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Examination of interdependencies between water and greenhouse gas mitigation pathways on country level

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Abstract

Rising levels of greenhouse gas (GHG) emissions and increasing water stress have been in the focus of the scientific debate for some time. As a result of mounting concern about the adverse consequences of these evolutions, some countries have already begun to discuss and implement sets of mitigation options.

So far, pathways to address water scarcity or rising GHG emissions have been developed independently from each other, and the assessment of interdependencies between the water and greenhouse gases has only been conducted for specific technologies [1] [2], or with regards to the overall impact of climate change on water resources [3].

This work aims to close this gap in research and assesses, at the example of China and South Africa, the interdependencies of pathways to mitigate water stress and unsustainable levels of GHG emissions that were developed independently from each other in earlier research [4] [5]. An integration of all mitigation options in one model then allowed to determine the benefits of an integrated approach to water availability and GHG emission reduction.

The results show that water–GHG interdependencies are for the most part positive in both countries, i.e., the implementation of the proposed set of measures to mitigate either water scarcity or high GHG emission levels generates overall savings of the other resource. It is furthermore shown that the majority of the investigated interlinkages are related to the nexus between water and energy, whose magnitude is again determined by the water intensity of that power generation mix that is replaced by or avoided primarily through the promotion of energy efficiency and alternative power sources.

The optimization of all mitigation measures by means of a linear programing approach shows that an integrated approach allows to better meet mitigation targets, in particular with regards to local water availability, and reduces cost by up to 23% compared to independent considerations.

Based on the study of China and South Africa, the hypothesis is brought forward that such interdependencies are also observable in other geographies that are similarly water-stressed and dependent on thermal power generation, while countries with little such generation capacities will experience less or different interdependencies. A study of Egypt supports this hypothesis, but also shows that an expansive agricultural sector might provide opportunities for positive water–GHG interlinkages there.

Contents

1. Introduction

Concerns about rising levels of anthropogenic greenhouse gas emissions and its consequences on the global climate were first articulated on a broader basis in the 1980s, and a multitude of publications has discussed this topic from different angles since then. The four assessment reports of the Intergovernmental Panel on Climate Change (IPCC), with the latest from 2007, are only the most most prominent of these.
Water as a scarce resource, in contrast, has only been in the focus of a global debate since more recently, likely triggered to part by the rise of water-scarce regions, such as the Middle East or China, to greater economic importance and the associated increase in water stress. The medial attention to conferences such as the annual World Water Week in Stockholm speaks for the growing importance of this topic.
Little research, however, so far focused on the interdependencies of water and greenhouse gas (GHG) emissions, and in particular on measures that aim at mitigating water scarcity or unsustainably high levels of GHG emissions: seawater desalination increases water availability, but adds to rising GHG emissions, to give only one example[1].
This thesis exploits these interdependencies at the example of two countries, China and South Africa. For this purpose, it builds on two reports that investigated sets of mitigation options for increased water availability and reduced GHG emission levels independently. It is structured as follows:

In **Part I**, **chapter 2** introduces to water supply and demand and greenhouse gas emissions. It discusses the current situation, and water demand and GHG emission projections until 2030 as well as associated risks.
Chapter 3 focuses on water supply/demand and GHG emissions statistics for China and South Africa. After a short country introduction, covering climatic conditions, land area, population and economic indicators, the present state and forecasts until 2030 are discussed for both countries.
Chapter 4 investigates sets mitigation options from all sectors of the economy that help to close a looming water gap and achieve sustainable levels of GHG emissions in China and South Africa. The cost and potentials of these mitigation options are debated at the

[1] If not powered to 100% by renewable energy sources.

example of *cost curves*.

The first chapter of **Part II**, **chapter 5** presents the research that has been conducted so far on the interdependencies of water and GHG emissions. It shows that a good understanding is obtained on large-scale consequences of climate change on local water resources, and on the individual water (energy) intensities of technologies that provide energy (water).
Chapter 6 explains why certain sources and terminologies were chosen in this work and discusses the methodical approach towards an integration of water and GHG mitigation measures.
Chapter 7 quantifies the cross-intensities of the considered water and GHG mitigation options. It therefrom discusses the impact on water resources if all envisioned GHG mitigation options were implemented, and vice versa, and presents this in the form of intensity curves, a modified form of the original cost curves.
The results of a full integration of all options are given in **chapter 8**. The benefits (and limits) of an integrated view of both resources are illustrated at the example of several scenarios, the last set of which allow to construct investment functions that set the required investments in relation to arbitrary increases in water availability and GHG emission reductions.
Chapter 9 will then abstract from China and South Africa and address the question to what extent the results from previous chapters are transferable to other regions. It concludes with a case study of Egypt.
The conclusion, **chapter 10**, summarizes the key results and discusses first recommendations for policy makers therefrom, before it concludes with an outlook that prognosticates that an integrated assessment of resources will become ever more important.

