Chapter 1

The nexus between land, water and energy

This first chapter outlines the context for the global analysis of the nexus between land, water and energy. The chapter first introduces the main concepts of the land-water-energy bottlenecks. It then lays out the main research questions as well as the structure of the report, and how it fits with other recent OECD analysis that looks at nexus bottlenecks. This chapter next presents an overview of the main linkages between water, land and energy, and describes how these together provide a nexus. It then describes the main bottlenecks that can be envisaged as they relate to water use, land use and energy use, as well as the materials dimension of the nexus. Finally, it motivates why an integrated dynamic modelling approach is most suitable for investigating the interlinkages of the nexus bottlenecks.

1.1. Introduction

Almost all economic activities are supported by the use of scarce water, land or energy, either directly or indirectly. We need water to grow food and for energy production, we need energy to grow food and to pump and treat water, and we need land to produce bioenergy. Unsustainable use of these resources raises serious concerns about their looming scarcity. There may be constraints or bottlenecks regarding the quantity and quality of supply of each of these resources, including pollution and degradation, and regarding increased demand for them in a growing global economy.

There are strong linkages between land, water and energy in biophysical and in economic terms. Nexus is a useful label to describe the way that these resources are bound together and that the bottlenecks in one area are tightly linked to the other resources. Policies neglecting these interlinkages may be sub-optimal and can actually create or exacerbate problems instead of solving them; i.e. they might resolve a specific problem with one of these resources but at the same time impact the others and create additional (and unforeseen) problems. Therefore some activities can impact indirectly other activities by increasing the scarcity or changing the quality of the resource they use in common. In terms of policy analysis, it implies that efficient management of the nexus resources needs to take into account the direct and indirect effects of changes in the demand and supply of the various resources on the whole biophysical and economic systems, as this is the only means to avoid negative side effects and to create synergies. For example, implementation of hydropower for electricity production can conflict with irrigation requirements where hydropower release schedules do not match the timing of irrigation needs. Under more favourable conditions and adequate operational management, a dam and reservoir can provide a win-win situation with both hydropower and agricultural benefits (Hellegers et al., 2008). This shows that a careful, simultaneous consideration of the land-water-energy resources is needed when designing policies, as ignoring their interactions can present negative side-effects. Therefore an integrated approach is needed to assess whether policies adequately resolves bottlenecks in the whole nexus, or effectively shift stress from one resource to another.

As part of the CIRCLE project,[1] the scope of this report is to provide a broad assessment of the global and regional implications of some of the main bottlenecks in the land-water-energy (LWE) nexus, and project how the consequences of these "nexus bottlenecks" affect the biophysical and economic systems by 2060. More precisely, it aims to shed light on the main trade-offs and synergies between the different bottlenecks in the LWE nexus, and their interactions with the global biophysical and economic systems. The report also examines the sensitivity of these indicators to the changes in biophysical conditions stemming from alternative assumptions on the evolution of the underlying assumptions regarding climate change. In other words, it addresses the following question: **What would be the global and regional biophysical and economic consequences by 2060 of policy inaction to account for the limited availability of land, water and energy, given all the complex relations between these resources?**

A full quantitative assessment of the global and regional consequences for the LWE nexus would require detailed modelling tools that can represent the key linkages in resource use and economic activity at the local level. Many of the nexus bottlenecks will occur within specific water basins (see Box 1.1 on recent OECD analysis of water risk hotspots), and have widely varying effects in different geographical locations, depending on the availability of all three key resources, and distances to economic markets. For instance, the IEA (2015) shows that the cost of water shortages for coal power generation

can be higher (albeit not very much) in water-stressed areas far from economic hubs such as in western China, than in regions that benefit from a local mix of abundant coal resources, water availability and nearby cities, such as northern India. But such a detailed bottom-up analysis is necessarily partial in scope. Therefore, specific insights can be drawn from a more top-down analysis of key interlinkages between land, water and energy in the global biophysical and economic systems. The current report hence does not aim to provide an exhaustive answer on the costs of inaction in all regions in the world. Rather, it limits itself to a top-down approach, by using large-scale global systems models to explore how major resource bottlenecks can affect the land use systems and economies of the major regions in the world.

Given the multi-faceted nature of the bottlenecks in the nexus, and their local nature, it is impossible to provide a full picture of the global economic consequences of all aspects of the nexus. Rather, insights are provided by investigating a carefully selected set of scenarios that are designed to illustrate the key bottlenecks: one scenario for each resource bottleneck, plus two scenarios that combine all bottlenecks, with and without an overlay of climate change. The different resource bottlenecks are quantified using specific examples of widespread trade-offs between different resources and policy objectives that are relevant from a macro perspective. Specifically, the water bottleneck investigated in this report concerns the use of unsustainable groundwater reserves, a key challenge for irrigated agriculture. The land bottleneck assesses the influence of nature conservation and urban sprawl to reflect the effects of reduced access to potentially very suitable land for agriculture. The energy bottleneck focuses on the feasibility and trade-offs in (partially) shifting away from reliance on imported fossil fuels, using an ambitious biofuel penetration scenario. As the precise timing of the bottlenecks is quite uncertain, the analysis focuses on the results in the longer run, in line with the larger CIRCLE project with a model horizon of 2060.

The core of the analysis of the consequences of the nexus for the costs of inaction is carried out by soft-linking two global dynamic systems models: a general equilibrium economic model with a detailed specification of sectoral and regional economic activity and their interlinkages (OECD's ENV-Linkages model; Chateau et al., 2014) and a spatially explicit biophysical model with detailed representation of resource use (PBL's IMAGE model; Stehfest et al., 2014). This systems modelling assessment is complemented by more generic anecdotal evidence of specific bottlenecks that can have significant impacts on local economies and on specific sectors, but that will likely not lead to significant changes in the macro economy.

The nexus bottlenecks are described in this report from the perspective of the natural resources that are needed to sustain economic activity. But these are clearly linked to the services they provide: land use allows agriculture to provide food, energy use provides heat, power and fuel, and water use provides water for irrigation, cooling, drinking, et cetera. Therefore the LWE nexus is effectively roughly the same as the food-water-energy nexus as discussed in the literature, with a different label and with a more explicit acknowledgement that other sectors than agriculture, not least energy production, also rely on scarce land resources. These links also make it clear that there are three specific economic sectors that are central to the analysis: agriculture, water production and energy production. But an essential part of the assessment in this report is to go beyond a partial investigation of direct impacts on these sectors. The report aims to highlight the sectoral linkages and indirect effects that the nexus bottlenecks have on the rest of the economy, and how bottlenecks in a certain region affect other regions.

