.04.014

Brouder, S. M., and Gomez-Macpherson, H. (2014). The impact of conservation agriculture on smallholder agricultural yields: A scoping review of the evidence. Agric Ecosyst Environ 187:11-12. doi: 10.1016/j.agee.2013.08.010

C Canning, P. (2010). Fuel for Food: Energy Use in the U.S. Food System. Amber Waves 8:10-15.

Chappell, M. J., and LaValle, L. A. (2011). Food security and biodiversity: Can we have both? An agroecological analysis. Agric Human Values 28:3-26. doi: 10.1007/s10460-009-9251-4

Childers, D. L., Corman, J., Edwards, M., and Elser, J. J. (2011). Sustainability Challenges of Phosphorus and Food: Solutions from Closing the Human Phosphorus Cycle. Bioscience 61:117-124. doi: 10.1525/bio.2011.61.2.6

Cordell, D., Rosemarin, A., Schröder, J. J., and Smit, A. L. (2011). Towards global phosphorus security: A systems framework for phosphorus recovery and reuse options. Chemosphere 84:747-758. doi: 10.1016/j.chemosphere.2011.02.032

Crews, T. E., and Peoples, M. B. (2004). Legume versus fertilizer sources of nitrogen: Ecological tradeoffs and human needs. Agric Ecosyst Environ 102:279-297. doi: 10.1016/j.agee.2003.09.018

Cuéllar, A. D., and Webber, M. E. (2010). Wasted food, wasted energy: The embedded energy in food waste in the United States. Environ Sci Technol 44:6464-6469. doi: 10.1021/es100310d

D Davies, T., and Konisky, D. M. (2000). Environmental Implications of the Foodservice and Food Retail Industries. Available at http://www.rff.org/files/sharepoint/WorkImages/Download/RFF-DP-00-11.pdf (latest access 1 Aug. 2016)

De Haen, H., Stamoulis, K., Shetty, P., and Pingali, P. (2003). The World Food Economy in the Twenty-first Century: Challenges for International Co-operation. Dev Policy Rev 21:683-696. doi: 10.1111/j.1467-8659.2003.00232.x

E Erisman, J. W., Sutton, M., Galloway, J., et al. (2008). How a century of ammonia synthesis changed the world. Nat Geosci 1:636-639. doi: 10.1038/ngeo325

G Glover, J. D., Reganold, J. P., Bell, L. W., et al. (2010). Increased Food and Ecosystem Security via Perennial Grains. Science (80-) 328:1638-1639. doi: 10.1126/science.1188761

H Hauggaard-Nielsen, H., Lachouani, P., Knudsen, M. T., et al. (2016). Productivity and carbon footprint of perennial grass-forage legume intercropping strategies with high or low nitrogen fertilizer input. Sci Total Environ 541:1339-1347. doi: 10.1016/j.scitotenv.2015.10.013

Heller, M., and Keoleian, G. (2003). Assessing the Sustainability of the US Food System: A life cycle perspective. Agric Syst 76:1007-1041.

I IPES-FOOD (2016). From uniformity to diversity. International Panel of Experts on Sustainable Food Systems. Available at http://www.ipes-food.org/images/Reports/UniformityToDiversity_FullReport.pdf (latest access 1 Aug. 2016)

J Jensen, E. S., Peoples, M. B., Boddey, R. M., Gresshoff, P. M., Hauggaard-Nielsen, H., Alves, B. J. R., and Morrison, M. J. (2012). Legumes for mitigation of climate change and the provision of feedstock for biofuels and biorefineries. A review. Agron. Sustain. Dev. 32:329-364 doi 10.1007/s13593-011-0056-7

K Kamp, A., and Østergård, H. (2016). Environmental sustainability assessment of fruit cultivation and processing using fruit and cocoa residues for bioenergy and compost. Case study from Ghana. J Clean Prod 1-12. doi: 10.1016/j.jclepro.2016.04.065

Kelessidis, A., and Stasinakis, A. S. (2012). Comparative study of the methods used for treatment and final disposal of sewage sludge in European countries. Waste Manag 32:1186-1195. doi: 10.1016/j.wasman.2012.01.012

