TRANSBOUNDARY WATERS

PRACTIONER BRIEFING

The Water Energy Food Nexus

Issue 4

Energy-Water-Food Nexus

For this Issue of the MEDRC Practitioner Briefing we have a guest expert author to write about the critical subject of the Energy-Water-Food Nexus; **Mike Hightower**, who helped bring the concept of the "nexus" into mainstream policy circles.

Mr. Hightower is Research Professor at the University of New Mexico and a technical mentor at Sandia National Laboratories in the areas of water and energy research and development, after serving 38 years at Sandia National Laboratories in Albuquerque, New Mexico. Mike holds Bachelor's and Master's degrees in civil and environmental engineering from New Mexico State University and has 40 years of experience in space, weapons, and energy and natural resources research and engineering.

His focus in the past two decades has been on the use of new distributed and renewable energy and water treatment and desalination technologies to enhance economic development, global public health, and critical infrastructure and resource security and resiliency. Since 2000 he has supported the U.S. government and industry in establishing science and technology programs to address the issues of the interdependencies between energy, water, food, and climate. These efforts have led to major initiatives by the National Science Foundation and the Electric Power Research Institute, and global organizations, such as the World Economic Forum, World Energy Council, and the World Bank.

Mike has authored over 120 technical papers and reports, many focusing on energy and water issues and research needs, desalination research needs, and system-level planning for critical infrastructure and natural resource security, reliability, resiliency, and sustainability.

Practical Summary

The term "nexus" is a realization—or recognition of reality—of the inherent connections and synergies between two major human needs, which are rather different when viewed individually. One has no weight, is relatively cheap, easy, and efficient to move, and can be produced far away from where it is consumed. The other is heavy, expensive, and inefficient to move, and can typically only be produced and consumed locally.

The Energy-Water Nexus, or Energy-Water-Food Nexus refers to the interdependent and interactive relationships between these key variables. This refers both to the usage requirements of one for the other (water for energy, and energy for water), and their interdependence in terms of policy outcomes, or the knock-on effects from one project to another.

This includes the potential for win-win solutions by taking a more holistic approach, and the potential for a positive impact in one sector to a cause a negative impact in the other. A further interaction to consider is the impact from climate change, further complicating matters for practitioners.

Consistently, one of the largest uses of water nationally is for food in the agricultural sector, as well as for the production of energy. Furthermore, the production and consumption of water, including its movement and transport, requires energy to move via pumps, or to produce with methods such as desalination.

As will be further explained by Mike Hightower, the nexus therefore is an approach, both in terms of analysis and policy response, which requires a wider and more complex view of issues, and necessitates new data points to help inform decision makers. However, it is not a silver-bullet for all three issues either. We must also be mindful of issues relating to equity, power, and environmental justice, which an overtly technical outlook may overlook. As usual, engagement with all stakeholders remains critical to policy success.

