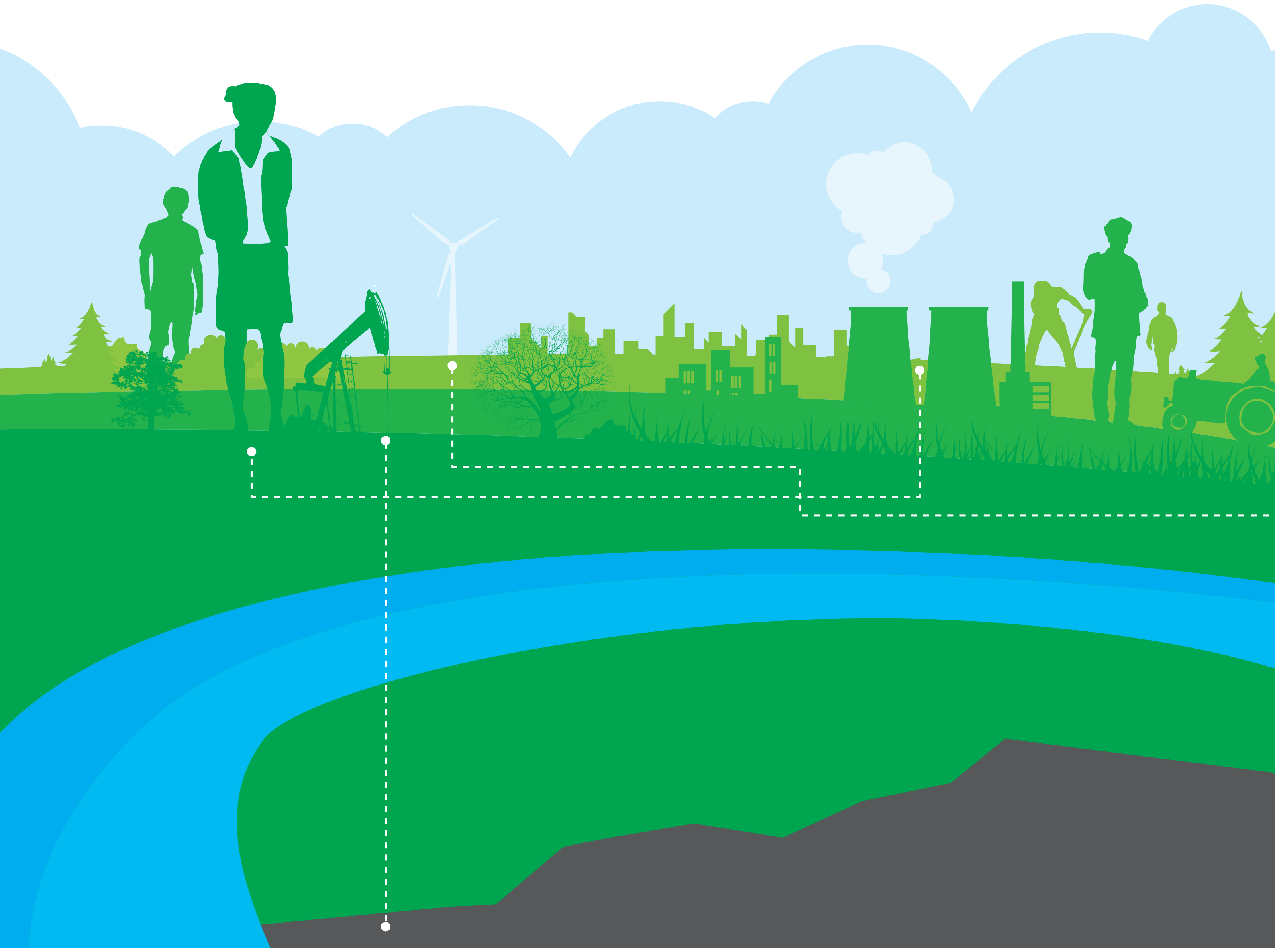
The Energy Sustainability Challenge

How will natural resource constraints change the way we produce and use energy?



This booklet outlines key insights from the Energy Sustainability Challenge research programme and presents a selection of the findings

A BP-funded consortium of experts from 15 leading universities is examining the complex relationships between natural resources and the supply and use of energy. This multi-disciplinary research programme – the Energy Sustainability Challenge (ESC) – is investigating the effects of natural resource scarcities on patterns of energy supply and consumption.

In the initial phase the research programme was under the academic guidance of a dedicated advisory group:

Advisory Group

Lynn Gladden
University of Cambridge

José Goldemberg
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The Energy Sustainability Challenge

Water, land, and minerals are essential to our way of life. These natural resources enable provision of food and feed and they underpin the ecosystems which regulate our planet. Energy provides the light, heat and mobility essential to humanity's infrastructure.

This booklet provides an introduction to the Energy Sustainability Challenge – a BP funded consortium of university researchers which has looked at the challenges of sustaining the world's energy systems. The aim is to address a big question: How will natural resource constraints change the way we produce and use energy?

Increasingly we not only recognise constraints on natural resources but also the linkages amongst these and energy. Developing a sound technical understanding of energy in a systems context, underpinned by robust data, will help policy makers and businesses to make better decisions.

The research outlined here stems from peer-reviewed papers published by ESC consortium universities and three new handbooks on water, materials and land for biomass.

Energy sustainability is one of the biggest challenges of this age. Increasing our understanding of energy's relationships with the natural resources that directly maintain life is important for making the right choices.

Ellen Williams
Chief Scientist, BP

December 2013

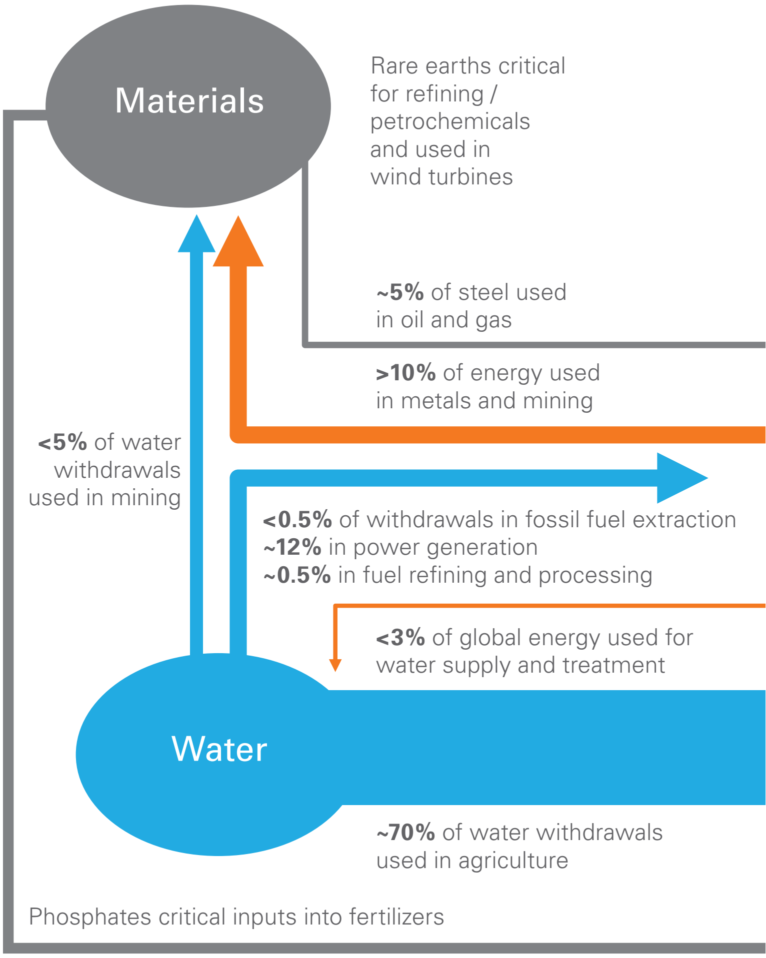
In this booklet

Making sense of the complexity, connections and scale

A growing human population uses increasing quantities of water, land, minerals and energy worldwide. The scale and complexity make it difficult to understand the significance of the information we receive.

The ESC consortium's research helps us to put this information in context. For example, the chart below shows a global analysis of the natural resource constraints related to energy other than the availability of energy reserves themselves – from land, water and materials to impacts on atmospheric carbon. Each arrow indicates the magnitude of the link between pairs of resources.