Kirkegaard J. A., Conyers, M. K., Hunt, J. R., Kirkby, C. A., Watt M., and Rebetzke G. J. (2014). Sense and nonsense in conservation agriculture: Principles,pragmatism and productivity in Australian mixed farming systems. Agriculture, Ecosystems and Environment 187 133-145

Kleijn, D., Kohler, F., Báldi, A., et al. (2009). On the relationship between farmland biodiversity and land-use intensity in Europe. Proc Biol Sci 276:903-9. doi: 10.1098/rspb.2008.1509

L Lachouani, P. (2013). Nitrogen Cycle Assessments and Greenhouse Gas Emissions in low-input Management systems. Technical University of Denmark, DTU

M Markussen, M. V., Kulak, M., Smith, L. G., et al. (2014). Evaluating the sustainability of a small-scale low-input organic vegetable supply system in the United Kingdom. Sustain 6:1913-1945. doi: 10.3390/su6041913

Markussen, M. V., Østergård, H. (2013). Energy analysis of the Danish food production system: Food-EROI and fossil fuel dependency. Energies 6:4170-4186.

Müller-Stöver, D., Ahrenfeldt, J., Holm, J. K., et al. (2012). Soil application of ash produced by low-temperature fluidized bed gasification: Effects on soil nutrient dynamics and crop response. Nutr Cycl Agroecosystems 94:193-207. doi: 10.1007/s10705-012-9533-x

N Nemecek, T., Dubois, D., Huguenin-Elie, O., and Gaillard, G. (2011). Life cycle assessment of Swiss farming systems: I. Integrated and organic farming. Agric Syst 104:217-232. doi: 10.1016/j.agry.2010.10.002

Nemecek, T., Jungbluth, N., i Canals, L. M., and Schenck, R. (2016). Environmental impacts of food consumption and nutrition: where are we and what is next? Int J Life Cycle Assess. doi: 10.1007/s11367-016-1071-3

O Olesen, J. E., and Bindi, M. (2002). Consequences of climate change for European agricultural productivity, land use and policy. Eur J Agron 16:239-262. doi: 10.1016/S1161-0301(02)00004-7

P Pelletier, N., Arsenault, N., and Tyedmers, P. (2008). Scenario modeling potential eco-efficiency gains from a transition to organic agriculture: Life cycle perspectives on Canadian canola, corn, soy, and wheat production. Environ Manage 42:989-1001. doi: 10.1007/s00267-008-9155-x

Pelletier, N., Audsley, E., Brodt, S., et al. (2011). Energy Intensity of Agriculture and Food Systems. Annu Rev Environ Resour 36:223-246. doi: 10.1146/annurev-environ-081710-161014

Peoples, M. B., Hauggaard-Nielsen, H., Jensen, E. S. (2009). The potential environmental benefits and risks derived from legumes in rotations. 349-385. doi: 10.2134/agronmonogr52.c13

Perryman, M. E., and Schramski, J. R. (2015). Evaluating the relationship between natural resource management and agriculture using embodied energy and eco-exergy analyses: A comparative study of nine countries. Ecol Complex 22:152-161. doi: 10.1016/j.ecocom.2015.04.002

Pimentel, D., and Burgess, M. (2014). An environmental, energetic and economic comparison of organic and conventional farming systems. In: Pimentel D, Peshin R (eds) Integrated Pest Management: Pesticide Problems, Vol.3. Springer, Dordrecht, pp 1-474

Pimentel, D., Williamson, S., Alexander, C. E., et al. (2008). Reducing energy inputs in the US food system. Hum Ecol 36:459-471. doi: 10.1007/s10745-008-9184-3

S Satterthwaite, D., McGranahan, G., and Tacoli, C. (2010). Urbanization and its implications for food and farming. Philos Trans R Soc Lond B Biol Sci 365:2809-20. doi: 10.1098/rstb.2010.0136

W Woods, J., Williams, A., Hughes, J. K, et al. (2010). Energy and the food system. Philos Trans R Soc B Biol Sci 365:2991-3006. doi: 10.1098/rstb.2010.0172

World Resources Institute (2013). Creating a Sustainable Food Future. Available at https://www.wri.org/sites/default/files/wri13_report_4c_wrr_online.pdf (latest access 1 Aug. 2016).