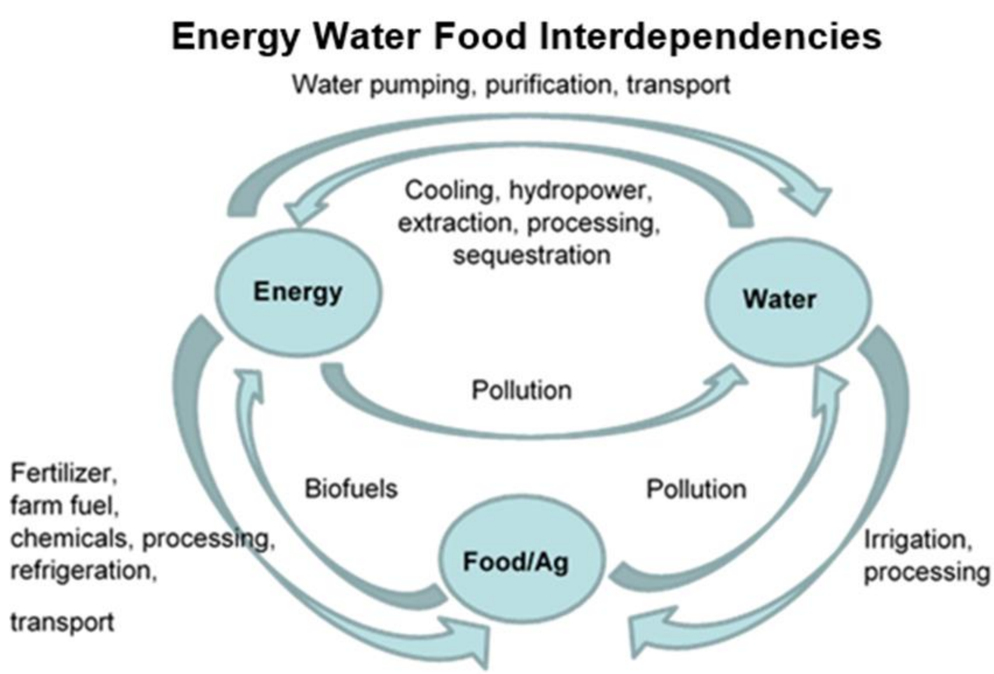
The Energy-Water-Food Nexus

Over the past decade, as nations have been forced to assess the impacts of climate change on natural resources, infrastructures, and social and economic systems, many regions have realized that energy, water, and agriculture / food production are inherently interconnected, with all three being both natural resources and critical infrastructures. Therefore, risks to one resource or infrastructure can create risks to each of the others. For example, a decrease in fresh water availability in a region could negatively impact not only water supply, but also both energy and food production, since energy and food require large volumes of fresh water for optimum generation and production.

Unfortunately, of even more concern is when a change made in one sector to solve an issue, such as the use of biofuels to reduce greenhouse gas (GHG) emissions in the energy sector, can have an unintended negative impact of reducing water and food availability in the short-term, and creating social and economic stress in the long-term. These examples show how important it is to fully understand the energy-water-food (E-W-F) cross-sector interdependencies and vulnerabilities in a region or watershed. This is required to fully understand the local connection between these three sectors and to manage emerging resource and infrastructure challenges, needs, and opportunities holistically as an integrated system.

The major connections and influences among the energy, water, and food sectors are shown in the figure below, followed by a general discussion of the relationships.

As shown in the figure below, the major cross-sector interdependencies include: the water need of the energy sector to support power generation and fuel processing and the water needs of the food sector for irrigation and processing. Likewise, the energy needs of the water sector to pump and treat water, and the energy needs of the food sector for natural gas to create fertilizers and farm chemicals, fuels for on-farm equipment operations and produce transportation, and electricity for produce refrigeration. Additionally, there is the food/agricultural product needs of the energy sector to create biofuel feedstocks. And finally, GHG emissions from the energy sector can cause climate issues that negatively impact water availability, and runoff from agricultural production negatively impacts water quality in the water sector.



These connections highlight how easily a change in one sector will impact the other two, and how emerging risks in one sector can translate into additional risks in the other sectors, causing a wide range of social, cultural, environmental, ecological, economic, and public health concerns. Unfortunately, most governments manage energy, water, and food, in completely separate agencies, leading to fragmented rather than an integrated, system-level, management approaches. For a variety of reasons, economies often drive development toward more water-intensive energy (biofuels and closed-loop electric power plant cooling), more energy-intensive water (deeper pumping, desalination, waste water reuse, fresh water pipelines), and more energy and water intensive food production.

Global Drivers to E-W-F Challenges

One global trend identified by the World Economic Forum in 2009 when they took their first look at the energy water nexus, found that developing economies commonly transition their water use and consumption from the agricultural sector to the energy and manufacturing sector. This transition helps support economic development, but creates pressure to intensify agricultural production efficiency and create more crops with less water, and pressure to provide cleaner and more water to expanding urban populations to enhance public health.