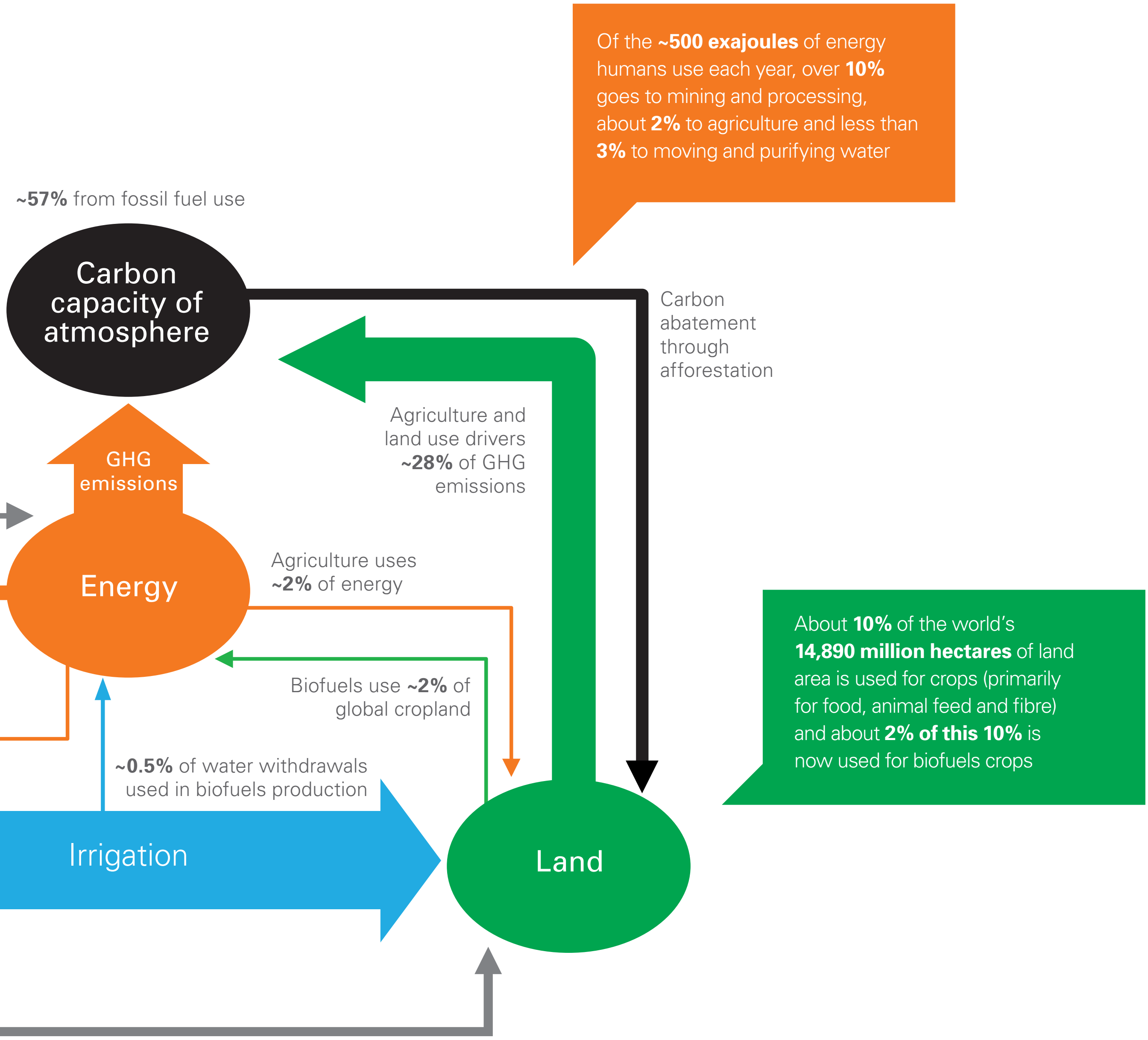
There is adequate physical supply of the materials needed for energy production, however some rare earth and platinum group metals along with chromium and cobalt are produced in few locations and are vulnerable to disruption



About **10%** of the world's annual renewable fresh water reserves is withdrawn for human use. About **70% of the water withdrawn** is used for agriculture

Combustion of fossil fuels is responsible for more than **60%** of the anthropogenic greenhouse gas emissions to the atmosphere, with agriculture and land use conversion contributing nearly **30%**

Source: BP/ McKinsey & Co analysis



Moving from the global picture to specific insights

The chart provides a global view based on physical world averages today. This only reveals part of the picture. Physical scarcity on a global basis is seldom the limiting factor, but natural resource constraints vary widely by region. Population growth and demographics – exacerbated by climate change – will be primary drivers of stress in the future.

These insights are discussed further in the remainder of this booklet, with a selection of research presented which addresses the impact of water, land and materials constraints on energy, shaped by supply chains, geographical variability and policy decisions.

The ESC systems analysis shows that physical scarcity on a global basis is seldom the limiting factor but that natural resource constraints vary by region. There is the potential to tackle these constraints through better informed technology choices, however this in turn will require targeted governance and thoughtful policy decisions. Examples of the work that underpins these insights are provided below.

Physical scarcity is seldom the limiting factor…

Example: Production and reserves for rare earth elements

Key Producers 2010	Annual production 2010		Reserves	R/P
Country	*Tonnes*	*%*	*Tonnes*	*Years*
China	130,000	97.31	55,000,000	423
India	2,700	2.02	3,100,000	1,148
Brazil	550	0.41	48,000	87
Others	350	0.26	51,852,000	148,149
World	**133,600**		**110,000,000**	**823**

Source: Materials critical to the energy industry: an introduction

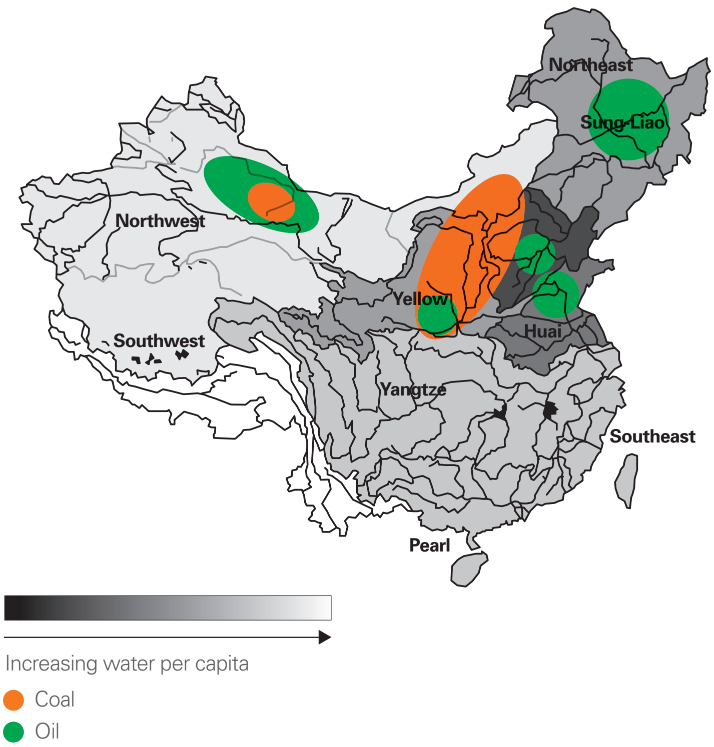
Energy systems rely on a large number of minerals and other materials. This dependence raises concerns that we might run out of crucial minerals such as rare earth elements or lithium.

Research from the University of Augsburg reveals that, in reality, physical scarcity is seldom the limiting factor: reserves are dynamic. Economics, geological understanding and new technologies drive reserve growth to meet demand, and recycling and substitutability create additional options.

Instead, the complex supply chains that lead from geological processes to the refined materials are a greater concern for the stability of energy systems.

…however natural resource constraints vary widely by region

Fossil fuels and water availability in China



Understanding global averages is helpful but masks considerable regional variability of natural resource stresses.

For instance, the ESC research from Tsinghua University and the University of California at San Diego addresses water issues in China. The per capita water resource of China is only 1/4 of the world average, and highly variable within the country. Northern China has less than 8% of the nation's water, but must support 1/3 of the population, cultivate 2/5 of its farmland, and produce 1/3 of its GDP.

At the same time, China continues to develop water-intensive industries (e.g. the power and coal-chemical industry) in coal-rich but water-stressed regions.