Chapter 8

A Angelidaki, I., and Ellegaard, L. (2003). Codigestion of manure and organic wastes in centralized biogas plants. Status and future trends. Appl. Biochem. Biotech. 109, 95-105.

Appels, L., Lauwers, J., Degréve, J., Helsen, L., Lievens, B., Willems, K., Van Impe, J., and Dewil, R. (2011). Anaerobic digestion in global bio-energy production: potential and research challenges. Renew. Sustain. Energy Rev. 15(9), 4295-4301.

B Bailera, M., Lisbona, P., Romeo, L. M., and Espatolero, S. (2015). Power to Gas-biomass oxycombustion hybrid system: Energy integration and potential applications. App. Energy. 167, 221-229.

Bassani, I., Kougias, P. G., Treu, L., and Angelidaki, I. (2015). Biogas upgrading via hydrogenotrophic methanogenesis in two-stage Continuous Stirred Tank Reactors at mesophilic and thermophilic conditions. Environ. Sci. Technol. 49(20), 12585-12593.

Bruun, S., Yoshida, H., Nielsen, M., Jensen, L. S., Christensen T. H., and Scheutz, C. (2016). Estimation of long-term environmental inventory factors associated with land application of sewage sludge. J. Clean. Prod. 126, 440-450.

C CEC (1999). Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste. Off. J. Eur. Communities L 182, 16/07/1999, 0001-0019.

Clavreul, J., Baumeister, H., and Christensen, T. H. (2014). An environmental assessment system for environmental technologies. Environ. Model. Softw. 60, 18-30.

D Danish Government (2009). Agreement on Green Growth. The Danish Government, Copenhagen, Denmark.

DEA (2015). Energy statistics 2013. Danish Energy Agency, Copenhagen, Denmark.

Delre, A., Mønster, J., Scheutz, C. (2016). Greenhouse gas emission quantification from waste water treatment plants using a tracer dispersion method. Submitted to Water Research, July 2016.

Delre, A., Mønster, J., and Scheutz, C. (2016). Greenhouse gas emission quantification from wastewater treatment plants using a tracer dispersion method. Submitted to Water Research, July 2016.

DEPA (2013). Innovationspartnerskab for anvendelse af fosfor fra spildevand og spildevandsslam fra spildevandsforsyninger. Danish Environmental Protection Agency, Copenhagen, Denmark.

De Vries, J. W., Groenestein, C. M., and De Boer, I. J. M. (2012a). Environmental consequences of processing manure to produce mineral fertilizer and bio-energy. J. Environ. Manage. 102, 173-183.

De Vries, J. W., Vinken, T. M. W. J., Hamelin, L., and De Boer, I. J. M. (2012b). Comparing environmental consequences of anaerobic mono- and co-digestion of pig manure to produce bio-energy – A life cycle perspective. Bioresour. Technol. 125, 239-248.

E Eurostat (2013). Eurostat website. Available at: http://ec.europa.eu/eurostat (accessed August 2016).

H Hamelin, L., Naroznova, I., and Wenzel, H. (2014). Environmental consequences of different carbon alternatives for increased manure-based biogas. Appl. Energy. 114, 774-782.

Hamelin, L., Wesnaes, M., Wenzel, H., and Petersen, B. M. (2011). Environmental Consequences of Future Biogas Technologies Based on Separated Slurry. Environ. Sci. Technol. 45, 5869-5877.

Henriksen, U., Ahrenfeldt, J., Jensen, T.K., Gøbel, B., Bentzen, J.D., Hindsgaul, C., and Sørensen, L.H. (2006). The design, construction and operation of a 75 kW two-stage gasifier. *Energy* 31, 1542-1553.