Part I.

Water and Greenhouse Gases

2. Global water scarcity and the greenhouse effect

This chapter introduces to water scarcity and greenhouse gas emissions. It discusses these issues on global scale and comes to the conclusion that current policies and related "Business-as-Usual" scenarios will most likely not be sufficient to stop the rise of global mean temperatures, or close looming water gaps.

2.1. The importance of water and greenhouse gases

Water is probably the world's most precious resource: there is no life without water. The first agricultural societies developed along major rivers such as the Nile, Euphrat and Tigris, Indus or the Yellow River, as these provided for a secure supply of water. Since their beginning, these societies struggled with the level of water availability. The well-being of Ancient Egypt for example depended on the Nile's annual bursting of the banks in summer, when the floods brought fertile silt to the fields – flood levels that were too low or too high reduced crop yields [6]. Also today, unusual water levels are among the most devastating catastrophes. In the lesser cases, such events lead to economic losses: during Europe's exceptionally dry summer of 2003, water levels in rivers fell to such an extent that intake of cooling water in thermal power stations was curbed [7], while Australia's long drought between 1995 and 2009 led to reductions in agricultural ouput, requiring the government to provide aids of 3.5 billion Australian Dollars between 2001 and 2007 [8].

Growing population levels, economic growth and behavioural changes have led to unsustainable levels of water abstraction in parts of the world such as the Midwest of the United States [9] [10] or the North of China [11]. If no action is taken, the structural gap between water availability and demand will not close, and likely lead to reduced welfare and economic activity.

Unlike other resources, bulk water is in general a local resource, due its low ratio of economic value to cost[1] – water scarcity in one region will therefore have only an indirect impact on other regions.

In contrast to water, anthropogenic greenhouse gas emissions of significant scale are a matter of fact of only the last 250 years. From the last ice age until the 1750s, atmospheric concentration of carbon dioxide (CO_2) – the most important greenhouse gas – stayed at about 280 part per million (ppm) [15]. They increase steadily since then, to 379 ppm in 2005 [16], driven mainly by increased exploitation and combustion of fossil fuels.
Also, in difference to water, greenhouse gas emissions are global: as they are emitted in the earth's atmosphere, one tonne has the same impact no matter where the emission takes place.
The global warming potential of carbon dioxide was first shown by Svante Arrhenius in 1896 [17], but long ignored. In 1958, Charles Keeling started to measure atmospheric CO_2 concentrations over several years, demonstrating the influence of human activities on concentration levels [18]. In the 1980s, the topic has become more widely known and environmental organizations started to urge countries to reduce their emissions of carbon dioxide and other greenhouse gases in order to avoid further damage to the environment. The latest (2007) report by the Intergovernmental Panel on Climate Change (IPCC) mentions that if emissions are not reduced, best estimates for mean global temperature predict a rise by between 1.8°C and 4.0°C over 1990 levels until the end of this century. As only one consequence, sea levels might rise by up to 59 cm until then [19].
Despite major efforts in recent years, the strong economic growth particularly in developing countries has led to ever further increasing levels of greenhouse gas emissions, which are not expected to fall in the next twenty years in the current policy scheme [19] [20].

2.2. Global water demand and supply

Water cannot be easily created or destroyed – the earth's total volume is therefore constant at about 1.4 billion km^3. However, only 35 million km^3, or 2.5%, of this water is freshwater, of which 68.9% (24 million km^3) are locked in glaciers, permanent ice, or snow cover. Groundwater – including deep groundwater, soil moisture, swamp water and

[1] Case studies conducted in different Asian, African and European countries found that the net value of water for irrigation lies between 3.0 and 27.3 USD cents/m^3 [12]. The value that was actually charged is lower, between 0.04 and 5.0 USD cents/m^3. In contrast, transport of one tonne (or the equivalent, one cubic meter) of bulk good by ship for 1,000 kilometers costs 0.4 USD cents/tonne [13]. These values are in the same range - in contrast to most other goods, where transportation accounts for about 1% of cost [14].

water locked in permafrost soils – makes up further 30.8%, or about 11 million km^3, of freshwater. Only 0.3%, about 105.000 km^3, of freshwater are found in lakes or rivers [21]. The freshwater that is available for ecosystems and human uses is estimated to be about 200.000 km^3, only 0.6% of the total [21] [22]. This amount is furthermore unevenly distributed: while a country such as Colombia has an annual freshwater supply of 2.132 km^3 [23], similar-sized (and more densly populated) Egypt can dispose of only 58 km^3 [24][2].