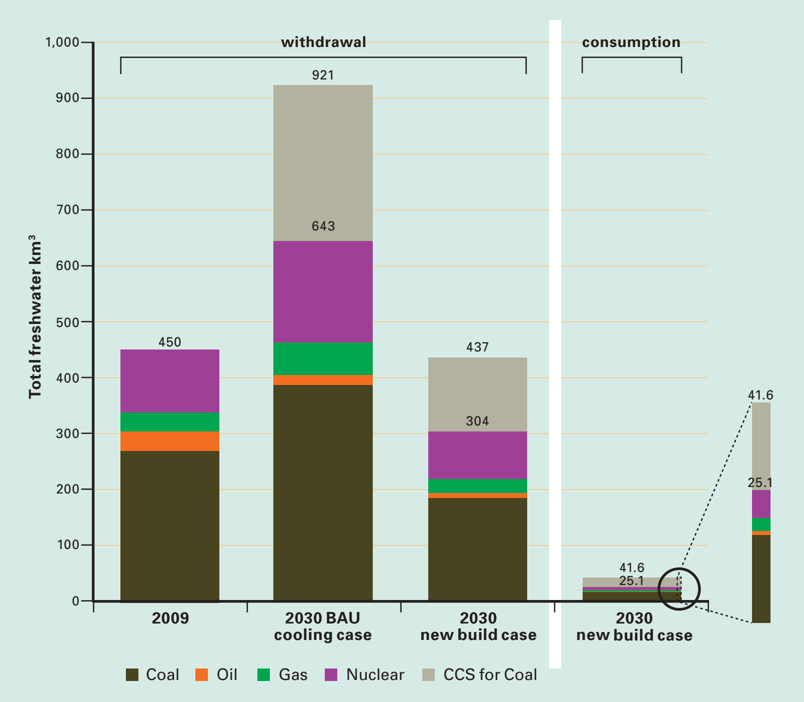
Source: UCSD

More information available at: www.tsinghua.edu.cn and http://ilar.ucsd.edu

See also: Rong, F. & Victor, D. G. (2011), Energy Policy, Vol 39, Issue 12

Better technology choices can make a difference…

Predicted fresh water withdrawals using different technologies



MIT's research suggests we can reduce the demands on natural resources with improved technology. An example is the use of cooling water in power production, which currently accounts for about 10% of world-wide fresh water withdrawals. A 'business as usual' technical approach would increase water withdrawals for cooling by nearly 50% by 2030, excluding the potential impact of carbon capture and storage (CCS). However, if all new-build power plants used closed-cycle cooling instead of once through, this would allow lower water withdrawals even with the addition of CCS. The final column in the chart shows water consumption for this case with all new build power plants using closed-cycle cooling.

Source: Water in the energy industry: an introduction

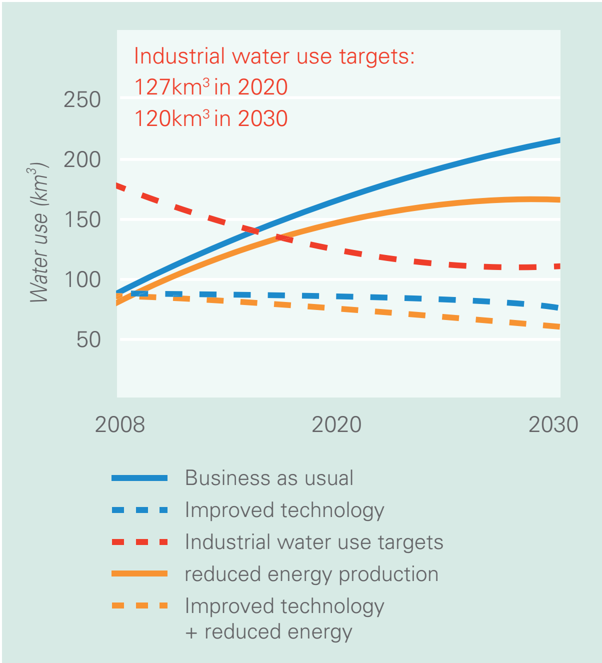
…and policy levers can guide better choices

To address water issues, China has established targets to limit the absolute quantities of water used in industry, which would otherwise more than double by 2030. A 'business as usual' scenario would fall short of the goals well before 2020, even if energy demand is reduced.

However, improved technical approaches, with effective policy leverage, could reduce water use below current levels. Water recycling in coal mining and water-efficient power plant cooling systems are obvious solutions. ESC research also shows that water used in washing coal improves efficiency of combustion and saves water use at power stations.

Improved efficiency of using washed coal is likely to be realized only if policy incentives overcome the increase in operational costs.

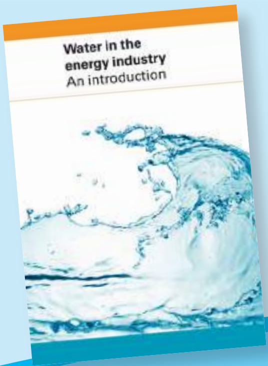
Water use projections in energy production and policy targets



Source: Tsinghua

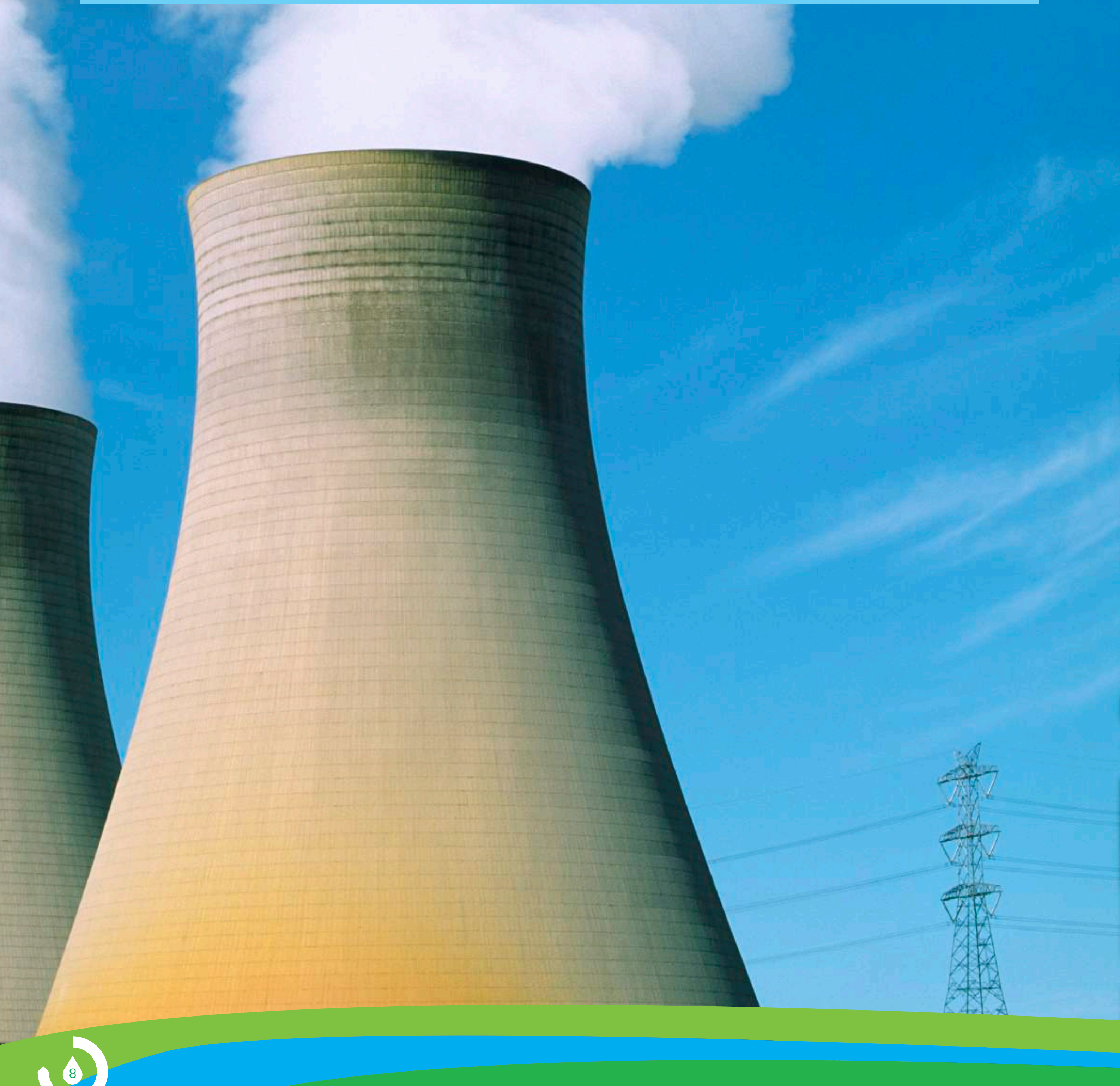
More information available at: www.tsinghua.edu.cn and http://ilar.ucsd.edu

See also: Pan, L., Liu, P., Ma, L., and Li, Z. (2012). A supply chain based assessment of water issues in the coal industry in China. Energy Policy, 48: 93-102



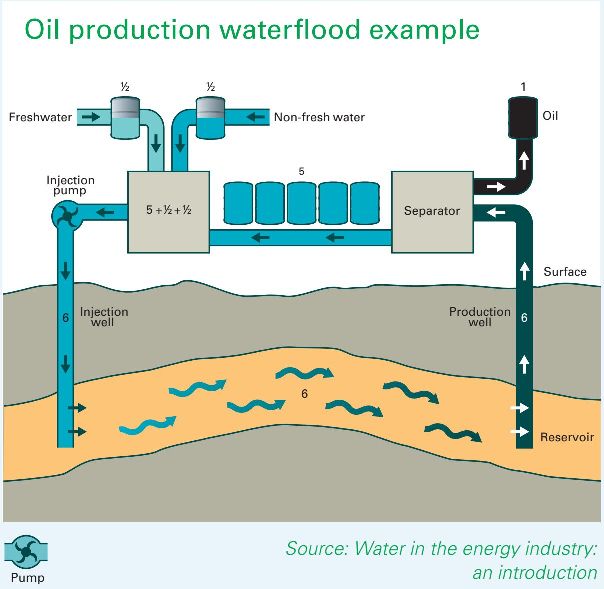
Water in the energy industry: an introduction brings together research from the Massachusetts Institute of Technology, the University of Texas at Austin, the University of Illinois Urbana-Champaign, Tsinghua University and the University of Cambridge on where and how energy connects to water. Its objectives are to facilitate understanding of the current challenges and opportunities and to provide sufficient data for the interested reader to estimate the expected water use for any particular energy pathway.