K Kougias, P.G., Kotsopoulos, T.A., and Martzopoulos, G.G. (2014). Effect of feedstock composition and organic loading rate during the mesophilic co-digestion of olive mill waste water and swine manure. *Renew. Energy*, 69, 202-207.

L Luo, G., Johansson, S., Boe, K., Xie, L., Zhou, Q., and Angelidaki, I. (2012). Simultaneous hydrogen utilization and in situ biogas upgrading in an anaerobic reactor. *Biotechnol. Bioeng.* 109(4), 1088-1094.

M Malkow, T. (2004). Novel and innovative pyrolysis and gasification technologies for energy efficient and environmentally sound MSW disposal. *Waste Manage.* 24, 53-79.

Manara, P., and Zabaniotou, A. (2012). Towards sewage sludge based biofuels via thermochemical conversion – A review. *Renew. Sustain. Energy Rev.* 16, 2566-2582.

Mathiesen, B.V, Lund, H., Hvelplund, F.K., Connolly, D., Bentsen, N.S., Tonini, D., Morthorst, P.E., Wenzel, H., Astrup, T., Meyer, N.I., Münster, M., Østergaard, P.A., Bak-Jensen, B., Nielsen, M.P., Schaltz, E., Pillai, J.R., Hamelin, L., Felby, C., Heussen, K., Karnøe, P., Munksgaard, J., Pade, L., Andersen, F.M., and Hansen, K. (2011). CEESA 100% Renewable Energy Scenarios towards 2050, Aalborg University.

Mønster, J., Samuelsson, J., Kjeldsen, P., Rella, C.W., and Scheutz, C. (2014). Quantifying methane emission from fugitive sources by combining tracer release and downwind measurements – a sensitivity analysis based on multiple field surveys. *Waste Manage.* 34, 1416-28.

Mønster, J., Samuelsson, J., Kjeldsen, P., and Scheutz, C. (2015). Quantification of methane emission from 15 Danish landfills using mobile tracer dispersion method. *Waste Manage.* 35, 177-186.

P Panoutsou, C., Eleftheriadis, J., and Nikolaou, A. (2009). Biomass supply in EU27 from 2010 to 2030. *Energy. Policy.* 37, 5675-5686.

R Reed, G.P., Paterson, N.P., Zhuo, Y., Dugwell, D.R., and Kandiyoti, R. (2005). Trace Element Distribution in Sewage Sludge Gasification: Source and Temperature Effects Trace Element Distribution in Sewage Sludge Gasification: Source and Temperature Effects. *Energy. Fuel* 19, 298-304.

Reinelt, T., Delre, A., Westerkamp, T., Holmgren, M.A., and Scheutz, C. (2016). Comparative use of different emission measurement approaches to determine methane emissions from a biogas plant. *Waste Manage.* Submitted.

S Searchinger, T., Heimlich, R., Houghton, R.A., Dong, F.X., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D., and Yu, T.H. (2008). Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science* 19, 1238-1240.

Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P.M. (eds.) (2013). IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Cambridge, United Kingdom.

T Tonini, D., and Astrup, T. (2012). Life-cycle assessment of biomass-based energy systems: a case study for Denmark. *Appl. Energy.* 99, 234-246.

Tonini, D., Hamelin, L., and Astrup, T. (2016a). Environmental implications of the use of agro-industrial residues for biorefineries: application of a deterministic model for indirect land-use changes. *GCB Bioenergy*, 8(4), 690-706.

Tonini, D., Hamelin, L., Merlin, A-M., and Astrup, T.F. (2016b). GHG emission factors for bioelectricity, biomethane, and bioethanol quantified for 24 biomass substrates with consequential life-cycle assessment. *Bioresour. Technol.* 208, 123-133.

Tonini, D., Hamelin, L., Wenzel, H., and Astrup, T. (2012). Bioenergy Production from Perennial Energy Crops: A Consequential LCA of 12 Bioenergy Scenarios including Land Use Changes. *Environ. Sci. Technol.* 46, 13521-13530.