2.2.1. Global water withdrawals today

Global annual freshwater withdrawals[3] were estimated at 3,788 km^3 in 1995, and 3,973 km^3 in 2000, according to UNESCO's International Hydrological Programme (1999) [22]. Other sources give comparable numbers: a 2002 report by the International Food Policy Research Institute (IFPRI) and International Water Management Institute (IWMI) estimates 1995 withdrawals at 3,906 km^3 [26], and a 2000 report by the University of Kassel mentions 3,572 km^3 [27] for 1995.
For 2010, UNESCO's International Hydrological Programme estimated withdrawals at 4,430 km^3 [22], while a report by the Water Resources Group (2009) mentioned global withdrawals of 4,500 km^3 (in 2010) [5] – of these, 69%, 3,100 km^3, were accounted for as agricultural use, mainly for irrigation, 13% (600 km^3) in the municipal sector, and 18% (800 km^3) for industrial purposes [5].
Water withdrawals vary widely between countries and can range from less than 10 m^3 per capita and year to more than 2.000 m^3 [28]. Table 2.1 gives overall data and a sectoral split for four very different countries, Chad, Egypt, Switzerland, and the United States. Domestic withdrawals are lowest in the dry and relatively poor Chad, but reach already high per capita levels in Egypt, while industrial withdrawals, to little surprise, are lower in those countries than in Switzerland or the United States.
A major agricultural producer in a desert climate, Egypt uses the bulk of its water, 83%, or 799 m^3 per capita and year, for agriculture (Egypt will be discussed in more detail at the end of this work, see chapter 9.2 on page 172ff)[4], while Chad, with comparable

[2]A complete list of renewable freshwater supply by country can be found in [25] (citing, amongst other, [23] and [24], p.217 ff.).

[3]Withdrawals are the amount of water taken from water bodies. In contrast to *consumed* water, which is lost to the local cycle for example through evaporation, *withdrawn* water can be returned, albeit possibly at impaired quality: many municipal points of water use withdraw water, but do not consume it, such as showers or washing machines. In 2000, consumptive uses accounted for 52% of global withdrawals [22]. More on definitions in chapter 6.2, page 77ff.

[4]Egypt's withdrawals in table 2.1 and its renewable supply (see page 5) do not match: part of the gap

climate but without access to a large river, uses only 17 m^3 per capita and year. In the United States, irrigated agriculture dominates in the Midwest, the South West, Texas and California – agricultural withdrawals account for 41% of total U.S. withdrawals [29]. In contrast, Switzerland's temperate climate with high annual rainfall makes irrigation superfluous in most cases, resulting in low agricultural water requirements[5].

Country	2010 pop. *million*	**Total** withdrawals *km*^{3}	**Domestic**	**Industry**	**Agriculture**
			per capita withdrawals *m*^{3}		
Chad	11	0.2	3	0	17
Egypt	81	72	113	16	799
Switzerland	8	2.5	80	245	6
United States	310	482	193	699	626

Table 2.1.: *Annual water withdrawals for selected countries. Population data from [30]. Water data except Egypt drawn from [25], p.223ff; original sources and year of data: Chad [28] 2000; Switzerland [31], 2002; United States [29], 2005. Egypt [32], 2008.*

2.2.2. The notion of water scarcity

Water stress or scarcity can be defined in multiple ways.

The *Falkenmark indicator* is a supply-side index, defined as the per capita annual water runoff that is available for human use [33]: a region is considered *water stressed* if annual runoffs are below below 1,700 m^3, and *water scarce* if below 1,000 m^3. According to this definition, all of the Middle East and Northern Africa as well as many city states and islands experience scarcity, whereas Eastern Africa, South Africa, India, but also South Corea or Denmark are water-stressed (see [34], chapter 2). The Falkenmark indicator however does not account for climatic and cultural differences [35], nor does it consider environmental requirements.

The Water Stress Indicator (WSI) considers both the supply and demand side and also takes environmental requirements into account [36]. It is defined as the ratio of

is closed through water reuse, part through exploitation of unsustainable sources. See also chapter 9.2.

[5] As withdrawals only refer to explicit human withdrawals from water bodies, the water provided to crops by rainfall is typically not accounted for in these statistics.

withdrawals to mean annual runoff (MAR), used as proxy for water availability[6], less environmental requirements (EWR),

$$\mathrm{WSI} = \frac{\text{Withdrawals}}{\text{MAR - EWR}} \tag{2.1}$$

According to this definition, a WSI>1 means overexploitation of the water resource; however, dry regions with low MAR do not necessarily experience water scarcity. Fig. 2.1 depicts a world map with the WSI, indicating that the major river basins of Europe, Northern Africa, the Middle East, South Africa, India, China, Central Asia, and the United States are overexploited.