Water



Extractive industries are developing ways to reduce fresh water requirements

Oil production waterflood example



Source: Water in the energy industry: an introduction

The scale and methods of extraction of fossil fuels and uranium vary widely. Water withdrawal and consumption intensities can vary from industry to industry and region to region. Within each of these, variations occur as a consequence of the geological setting, the local climate and the investment in water efficient technologies.

The extractive industries have developed many ways to reduce the volumes of fresh water used in their processes. Using poor quality water (e.g. seawater) has had a large impact on reducing fresh water demand, along with re-use and recycling methods. The illustration here shows how water injection is used to displace oil and the original oil field water.

In this example, one barrel of oil and five barrels of oil field water is produced for every six barrels of water injected into the reservoir. The injection water is made up of five barrels of returned produced water, 0.5 barrels of non-fresh water and 0.5 barrels of fresh water, giving a fresh water intensity of 0.5 barrels fresh water/barrel of oil produced.

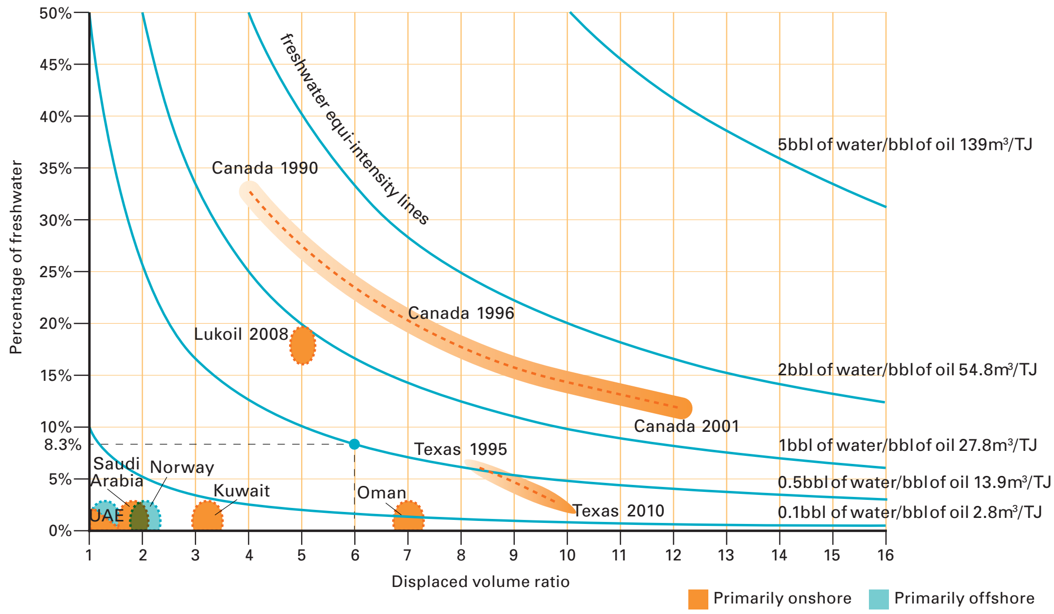
The displaced volume ratio is 6:1 (Not to scale).

Water consumption varies greatly in conventional oil production

While water is used extensively in conventional oil production, it does not need to be fresh water. This chart shows how fresh water intensity can be reduced. Using the chart, we can compare the differences in water consumption for different oil production operations and regions:

- The use of seawater and brackish water in offshore fields and the Middle East reduces fresh water consumption, yielding fresh water consumption intensities close to zero barrels of water/barrel of oil.
- Data from Texas and Canada shows that, even as the amount of produced water per barrel of oil is increasing, the consumption of fresh water has has been held constant or even reduced.
- For a sample of the world's oil producing regions, the fresh water consumption intensity is no more than about 1.5 barrels of water/barrel of oil, with significant production at intensities at least a factor of 10 lower.

Fresh water consumption in conventional oil production for different regions and at different stages of field maturity



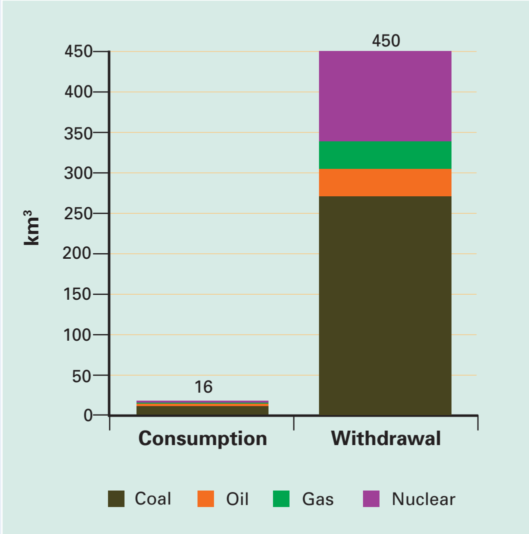
Source: Water in the energy industry: an introduction

The majority of water withdrawn for power production is not consumed

Withdrawn water is removed from surface or groundwater, at least temporarily, whereas consumed water is the portion of withdrawn water not returned to the surface or groundwater in the same drainage basin from which it was abstracted.

The chart on the right compares estimated global water withdrawal with consumption volumes for coal, oil, gas and nuclear powered electricity generation, illustrating that the majority of water withdrawn for power production is not consumed.

Estimated annual cooling water consumption and withdrawals by fuel type (2009)



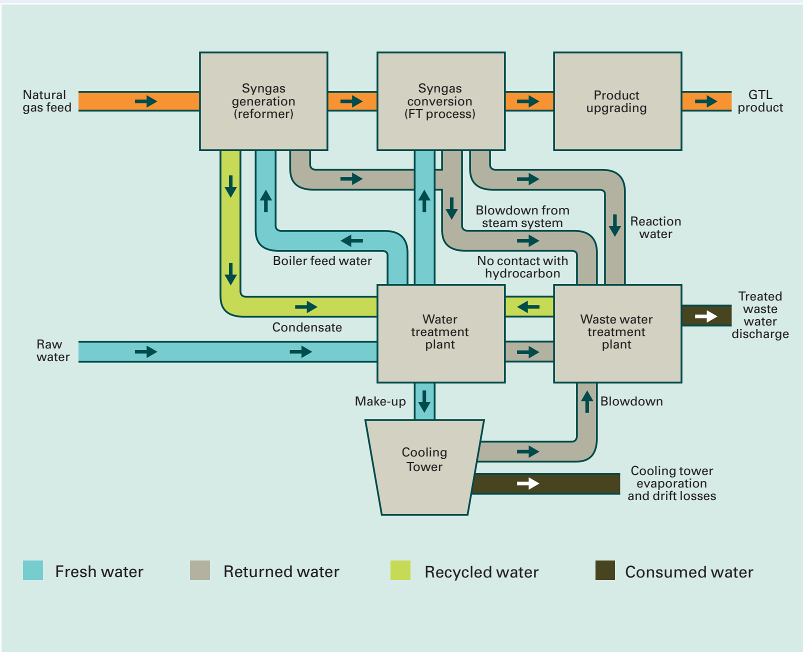
Source: Water in the energy industry: an introduction

Rigorous water management in gas-to-liquids plants can remove the need for fresh water withdrawals

Enhancements of the Fischer Tropsch (FT) process are at the heart of modern gas-to-liquids plants. First, natural gas is reformed into a mixture of carbon monoxide (CO) and hydrogen (H_2) called synthesis gas (syngas). The syngas is then converted via the FT process over a catalyst producing a mixture of hydrocarbons. From the water use perspective, a key point is that the net chemical reaction sequence produces a surplus of water.

Thus, with careful management to separate and recycle the output water, process water can be managed as a closed cycle and provide the water needed for other parts of plant operations and/or even provide a useful water product. Where water is scarce, rigorous internal recycling of water and use of dry cooling techniques can remove the need for fresh water withdrawals.