Agriculture is central to the nexus analysis, as it relies heavily on water, land and energy as inputs, in fact agriculture is by far the most important driver of land-cover and land-use changes and irrigation is the biggest water consuming activity at the global scale and in many regions and countries. In terms of economic impacts, challenges posed by restricted availability of LWE resources on agriculture come primarily in the form of yield reductions and/or limited availability of suitable land. Such impacts can be assessed with the IMAGE model. In the CGE framework of ENV-Linkages these sectoral impacts are introduced as exogenous shocks, which in turn induces economic impacts throughout the economy, and on other economies, not least due to shifts in competitiveness between regions.

The challenge is to move beyond the nexus as a "slogan" and develop a methodology to assess quantitatively the biophysical and economic consequences of bottlenecks in the linked use of land, water and energy. By using a soft-linking of two major systems models, one for the biophysical aspects and the other for the economic system, a wide range of indicators of the negative and positive consequences of the nexus bottlenecks can be investigated. These include indicators for (economic) welfare, environmental sustainability, as well as food security, water security an energy security.

In line with the wider objectives of the CIRCLE project, and as part of the economic assessment, expressing the costs of inaction on the bottlenecks in the same terms as the usual indicator for economic growth, i.e. in terms of GDP losses, helps to communicate the importance of the nexus for economic policy making, despite its well-known drawbacks as a welfare indicator. But by embedding this indicator in a much wider set of indicators that capture different aspects of the multiple policy objectives, one can create clear insights into the major trade-offs and synergies in the feedbacks of the bottlenecks in the nexus on the biophysical and economic systems.

The land-water-energy nexus analysis in CIRCLE has several innovative aspects. Few studies have analysed linkages between land-water-energy simultaneously in an integrated framework and then translated the biophysical indicators into economic impacts. Despite the complexity of the modelling tools, and their suitability to explore future pathways of economic activity, environmental pressure and their interlinkages and feedbacks, this report contains only exploratory insights into the costs of inaction on the nexus. A limited number of scenarios are explored, with only a limited number of interlinkages between the nexus elements quantified. It is not a prediction of what will happen, nor a synthesis of the full literature on LWE nexus concerns. Some studies have looked at linkages and trade-offs between individuals pairs of the land-water-energy sectors (Bartos and Chester, 2014; Howells and Rogner, 2014; Dale et al., 2011; Hoff, 2011; Monaghan et al., 2007). Some other studies have looked at individual links between bottlenecks for a single resource and the economy (Berrittella et al., 2007; Veldkamp and Verburg, 2004). However, none of the above studies have adequately addressed all three aspects of the land-water-energy nexus together and their link with the economy. The analysis of the land-water-energy nexus in the CIRCLE project follows such an integrative approach, and is thus complementary to earlier and ongoing research efforts.

The report is structured as follows. The remainder of this chapter introduces the LWE nexus in more detail and explains how the different aspects interact. Chapter 2 describes the methodology used for the quantitative analysis, with a brief description of the modelling tools, and a brief explanation of the modelling scenarios. Chapter 3 introduces the baseline projection of economic activity and environmental pressure, while Chapter 4 presents the main results from the modelling analysis. Chapter 5 concludes.

Box 1.1. **OECD project on water hotspots**

Agriculture is expected to face increasing water risks in the future, ranging from water shortages, to floods and water quality risks. These risks could affect agriculture production, markets, trade and food security. Targeted policy action by defining hotspots, or localised agricultural productive region subject to acute water risks, can help increase the efficiency and effectiveness of efforts to mitigate these future water risks.

A comprehensive assessment of the water risk literature, combined with baseline projections on agricultural production in 2024 and 2050, was used to assess future water risk hotspots for agriculture. China, India and the United States lead the global production of major commodities, but they are also considered to be the most exposed of 141 countries to future water risks. More specifically, agriculture water risks are especially prevalent in the regions of Northeast China, Southwest United States and Northwest India.

The materialisation of agricultural water risks in hotspots can generate three levels of impacts: they can lead to falls in production in hotspot locations; affect agricultural markets and trading partners of the affected country; and lead to broader food security and socio-economic concerns in a larger set of countries. The evidence collected shows that these impacts can be significant including in the case of the three identified hotspot regions. In the absence of policy action, agriculture production in Northeast China, Northwest India and the Southwest United States will be significantly impacted by water quantity constraints. Activities generating low economic value per water use will be the first affected by these changes. A simulation of projected impacts of gradual increases in surface and groundwater irrigation stresses and droughts only in the three hotspot regions reduces global production and increases prices of major field crops – in particular maize, wheat and cotton, but also fruits and vegetables. National production in the three countries falls by a few to a dozen percentage points, affecting their trade balance. Partner countries' trade balances are also affected significantly. Some of these effects may intensify when climate change projections are taken into consideration. Acute agricultural water risks can also result in broader food security and socio-economic consequences, manifested for instance via foreign land purchases from water scarce regions that are sometimes detrimental to food and water security.

Responding to these risks effectively require considering three types of policy actions. As a priority, governments of countries facing water risks should focus their attention to hotspot regions, introduce targeted agriculture and water instruments, including information, extension services, technical and institutional measures in the area, and customise some of their key water and agriculture policies locally. As a complement, they should co-ordinate their efforts with that of active private companies and with other water users. Second, to limit market effect, these governments should work with trade partners to strengthen domestic and international market linkages. Third, at a broader level, all governments should engage into international collaboration to support the resilience of vulnerable countries to future water risks, exchange information to reduce the diffusion of indirect impacts, and increase their preparation and their resilience to unexpected indirect effects.