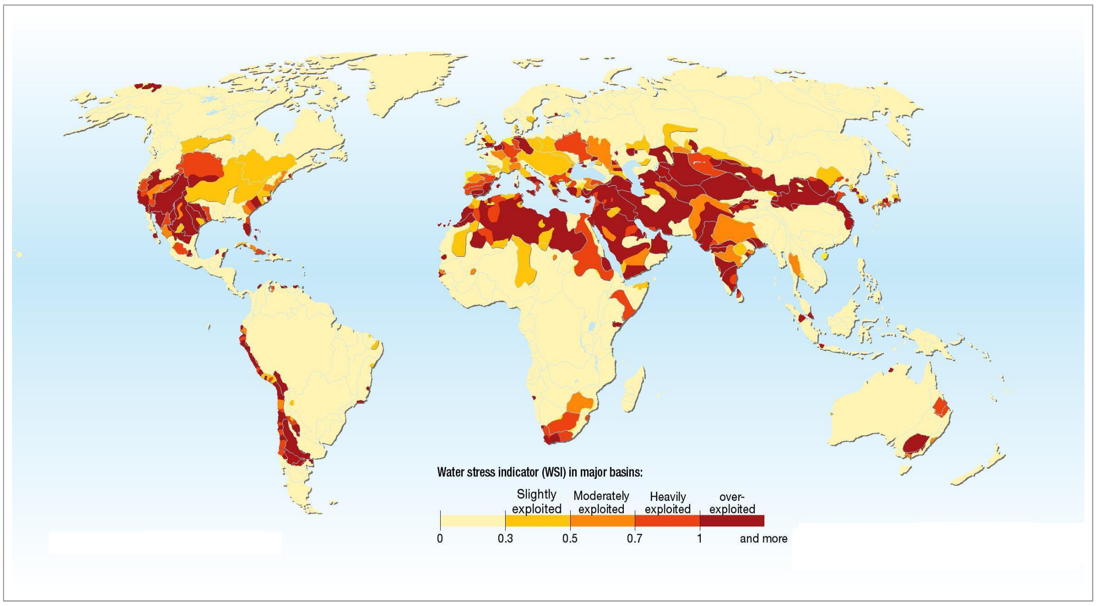

Figure 2.1.: *From [37]: World map showing the Water Stress Indicator (WSI) in the major river basins (see 2.1).*

Interestingly, large parts of Europe and the Eastern United States, but also basins in Japan that are normally not considered as water-scarce have a WSI>1, presumably due to neglects of environmental requirements – if EWR was omitted in equation 2.1, these regions would drop from the water scarcity map [38].

A definition of water scarcity that takes both suply and demand into account, and adds the notion of *economic* water scarcity was provided by International Water Management

[6]Intrabasin return flows that are recycled are accounted for – MAR can thus be higher than the primary, natural runoff. This already indicates that one way to mitigate water scarcity is to increase usable return flows, e.g., through buildup of wastewater treatment facilities or the reduction of leaks in municipal networks.

Institute [39]. There, *physical* water scarcity means that more than 75% of available water is withdrawn[7], whereas *economic* water scarcity prevails if less than 25% of available water is withdrawn, but lack of infrastructure impedes its put to use. In that definition, much of South East Asia, Sub-Saharan Africa and parts of Central and Latin America are considered economically (but not physically) water scarce[8].
Further definitions of water scarcity exist – a review of the different indices can for example be found in [35] or [38].

Water stress and scarcity are therefore not only a problem of arid regions. Depending on the definition, Africa's tropical belt can be considered water-scarce, as can be more humid parts of Europe and North America. In all cases, however, the principle set of mitigation options apply: a reduction of demand through more efficient uses, and infrastructure improvements to increase supply.

2.2.3. Water withdrawals and supply until 2030

Drivers for increasing water withdrawals

Over the next decades, water demand is expected to increase as population levels rise, economies grow and behavioural changes, driven by higher individual wealth, proceed.
The world population is expected to from 7.0 billion at the end of 2011 to 8.3 billion in 2030, with the developing regions[9] contributing most of this growth [30]. These are also the regions that experience most of the water stress already today, as figure 2.1 has shown.
Economic growth will put further stress on water resources:
Global Gross Domestic Product (GDP) is expected to almost double between 2010 and 2030 [30] [40]. This will increase pressure on water resources as economic activity drives water demand, either directly, as in agriculture, or more indirectly, e.g., for cooling of power plants that produce electric power. The water intensity of GDP in the industrial sector was assessed to be in the range of 0.01 m^3 to 1 m^3 per USD of GDP in [41][10]. A second source gives similar numbers, stating an water productivity in the United States of about 15 USD per m^3, i.e., about 0.07 m^3 per USD [42][11].