Schematic flow diagram of water use in a gas-to-liquid (GTL) plant



Source: Water in the energy industry: an introduction

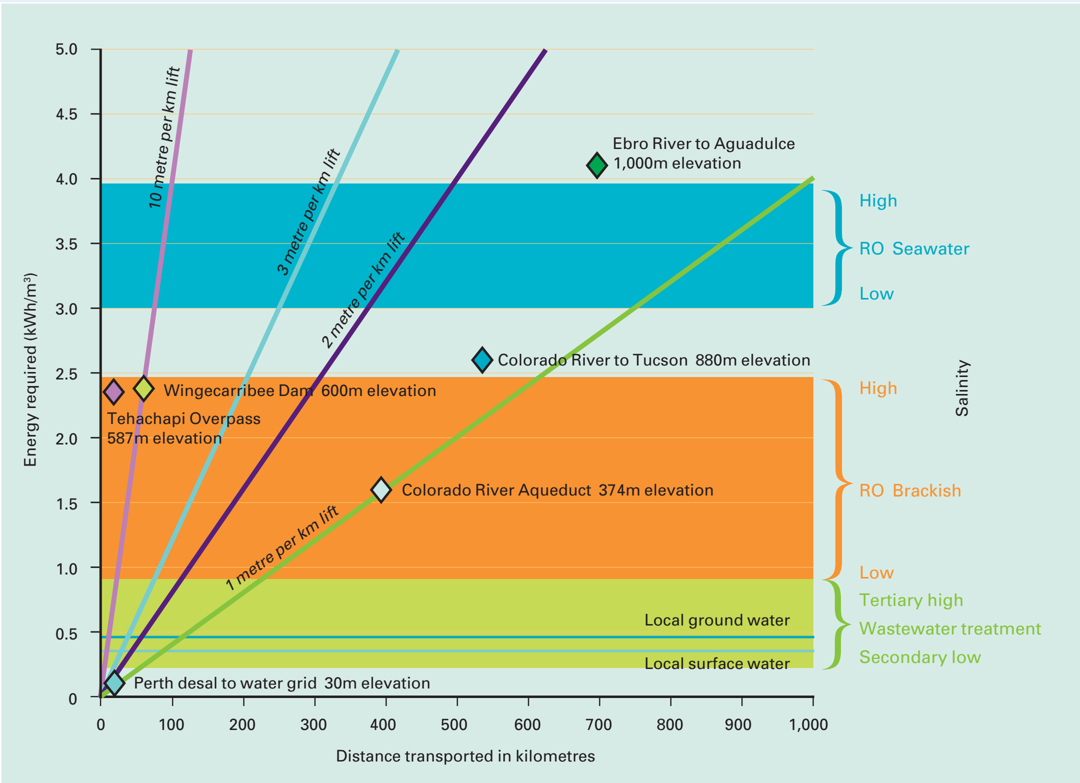
The energy cost can influence water choices

The energy used for supply and treatment of water is surprisingly small, at only ~2% of total primary energy. However, understanding the energy requirements for different types of processes helps us to make better choices for how we deliver and treat water.

For example if fresh water has to be pumped to high elevations or a long way to consumers, the energy cost of water transport can reach or exceed the cost of desalination. The figure below shows the relative energy usage for different net lift (elevation gain) and conveyance distances versus various desalination technologies. It also illustrates a number of conveyance projects in terms of their elevation gain and their energy costs.

The chart illustrates the trade-off between transport and desalination in terms of energy required. For example, transporting water in Northern Spain from the Ebro river to Aguadulce, through a distance of approximately 700km, at a net elevation of 1km, requires more than 4 kWh/m^3. This exceeds the power requirements for reverse osmosis of brackish water, indicating that local desalination would be more energy effective if a source of brackish water is available.

Comparison of energy required to supply water by reverse osmosis (RO) desalination versus transportation



Source: Water in the energy industry: an introduction

The energy requirement to transport water across a range of distances and elevation is shown by the solid lines each indicating a different net slope. The fixed energy costs to supply water by normal treatment of fresh ground or surface water, or by reverse osmosis (RO) of brackish water or seawater are shown as horizontal lines and bars. Reported energy costs for different energy transport projects are shown as diamonds.

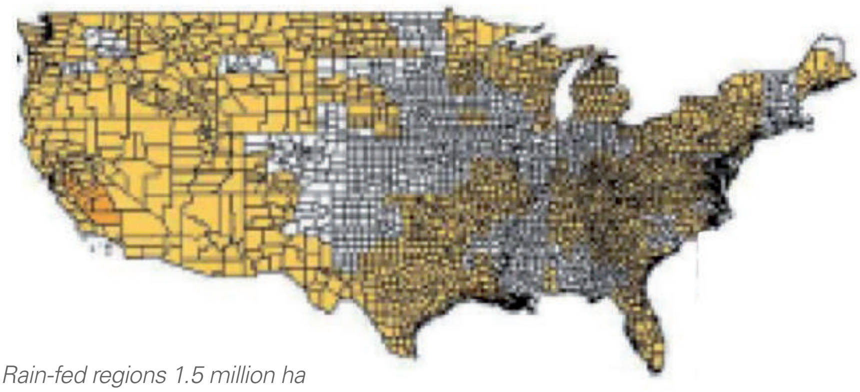
Biomass in the energy industry: an introduction seeks to place the growing interest in renewable sources of energy derived from biological materials in the context of our overall energy supply. It identifies the unique characteristics associated with the production and use of renewable, biological feedstocks for energy. In doing so it explores the potential for – as well as the issues related to – using biomass as an energy source.

Biomass

Accurate assessments of land use could improve decision making

Careful land use assessment is needed to balance land needs for ecosystem services, food production and biofuels. An example of such a survey, carried out for the continental United States in 2007, identified over 10 million hectares of rain-fed idle land or land of limited agricultural productivity outside of the 150 million hectares in agricultural production and 15 million hectares in the conservation reserve program. A similar survey in Brazil reveals 21 million hectares of pasture land that could be made available for sugar cane biofuels crops without displacing agriculture or inducing deforestation.

Idle land outside of the conservation reserve programme

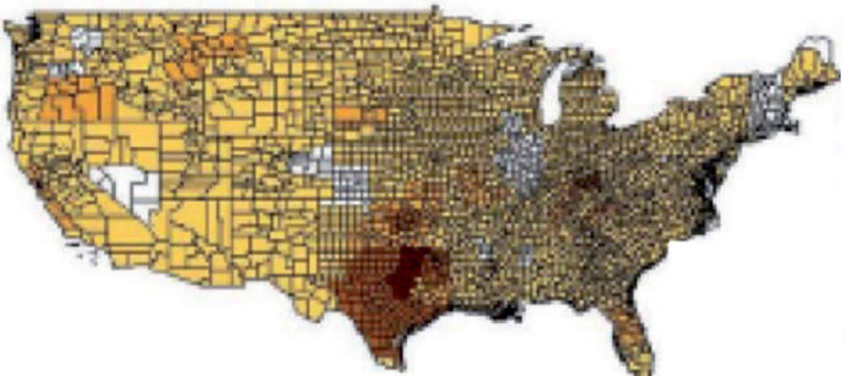


Rain-fed regions 1.5 million ha
Non-rain-fed regions 0.6 million ha

0 1600

Colour scale: 1000s acres within country

Pasture

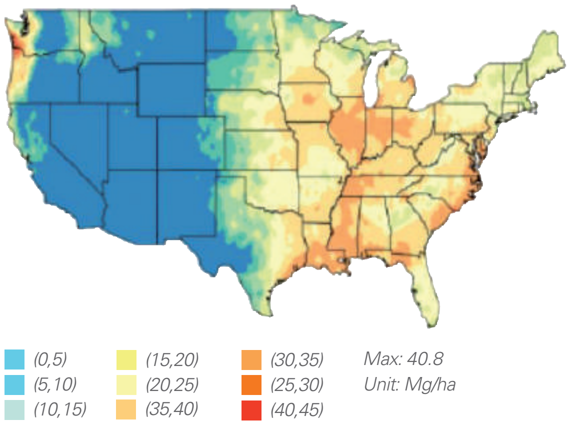


Rain-fed regions 9 million ha
Non-rain-fed regions 2 million ha

Source: UC Berkeley and UIUC

See also: Chen, X., H. Huang, and M. Khanna (2012) Land Use and Greenhouse Gas Implications of Biofuels: Role of Policy and Technology (available at http://ssrn.com/abstract=2001520)

Projected productivity of Miscanthus across mainland USA



Source: UC Berkley and UIUC
See also: Somerville et al. (2010) Science 329, 790

Lignocellulosic crops could boost biofuel productivity

Biofuels produced through lignocellulosic conversion may create opportunities to use crop residues or plants that can be grown on land unsuited for conventional arable crops. Perennial feedstocks suited to non-agricultural or marginal (degraded or low productivity pasture) land include Miscanthus, switchgrass and energy cane.