Tsapekos, P., Kougias, P.G., and Angelidaki, I. (2015). Anaerobic mono-and co-digestion of mechanically pretreated meadow grass for biogas production. *Energy. Fuel.* 29(7), 4005-4010.

Tyagi, V.K., and Lo, S.L. (2013). Sludge: A waste or renewable source for energy and resources recovery? *Renew. Sustain. Energy Rev.* 25, 708-728.

Y Yoshida, H. (2014). Life cycle assessment of sewage sludge and its use on land. PhD thesis. Department of Environmental Engineering, Technical University of Denmark (DTU), Lyngby, Denmark.

Yoshida, H., Mønster, and J., Scheutz, C. (2014). Plant integrated measurement of methane and nitrous gas from a municipal waste water treatment plant. *Water Res.* 61, 108-118.

Yoshida, H., Nielsen, M.P., Scheutz, C., Jensen, L.S., Bruun, S., and Christensen, T.H. (2016). Long-Term Emission Factors for Land Application of Treated Organic Municipal Waste. *Environ. Model. Assess.* 21(1), 111-124.

Yoshida, H., Nielsen, M.P., Scheutz, C., Jensen, L.S., Christensen, T.H., Nielsen, S., and Bruun, S. (2015). Effects of sewage sludge stabilization on fertilizer value and greenhouse gas emissions after soil application. *Acta Agr. Scand. B-S* P. 65, 506-516.

Chapter 9

B Bjerg, J.E., Grum, M., Courdent, V.A.T., Halvgaard, R.F., Vezzaro, L., and Mikkelsen, P.S. (2015). Coupling of weather forecasts and smart grid-control of waste water inlet to Kolding WWTP (Denmark). In: Proceedings of the 10th International Urban Drainage Modelling Conference. Mont-Saint-Anne, Quebec. 20-23 September 2015.

Booker, J.F., Howitt, R.E., Michelsen, A.M., and Young, R.A. (2012). Economics and the modeling of water resources and policies. *Nat. Resour. Model.*, 25, 168-218.

C Courdent, V., Grum, M., and Mikkelsen, P.S. (2016). Distinguishing high and low flow domains in urban drainage systems 2 days ahead using numerical weather prediction ensembles. *Journal of Hydrology*, in press, doi: 10.1016/j.jhydrol.2016.08.015.

D Daher, T.B., and Mohtar, R.H. (2015). Water-energy-food (EwF) Nexus Tool 2.0: guiding integrative resource planning and decision-making. *Water International* Volume, 40, Issue 5-6, 748-771. Available at http://wefnexus.tamu.edu/files/2015/09/Daher-Mohtar_WEFNexusTool2.pdf (latest access 2 Aug. 2016)

Dale, L.L., Karali, N., Millstein, D., Carnall, M., Vicuña, S., Borchers, N., Bustos, E., O'Hagan, J., Purkey, D., Heaps, C., Sieber J., Collins W.D., and Sohn M.D. (2015). An integrated assessment of water-energy and climate change in Sacramento, California: How strong is the nexus? *Clim. Chang.*, 132, 223-235.

Davidsen, C., Pereira-Cardenal, S.J., Liu, S., Mo, X., Rosbjerg, D., and Bauer-Gottwein, P. (2014). Using Stochastic Dynamic Programming to Support Water Resources Management in the Ziya River Basin, China. *J. Water Resour. Plan. Manag.*, 141(7), 04014086.

de Strasser, L., Lipponen, A., Howells, M., Stec, S., and Bréthaut, C. (2016). A Methodology to Assess the Water Energy Food Ecosystems Nexus in Transboundary River Basins. *Water*, 8(2), 59.

E Edmonds, J., Wise, M., Pitcher, H., Richels, R., Wigley, T., and MacCracken, C. (1997). An Integrated Assessment of Climate Change and the Accelerated Introduction of Advanced Energy Technologies, Mitigation and Adaptation Strategies for Global Change, 1, 311-39.

F Falkenmark, M., and Rockström, J. (2006). The New Blue and Green Water Paradigm: Breaking New Ground for Water Resources Planning and Management. *J. Water Resour. Plan. Manag.*, 132, 129-132.

