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

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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.
**Drivers that affect the Energy-Water-Food Nexus balance**

- Market, regulations
- Governance
- Technology shifts
- Nexus balance
- Climate change
- Food demand
- Energy demand
- Water demand

**Drivers for rebalancing the Energy-Water-Food Nexus**

- R&D: Develop new tools, assessment and monitoring methods for cross-sectoral Nexus analyses.
- Policy: Introduce or improve policies and regulations at local, national, regional and international levels.
- Technology: Foster innovation, research and development of sustainability-enhancing technologies and strategies.
- Finance: Mobilize financial resources for sustainable Nexus solutions.
- Capacity: Build capacity and knowledge among stakeholders.

**Resilience to climate change**

- Power plants across the world are now being affected by changes in precipitation patterns, sea level rise, and increasing frequency and intensity of extreme weather events, such as droughts and floods.
- The vulnerability of the Nexus is exacerbated by the interdependence of the energy, water and food sectors, with each system affecting the resilience of the others.

**Strategies for adaptation and mitigation**

- Implement climate-resilient practices in agriculture, water management and energy production.
- Enhance water and energy use efficiency in the food sector.
- Promote the use of renewable energy sources to reduce greenhouse gas emissions.
- Strengthen international cooperation to address transboundary water and energy issues.

**Drivers for rebalancing the Energy-Water-Food Nexus**

- Market, regulations: 
  - Nexus effects related to the market, costs and prices of energy, water and food need to be monitored.
  - Economic and legislative tools can be used to support the use of sustainable energy and water management practices.

- Governance: 
  - Appropriate legal Nexus instruments and frameworks are necessary to ensure that policies and decisions benefit the Nexus.
  - Integrated policies and regulations can help manage the interdependence of the energy, water and food sectors.

- Technology shifts: 
  - The rapid development of new technologies offers opportunities for rebalancing the Nexus.
  - Greenhouse gas emissions are expected to decline in the energy sector, with implications for the Nexus.

- Finance: 
  - Mobilizing financial resources is crucial for sustainable Nexus solutions, including investments in renewable energy, water efficiency and sustainable agriculture.

- Capacity: 
  - Building capacity and knowledge among stakeholders is essential for implementing sustainable Nexus solutions.
  - Training and education programs should be developed to increase awareness and capacity in the Nexus areas.

**Energy-water-food Nexus**

- Drivers that affect the Nexus balance include climate change, energy demand, water demand and food demand.
- Strategies for rebalancing the Nexus involve market, regulations, governance, technology shifts, finance, capacity and resilience to climate change.
- Appropriate legal Nexus instruments and frameworks are necessary to ensure that policies and decisions benefit the Nexus.
- Integrated policies and regulations can help manage the interdependence of the energy, water and food sectors.
- The rapid development of new technologies offers opportunities for rebalancing the Nexus.
- Mobilizing financial resources is crucial for sustainable Nexus solutions, including investments in renewable energy, water efficiency and sustainable agriculture.
- Building capacity and knowledge among stakeholders is essential for implementing sustainable Nexus solutions.
- Training and education programs should be developed to increase awareness and capacity in the Nexus areas.

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Preface

Chapter 1

Preface

Energy, water, and food systems are closely interlinked 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 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.
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-offs 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**
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.

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.

It is important to stimulate R&D in new sources of renewable energy based on energy conversion of food and water sector residues through thermochemical 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, as lack of access to quality data often is 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 increases 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 trans-boundary 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.
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 will therefore be concentrated in rural settings. While global population is projected to increase by more than 2.5 billion 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.

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 systems.

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...
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 unconventional 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 scarce 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 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 water waste adequately cover 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 for 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 to convert poorer water qualities to drinking water quality when
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 system's 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 ef- fluent water quality standards. In areas where legislation creates 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. This cost energy for transporting the waste water.

Some water waste utilities recover parts of their electricity use by sludge digestion. In Denmark, the waste water utility Vændercenter 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 sources, this would continue to be an energy-intensive approach. The most apparent alternative is to biologically fix 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 the developing world is typically stored and applied to crops to much higher than farm animal products.

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.

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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.

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 wastewater 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.

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.

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 across 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 stake- holders 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.