Global Water Use by Sector		
Sector	Developed Economies	Developing Economies
Energy and Manufacturing	27 – 40%	8-10%
Domestic Supplies	9-10%	6-8%
Agriculture	60-70%	80-90%

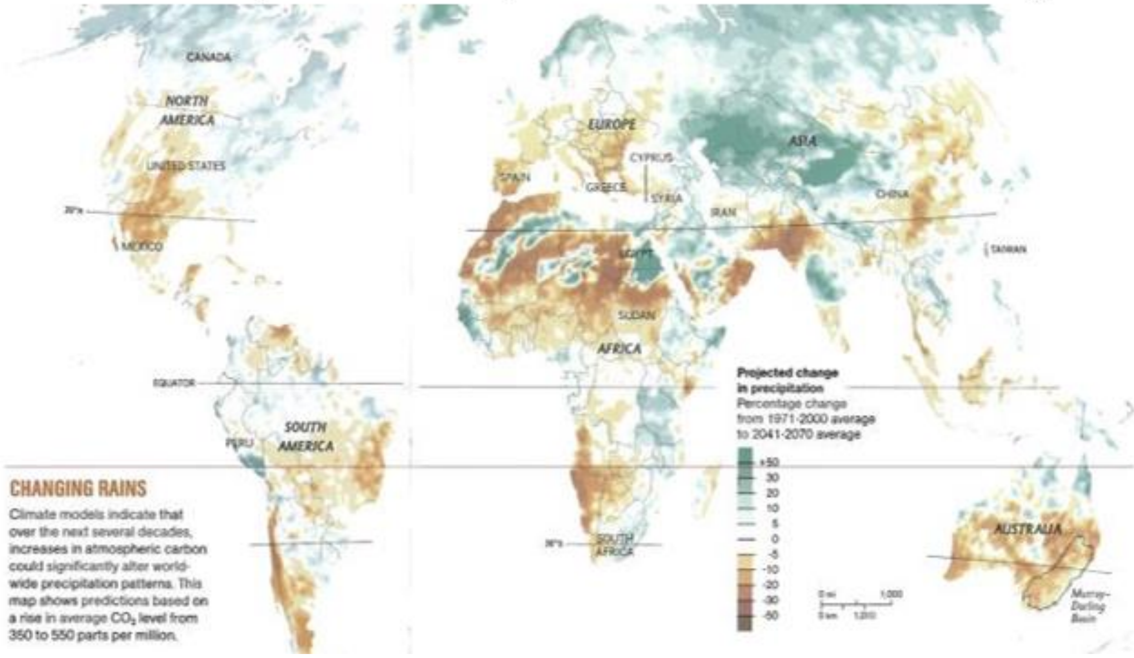
Therefore, while economic development and improvement is a logical goal of any economy, the ability to foster long-term, sustainable development will depend on how well the management of E-W-F resources and infrastructures are integrated into a coherent and sound regional strategy.

A second global trend is the large impact climate change will have on precipitation or rainfall, water availability, and therefore water supply risks and stress across the planet. While a number of studies have been done and many charts and figures developed, one of the more detailed evaluations was published by the National Geographic in April 2009. It provides information not on current water stress like many studies, but more importantly provides information on the projected changes in precipitation and rainfall by 2040-2070, relative to average regional rainfall between 1970-2000, in relation to latitude, which provides insight by region and geographic area of the global winners and losers in future average yearly rainfall and precipitation.

This provides information on the future risks to agriculture and food production capacity, risks to future surface water availability and water supplies for domestic and energy generation. Overall, the figure provides a regional glimpse of future global energy-water-food risks and challenges, and those areas that need to address these interdependencies through an integrated E-W-F natural resource and infrastructure management and operation strategy to create sustainable natural resources and resilient economic development.

To address climate change drivers such as GHG issues and water vulnerability, a number of new technical approaches to energy development, carbon capture, agricultural practices, and water supply augmentation have been developed and are being adopted. These technologies and approaches have both positive and negative impacts that should be considered when evaluating overall risks to the energy-water-food

Climate Impact on Precipitation and Water Availability



nexus. Five examples are given that highlight how integrated energy, water, and agriculture approaches can provide robust regional E-W-F solutions.

Regional Drivers to E-W-F Challenges

The first example is presented in the table below of water use and consumption by different electric power generation technologies in terms of liters per megawatt hour of electricity (L/MWhre) generated. It shows generation type, cooling type, and water use for various uses, steam condensing, make-up steam, and miscellaneous plant needs. The table also has the water needs of several renewable energy technologies and current carbon capture and sequestration technologies. As can be seen, most water use in electric power generation is for cooling water.