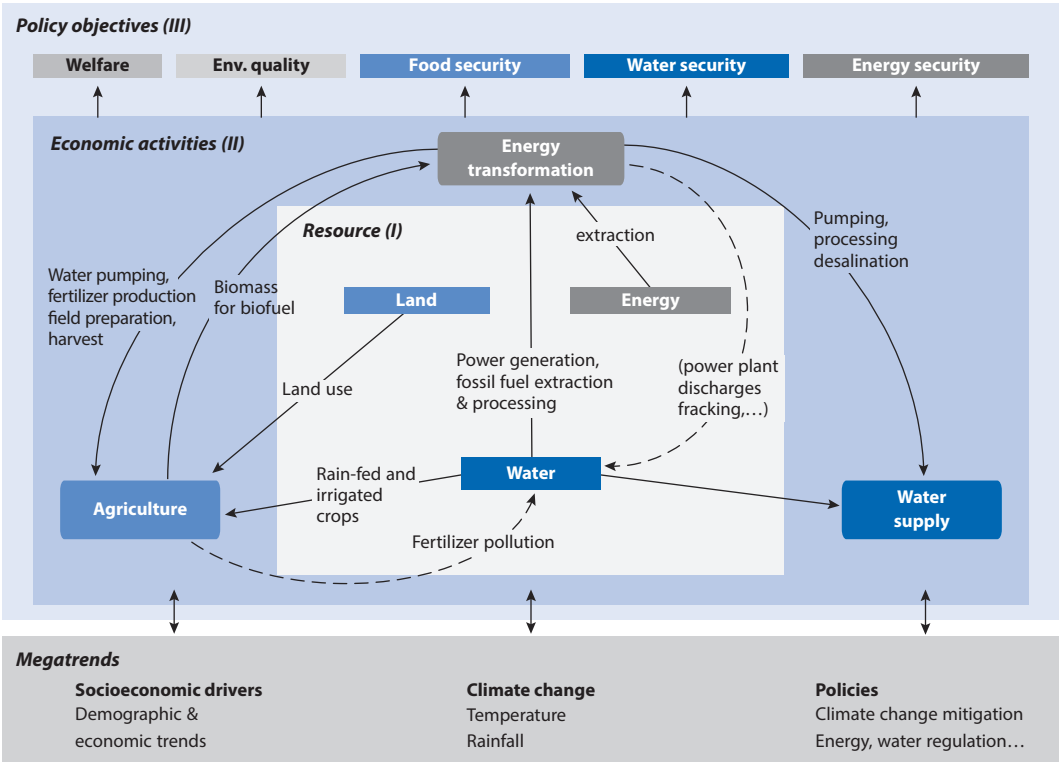
Source: OECD (2017).

1.2. Overview of the LWE nexus and interlinkages

Key interactions within the LWE nexus are shown in Figure 1.1, which indicates how the biophysical resources are linked to economic activities and – mostly indirectly – to a number of key policy objectives. Resources are often understood to be exhaustible, and attention tends to go to scarcity and depletion. But resources can also be renewable, such as fresh

water supply from the hydrological cycle. Still, the supply can be constrained locally and/or seasonally, and also due to poor quality. In the first domain in Figure 1.1, the LWE resources represent a biophysical system, characterised both in terms of quantity (for instance, surface of land, energy equivalent of in situ oil, volume of aquifer water and rainfall) and quality (for instance the fertility of land, the accessibility of water supplies, and the access to oil fields). Concern over availability of adequate volume and quality of resources emerges from their vital role as inputs for economic activities; the second domain in Figure 1.1. These resources provide various goods and services that meet the needs of the population, including agriculture providing food (and biomass), energy transformation providing power and heat, and water supply providing clean water services and sanitation. Finally, the third domain transcends the sectoral scope and highlight how the resources in the nexus, through the economic services they provide, contribute to a range of policy objectives; obvious examples include "security of supply" for food, water and energy, welfare and environmental quality.

Figure 1.1. **Main linkages within the land, water and energy nexus**



In a narrow sense, security of supply is met only when there is no physical or economic scarcity, but definitions often go beyond pure access and include notions of satisfaction or preferences. Food security is defined in the 1996 Rome Declaration on World Food Security as "when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life" (FAO, 1996). Similarly, the IEA defines energy security as "uninterrupted physical availability at a price which is affordable, while respecting environmental concerns" (Jewell, 2011). On water security, UN (2015) writes "The availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems and production, coupled with an acceptable level of water-related risks to people, environment and economies (Grey and

Sadoff, 2007)". However, the broader connotation, i.e. a movement in the direction towards security, is more relevant for this report: do the bottlenecks in the nexus, and the policies that aim to address these, bring the world closer to the objectives of security of supply.

The food, energy and water aspects are not independent of each other. Agriculture depends on land and water resources, and also on the energy transformation sector. The energy transformation sector needs energy resources and water. In the case of biofuel developments, it will also interact with the agriculture sector. Water supply services require indeed water resources, but also energy services. Unsustainable use of one resource can hence affect the other resources. Firstly because some sector use the same resource and will thus rival for access in particular when the resource is under stress. This is for instance the case for agriculture and energy transformation which both use water. Hence, operations in the energy sector may affect the water availability for agriculture and therefore crop yields. Secondly, when the resource becomes scarcer and less accessible it may be overcome by using more of other resources (substitution). For instance, with depletion of conventional oil reserves, oil and gas resources require more water to be processed, which may put pressure on water resources. Lastly, resource scarcity may require redirecting the inputs or output of a sector towards other sectors in order to ensure security of supply. For instance, in the Middle East where water is scarce, a significant share of regional energy production is used for pumping, transporting and desalinating water. This is beneficial to the water security objective, but it represents a cost for the society in the form of lower national revenues from energy exports.

In general, the economic cost of bottlenecks through constraining production is not easy to assess. On the one hand, if bottlenecks are well managed and the change of resource availability is well anticipated, all the options available to limit the effect of scarcity will be implemented in a cost effective way. In that case, the cost of adjusting to the bottleneck is quite low for the economic system. On the other hand, if disruptions in key sectors cannot be avoided, they can be very costly. Therefore one needs to take into account the cost of investments to hedge systems against the risk of disruption, for instance by providing more back-up production capacity. Lastly, a major policy problem is that currently a large part of the world population has no access to electricity or clean water. Nexus bottlenecks can make the deployment of the necessary infrastructure more difficult, and thus hamper energy and water security.

The nexus interactions imply that a potentially large part of the cost of resource scarcity cannot be captured if not taking all the elements of the nexus together. It is also true for assessing the benefits of policy action. For instance, policies that favour biofuel, for climate policy of energy security (independence) reasons, can put pressure on land use and water resource and conflict with food security concerns.

The trade-offs and synergies within the land-water-energy-nexus and their impact on the economy are substantially influenced on the long run by a number of socio-economic and environmental "megatrends". The term "megatrends", which is further explained in Box 1.2, includes the consequences of demographic and economic growth, climate change and also climate change policies.

The next sections discuss in more detail how constraints in the quantity or the quality of these environmental resources can be a bottleneck for economic activities, and how economic competition for scarce resources affect the bottleneck. This discussion is grouped per bottleneck; i.e. each paragraph explains which factors and nexus linkages contribute to respectively land, water and energy bottlenecks, and highlights which economic activities are most affected by each bottleneck.

Box 1.2. **Megatrends and the LWE nexus**

There are a number of important trends that underlie this baseline projection.