Increased groundwater consumption for irrigation is a consequence of the availability of cheap energy, and it is estimated that 70% of the global human water consumption is attributable by agriculture. Most modern crop production is irreversible without external inputs of water.
Chapter 4

The Energy-Water-Food Nexus in a global perspective

By Leif Sønderberg Petersen, DTU Office for Innovation and Sector Services; John M. Christensen and Todd Ngara, UNEP DTU Partnership; Kirsten Halsnæs, DTU Management Engineering

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 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. 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
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 3 – Global water demand, baseline scenario, 2000 and 2050. (OECD, 2012)

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 1 – The world’s population. (The Economist, 2015)

Figure 2 – Overview of the major water abstraction sectors in Europe in 1990 and 2007. Source: (European Environmental Agency, 2012 a).

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

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

Figure 5 – Changing dynamics of global energy demand. 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.

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<tr>
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<tbody>
<tr>
<td>Population (million people)</td>
<td>398</td>
<td>678</td>
<td>898</td>
<td>17.7%</td>
<td>13.2%</td>
</tr>
<tr>
<td>Cereals (million tonnes)</td>
<td>843</td>
<td>2012</td>
<td>3609</td>
<td>139%</td>
<td>49%</td>
</tr>
<tr>
<td>Meat production (million tonnes)</td>
<td>94</td>
<td>249</td>
<td>461</td>
<td>380%</td>
<td>86%</td>
</tr>
<tr>
<td>Developing (93 countries)</td>
<td>21.19</td>
<td>50.37</td>
<td>74.93</td>
<td>159%</td>
<td>48%</td>
</tr>
<tr>
<td>Cereals (million tonnes)</td>
<td>353</td>
<td>1113</td>
<td>1707</td>
<td>215%</td>
<td>61%</td>
</tr>
<tr>
<td>Meat production (million tonnes)</td>
<td>42</td>
<td>141</td>
<td>328</td>
<td>236%</td>
<td>132%</td>
</tr>
<tr>
<td>Developed (53 countries)</td>
<td>904</td>
<td>1395</td>
<td>1962</td>
<td>34%</td>
<td>27%</td>
</tr>
<tr>
<td>Cereals (million tonnes)</td>
<td>490</td>
<td>700</td>
<td>1212</td>
<td>144%</td>
<td>64%</td>
</tr>
<tr>
<td>Meat production (million tonnes)</td>
<td>52</td>
<td>108</td>
<td>193</td>
<td>296%</td>
<td>23%</td>
</tr>
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</table>


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.
The Nexus is calling for a broad involvement of stakeholders to collaboratively work toward sustainable development.

- Responsible governance of natural resources is the necessary first step for action on the Energy-Water-Food Nexus.

- The Nexus is calling for support from stakeholders to work toward sustainable development.

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

- 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 other two 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:

- Extraction and refining
- Irrigation of bioenergy crops
- Hydropower
- Irrigation of bioenergy crops
- Extraction and refining
- Crop and livestock production
- Processing and transport
- Food consumption
- Energy for irrigated crops
- Competition between (bio)energy and food/fiber production for water and land

Figure B - The water-energy-food nexus as related to climate change, with implications for both adaptation and mitigation strategies (Field et al, 2014)
likely start with alternative energy supply options in Ghana. Based on the findings by the Working Group II in the 2011/2012 European Report on Development, produced 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.

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 earth’s land surface.

Harnessed 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 supra-national. An example is bilaterally agreements between countries in flood protection and hydropower generation. At regional level it could be agreements for trading 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 such as the Nile Basin.
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.
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.

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 experiences scarcity of water, total lack of electricity, an estimated 11-17% (depending on source and definition) (WWAP, 2006, WWAP, 2014) experience lack of access to a proper source of drinking water, whereas there is an estimated scarcity of water for roughly 42% of the global electricity production (WWAP, 2014). An estimated 52% of the 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 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 evolve 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 scarce 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 re-injected 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 differences between water 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 disassembly. 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.
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 (225,000-2,300,000 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 and towers/ponds 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 to steam based steam 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 tend to be more flexible in the choice of location than e.g. coal plants, to the highest 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 43-98 L/MWh 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 (30 T 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, 2018). 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 gases from fossil fuel power plants. The characteristics of bioenergy 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 10%-48 000 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 vary 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 and in the future. In the use of second generation biofuels, the higher 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 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) (IEA, 2018), and exploitables, 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 water temperature results in lower boiling point (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 lower 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 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 (Spag 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 – JSEA (2015)).