From the table on the next page a couple of surprising results are identified. For example, changing from open-loop cooling (often called once-through cooling because the water simply flows through the plant increasing the cooling water temperature by about 15 degrees Centigrade) to closed loop (also called evaporative cooling it uses cooling towers) significantly reduces water use, but increases water consumption. Therefore, selecting the best alternative requires regional considerations of whether water availability or water consumption is a more important issue. Additionally, dry cooling, or cooling with air, requires almost no water, but requires large air flows and cool air to be most effective, not generally available in desert environments except at night or during the winter.

In these regions, a hybrid system using dry cooling in the winter and at night, and a cooling tower during the summer is beginning to see use as a good overall compromise approach. The costs are higher, but the water use is dropped significantly.
Also, from the table it can be seen that the use of renewable energy technologies, with low GHG emissions, are often very water efficient, though some are not. Therefore, the use of renewables to reduce GHG emissions must be looked at carefully to ensure that they are also water efficient. In efforts to reduce GHG emissions from fossil fuel plants, the use of carbon capture and sequestration technologies is often suggested. As seen in the table, current approaches for carbon capture are very water intensive. Therefore, a more common approach is the combined use of

Electric Power Plant Water Use

Plant-type	Cooling Process	Water Use Intensity (L/MWhr$_e$)		
		Steam Condensing[a]		Other Uses[b]
		Withdrawal	Consumption	Consumption
Fossil/ biomass steam turbine	Open-loop	80,000–200,000	800-1200	120-360
	Closed-loop	1200–2400	1200–2000	
	Dry	0	0	
Nuclear steam turbine	Open-loop	100,000–240,000	1600	120
	Closed-loop	2000–4400	1600–2900	120
	Dry	-	-	-
Natural Gas Combined-Cycle	Open-loop	30,000–80,000	400	40
	Closed-loop	900	800	
	Dry	0	0	
Coal Integrated Gasification Combined-Cycle	Closed-loop	800	750	600
	Dry	0	0	
Geothermal	Closed-loop	8000	3000	20
	Dry	0	0	
Concentrating Solar	Closed-loop	3000	2800	40
	Dry	0	0	
Solar Photovoltaics	None	0	0	10
Wind	None	0	0	10
Carbon sequestration for fossil energy generation				
Fossil or bio-mass	Open and closed-loop	~80% increase in water withdrawal and consumption		

[a] Values are included for a range of plant designs, cooling water temperatures, and locations

[b] Includes water for equipment washing, air emissions control, restrooms, and other water uses

combined cycle natural gas with wind and solar PV, which together are relatively inexpensive, have low GHG emissions, very low water consumption, and high reliability. This highlights how looking at integrated benefits across multiple sectors like climate, energy, water, and economics can provide solutions that might not be optimal for any single sector, but provides a good solution that benefits all sectors equally well.

The second example is transportation fuel production from a range of feedstocks, including several types of biofuels, as well as general water quantity and water quality impacts. Like in the electric power sector, some interesting issues occur, especially when looking at the use of irrigated, grain-based biofuels. When looking at biofuels, both land and water use are important, so the land use of several biofuel feedstocks are noted below.

From the below table, other than microalgae, biofuel yields per hectare are small and therefore could require a major transition of agricultural land from food production to fuel production in regions that chose to move to biofuels to replace fossil-based fuels.

Typical Biofuel Production (Liters/Hectare per Year)	
Corn	40
Soybeans	100
Safflower	150
Sunflower	200
Rapeseed	250
Oil Palm	1300
Micro Algae	2000 - 12000

As shown in the table below, the water consumption for processing most of the alternative transportation fuels is from 2-5 times higher than traditional crude oil refining water needs. For irrigated biofuels, the water consumption to grow the biofuel crop jumps to 500 to 4000 times more water intensive. It is obvious that the amount of land and irrigation water needed to grow biofuels in arid environments is not sustainable, though growing biofuels in wet environments is much less of an issue. This is already driving agriculture to shift to wetter and more humid climates to reduce the need of irrigation. The exception is microalgae, where there continues to be interest in growing this fuel crop in arid regions that have high temperatures and abundant brackish water. Many algae are adaptable to brackish water, minimizing the need for fresh water, which is required by all other biofuel feedstocks. There have already been protests about food shortages caused by grain being diverted to fuel production in the Midwest U.S. in the past few years.