FAO (2013). An Innovative Accounting Framework for the Food-Energy-Water Nexus. Application of the MuSIASEM approach to three case studies. Available at <http://www.fao.org/docrep/019/i3468e/i3468e.pdf> (latest access 2 Aug. 2016).

Flammini, A., Puri, M., Pluschke, L., and Dubois, O. (2014). Walking the Nexus Talk: Assessing the Water-Energy-Food Nexus in the Context of the Sustainable Energy for All Initiative. Report from the Climate, Energy and Tenure Division (NRC), Food and Agriculture Organization of the United Nations. ISBN 978-92-5-108487-8. Available at <http://www.fao.org/3/a-i3959e.pdf> (latest access 2 Aug. 2016).

G Gao, H., Scherson, Y.D., and Wells, G.F. (2014). Towards energy neutral waste water treatment: methodology and state of the art. *Environmental Science. Processes & Impacts*, 16(6), 1223-46.

Garrido, A., Llamas, M.R., Varela-Ortega, C., Novo, P., Rodríguez-Casado, R., and Aldaya, M. (2010). Water Footprint and Virtual Water Trade in Spain. Policy Implications. In: *Natural Resource Management and Policy*, Vol. 35, Springer, New York.

Global Water Partnership (GWP). The challenge. What is IWRM? Available online: <http://www.gwp.org/The-Challenge/What-is-IWRM/>.

Granit, J., Fogde, M., Hoff, H., Joyce, J., Karlberg, L., Kuylenstierna, J., and Rosemarin, A. (2013). Unpacking the Water-Energy-Food Nexus: Tools for Assessment and Cooperation Along a Continuum. In: Jägerskog, A., Clausen, T.J., Lexén, K., and Holmgren, T. (eds.) (2013). Cooperation for a Water Wise World – Partnerships for Sustainable Development. Report Nr. 32. SiWI, Stockholm. Available at http://www.siwi.org/wp-content/uploads/2015/09/2013_WWW_Report_web.pdf (latest access 2 Aug. 2016).

H Halvgaard, R.F., Munk-Nielsen, T., Tychsen, P., Grum, M., and Madsen, H. (2015). Stochastic Greybox Modeling of an Alternating Activated Sludge Process. In: 9th IWA Symposium on Systems Analysis and Integrated Assessment (Watermatex 2015). Gold Coast, Queensland, Australia, 14-17 June 2015.

Harou, J.J., Pulido-Velazquez, M., Rosenberg, D.E., Medellín-Azuara, J., Lund, J.R., and Howitt, R.E. (2009). Hydro-economic models: Concepts, design, applications, and future prospects. *J. Hydrol.*, 375, 627-643.

Howells, M., and Rogner, H. -H. (2014). Water-energy nexus: Assessing integrated systems. *Nat. Clim. Chang.*, 4, 246-247.

Howells, M., Hermann, S.,Welsch, M., Bazilian, M., Segerström, R., Alfstad, T., Gielen, D., Rogner, H. -H., Fischer, G., van Velthuizen, H.,Wiberg, D., Young, C., Roehrl, R.A., Mueller, A., Steduto, P., and Ramma, I. (2013). Integrated analysis of climate change, land-use, energy and water strategies. *Nat. Clim. Chang.* 3, 621-626.

Howells, M., Rogner, H. -H., Strachan, N., Heap, C., Huntington, H., Kypreos, S., Hughes, A., Silveira, S., DeCarolish, J., Bazillian, M., and Roehrl, A. (2011). OSeMOSYS: the open source energy modeling system: an introduction to its ethos, structure and development. *Energy Policy*, 39(10), 5850-5870.

I IRENA (2015). Renewable Energy in the Water, Energy & Food Nexus. Available on-line from www.irena.org/Publications.