CO2 capture, storage and utilisation

Global warming has been attributed to the increasing concentration of greenhouse gases (GHGs), including carbon dioxide (CO2), carbon monoxide (CO) and methane (CH4) and CO2 represents more than 75% of global 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 remote regions and insufficient water leakage rates and, likewise, CCU can cause enviromental impacts and faces vast development to be readily applicable (Cuellier-Krause 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 approx. 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/what 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 kW/m2 annually by 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 electric energy in periods of low 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 Zaatma 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 in these systems is minimal. 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 on application and region and (IEA-ETP and IEA-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 requirement estimated total of 1000 m³/year per 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 (with increased irrigation and even total plant shutdowns in Europe water scarcity has led to reductions in energy projection at an international level is essential. The Water-Energy Nexus is made up of an exhaustingly vast number of facets. For more definite 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. Hydrib 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 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

**Figure 11** Primary energy consumption in 2000 and by 2100 according to the different RCP scenarios (reworkefrom van Vuuren et al., 2011).
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.
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 rainfall 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 rainfall 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 hot water demands (Rygaard et al., 2009). In the literature, rainfall 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.
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 0.53 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 0.76 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 1.16 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).**

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 15).

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 (Langelev, 2015), it is important to consider how new infrastructure investments will respond to future changes to power generation.
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 15-54% 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 the Cloudburst Management Plan for a 2.6 km² sub-catchment of Copenhagen, reveals a 100-year CO₂-emission of 12 million kg CO₂eq for a new surface-based alternative and 42 million kg CO₂eq 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-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 Gibbs 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 rechlorinated 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 (~0.6 M NaCl) with 1 m³ river water (~0.015 M NaCl) is 0.92 MJ or 0.26 kWh/m³ 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 perme selectivity 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 perme selectivity: namely using biological cation and anion selective channels.

In November 2014 the world’s first RED power generation 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 delta project in the Netherlands. As a result 100 MW of RED energy generation is expected to be installed on the Afsluitdijk, resulting in 4.7 TWh/year of energy generation. Additionally, the use of RED for power generation offers another unique feature of RED: it can be used to produce fresh water and desalinate seawater or brackish water. The process involves applying a reverse osmosis membrane to the brine feed stream and a high pressure filter to remove the highly concentrated feed stream. The high pressure filter uses a smaller than the osmosis membrane area. The energy required to produce the fresh water is recovered by the RED process. This results in 80% energy recovery for the RO membrane and 50% energy recovery for the RED membrane.

**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 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 is pressurized 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 solute 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 Koyosakiden 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 Qingyang Municipal Waste Water Treatment Plant, Shanghái, 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 waste infrastructure as the city’s growth put strain on municipal water and sewerage 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 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 made from 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

| 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 dewatering | 0.09 |
| Post treatment (O3, GAC, UV) | 0.37 |
| Advanced treatment to avoid odour issues | 0.52 |
| Total | 2.30 |

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 Energy 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 emphasize 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=1015J). 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 Keeleman, 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).

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 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., 2018).

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 (Altherr, 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 (Brouwer 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, 2012).

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

<table>
<thead>
<tr>
<th></th>
<th>Straw</th>
<th>Grain</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SE (g DM m⁻²)</td>
<td>LER</td>
<td>Mean ± SE (g DM m⁻²)</td>
</tr>
<tr>
<td>Faba sole</td>
<td>657 ± 34a</td>
<td>-</td>
<td>389 ± 23b</td>
</tr>
<tr>
<td>Pea sole</td>
<td>437 ± 24b</td>
<td>-</td>
<td>490 ± 17ab</td>
</tr>
<tr>
<td>Oat sole</td>
<td>415 ± 57a</td>
<td>-</td>
<td>415 ± 38a</td>
</tr>
<tr>
<td>Faba + Oat</td>
<td>435 ± 20bc</td>
<td>0.91</td>
<td>516 ± 29a</td>
</tr>
<tr>
<td>Pea + Oat</td>
<td>475 ± 38b</td>
<td>1.10</td>
<td>519 ± 40a</td>
</tr>
<tr>
<td>Faba + Pea</td>
<td>530 ± 52ab</td>
<td>1.17</td>
<td>595 ± 48a</td>
</tr>
</tbody>
</table>

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 letters indicate significantly different groups. Values are the mean ± (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 (Ersman 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 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-intensive 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...
negligible 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., 2006).

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 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 more often recalci tant residual carbon fractions from bioenergy conversion technologies like anaerobic digestion (Alburquerque et al., 2012), thermal gasification (Müller-Stöver et al., 2012) and incineration (Kelesidis and Sasinakis, 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.