Firstly, over the long run, there are important factors that influence the demand for goods and services, and therefore the demand for resources by the producing sectors. Population growth increases consumer demand for food, water and energy, thus increasing the pressure on the scarce resources, not least land, through agricultural production. It also exacerbates the competition for these scarce resources: more water is needed for final consumption, but also for agriculture. Similarly, income growth leads to stronger demand for high-quality commodities, often produced in ways that are more water and energy-intensive (a typical example is the shift in diet towards more meat-based food consumption). But the net influence of income growth is not a priori trivial. For example, it also means that people are more versatile in avoiding the negative consequences resulting from shortages or quality issues in the nexus. And it is often argued that people with higher income demand a higher quality of their environment, thereby increasing efforts to improve resource efficiency through re-use and recycling, and inducing governments to do more to protect the essential resources. Education and urbanisation influence both population and income levels (and are affected by them), but also the composition of sectoral demand.

Secondly, on the supply side, climate change is probably the most important megatrend. Climate change affects all aspects of the nexus directly and indirectly. IPCC (2013, 2014a,b) and others have shown that there are significant direct effects on land availability (not least due to land loss from sea level rise), water stress, and energy demand and supply. Not least, climate lchange influences the hydrological cycle, resulting in shifts in annual water availability in many regions, and also in more erratic precipitation patterns including extreme events such as droughts and excess rainfall. Reduced water availability can increase competition for water between sectors, as described above. Moreover, climate change is projected to have negative impacts on agricultural productivity in most regions, e.g. through loss of yields due to excess temperatures. Lower agricultural yields due to climate change means additional intensification and/or expansion of agriculture to meet the demand for agricultural products with implications for land and energy requirements. As all sectors are linked in the economic system, impacts on one sector in one region trickle through to other sectors and regions through changes in the allocation of production factors, changes in final demand and changes in trade patterns (OECD, 2015a). By using a multi-sectoral, multi-regional general equilibrium model, the economic analysis in this report picks up such indirect effects in the same way.

Thirdly, there are a number of megatrends that affect both demand and supply, but in opposite ways for the different resources in the nexus. As a prime example, substitution of fossil fuels by bio-energy reduces energy stress, but exacerbates stress levels for land and water. Large-scale biofuel crop cultivation negatively interacts with the other elements in the land-water-energy nexus. Considerable land areas are required for biofuels to supply a substantial share of the global energy demand, which raises concerns over competition with food production and higher prices. Moreover, if and where additional land for biofuel production goes at the expense of naturally vegetated land, this will affect the hydrological cycle. Additional water stress can result on irrigated land, and this competition over water between food and fuel crops can affect agricultural production in drought-prone regions and potentially lead to yield reductions.

1.3. Land-related bottlenecks

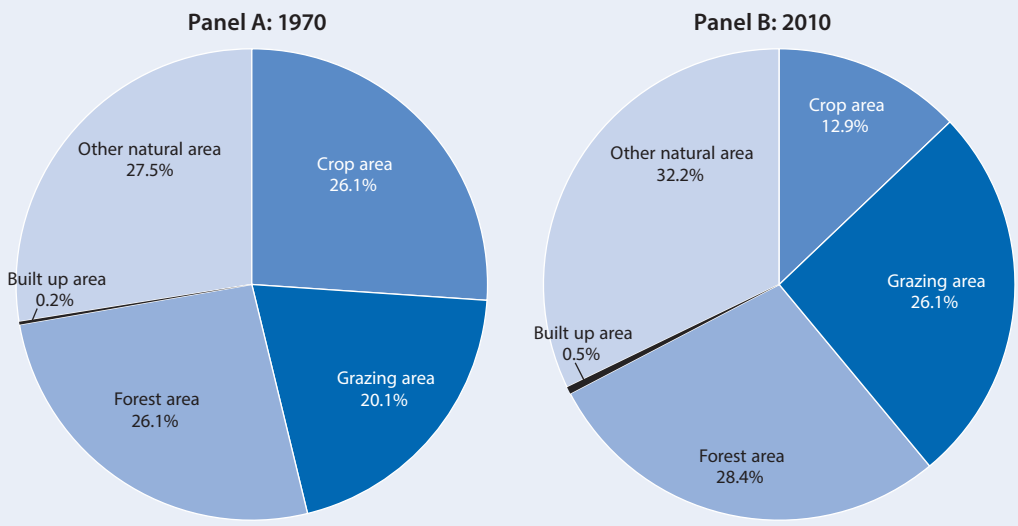
Agriculture is globally the most land-demanding human activity (see Box 1.3). Currently around 33% of the earth's surface (excluding Greenland and Antarctica) is used for crops and livestock farming (PBL, RIO+20). Projections indicate that agricultural land use is likely to increase even further in coming decades due to population and welfare growth.

Meeting an increasing demand for food can be met either by increasing exploitation of the land resource (extensification), or by increasing the inputs of other resources per unit of land (intensification). Evidently, intensive agriculture also requires substantial water and energy inputs and has therefore a clear link with the nexus.

Box 1.3. **Agriculture as a key driver of global land and water use**

Agricultural production has increased strongly over recent decades to meet rising food demand driven by both population growth and changes in diets. About 80% of the production increase has been achieved through higher yields from existing land, and about 20% through expanding agricultural land (Bruinsma, 2003). Between 1970 and 2010, the share of agricultural land use (crop and grazing land), expanded by about 4 percentage points, largely at the expense of forest area (OECD, 2012a: Figure 2.12). A somewhat lower pace of expansion has been observed over the last decade.

Figure 1.2. **Global land use, 1970 and 2010**



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Source: IMAGE model.

The *OECD Environmental Outlook* baseline projects that competition between agricultural land use and other land uses will intensify in the coming decade under current policies. This is also the conclusion of the *OECD/FAO Agricultural Outlook to 2020* (OECD/FAO, 2011). A converging GDP per capita and a growing population will both increase the demand for food, especially animal products. Moreover, policies that stimulate the use of biofuels also increase the demand for agricultural production and land area (Chapter 4). Given the limited supply of land, this means that in the short run deforestation will continue, although at slower rates than in past decades.

Source: OECD Environmental Outlook to 2050 (OECD, 2012a).

Various forms of renewable energy production require substantial land areas. Hydropower plants, biofuel plantations, solar and wind "farms", for example, require significant quantities of land, and sometimes even require relocation of existing activities and local communities (Bazilian et al., 2011). They often also interfere with existing hydrological flows and regimes. "Regular" coal or gas fired power plants also require land for their site locations, but their land claim is relatively minor.

The combined land claims of economic activities can result in a regional competition for land, and such a land bottleneck can impact certain economic activities such as agriculture. Land competition reduces the available land supply for agriculture and increases land rental rates. In turn, this results in an agricultural expansion onto marginal lands if possible, or agricultural intensification (Van Meijl et al., 2006). Agricultural production on marginal lands often leads to lower overall yields unless more inputs are used. Likewise, agricultural intensification necessitates higher input requirements (Van Meijl et al., 2006; Smith et al., 2010; Bazilian et al., 2011; Lal, 2013; Ringler et al., 2013). This implies not only more capital/labour inputs (Van Meijl et al., 2006), but also more energy/water inputs. Overall, land competition seems to imply lower yields or a higher input use, and can thereby result in higher production costs and a shift in the pressure on other nexus resources (Bazilian et al., 2011; Lal, 2013; Ringler et al., 2013).