[7] Again, return flows that are recycled and fit for reuse are accounted for.
[8] See [39] for a water scarcity map according to this definition.
[9] According to the UN [30], developing regions comprise all of Africa, Asia (excluding Japan), Latin America and the Caribbean plus Melanesia, Micronesia and Polynesia.
[10] [41] (1997) refers to 1990 USD numbers. Industrial water efficiency likely has improved since then, but increased industrial activity will very likely still have an impact on water withdrawals.
[11] In 1996 U.S. Dollars.

As much of the economic growth will happen in countries that are exposed to water scarcity already today[12], constraints on water resources will likely grow.
Furthermore, about 3 billion people will advance into the middle class between 2009 and 2030 [44], which will drive a growth in power demand – indirectly increasing water demand again – and likely also lead to dietary changes: the average Chinese person eats 4 kg of beef per year today, compared to 15 kg for an average European [45]. As China's per capita beef consumption is expected to increase [46] and as 1 kg of beef requires 16,000 liters of water, more than any other food [47] [48], this will likely increase pressure on water resources.

Global water withdrawals until 2030

Projections of global withdrawals can only be rough estimates, and depend on many assumptions. Next to the growth of populations and economies, estimates on water productivity gains and the future power mix need to be included[13]. Such projections should therefore be considered as potential *scenarios*, i.e., possible pathways under the given assumptions. Keeping this in mind, such scenarios can give a sense for the challenges ahead, and help in identifying potential supply-demand gaps.
According to UNESCO's International Hydrological Programme (1999) [22], 2025 global water withdrawals are estimated at 5,253 km^3. The other sources mentioned earlier give lower forecasts for 2025: 4,772 km^3 according to IFPRI and IWMI (2002) [26], 4,092 km^3 according to the University of Kassel (2000).
The 2009 report by the Water Resources Group [5] is the most recent projection of future water withdrawals to our knowledge. According to it, global withdrawals continue to grow at 2% annually until 2030, the growth rate of recent years, if no future water productivity gains are captured. Between 2010 and 2030, withdrawals would then increase from 4,500 km^3 to 6,300 km^3 in 2025, and 6,900 km^3 in 2030 [5], which is at first sight higher than projected in the other sources ([22], [26], [27]); the difference mainly stems from the exclusion of productivity improvements in [5]: if those were included at 1% per year in agriculture and industry, the average rate of improvement between 1990 and 2004 [5], 2025 withdrawals would be about 5,000 km^3, comparable to [22] and [26][14].

[12] 2010-2030 GDP growth in Africa, China and India's is expected to be 134%, 314% and 375%, respectively, wheras growth in the European Union will only be 46%, and United States 63% in the U.S.([30] [40] [43]).

[13] A power system dominated by thermal plants requires considerable amounts of water for cooling, whereas a system based on photovoltaic and wind only needs a fraction of that amount. Also see section 5.2.1, 67ff.

[14] Reasons for the comparatively low number of 4,092 km^3 given in [27] are more conservative estimates on economic growth – e.g., Chinese GDP growth 1995-2025 was assumed to be only 4.2% per year,

Water stress and water gap in 2030

Figure 2.2 shows the projection for global water demand and suply according to [5]. It gives the 2010 and 2030 demand on the left side and opposes it with the existing water supply which is assumed to stay constant in the reference scenario. The water considered as supply is subject to the following restrictions:

- *Accessible.* Freshwater that can be conveyed to a point of usage when needed with the existing infrastructure. I.e., water locked in glaciers or inaccessible aquifers etc. is not included, as is not snowmelt in excess of immediate needs and reservoir storage capacity. The water must furthermore be of sufficient quality to be ready for basic uses.
- *Reliable.* Water that can be supplied in 90% of the time. I.e., stormwater or floodwater is not included.
- *Sustainable.* Water can only be extracted to such an extent that the annual fill level of the water body stays constant over the years.
- *Less environmental requirements.* Freshwater less environment needs to sustain ecosystems.