The next example highlighted below, are improvements in irrigation efficiency that have improved water use in agriculture, and is becoming even more efficient with the advent of precision agriculture. Historically, and still commonly practiced all over the world today, is flood irrigation, which is relatively inefficient from a water use standpoint, but is low-tech, inexpensive, has no energy costs, and is compatible with surface water irrigation.

Irrigation Approach	Water Use Efficiency
Flood	50%
Sprinkler	75%
Drip	95%

With the beginning of the “green revolution” of the 1950’s, and a move to the use of ground water for agricultural irrigation, the use of multi-stage pumps and center-pivot sprinkler systems has become very common. These systems enabled

Transportation Fuel Processing Water Consumption

Fuel Type and Process	Water Consumption (L of water per L of fuel)	Water Quantity Issues	Water Quality Issues
Conventional Fossil Fuel Crude oil refining	1.5	Water needed to refine crude oil	Waste water from refining
Biofuel Processing and Refining Grain ethanol processing Irrigation of corn for ethanol Biodiesel processing Irrigation of soy for biodiesel	~4 ~1000 ~1-2 ~6000	Water needed for processing and irrigation where required	Waste water from processing, ag runoff contamination from fertilizers, herbicides, and pesticide
Lignocellulose processing Biomass to liquids	~2-6 ~2-6	Water for processing and hydrologic flow impacts	Waste water from refining, water quality changes with perennial crops
Non-Conventional Fossil Fuel Oil shale – in situ retort Oil Shale – ex situ retort Oil sands	~2 ~3 ~2-6	Water needed to heat, extract, and refine	Waste water from mining and refining, in situ water contamination, and surface runoff
Synthetic Fuels Coal to Liquids (CTL) Hydrogen/electrolysis Hydrogen/NG reforming	~4-9 ~3 ~7	Water needed for synthesis or for steam reforming of natural gas (NG)	Waste water from processing

easier watering of large land parcels, more efficient water use, larger crop yields, and farming of land that had previously not been compatible with flood irrigation. So, while this irrigation approach has optimized farmland use and water use efficiency, it has also led to significantly increased energy use for irrigation and has led to significant ground water depletions across many agricultural regions of the globe, especially in the Middle East, India, China, and the U.S. southwest. These are the same regions most negatively impacted by the reduction in precipitation from climate change. As noted by the World Resources Institute, it is likely that with the major drops in precipitation over the next five or six decades, that ground water recharge in many areas will be significantly reduced, and ground water resources, like fresh surface water resources will become increasingly stressed.

This is why many regions are moving to precision agriculture using GPS and GIS systems to install drip irrigation technologies for high-cash, row crops. This reduces excess water use as well as water loss, optimizes 'more crop per drop'. This can be very energy efficient because of the lower amounts of water used and lower pressures, especially if integrated with small on-farm renewable energy systems. So, the agriculture sector is also developing approaches that can be used to reduce impacts on the energy and water sectors.

The final example is focused on the use of non-traditional water resources to help supplement fresh water supplies. Many regions expected to experience reductions in rainfall and precipitation have other water resources at their disposal, such as seawater, brackish groundwater, and even industrial and municipal wastewater. But these water sources will require some level of treatment to be useable to substitute for fresh water in many applications. In the past, treatment has been very energy intensive and was often cost prohibitive. But in the past few decades desalination of seawater and brackish ground water has become much more cost-effective and waste water reuse has also become much more cost effective. This has occurred at a time when fresh water costs are increasing significantly because of greater scarcity, and concepts such as 'fit for purpose' and 'fit for use' are driving the level of water treatment needed for various applications is being reduced. This is driving the cost and energy demand for the treatment of these non-traditional waters for many applications down even further.