The pressure on land resources and the need to extend land use for agriculture has also led to other detrimental impacts, including deforestation, degradation of biodiversity and local water pollution, and loss of recreational spaces which all represent an additional cost involved by land scarcity and comprise of a trade-off between the nexus resources.

Climate change may influence the land resource. The change in temperature and precipitation will influence soil properties and, apart from the CO_2 fertilisation effect, may lead to decreases in yields, a loss of agricultural land due to sea level rise, etc. (OECD, 2015a).

Climate policies reduce these impacts from climate change, but may also negatively affect the land bottlenecks, especially if they imply large scale development of biofuels in order to achieve climate change mitigation targets. The land claim of biofuels and biomass feedstock for energy production could be potentially very large, but will depend on the level of biofuel deployed and on the type of crop, especially whether it concerns first or second generation bioenergy. There has been concerns over competition over land with current land uses (Anderson and Fergusson, 2006; Smith et al., 2010; Cai et al., 2011) and the consequences for food security (FAO, 2012). Moreover, a need for additional agricultural land for bioenergy production – at the expense of naturally vegetated land – will increase water demand and affect hydrological cycles (Berndes, 2002; Rowe et al., 2009). Similarly, climate policies aimed at reducing the use of fossil fuels provide an incentive to increase the amount of hydro, wind and solar power, which may lead to increased land use, e.g. from flooded areas behind dams. Thus, both "renewable" power and large scale bioenergy production have substantial land claims and affect both water and energy, and thus interact within the land-water-energy nexus (Ringler et al., 2013).

An important final remark on this topic is that competition for land is currently mostly a regional phenomenon. At the global level, physical scarcity of land seems less of an issue; i.e. the world is not immediately running out of land as "only" 33% of global land is used for agriculture. But agricultural commodities are heavily traded internationally, implying that a shock to the agricultural system in one region will have spill-over effects on other regions, the sign of which cannot be determined a priori. Furthermore, the lack of global scarcity may evaporate over time. Restrictions may be put on the use of land for agriculture, for instance because of biodiversity concerns. Under more stringent environmental restrictions,

land competition may become increasingly important in the future. In combination with the socioeconomic developments (see the description of megatrends), this can put a significant strain on the available land resources, and may eventually lead to global scarcity, price increases and lower welfare.

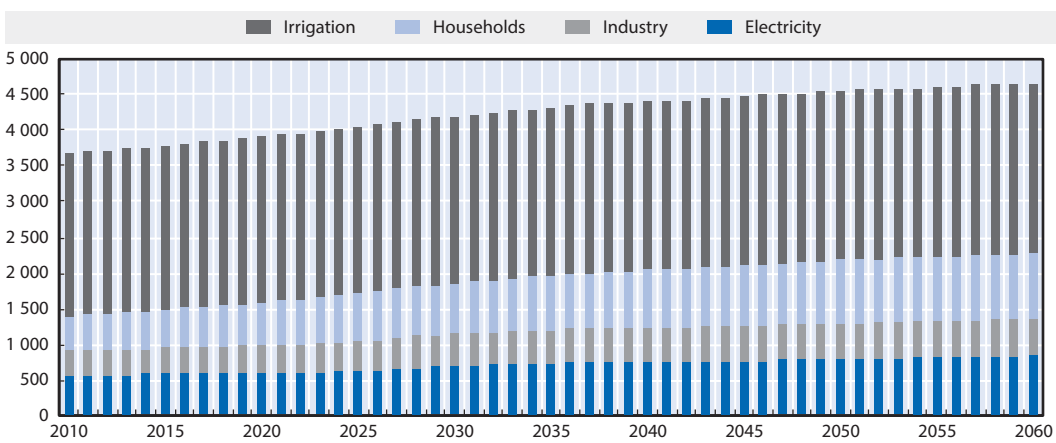
1.4. Water-related bottlenecks

Many economic activities, including agriculture, require extensive water consumption, with impact on the quantity and the quality of water resources.[2] The energy industry requires water for power generation and also for fossil fuel extraction and processing, adding pressure to the resources. If trends in food consumption outpace increases in agricultural productivity, the bottlenecks and competition for access to water will increase, in particular between (irrigated) agriculture and energy. In addition, in regions with severe water stress, it may be necessary to use large amounts of energy for groundwater pumping and transporting water to consumption areas.

Agriculture is globally the most important water user; i.e. around 70% of all global water withdrawals are for irrigated agriculture, which provides 40% of the world's food supply (Figure 1.3). Irrigated areas and subsequent water withdrawals differ significantly between regions (Siebert et al., 2010). For irrigation water, some regions rely mainly on surface water withdrawals, whereas others rely more heavily on groundwater withdrawals. In some regions, concerns of groundwater overexploitation have emerged due to large groundwater withdrawals in combination with limited natural recharge (Wada et al., 2012). Projections by e.g. FAO and Wada et al. (2012) and confirmed by OECD (2012a, 2015b), indicate that irrigated agriculture and groundwater withdrawals will increase even further in coming decades, which means that irrigated agriculture will remain a great user of both surface and groundwater.

Figure 1.3. **Projected water withdrawals by sector**

(Cubic kilometres)



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Source: IMAGE model.

While not the only sector responsible for water pollution, agriculture also has an impact on water quality through the release of excess nutrients and micro-pollutants into surface water and groundwater (OECD, 2012b). Excess nutrient availability in surface and groundwater can lead to eutrophication problems, and make water unsuitable for human uses such as drinking and bathing. Such deterioration in water quality can thus also cause

a water bottleneck by constraining the amount of water that is suitable for other uses. Municipal wastewater treatment at the intake can be used to manage water quality for most end users, but this requires energy.

These combined claims on the available water have the potential to constrain the quantity and/or quality of remaining water, and such a water scarcity can seriously impact certain economic activities. There is a clear reason why water scarcity particularly affects irrigated agriculture: irrigated agriculture is the largest global water user, while non-agricultural sectors often place a higher economic value per litre water than the agricultural sector. This makes it often the residual claimant in case of water scarcity (OECD, 2015b). Water scarcity can directly impact irrigated agriculture; i.e. less available irrigation water can lead to yield reductions during droughts and thus result in regional production losses (Berndes, 2002; De Fraiture et al., 2008; Havlik et al., 2011). But water scarcity and competition can also indirectly impact irrigated agriculture by compelling it to use alternative water sources (groundwater extraction, desalinisation, etc.). Such alternative water resources necessitate a higher energy use (e.g. diesel for pumps), which ultimately translates into higher production end costs (Bazilian et al., 2011; Ringler et al., 2013). Furthermore, the investments needed for improving water quality or consumption efficiency link this to the rest of the capital market, and therefore to the entire economy.