It can be seen that global withdrawals were by about 300 km^3 higher than supply already in 2010 if environmental needs are taken into account, which means that the world's Water Stress Indicator (WSI) is greater than 1 according to equation 2.1.
Until 2030, the gap between water withdrawals and supply is estimated to increase. As some basins will still have higher supply than demand, summing up to 100 km^3, the gap in the basins with deficits is forecasted at 2,800 km^3.
It has to be noted that figure 2.2 does not include potential consequences of climate change. Water supply in many arid and semi-arid regions will likely decrease if greenhouse gas emissions continue to rise, further aggravating water stress in these areas [19][15]

Figure 2.3 shows how the global water gap distributes across countries. It can be seen that the vast majority of the world population will live in water-stressed regions by 2030[16];

whereas actual annual 1995-2010 growth was 8.5% and is expected to be 7.9% between 2010 and 2025, according to [43] – and the assumption that withdrawals for irrigation either stabilize or decrease slightly, whereas this is expected to increase in all other sources ([5], [22], [26]).

[15] This topic will be discussed in more detail in chapter 5.1, page 64ff.

[16] Underlying population estimates in [5] differ slightly from the latest UN figures cited above [30]: [5] assumes a 2030 world population of 8.2 billion (versus 8.3 billion in [30]).

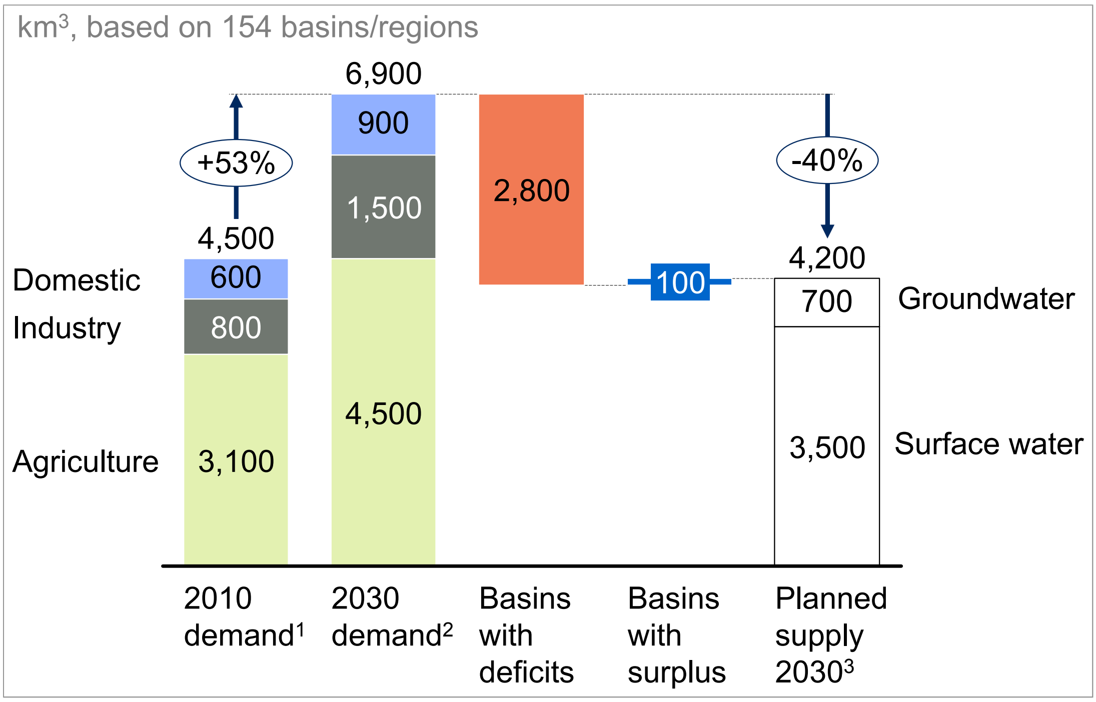

Figure 2.2.: *Global water demand and supply, 2005 and 2030. From [5], p. 44.; footnotes:* [1]*Based on the International Food Policy Reseach Institute (IFPRI);* [2]*Based on frozen technology and no increase in water efficiency after 2010;* [3]*2030 accessible, sustainable supply at 90% reliability (4,866 billion m^3) net of minimal environmental requirements (666 billion m^3).*

only a small fraction of regions, amongst them for example Japan and Scandinavia, are expected to still have a surplus by 2030.
As already suggested by the WSI map (page 8), which depicted water stress on a basin level, the two insets in figure 2.3 demonstrate that a country view can give superficial information, especially for countries as diverse as China or India: whereas China's humid and mountaineous South West and Song basin in the north are not expected to experience water stress by 2030, all other basins are expected to do so, with a tendency of higher stress in the drier north of the country (Hai and Huang basins) than in the more humid south (Yangtze, Pearl).