This is highlighted in the table below, where the energy requirements for bringing in new fresh water supplies to a region are compared with the energy requirements to utilize different locally available non-traditional water sources.

Non-traditional Water Supply Options	**Energy Demand ($kWhr/m^3$)**
Fresh Water Importation (100-300 miles)	3.0 - 4.5
Seawater Desalination	3.0 - 5.0
Brackish Groundwater Desalination	2.0 - 3.0
Waste Water Treatment and Aquifer Storage and Recovery	2.0 - 2.5

As can be seen in the table, the use of locally available non-traditional water resources is competitive with bringing in fresh water from new sources 100's of miles or kilometers away. The table highlights energy costs, but energy is often the largest unit cost for treatment of non-traditional waters, accounting for 30% to 50% of the total costs. Many regions have implemented desalination and waste water reuse cost-effectively in the past two decades and have continued to reduce costs by integrating with renewable energy projects, integrated energy recovery systems, and used the treated water to replace the use of fresh water in industrial and manufacturing applications where fresh water quality is not required. This highlights ways the water sector can support the needs of the energy and food sectors by increasing access to additional non-traditional water supplies.

Integrated Management Strategies at the Energy Water Food Nexus

As noted in the above discussions, future regional economic development will depend on how well the management of energy water and food resources and infrastructures are integrated into a coherent and sustainable strategy. While many environmental and social groups want to focus sustainability on a single factor, GHG issues, these can lead to the implementation of solutions, such as the large-scale use of irrigated biofuels or coal plant carbon capture and sequestration, that have been shown to cause severe water supply and food supply vulnerabilities and therefore significant social and economic risks.

This paper has highlighted several innovative technical approaches and management strategies for energy development, carbon emission mitigation, agricultural practices, and water supply conservation and augmentation that can be used to support an integrated and sustainable energy water food strategy. These technologies and approaches have both positive and negative impacts including costs and social and environmental impacts that should be considered when evaluating overall sustainability risks. But hopefully, looking at this from a coordinated energy water food perspective will lead to effective solutions that can create an optimized sustainable solution that equally support each of the three sectors, energy, water, and food, not just one.

The following paragraphs highlight some of the technologies and approaches that would help support a regional sustainable integrated energy water food strategy.

Reduce Water Use for Energy – implementation and use of 1) advanced cooling technologies, hybrid cooling, 2) use of non-traditional waters (brackish water, waste water) rather than using fresh water for cooling, 3) integration of low water use renewables with natural gas to reduce water use, GHGs, and maintain energy reliability, 4) minimize use of fresh water for irrigated biofuels, and 5) use brackish water for biofuels.

Reduce Energy Use for Water – implementation and use of 1) lower cost, lower energy, and energy recovery for desalination, 2) advanced industrial, municipal, and storm waste water recycling to replace fresh water for cooling and irrigation, 3) urban infrastructure water harvesting and reuse, 4) combined renewable energy and water treatment systems, and 5) distributed smart grid and smart water and energy and systems.