In the context of the land-water-energy nexus, it is also important to note that lower agricultural yields due to water scarcity could induce agricultural intensification and/or expansion onto natural lands to compensate for production losses and to still meet the regional demand for agricultural products. In turn, this requires more inputs and can increase land competition (Ramankutty et al., 2002; Godfray et al., 2010; Smith et al., 2010; Lal, 2013). This is discussed in more detail in Section 1.3.

Even though the energy sector uses less water than agriculture at the global level (15% vs. 70% of withdrawal in 2010; IEA (2016), FAO (2012)), the energy sector's share in overall water use can nonetheless be significant in some countries. The share of water used for energy production is projected to increase in the next decades (IEA, 2016; King et al., 2013). Water needs are high for fossil fuel production, power generation and biofuel production.

Most power generation technologies need water (see Box 1.4). Hydropower needs water to activate the turbines. Although most of this water can be reused for other purposes such as agriculture, hydropower does interfere with existing hydrological flows and can alter hydrological regimes due to higher evaporation rates. Moreover, naïve hydropower implementation can conflict with other purposes as hydropower release schedules do not always match the timing of other water needs such as irrigation (Hellegers et al., 2008). Thermoelectric plants (nuclear, coal, oil gas fire) need large amounts of water for cooling and condensation the steam that passes through turbines. Globally, electric production depends strongly on this type of technology and therefore on cooling water availability. Water withdrawals for this technology are growing fast (Feeley et al., 2008; Roy et al., 2012; Ringler et al., 2013). Although this water use is largely non-consumptive, it can nonetheless have consequences for water quality (e.g. thermal pollution) and availability for other uses during droughts (Feeley et al., 2008; Bazilian et al., 2011; Ringler et al., 2013).

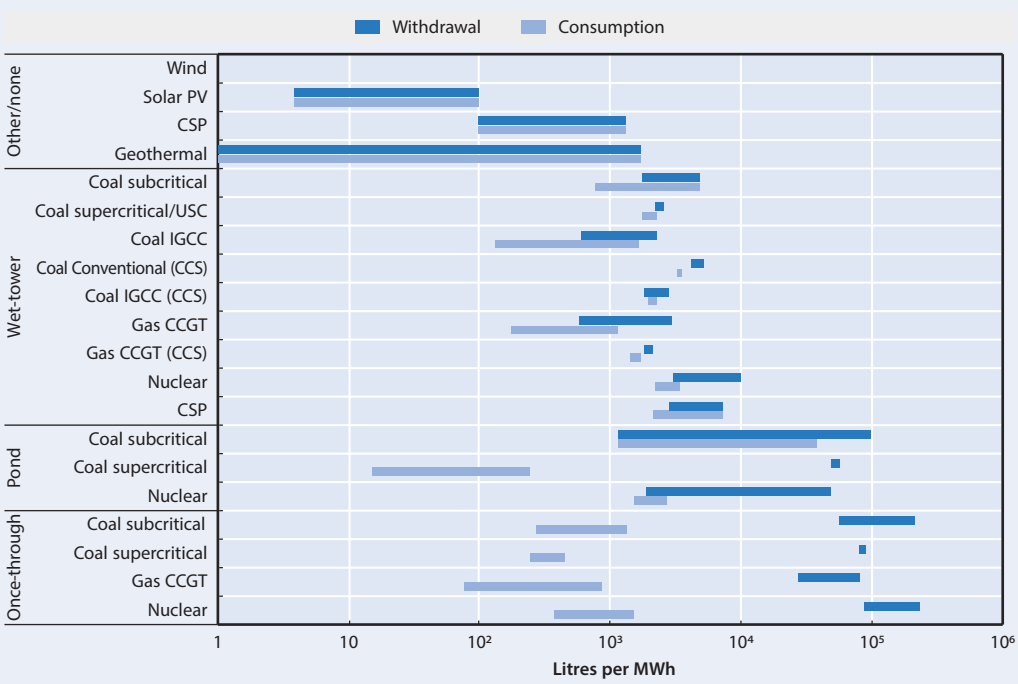
The energy sector might respond to sustained events of water scarcity and competition by switching to alternative cooling techniques for power plants such as wet-tower or dry-cooling (see Box 1.4). These cooling techniques require less water volume as input and their water withdrawal is therefore lower. A disadvantage is that their capital costs are higher, and that their water consumption is higher than regular cooling (i.e. although they withdraw less surface water, they actually evaporate a larger share of this water before

returning it; IEA, 2016). Moreover, dry-cooling is less efficient and can affect power plant performance. Another response of the energy sector to sustained water scarcity could be to locate new plants along the coast so they can use sea water for cooling, although land-locked countries do not have this option.

Box 1.4. **Water use by type of power plant**

The water requirements for operating different types of power generation technologies differ markedly (Figure 1.4). Hydroelectric plants produce electricity from water that passes through turbines. The water is mostly discharged with no change of quality (the temperature is the same). But for hydropower with reservoir water storage (as opposed to run-of-the-river hydropower), water is consumed through evaporation. The consumption intensity, which depends on the weather condition and on the shape of the reservoir, can be higher than for the other power generation technologies (IEA, 2016; Mekonnen and Hoekstra, 2012). Thermoelectric power plants (i.e. plants where power is produces by steam that passes through a turbine) use large amounts of water for cooling. In these types of plants, that can be fuelled by coal, oil, gas biomass or nuclear energy, water cycles into a circuit where it is boiled to activate turbines, and then condensed. For this purpose, cooling water (mostly surface water) is passed through a steam condenser and where its temperature increases as it receives discharge of the heat of the steam. There are technologies that are much less water intensive. Open cycle power plants need less cooling, because the heat produced by the combustible is passed to the turbine directly and no steam condensation is needed. But the cost of such plants is high. Renewable technologies solar and wind consume almost no water. Concentrating solar power, where solar energy created steam to activate a turbine can be more water intensive. The more efficient the plant is, the less waste heat per unit of electricity produced has to be cooled and thus the lower the water requirement. Because they are the less efficient, coal power plants use in general more water. But water intensity also depends on the cooling techniques.

Figure 1.4. **Water use for energy technologies**



Source : IEA (2016), *World Energy Outlook*.