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 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). Furthermore, it may signal a general de-mechanisation strategy that attempts to rebuild 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...
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 Pi-mentel 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 foods, 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 inputs, ranging from the growth of foodstuffs, many of which are energy intensive in production and distribution (De Haen et al., 2003). Food processing energy use in the last few decades.

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 low 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 food supply systems 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-techniques to manage soil fertility;
- Downsacle 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

By Davide Tonini, Panagiotis G. Kougias, Charlotte Scheutz, DTU Environment; Zsuzsa Sárossy, Tobias P. Thomsen, Jesper Ahrenfeldt, Ulrik B. Henriksen, DTU Chemical Engineering; Thomas F. Astrup, DTU Environment (thas@env.dtu.dk)

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.

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. 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). 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).

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. 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. 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).

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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 (10¹⁰ J) (Mathiesen et al., 2011; Tonini and Astrup, 2012). For the purpose of comparison, this potential 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 (10¹⁵ 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...
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 synthetic 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 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 chemicals and valuable fertiliser ashes.

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 macromolecules, such as carbohydrates, proteins and lipids, which can be converted into valuable products such as biofuels, fertilisers and other value-added products. The use of sewage sludge as a feedstock for bioenergy production offers several advantages over traditional feedstock sources, such as agricultural residues and crop residues.

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

<table>
<thead>
<tr>
<th>Residue</th>
<th>Use as feed</th>
<th>Use as biofuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste residue</td>
<td>kg maize-eq</td>
<td>kg soy meal-eq</td>
</tr>
<tr>
<td>Maize straw</td>
<td>59 (160)</td>
<td>16 (45)</td>
</tr>
<tr>
<td>Brewer’s grains</td>
<td>60 (180)</td>
<td>120 (360)</td>
</tr>
<tr>
<td>Wheat straw</td>
<td>520 (1560)</td>
<td>226 (684)</td>
</tr>
<tr>
<td>Wheat pellets</td>
<td>170 (510)</td>
<td>49 (150)</td>
</tr>
<tr>
<td>Wheat bran</td>
<td>96 (280)</td>
<td>87 (260)</td>
</tr>
<tr>
<td>Distillers grains</td>
<td>122 (360)</td>
<td>20 (60)</td>
</tr>
</tbody>
</table>

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).

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 to both 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:

- Valourisation 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.
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 (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:

- 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).

Due to the high energy content and predictable generation of biogas, biogas plants are 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 focusing 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; Baidera 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 (Bussani 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).

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

<table>
<thead>
<tr>
<th>Organic residue</th>
<th>Methane yield (m³/kg VS)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pig manure</td>
<td>0.23</td>
<td>Kragh et al., 2014</td>
</tr>
<tr>
<td>Litter manure</td>
<td>0.32</td>
<td>Toupou et al., 2015</td>
</tr>
<tr>
<td>Chicken manure</td>
<td>0.43</td>
<td>Toupou et al., 2015</td>
</tr>
<tr>
<td>Horse manure</td>
<td>0.23</td>
<td>Toupou et al., 2015</td>
</tr>
<tr>
<td>Sheep manure</td>
<td>0.36</td>
<td>Angelidaki &amp; Ellegaard, 2008</td>
</tr>
<tr>
<td>Pig manure</td>
<td>0.29</td>
<td>Angelidaki &amp; Ellegaard, 2004</td>
</tr>
<tr>
<td>Meadow grass</td>
<td>0.29</td>
<td>Angelidaki &amp; Ellegaard, 2004</td>
</tr>
<tr>
<td>Wheat straw</td>
<td>0.15</td>
<td>Angelidaki &amp; Ellegaard, 2004</td>
</tr>
<tr>
<td>Fish oil</td>
<td>0.60-0.80</td>
<td>Angelidaki &amp; Ellegaard, 2008</td>
</tr>
<tr>
<td>Precipitation</td>
<td>0.31</td>
<td>Angelidaki &amp; Ellegaard, 2008</td>
</tr>
<tr>
<td>Whiskey</td>
<td>0.15</td>
<td>Angelidaki &amp; Ellegaard, 2008</td>
</tr>
<tr>
<td>Meat and bone flour</td>
<td>0.37</td>
<td>Angelidaki &amp; Ellegaard, 2008</td>
</tr>
</tbody>
</table>
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 meats.

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,

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**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).**

*Note: Figure 19 shows GHG emission factors for different biomasses used in electricity and transport fuel production.*
energy recovery from water and food sector residual resources

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.