Figure 2.2 does neither assume improvements in water productivity nor supply infrastructure, which might however be well realized: continuing water productivity improvements at historic rates would reduce the 2030 water gap by about 20% [5], which includes efforts towards more efficient use of water in all sectors – for example reduced leakage in water networks, methods to reduce cooling water needs in power stations, or water-saving

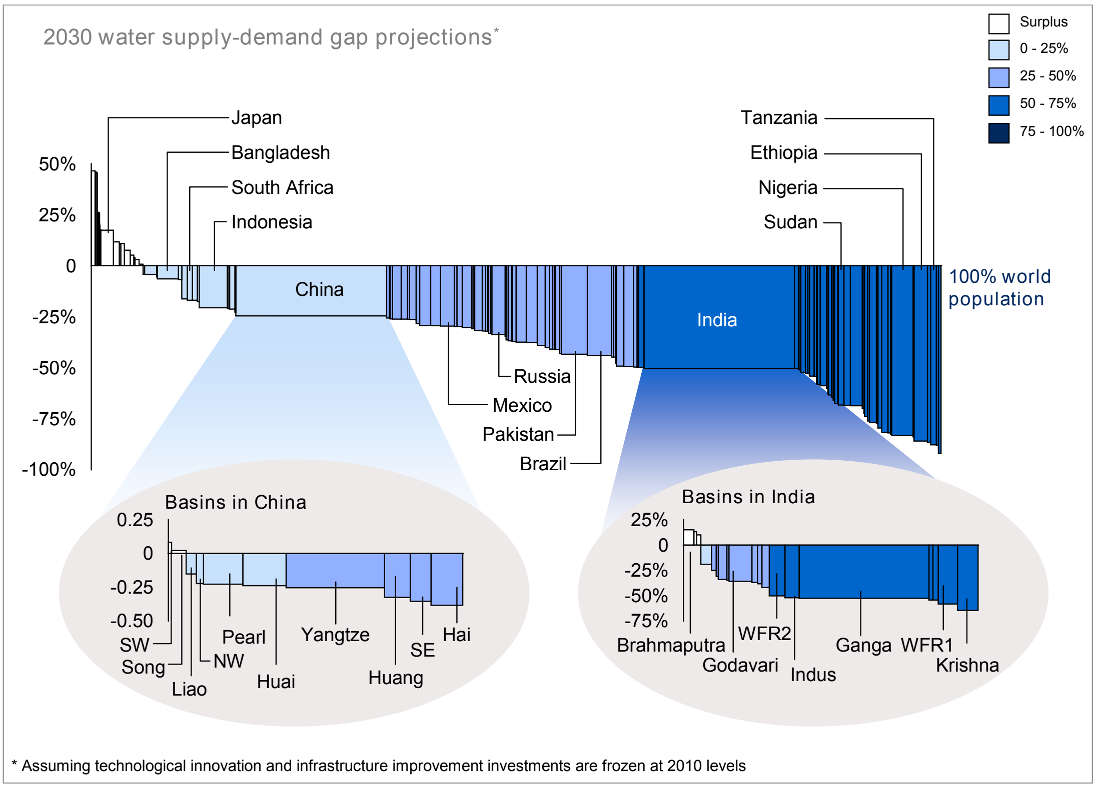

Figure 2.3.: *From [5]. Water gap as percent of 2030 withdrawals per country. A negative percentage means that projected water withdrawals exceed accessible, reliable and sustainable supply after accounting for enviromental needs.*

irrigation methods such as drip irrigation, and another 20% of the water gap could by closed by increasing water supply at historic rates [5]. As these efforts will not suffice to close the gap in most regions, further measures need to be implemented. The alternative, that no additional action is undertaken, will, by definition, still lead to a balanced supply and demand situation. Such a scenario would however lead to ecosystems that do not receive their required share of water, hampered economic growth, or a lower standard of living.

2.3. Global greenhouse gas (GHG) emissions

Rising levels of greenhouse gases very likely have an impact on global climate. In most regions, this will lead to higher average temperatures and an increased frequency of weather extremes, including an increase in the likelihood of natural disasters [49] [50]. The following section first gives an overview of the most important anthopogenic greenhouse gases. Afterwards, it discusses the historic evolution and present state of anthopogenic GHG emissions, as will future scenarios for GHG emissions. The last part then summarizes likely effects of high atmospheric GHG concentrations.

2.3.1. Greenhouse effect, radiative forcing and the types of greenhouse gases

The earth is warmed by the sun, which radiates primarily in the visible and near-visible sprectrum[17]. About one third of the incoming solar radiation of about 342 W/m^2 is reflected directly [51], but the remainder is absorbed by the earth and its atmosphere. The warmed earth surface then re-emits radiation in the infrared spectrum (i.e., at lower energy). While a small part of this radiation leaves the atmosphere, the larger part is absorbed by substances in the atmosphere and re-emitted in all directions, also back to the surface. This is commonly referred to as the *Greenhouse Effect* (see for example [52]). The earth's average temperature would be below 0°C without this re-direction of radiation back to earth, so this natural greenhouse effect is essential to our ecosystem.