K Kraucunas, I., Clarke, L., Dirks, J., Hathaway, J., Hejazi, M., Hibbard, K., Huang, M., Jin, C., Kintner-Meyer, M., Kleese van Dam, K., Leung, R., Li, H. -Y., Moss, R., Peterson, M., Rice, J., Scott, M., Thomson, A., Voisin, N., and West, T. (2015). Investigating the Nexus of Climate, Energy, Water, and Land at Decision-Relevant Scales: the Platform for Regional Integrated Modeling and Analysis (PRIMA). *Climatic Change*, 129, 573.

L Labadie, J.W. (2004). Optimal operation of multireservoir systems: State-of-the-art review. *J. Water Resour. Plan. Manag.*, 130, 93-111.

M Mo, W., and Zhang, Q. (2013). Energy-nutrients-water nexus: integrated resource recovery in municipal waste water treatment plants. *Journal of Environmental Management*, 127, 255-67.

N Nicklow, J., Reed, P., Savic, D., Dessalegne, T., Harrell, L., Chan-Hilton, A., Karamouz, M., Minsker, B., Ostfeld, A., Singh, A., and Zechman, E. (2010). State of the Art for Genetic Algorithms and Beyond in Water Resources Planning and Management. *J. Water Resour. Plan. Manag.*, 136, 412-432.

O Olsson, G., Carlsson, B., Comas, J., Copp, J., Gernaey, K.V, Ingildsen, P., Jeppsson, U., Kim, C., Rieger, L., Rodríguez-Roda, I., Steyer, J. -P., Takács, I., Vanrolleghem, P.A., Vargas, A., Yuan, Z., and Åmand, L. (2014). Instrumentation, control and automation in waste water – from London 1973 to Narbonne 2013. *Water Science and Technology*, 69(7), 1373-85.

P Pereira, M.V.F., and Pinto, L. (1991). Multistage stochastic optimization applied to energy planning. *Math. Program.* 52, 359-375.

Pereira-Cardenal, S.J., Mo, B., Gjelsvik, A., Riegels, N.D., Arnbjerg-Nielsen, K., and Bauer-Gottwein, P. (2016). Joint optimization of regional water-power systems. *Adv. Water Resour.*, 92, 200-207.

Pereira-Cardenal, S.J., Mo, B., Riegels, N.D., Arnbjerg-Nielsen, K., and Bauer-Gottwein, P. (2015). Optimization of multipurpose reservoir systems using power market models. *J. Water Resour. Plan. Manag.*, 141(8), 04014100.

Pereira-Cardenal, S.J., Madsen, H., Arnbjerg-Nielsen, K., Riegels, N., Jensen, R., Mo, B., Wangensteen, I., and Bauer-Gottwein, P. (2014). Assessing climate change impacts on the Iberian power system using a coupled water-power model. *Clim. Change*, 126, 351-364.

Phillips, D., Allan, A., Claassen, M., Granit, J., Jägerskog, A., Kistin, E., Patrick, M. and Turton, A. (2008). The TWO Analysis: Introducing a Methodology for the Transboundary Waters Opportunity Analysis. Report No. 23, SIWI, Stockholm. Available at http://www.unwater.org/downloads/TWO_report.pdf (latest access 2 Aug. 2016).

Stage, S., and Larsson, Y. (1961). Incremental cost of water power. *Trans. Am. Inst. Electr. Eng.*, 80, 361-364.

Stedinger, J., Sule, B., and Loucks, D., (1984). Stochastic dynamic programming models for reservoir operation optimization. *Water Resour. Res.*, 20, 359-375.

Sweetapple, C., Fu, G., and Butler, D. (2015). Does carbon reduction increase sustainability? A study in waste water treatment. *Water Research*, 87, 522-530.

Welsch, M., Hermann. S., Howells, M., Rogner, H.-H., Young, C., Rammad, I., Bazilian, M., Fischer, G., Alfstad, T., Gielen, D., Le Blanch, D., Röhl, A., Steduto, P., and Müller, A. (2014). Adding value with CLEWS Modelling the energy system and its interdependencies for Mauritius. *Appl Energy*, 113, 1434-1445.

Young, R. A. (2005). *Determining the Economic Value of Water: Concepts and Methods. Resources for the future.* Routledge, Washington, DC, 376 pp.

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