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.

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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 at all 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.

At the local level, nexus assessments at the appropriate scales might focus on integrated water resource 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, change 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 Mohlar, 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 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.

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

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

<table>
<thead>
<tr>
<th>Tool and reference</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transboundary Waters Opportunity Analysis (Phillips et al., 2008)</td>
<td>I</td>
<td>Qualitative approach for assessing the EWF nexus at a highly aggregated level</td>
</tr>
<tr>
<td>FAO’s Nexus Assessment Methodology (Phillips et al., 2014)</td>
<td>I</td>
<td>Qualitative approach for assessing the EWF nexus based on indicators that are already available, including country typologies</td>
</tr>
<tr>
<td>PRIMA (Platform for Regional Integrated Modelling and Analysis) (Gómez et al., 2013)</td>
<td>I</td>
<td>Systematic approach to nexus assessments, which is well suited for regional applications but which can be applied at virtually any scale</td>
</tr>
<tr>
<td>Water, Energy, Food Nexus Tool 2.0 (Daher and Mohlar, 2015)</td>
<td>I</td>
<td>Scenario-based framework and a set of methodologies that define the linkages between the inter-related resources of water, energy and food, and enable explicit corresponding quantifications</td>
</tr>
<tr>
<td>IFN/FAO’s Nexus Assessment Methodology with a storm approach to assess the governance aspects of the EWF nexus</td>
<td>IV</td>
<td>Integrated approach which explicitly combines regional climate modeling/impact models with a modular integrated assessment model. PRIMA can virtually address all scales</td>
</tr>
</tbody>
</table>

See also IRENA (2015). * The Roman numerals refer to Figure 20.
Nexus at aggregated scales. Current trends within the offer valuable insight into the Energy-Water-Food models e.g. OSeMOSYS (Howells et al., 2011) can (Edmonds et al., 1997), or extended energy system water for industry and domestic use. In the same and food, biofuels and hydropower production in land and energy for e.g. agricultural intensification to assess conflicting nexus needs between water, macro-regional levels; moreover they can be used support national and local planning at regional to with deep stakeholder involvement – well suited to Zoning (AEZ) land use model are – if combined explicitly to e.g. land use through Graphical Information Systems. Tools like the integrated CLEWS modelling approaches, which can often be linked sector-specific and data-intensive (Howells et al., 2013; Welsch et al., 2014; Dale et al., 2015) are sector-specific and data-intensive 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, con- sidering both present conditions and future scenar- ios. 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 de- signed 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 climate, energy, water, and land use using a flexible modular approach. The idea behind the TRBNA approach is formally linked. For this aim the methodology of a two of the abovementioned methodologies based on 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 Na- tions (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).

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 (TR-BNA) 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 plan- ning” (de Strasser et al., 2016). Hence the method- ology 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 Na- tions (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 sy- The idea behind the TRBNA approach is nexus at the local scale. These tools include ICT-intelligent systems for real-time model predictive con- trol and optimisation, which are extremely data in- tensive and highly located. 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.

At the end of the continuum (Figure 20) are opera- tional tools for managing the Energy-Water-Food Nexus at aggregated scales. Current trends within the
and irrigation agriculture (lower).

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 fluid 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 freshwater 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 ‘willingsness-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 affects 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, 1999) 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 account 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, 1999) 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.

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account water demands from the agricultural, domes
tic and industrial sectors as well as environmen
tal flow requirements in order to avoid excessive curtailment costs for those users. In the optimisa
tion 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: regional 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 man
aged 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 hydra
lactic infrastructure have inherent time scales of days and longer.

Lastly, a key question is how trade-offs between wa
ter for food, water for energy and water for ecosys
tems are going to change under the future climate. A number of effects are important in this context: Climate change will change water availability, wa
ter demands (especially in irrigation agriculture) and energy demand (due to changes in heating/cooling requirements). Also, cooling constraints on thermal power plant 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 sce
nario period (2036-2065). Under a climate change scenario causing lowered precipitation and higher temperatures and consequently reduced water availabil
ity and increased irrigation demand on the I
P, the authors find an estimated reduction in hydro
drop 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 underg
oring 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 increas
ingly recovered from the water fluxes for reuse in e.g. agriculture (Guo et al., 2014; Olsson et al., 2014; Mo & Zhang, 2013). The transition from the “tradi
tional” 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 embodies both reduction of energy demands and utilisation of electricity sources with lower CO2 impact, creating a new link between the water and the sensors sectors at the urban scale as well as con
nections with food production.