Box 1.4. **Water use by type of power plant** *(continued)*

Once through systems: water passes through a steam condenser. The capital costs systems are low and the water consumption (evaporation) is small. But the withdrawal is high and the discharge is at a high temperature which detrimental to aquatic life and ecosystems. This is why permitting requirements for these systems have become more stringent, for instance in the United States, and they are being gradually phased out.

Wet re-circulating systems: the water passed through the steam condenser is cooled in a wet tower or a pond. Water not consumed by evaporation is returned to the steam condenser for reuse. This reduces the water withdrawals and exposure to risks posed by constrained on water resources and environmental impacts. But compared with once-through systems water consumption is higher and installation is more costly (40% higher than for once-through systems; NETL, 2008) and requires more land.

Dry cooling systems: instead of water this system uses air flow through a cooling tower to condense steam. Water requirements are very limited. Their cost is about 3-4 times higher than for re-circulating systems and they can reduce power plant efficiency. In addition, they may not suffice during warm periods.

Fossil resource extraction, processing and transportation also require water. For instance, water is injected in oil wells for increasing the reservoirs' capacity, or used to remove dust from coal. The water intensity of fuel exploitation depends heavily on the type of resource used (IEA, 2016). The exploitation of non-conventional fuel resources which are abundant in some regions can be very water-intensive compared with "conventional" resources (this will be discussed in Section 1.5).

Biofuels and biomass also have water requirements, but their water use depends enormously on the type of bioenergy crop and whether these crops are irrigated or rainfed. In the latter case, additional water use is often modest. Nonetheless, biofuel/biomass production can exacerbate water stress in already drought-prone regions, including through the increased water pollution that this activity would also induce. Presently the share of biofuels/biomass in energy supply is modest, but this share could increase significantly to meet climate change mitigation targets (De Fraiture et al., 2008; Dominguez-Faus et al., 2009).

With climate change policies, energy efficiency and renewable deployment become more prominent, reducing thermodynamic fossil fuel power generation and the extraction of water-intensive fuel resources. There should be less need for cooling water. But on the other hand, there would be more need for more land-intensive renewables, including hydropower. Thus, climate change policies may influence the nexus in opposing ways, the net effect of which is difficult to determine. On the one hand the stress on water can be decreased by less climate change and less use of water for energy. But on the other hand a decarbonisation with biofuel deployment mays create stress on land use and water requirements, displacing some of the water requirements from the energy to the agricultural sector.

Several industries, not least steel production and mining, use water for cooling or for processing purposes. In many cases water use by industry is non-consumptive, although it can have consequences for water quality (pollution) and can constrain the availability for other users during droughts (Feeley et al., 2008; Bazilian et al., 2011; Ringler et al., 2013). Households are also important water users. Globally, water demand for domestic uses is

modest, but projections indicate a substantial increase due to factors including population growth, higher sewer connectivity levels (OECD, 2012b).

Large quantities of energy are used for supplying clean water to the populations and industries. According to IEA (2016) which provides a global assessment of energy consumption from the water sector, in 2014, the water sector represented around 4% of world electricity consumption. This electricity was used mostly for extraction (40%) and then for waste water treatment and water distribution. The water sector is also a large consumer of thermal energy; for pumping in agriculture and for desalination (IEA, 2016). In the United States, energy use in the residential, commercial, industrial sectors (including agriculture but excluding power) for direct water and steam services was in 2010 approximately 6.3%[3] of the primary energy consumption (Sanders and Webber, 2012). When surface water is abundant there is limited need for pumping and thus for energy use. But energy consumption will increase when water is scarce and needs to be pumped from deeper aquifers, or transported from other locations. In extreme cases, such as in parts of the Middle East, desalination and reuse of wastewater can be used, which in general has a high energy intensity compared with "conventional water" (Ghaffour et al., 2013).

However it is very difficult to evaluate the energy consumption of water. Firstly, a large part comes from individual pumping in agriculture which is not well monitored. Secondly, the energy consumption of water supply largely depends not only on the volume of water consumption, in particular in the agricultural sector, but also on the availability of the water resources in the regions considered, and the distance from the place of consumption.

As with global land supply, water is not physically scarce at the global level. The global total quantity of freshwater is more than sufficient to meet current demand, but its uneven distribution makes water a scarce resource in some regions and watersheds. Moreover, part of the water reserves may be reserved for ecosystem functioning in order to maintain ecosystem services and biodiversity values. Under those environmental restrictions, water can already be considered a scarce resource in many regions and may become so in many more regions and watersheds as indicated by environmental outlooks (e.g. OECD, 2012a).

1.5. Energy-related bottlenecks

Energy is a key driver of economic activity. But energy resources are limited. For instance fossil fuel resources, including coal, oil and gas, decrease with extractions, and they become less and less accessible. The issue of depletion is not a matter of absolute depletion, but rather of the need to use a more diverse and more complex and thus more costly set of technologies to get them.

Over the last decade, instead of depletion there has been an increase in the use of costly technologies for exploration and productions. Most notably the booming shale oil and shale gas production has substantially increased the scope of fossil fuel resources. Shale gas and oil production require hydraulic fracturing (fracking) which consumes a lot of water and large quantities of water are needed for releasing and processing bitumen. At the global level, there is way less water used for fossil fuel extraction than for power generation (IEA, 2016), but this part of the nexus can be crucial for many reasons.

Firstly because due to resource depletion, the share of non-conventional sources in fossil fuel supply is projected to increase steeply. Therefore, the water intensity will be pushed up and in the absence of water regulation it might significantly increase water withdrawals and consumption from the fossil fuel sector, although IEA (2016) argues that water consumption may not have to increase.

Secondly, in some regions, water intensive extraction activities and potentials are located in water stressed areas. When the resource is exploited, water stress becomes very high. For instance, if water for hydraulic fracturing is 1% of US water withdrawal, it is 20-30% in some counties of Texas that are semi-arid (Reig et al., 2014). The Monterey shale play in California, which is projected to contain the biggest shale oil reserve in the United States (EIA, 2011), is located is an area where water is scarce, and therefore, if large-scale production starts, water stress will be high in these regions. In the case of China, the regions where shale resources are abundant are arid and therefore the competition for water is high according to IEA (2016).

Thirdly, there is not only an issue of water quantity but also of reduced quality (Kuyama et al., 2013; Allen et al., 2011). Even in regions where water is abundant, there can be problems because water effluents are polluted. The effluents need to be treated and stored by industrial and municipal facilities, which can have a high cost. In addition, there can be leakages and local pollution before and during clean-up. In areas where water regulation is not enforced, polluted water might be released and damage ecosystems. The water quality impacts are not well known for the moment, but can be significant.