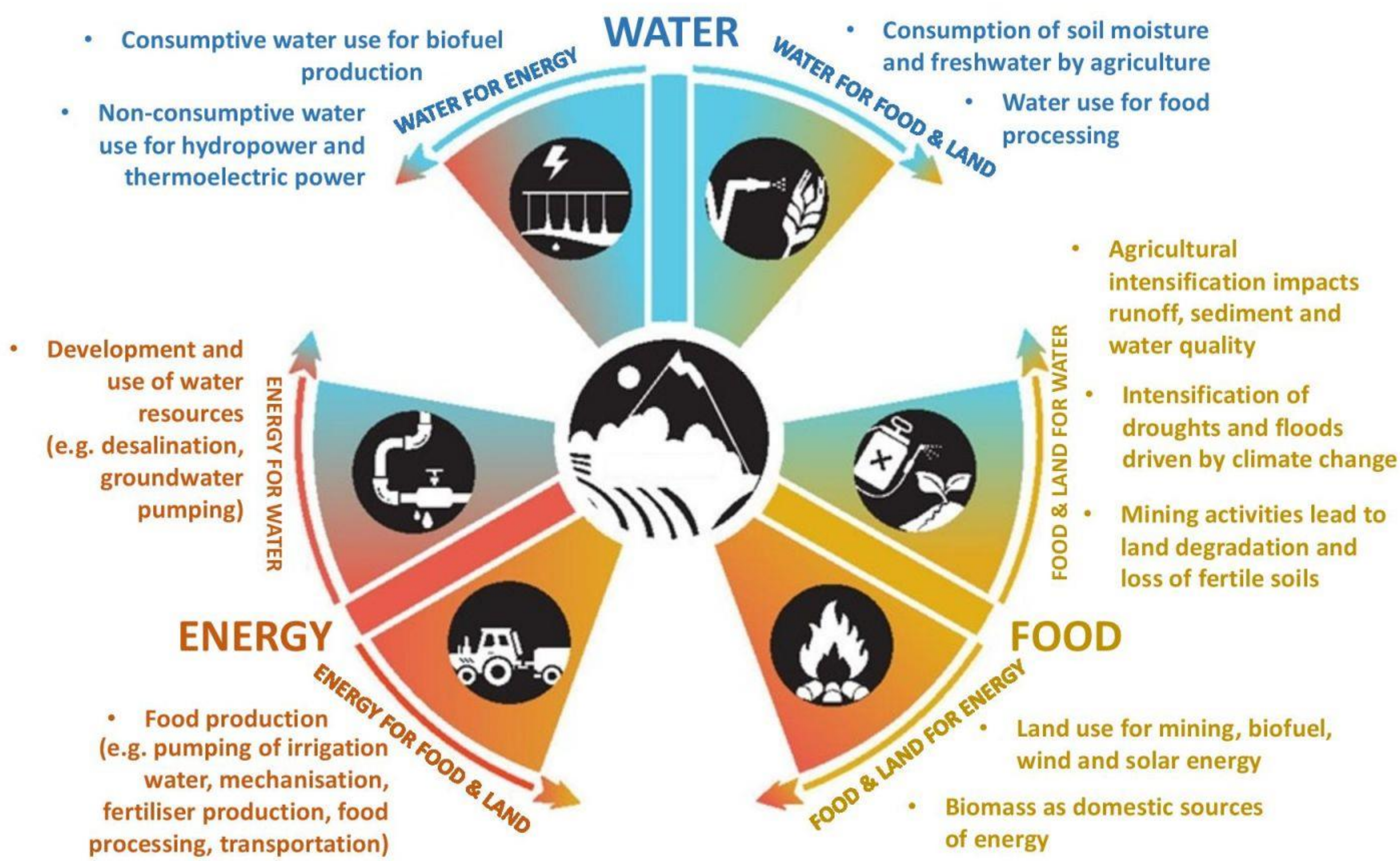
Reduce Water Use for Food – implementation and use of 1) improved irrigation technologies, and address social and market barriers for advanced irrigation, 2) application of no till agriculture, 3) controlled environment ag – including vertical ag, aquaponics and hydroponics, 4) treatment of non-traditional water for ag – including brackish water and ag drainage and return flow reuse.

Reduce Energy Use for Food – implementation and use of 1) improved energy efficient fertilizer and chemical manufacturing, 2) smart farming to enhance energy efficiency, 3) energy efficient refrigeration, 4) improved local and urban farming approaches and markets, and 5) improved energy efficiency of farm equipment and produce processing approaches.

Reduce Food Use for Energy – implementation and use of 1) non-food feedstocks for biofuels, 2) improved pathways for farming waste biomass to energy such as cellulosic biofuels, and 3) turn food waste to energy.

Improve Integrated Resource Planning – implement and develop accepted strategies to 1) address policy and regulatory inconsistencies, 2) address social and cultural challenges, 3) eliminate economic disincentives and improve adoption of economic incentives, and 4) improve urban and rural planning metrics and milestones to drive sustainable energy water food management.