To complement the extensive potential for sugar cane ethanol, which has been developed in Brazil, the University of Illinois Urbana-Champaign has examined the potential for lignocelluosic fuel production in the US. The projected agricultural productivity of Miscanthus shown on the map ranges from 0 to 40.8 dry tonnes/hectare. Using the estimates of available rain-fed non-crop land, this would be enough to more than double the present US bio-ethanol production of ~13 billion gallons (~49 billion litres) a year without decreasing land available for food and feed production.

Greenhouse gas value calculation over a 50 year period

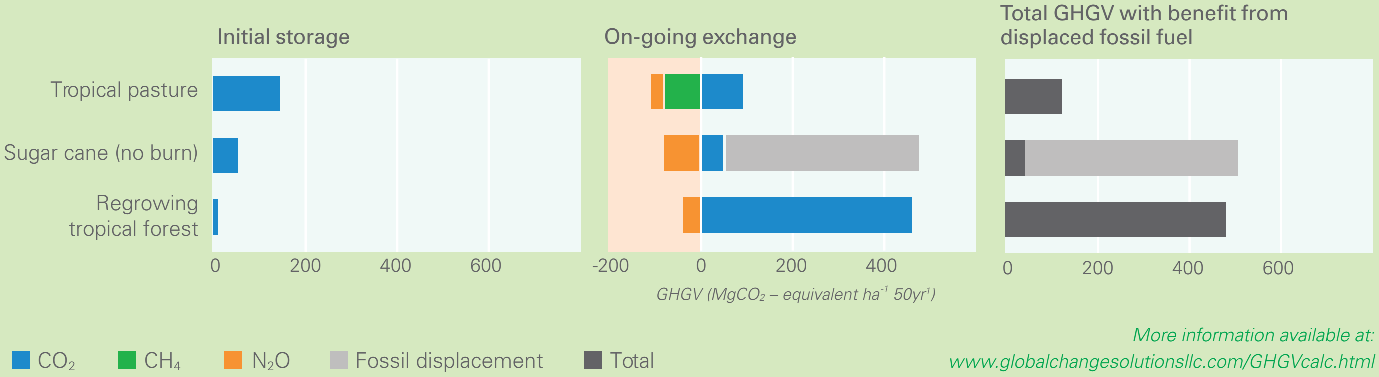
Greenhouse Gas Value (GHGV) is a measure of the total greenhouse gas benefit of an ecosystem. It is measured in terms of how many tonnes (Mg) of greenhouse gases (measured in CO_2 equivalents) are initially stored, and also how many are removed from the atmosphere by the ecosystem over a specified time period.

The Greenhouse Gas Value Calculator, developed at the University of Illinois, is an online tool for calculating the GHGV of terrestrial ecosystems.

In the example shown, it is used to assess the relative benefits over a 50 year period of replacing tropical pasture either with tropical forest or sugar cane for biofuels.

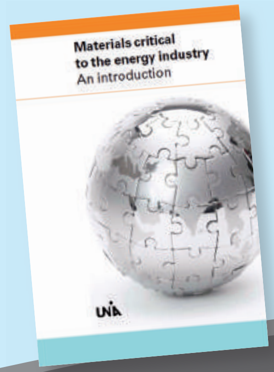
Both approaches show reduced methane emissions from displaced animal husbandry. The growing forest takes up CO_2 and stores it in wood initially quickly, and then more slowly as trees mature. The biofuels crop stores less carbon in the plants, but displaces emissions from the use of fossil fuels.

Comparing GHG values for tropical pasture, sugar cane and tropical forest



More information available at: www.globalchangesolutionsllc.com/GHGVcalc.html

Note: The displaced emissions are approximate based on the combustion energy of ethanol replacing an equal amount of energy from gasoline. These emissions do not include the impact from processing, transport or co-produced electricity in ethanol production, nor do they include the GHG costs of gasoline production.



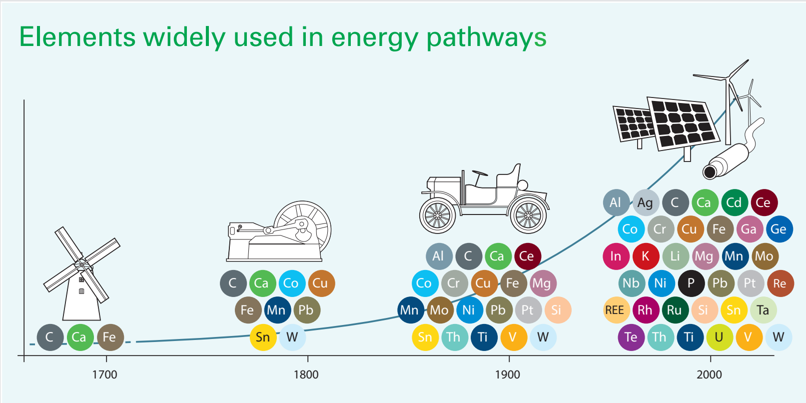
Materials critical to the energy industry: an introduction provides an overview of the complex supply chains that lead from geological processes to the refined materials needed to maintain existing energy pathways and build new ones. It focuses on 19 materials essential to current and foreseen energy pathways.

Materials

Supply chains are a key influence

As the diagram illustrates, elements are increasingly widely used in energy pathways. Sufficient supply of critical minerals at a price that makes economic sense will enable existing pathways and ensure the uptake of new sustainable energy supplies. Therefore although reserves of materials may be sufficient for many years, it is the complex supply chains that will be a key influence.

Source: Materials critical to the energy industry: an introduction



Reserves of materials are sufficient for many years

The table from which this extract is taken shows the percentages of world total reserves by major producing countries for elements identified as critical to energy production. For each country, where data is available, the most recent reserves to production (R/P) ratio is identified.

In all cases, at current production rates there are several years supply available in each of the five major producing countries and global R/P ratios exceed twenty years.

Source: Materials critical to the energy industry: an introduction

Materials	World (tonnes)	Argentina	Australia	Austria	Belarus	Bolivia	Brazil	Canada	Chile	China	DR Congo
Cd Cadmium	660,000							3% 12		14% 16	
Cr* Chromium	>350M										
Co Cobalt	7.3M		19% 304							1% 13	47% 76
Cu Copper	630M		13% 89						24% 27	5% 26	
Ga** Gallium	n/a										
Ge** Germanium	n/a										
In Indium	n/a										
Li Lithium	13M	7% 293	4% 68						58% 852	27% 778	

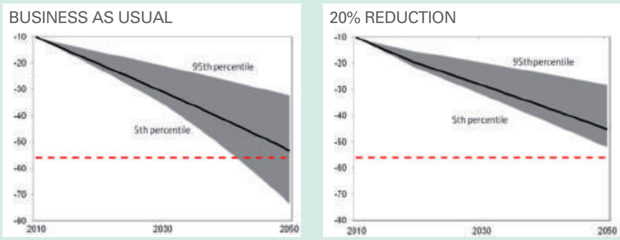
Seeing the bigger picture with visualisation tools

To make informed decisions about managing natural resources, we need to consider water, land and energy holistically along the entire path from sources to end use. The Foreseer tool, developed at the University of Cambridge, allows us to visualise the impact of different decisions about one resource on all of the others.

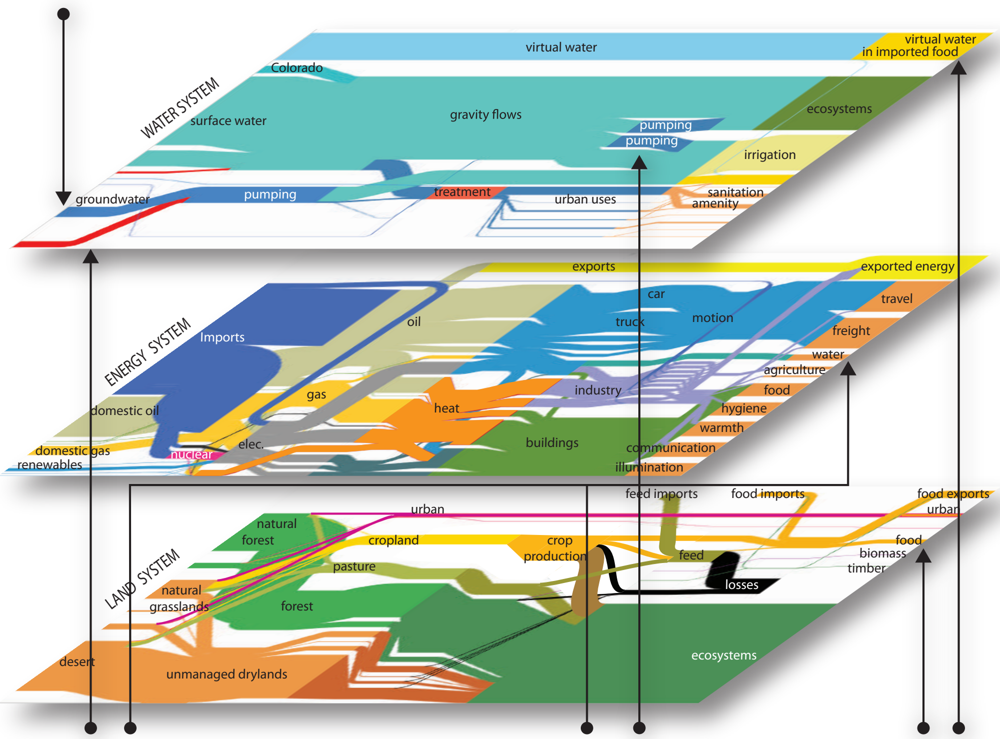
The example below shows the use of Foreseer to track changes in groundwater stocks in California, allowing for interannual variability in rainfall. Increases in population and wealth will lead to increased extraction of groundwater, and may exhaust known reservoirs within the next century.