Climate change policies may influence the energy resource bottleneck and thus the nexus. A reduction in CO_2 intensity would involve less fossil fuel consumption, and therefore less depletion and less need to develop very water intensive non-conventional resources. Therefore, one of their co-benefits would be to limit the energy and water bottlenecks. On the other hand, as outlined above, increased reliance on bioenergy may aggravate the competition for scarce land.

In the sense of the nexus, the energy resources bottlenecks are less stringent than the land and water bottlenecks, because the dependence of the services provided by energy on availability of local resources is less strong. Firstly, energy can be relatively easily transported and traded (compared with water and land). In addition, there are several options to produce energy from natural resources and various possibilities of substituting one fuel for another. Lastly, markets for energy products and services tend to be functioning better than those for land and water, thus helping to co-ordinate the supply and the demand and prioritise access for the most efficient uses. The notion of energy scarcity is therefore more one of increasing costs of supply rather than absolute scarcity, and its role in the nexus is primarily one of essential interlinkages with water and land resources.

1.6. The materials aspects of the land-water-energy nexus

An important link between the economy and the land-water-energy nexus not covered in the modelling analysis comes from the interactions with materials; together, they form the resource fundament of economic activity. For instance, agricultural yields rely on the material fertilisers nitrogen, phosphor and potassium; most energy is produced from the fossil resources coal, oil and gas. Mining, beneficiation, and processing activities make considerable claims on energy and water; future output expansion in the metal sector, most likely utilising lower grade ores, will tend to increase pressures on these resources. On the output side, the wastes generated by mineral and metal production can have negative consequences for the quality of land and water resources, and therefore for the economic productivity of sectors that utilise these as inputs. All extraction of materials requires inputs of land, water or energy, and often at least two of these.

Like the nexus resources, material resources represent the physical basis for economic growth. They are essential for the global economy and future economic and social

development depends on their continued supply (Coulomb et al., 2015). Like land, water and energy, minerals are in finite supply. Their distribution within the Earth's crust is highly geographically clustered, more so than land, water and energy. This makes security of supply a potential risk – no country is completely self-reliant across the entire range of materials. For a number of mineral commodities, the depletion of higher grade ores in industrialised countries has exacerbated this issue; global supply has become more dependent on the political stability of a small number of resource rich countries. At the same time, increasing demand from emerging markets, the emergence of low-carbon technologies that require significant quantities of rare minerals, the lack of substitutes for metals with particular properties, and currently low rates of recycling have all made economies more vulnerable to potential supply bottlenecks or disruptions.

Raw materials can serve to ease, or aggravate, bottlenecks within the land-water-energy nexus. Finite carbon budgets, and the need to transition a low carbon energy system, will lead to greater claims on a number of speciality metals. In a similar way, the limited availability of new arable land will mean that increased food demand will have to mostly be met though yield improvements which, in many cases, will place additional claims on mineral fertilisers. The availability of these materials, or lack thereof, will determine to a significant extent the costs of meeting these constraints. Mineral and metal production can also influence bottlenecks in the land-water-energy nexus through their effect on resource quality. Emissions to land, water, and the atmosphere from mining and mineral processing activities are well documented and serve to lower the availability and productivity of these resources.

Increased resource efficiency and a transition towards a circular economy can reduce the threat of materials scarcity. An economic analysis of such a transition is left for future study.

1.7. The need for an integrated and dynamic analysis

The linkages in the nexus are complex. It is hard to say which link is most important or deserves most attention. Bottlenecks resulting from resource scarcity are time and place specific. The linkages with water deserve special attention. Projections show that over time limited supply and increasing demands will lead to increasing water stress. The OECD Environmental Outlook to 2050 projects that the number of people living in severe water stressed basins will threefold in the next decades to 4 billion in 2050 (OECD, 2012a). Competition for this scarce resource will increase. Depending on how scarce water is allocated among different users, lack of water may lead to lower agricultural yields, high energy costs or both. The water-agriculture link may currently be the most relevant, with a majority of global water withdrawals for agricultural use. However, the water-energy link may become more relevant in the future with rapidly increasing water withdrawal by non-agricultural users (households, industry, and electricity). Also the links between agriculture, land-use and energy may become increasingly important in the future. Biofuels only play a limited role in baseline scenarios. However, most climate mitigation pathways rely heavily on the input of biofuels. Whether biofuel production competes with food production for scarce water and land depends on the production technology, i.e. whether it is rainfed or irrigated, whether it concerns food crop land or abandoned land. Population growth, income growth and climate change, all affect the demand and supply of the nexus resources in different ways, and has the potential to shift pressures from one side of the nexus to others. This calls for a dynamic analysis that takes changing trends into account to paint a plausible picture of how the situation may look by 2060.[4]

This section showed that there are large interactions between the different resources in the land-water-energy nexus, and intricate connections to sectoral economic activity; increasingly strong links between economic sectors and between regions further spread the bottlenecks in the nexus to other parts of the global economic system. This calls for integrated analysis. An integrated systems approach is needed to shed light on how bottlenecks in the nexus affect the various aspects in the biophysical and economic systems.

In addition, physical scarcity may be less of an issue at the global level: the global economy is not running out of its most important resources any time soon. But the uneven distribution over space and time and often limited transferability make resources scarce in specific regions in specific periods. The global megatrends are also not manifesting themselves equally across the globe: population growth and income growth are projected to vary widely between OECD and non-OECD countries, climate change impacts primarily affect countries in Asia and Africa, etcetera. Therefore, tensions are more manifest on a disaggregated level. This calls for an analysis at a disaggregated level.

Notes

1. CIRCLE stands for Costs of Inaction and Resource scarcity: Consequences for Long-term Economic growth.
2. Water consumption is not the same as water withdrawals. For instance in cooling of power plants, a large part of the water intake is given back to the system, leading to high withdrawals but relatively small consumption. However, non-consumptive withdrawals of water may affect the quality of the water resource (such as an increase of water temperature which may be detrimental to the functioning of aquatic ecosystems) and therefore still represent a water use.
3. And 12.6% if including power which is 49% of the withdrawal.
4. While the modelling tools are all recursive-dynamic in nature and calculate a full path of the evolution of the biophysical and economic systems between 2010 and 2060, the transitional dynamics of the scenario shocks are somewhat less clear; therefore, the modelling results presented in this report largely focus on the situation in 2060.

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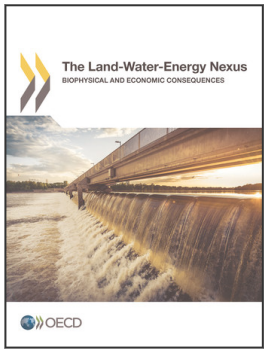

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