The principal condition to achieve an optimal op
eration of a WRRF is the availability of a storage capacity where waste water can be stored and sub
sequently 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 capac
ity 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, re
sulting 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 multi
ple objectives: the WRRF needs to comply with efflu
tent quality criteria (in Denmark these are enforced by taxation on pollution discharge), while maximis
ing 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 ba
sis) and the most energy demanding process in the WRRF, namely ammonia removal (which requires updated set points every 2 minutes). Well-estab
lished 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 drain
age 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 Insti
tute) 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 char
acterised by different temporal resolutions, levels of detail, and levels of uncertainty. The results are
promising and suggest that this new integrated con
trol 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 poli
cy-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 ac
tors. Conversely, research has clearly demonstrated the advantages of integrated resources management (Howell and Rogner, 2014). In this chapter we dis
cuss different examples of quantitative, qualitative, and mixed assessment methodologies ranging from purely qualitative to highly data-intensive and da
ta-driven approaches suitable for underpinning the EWF nexus approach; we demonstrate and argue the potential for such methods to increase our under
standing not only of the interdependencies but also of the range of management tools, energy use, and water use 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 (Grant 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 discus
sion of different tools and examples is that lack of access to quality data often serves as a major con
straint 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 un
available. This may include separate information about the different elements of the EWF nexus like renewable and non-renewable energy resources,
their production potential, costs, accessibility of water resources, the quality and availability of land resources, different levels of food self-sufficiency, climate change impacts, etc. Similarly, detailed data are needed to show the different roles of the different elements of the EWF nexus in relation to water treatment processes, water usage by energy production, and land-use requirements for power generation. Needless to say, it is essential for 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 information or finding a common language for these assessments, leading to a real lack of consistent data collection routines. Furthermore, 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.
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Energy systems integration for the transition to non-fossil energy systems

November 2015.
ISBN 978-87-550-3970-4

One of the challenges in the transition to a non-fossil energy system with a high share of fluctuating renewable energy sources is to secure a well-functioning and stable electricity infrastructure. Clos-er integration of the various energy infrastructures is a means to solving some of the challenges introduced by the broader integration of renewable sources. Clos-er integration and coordination of energy infrastructures might also lead to a more cost-effective energy system with a lower impact on the environment and cli-imate. The DTU International Energy Report 2015 discusses these issues and analyses the possibilities for – and chal-lenges to – the wider introduction of inte-grated energy systems.

Wind-energy drivers and barriers for higher shares in the global power generation mix

November 2014.
ISBN 978-87-550-3959-8

In areas with good wind resources and fa-vourable financing conditions, wind ener-gy is now competitive with fossil fuel-ba-sed energy technologies. DTU Internatio-nal Energy Report 2014 addresses a se-lection of scientific and technical issues relevant to further increase the share of wind power in the global electricity mix. It covers the assessment and fore-casting of wind resources, the develop-ment of wind-energy technologies, the in-tegration of large amounts of fluctuating wind power in future energy systems, and the economic aspects of wind power.

Energy storage options for future sustainable energy systems

November 2013.
ISBN 978-87-550-3958-1

Energy storage technologies can be de-fined as technologies that are used to store energy in the form of thermal, elec-trical, chemical, kinetic, or potential ener-gy and discharge this energy whenever required. Energy storage technologies and systems are diverse and provide stor-age services at timescales from seconds to years. One of the great challenges in the transition to a non-fossil energy sys-tem with a high share of fluctuating re-newable energy sources – such as solar and wind – is to align consumption and production in an economically satisfac-to-ry manner. This report provides commit-ting evidence that energy storage can pro-vide the necessary balancing power to make this possible.

Energy efficiency improvements – a key element in the global transition to non-fossil energy

November 2012.

Increasing energy efficiency, much of which can be achieved through low-cost measures, offers huge potential for redu-cing CO2 emissions during the period up to 2050. On this background, the re-port addresses the global, regional, and national challenges in pursuing energy efficiency improvements, together with the main topics in research and devel-opment for energy efficiency. The report also analyses a selection of barriers hinder-ing the broader implementation of energy efficiency improvements. Finally, it gives examples of how more stringent performance standards and codes, as well as economic incentives, can unlock energy efficiency potential and scale up the financing of energy efficiency im-provements.

An overview of the complete report series is available at: http://www.natlab.dtu.dk/english/ Energy_Reports