To address this threat, a policy targeting, say, a 20% reduction in groundwater used for irrigation would help reduce the withdrawal of groundwater stocks, but would have other resource impacts. The boxes below show how Foreseer can be used to examine these impacts.

Cumulative non-renewable groundwater withdrawals



The red line is the optimistic estimate of the amount that can currently be economically withdrawn. (Davis et al., 2003).



Increase supply of water
An increase in recycled wastewater or desalination could increase supply. However this would increase total demand for electricity.

Increase in irrigation efficiency
Switching to more water efficient systems such as drip irrigation could allow crop productivity to be maintained, but will require more energy.

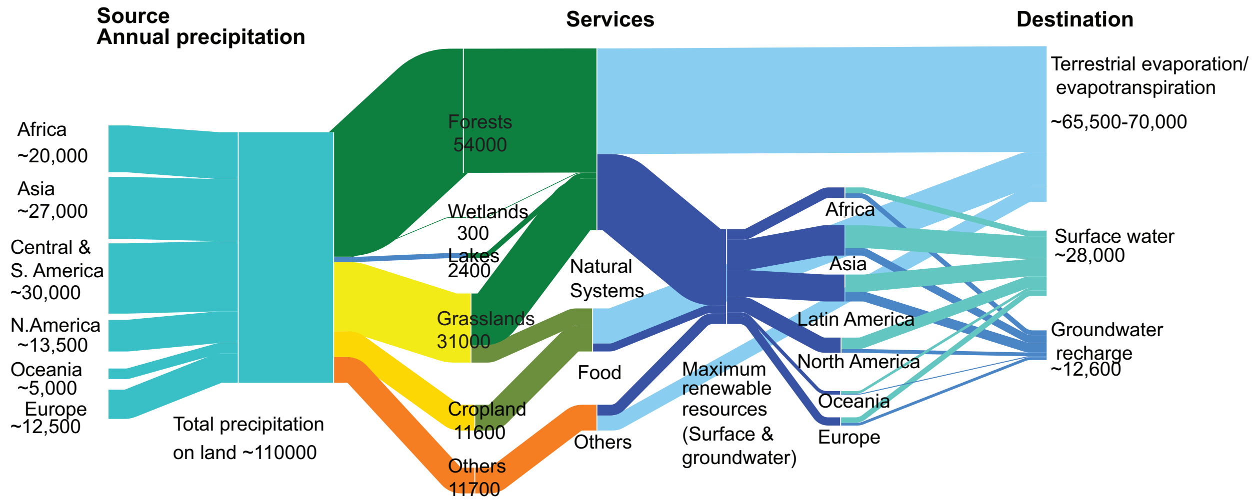
Reduce food crops
Reducing the quantity of crops grown would save water, but hurt the State's $32bn agricultural sector and increase dependence on imported food.

Source: Cambridge More information available at: www.foreseer.org

Using Sankey diagrams to visualise transfers within a system

Sankey diagrams are used to visualise how a resource moves from source to use. The two Sankey diagrams here provide illustrations of water as a resource. For more information see: Curmi *et al.* Effective and integrated management of the services provided by global water resources, *Journal of Environmental Management,* under review.

The flow of water in the hydrologic cycle



Note: volume of water is measured in cubic kilometres (km³)

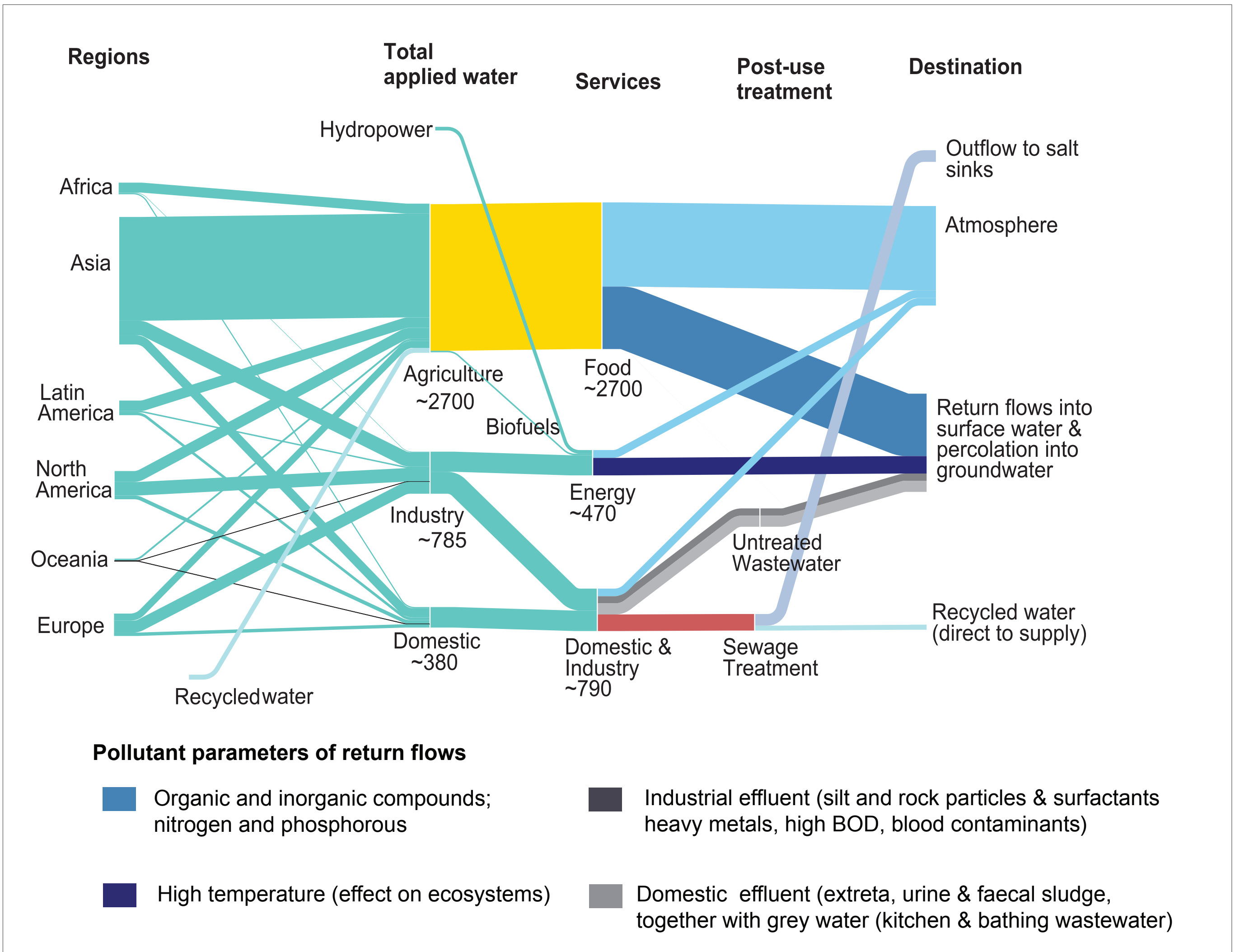
Source: Water in the energy industry: an introduction

Starting at the left, the distribution of rainfall among the continents is illustrated, with the numbers indicating the volume of water measured in km³. Of that water, the majority falls on forests, followed by grasslands, cropland and other land types. The water contributes to the products of these lands – terrestrial ecosystem services, food and other land use. Precipitation is extremely important for food production; in fact approximately 60-70% of the world's food production is produced on rain-fed land.

As shown on the right of the diagram, the total difference between precipitation and terrestrial evapotranspiration, which is known as the renewable fresh water resources (RFWR) is estimated at about 41,000 km³; this includes both surface and groundwater. Groundwater and surface water are interconnected with surface water recharging aquifers and groundwater discharge providing baseflow in many river systems. Not all this water is available for direct human use (refer to the Sankey diagram on the following page for agriculture, industrial and urban use); some rivers are remote from population centres and some is needed to maintain freshwater ecosystems in good condition. It is also important to note that this available water is unevenly distributed seasonally, therefore when analysing water resources it is important to take into consideration that water resource availability is highly variable in time and space.