These considerations will help economies transition to economic development practices that can create more 'watts per drop', more 'crop per drop', more 'crop per watt' and more 'drops per watt'. This will change the paradigm by using innovation to expand integrated energy water food management and create a sustainable economic and natural resources future that supports social and public health and safety.



UN Economic Commission for Europe 2016

MEDRC

Sources for Further Learning

Websites

UN Water – Water, Food & Energy

Water-Energy-Food Nexus Knowledge-Action Network

Water, Energy & Food Security Resource Platform

Water in the West - Water-Energy

Books and Reports

Water Security – The Water, Energy, Food, Climate Nexus – World Economic Forum, 2011

Climate, Energy, and Water, Chapters 14, 15, 17, 18 – Cambridge University Press, 2015

Reconciling resource uses in transboundary basins: assessment of the water-food-energy-ecosystems nexus in the Sava River Basin – UNECE, 2016

Water-Energy-Food Nexus Knowledge-Action Network, Research and Engagement Plan – FutureEarth

Sustainability in the Mineral and Energy Sectors, Chapter 20 – CRC Press, 2017

The Water-Energy-Food Nexus: A systematic review of methods for nexus assessment – 2018 *Environ. Res. Lett.* **13** 043002

Acknowledgements

The MEDRC Transboundary Waters Practitioner Briefing series has been developed for water industry practitioners and government officials at the request of MEDRC's member countries, with sponsorship provided by the Netherlands and Sweden. The briefings are meant to be informative and practical, providing an overview of the subject matter material, while remaining accessible to various backgrounds and disciplines. The briefings serve to develop shared knowledge and serve as a basis of further discussions between partners. If you would like to learn more about these subjects, please see the section "Sources for Further Learning."

References

1. CH2M HILL, 2003. Water use in industries of the future. In *Industrial Water Management: A Systems Approach*, 2nd ed., Center for Waste Reduction Technologies, American Institute of Chemical Engineers.
2. Feeley, T. et al., 2005. Addressing the critical link between fossil energy and water. National Energy Technology Laboratory.
3. Groundwater Protection Council, 2009. Modern shale gas development in the U.S.
4. Hightower, M, 2010a. Water and energy challenges – emerging hydropower opportunities. 78th International Conference on Large Dams.
5. Hightower, M. and R. Pate, 2010b. Improving water efficiency in biofuels production - energy supply reliability and environmental considerations. Seventh International Starch Technology Conference.
6. International Energy Agency, 2012. 2012 World energy outlook.
7. Llewellyn, D. and S. Valdez, 2013. West wide climate risk assessment: upper Rio Grande impact assessment, Bureau of Reclamation.
8. Macknick, J., R. Newmark, et al, 2012. Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature. National Renewable Energy Laboratory.
9. Moore, S., 2010, The water cost of carbon capture. IEEE Spectrum.
10. National Academy of Sciences, 2007. Colloquium on the water implications of biofuels production in the U.S.," Washington DC.
11. National Geographic, April 2009.
12. National Energy Technology Laboratory, 2006. Estimating freshwater needs to meet future thermoelectric generation requirements. DOE/NETL-2006/1235.
13. Organization for Economic Co-operation and Development, 2007. Environmental outlook baseline. Paris, France.
14. Pate, R., M. Hightower, et al, 2007. Overview of energy-water interdependencies and the emerging demands on water resources, SAND2007-1349C, Sandia National Laboratories.
15. Schreir H. and G. Pang, 2012. Virtual water and global food security, www.wmc.landfood.ubc.ca/webapp/VWM/
16. U.S. Department of Energy, 2007. Energy demands on water resources: Report to Congress on the interdependency of energy and water.
17. U.S. Department of Energy, 2014. The water energy nexus – challenges and opportunities.
18. World Economic Forum, 2009. Energy vision update 2009, Thirsty energy: water and energy in the 21st century.
19. World Energy Council, 2010. Water for energy report.
20. World Resources Institute, 2015. Aqueduct – Monitoring and Mapping Water Risk. http://www.wri.org/our-work/project/aqueduct
21. UNECE, 2016. Reconciling resource uses in transboundary basins: assessment of the water-food-energy-ecosystems nexus in the Sava River Basin