Distribution by sector of the water withdrawn annually for human use

About 10% of the world's RFWR is withdrawn for human use as shown below. About 70% of these human fresh water withdrawals are used for agriculture; of that a little more than half is returned to the atmosphere through evapotranspiration and the rest returned to surface and groundwaters. About half of the water withdrawn for industrial use is for cooling, especially in the energy sector. This cooling water, minus some losses to evaporation and with some limited material contaminants added, is returned to waterways but typically at a higher temperature, which can affect aquatic ecosystems. The remaining industrial returns and returns from the domestic sectors are discharged to surface water bodies or groundwater, with strong regional variations in the level of wastewater treatment.



Note: volume of water is measured in cubic kilometres (km^3)

Source: Water in the energy industry: an introduction

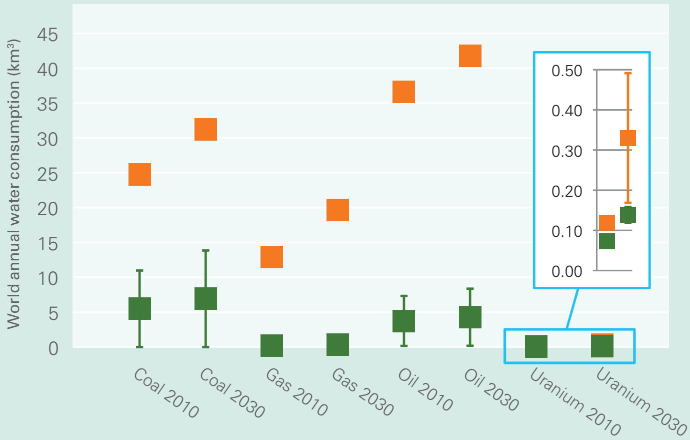
Technology and governance are key

The ESC consortium research has concluded that with wise policy and continued improvements in technology, the world's water, land and materials resource base can be sufficient to support energy needs out to 2050 and probably well beyond. This finding is especially robust for globally traded commodities, such as minerals, along with resources for which there are opportunities for technological substitution.

Technology reducing water consumption: potential water use in fossil fuel production

Improved technology is available today that provides options to manage natural resources more efficiently. This is illustrated through the work from the University of Texas at Austin, which shows the changes in water use practices for fossil fuel extraction and processing over the last 50 years.

While this example concerns just the use of water in some parts of the energy system, huge technical improvements are available in nearly every activity that uses water – given the right governing frameworks.



Water use estimates based on mid- 20th century practices
Water use estimates based on best current practices

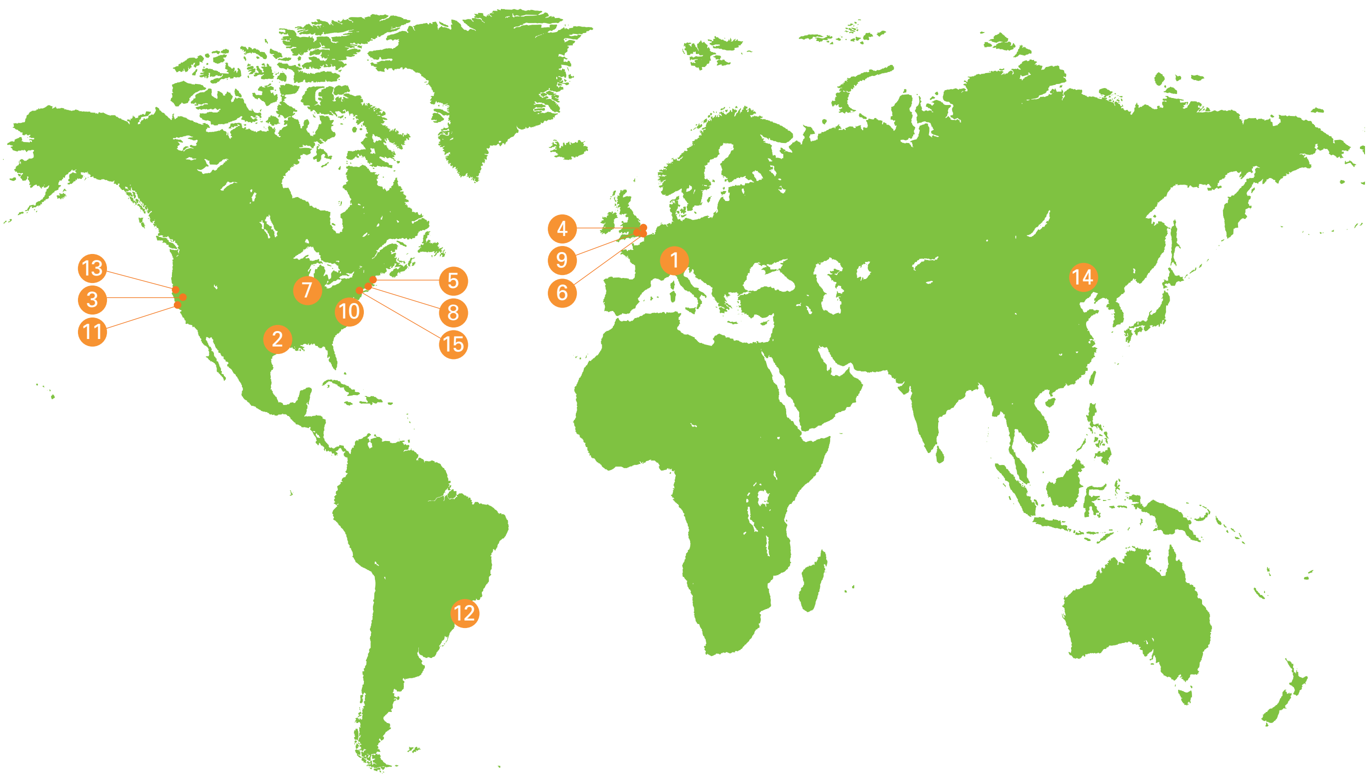
Source: Ian Duncan, University of Texas at Austin

Next phase of research

The next phase of research is focusing on topics and regions particularly relevant to businesses and their operations. The research will examine:

- The global economic potential for biomass.
- Allocation and use of fresh water in the Middle East.
- The effects of climate variability expected from global warming.
- Potential stresses on water and land from different energy pathways in specific regions.
- Investigation of minerals criticality with deep dive on the phosphorus cycle.

BP would be pleased to see co-operation and collaboration with others to build a robust body of energy systems knowledge.



1 Augsburg
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2 UT Austin
Ian Duncan, Michael Young

3 UC Berkeley
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4 Cambridge
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11 UC San Diego
David Victor

12 São Paulo
José Goldemberg

13 Stanford
Mark Thurber

14 Tsinghua
Lin Wei Ma, Pei Lui

15 Yale
Tom Graedel

Further ESC published materials

ESC research has led to the publication of various materials, including peer-reviewed papers, policy briefs and working papers. New publications which draw on the ESC research continue to emerge and a selection of peer-reviewed papers published to date is set out below:

- Anderson-Teixeira, K.J. & DeLucia, E.H. (2011). *The greenhouse gas value of ecosystems.* Global Change Biology, 17, 425-438.
- Anderson-Teixeira, K.J., Snyder, P.K. & DeLucia, E.H. (2011). *Do Biofuels Life Cycle Analyses Accurately Quantify the Climate Impacts of Biofuels-Related Land Use Change?* Illinois Law Review. 2011, 589-622.
- Anderson-Teixeira, K.J., Duval, B.D., Long, S.P., DeLucia, E.H. (2012). *Biofuels on the landscape: Is "land sharing" preferable to "land sparing"?* Ecological Applications, 22, 2035-2048.
- Plappally, A.K. and Lienhard, V, J.H. (2012). *Energy requirements for water production, treatment, end use, reclamation, and disposal.* Renewable and Sustainable Energy Reviews. V. 16(1) 4818-4848.
- Pan L.Y., Liu P., Ma, L.W., Li, Z. (2012) *A supply chain based assessment of water issues in the coal industry in China.* Energy Policy, 48: 93-102
- Ma, L., Allwood, J.M., Cullen, J.M., and Li, Z.i (2012). *The use of energy in China: Tracing the flow of energy from primary source to demand drivers.* Energy, V. 40(1) 174 – 188.
- Jordaan, S.. *"Land and Water Impacts of Oil Sands Production in Alberta."* Environmental Science and Technology 46, no. 7 (April 3, 2012): 3611–3617.
- Curmi et al., *Water Resources Management*, 2013, DOI:10.1007/s11269-013-0331-2
- Anand K. Plappally & John H. Lienhard V (2012) *Costs for water supply, treatment, end-use and reclamation, Desalination and Water Treatment,* 51 (1-3) 200-232
- Siddiqi, A., Kajenthira, A., Anadon, L.D. *"Bridging Decision Networks for Integrated Water and Energy Planning."* Energy Strategy Reviews, In press, 2013.

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