The most abundant elements in the atmosphere, oxygen and nitrogen[18], exert no greenhouse effect [52]. Indeed, the strongest contributors to it are water vapour and carbon dioxide (CO_2), with other gases such as ozone, methane, nitrous oxide and halocarbons conributing to a lesser extent [51].

The strength of the greenhouse effect is defined by the strength of the *radiative forcing*, which in turn depends on the concentration levels of those substances that do exert a greenhouse effect.

The radiative forcing, measured in W/m^2, is the difference between the integrated outgoing emission spectrum at the earth's surface and at top-of-atmosphere. The difference is related to the fact that part of the infrared radiation is absorbed on its way through the atmosphere and re-emitted in all directions. The various substances thereby absorb at specific wavelengths: CO_2 has an absorption peak at λ=1400-1600 nm, water vapour at wavelengths of 800-900 nm and again at 2000 nm [51] [52].

The higher the atmospheric concentration of these substances, the higher the radiative forcing, and the higher the energy that is kept in the system. For 1990 concentration levels, $CO_2 = 353$ ppm[19], $CH_4 = 0.31$ ppm and $N_2O = 0.31$ ppm, atmospheric radiative forcing, corrected for cloud effects, was determined at 125 W/m^2 [51] [53].

[17] The solar radiation spectrum starts in the ultraviolet part, at wavelengths of about 250 nm, rises sharply to its maximum at $\lambda \approx 500$ nm, i.e. in the visible sprectrum, and has a long tail in the infrared spectrum (see for example [51]).

[18] 78% of the dry atmosphere are composed of nitrogen, 21% of oxygen [52].

[19] ppm: parts per million, a measure for the concentration of a gaseous substance in a volume.

Gas	**Formula**	**Contribution**	
		W/m^2	%
Water vapour	H_2O	75	60
Carbon dioxide	CO_2	32	26
Ozone	O_3	10	8
Methane + nitrous oxide	$CH_4 + N_2O$	8	6

Table 2.2.: *From [51]. Contribution of the most important absorptive substances to radiative forcing at clear sky, corrected for overlap effects.*

Table 2.2 separates the main contributors to the radiative forcing: water vapour and carbon dioxide account for a combined 86% of the greenhouse effect, and ozone, methane and nitrous oxide for the remaining 14%. The impact of halocarbons[20] is estimated to be less than 1 W/m^2.

While the direct influence of human activity on water vapour and atmospheric ozone is negligible[21], CO_2, CH_4, N_2O and halocarbons are emitted by human activities at meaningful scale:

- **CO_2** is primarily released through the burning of fossil fuels, e.g., for power and heat generation or transportation.
- **CH_4** emissions stem from agriculture (e.g., from cattle or rice paddies) or the extraction and distribution of natural gas.
- **N_2O** is also emitted from burning of fossil fuels, or for example from fertilizer use.
- **Halocarbons** are used as refrigerants, cleaning agents or pesticides and can enter the atmosphere for example if old household fridges are not properly disposed of.

The 2007 IPCC report estimates that between 1750 and 2005, radiative forcing has increased by 1.66 W/m^2 through increased atmospheric concentrations of CO_2, and 0.98 W/m^2 through increases in CH_4, N_2O and halocarbons concentrations.

Next to these *greenhouse gases*, increased emissions of aerosols, e.g. from mining or burning of fossil fuels and biomass, had an in sum negative impact on radiative forcing

[20] Halocarbons are an umbrella term for organic compounds that contain halogens such as fluroine, chloride or bromide. Subgroups are fluorocarbons (HFCs, PFCs), which contain only fluorine, and chlorofluorocarbons (CFCs) that also contain chlorine. HFCs and PFCs started to replace CFCs since the Montreal Protocol in 1987, which exert a negative effect on the ozone layer [54].

[21] Or, in fact, negative, as in the case of ozone.

(about -1.2 W/m^2) over the same period. Combined with smaller human and natural effects, such as changes in water vapour[22] or solar irradiance leave an overall change in radiative forcing of about 1.6 W/m^2 between 1750 and 2005 [55] [52].

The *Global Warming Potential* (GWP) allows to compare the greenhouse effect of a given amount of different greenhouse gases. It is defined as the global mean radiative forcing impact 1 kg of some compound has relative to 1 kg of CO_2 over a given time horizon [56]. It thus depends on a substance's lifetime and its radiative forcing efficiency. Table 2.3 gives an overview of the GWP for the most important greenhouse gases. Methane for example has a GWP of 25 on the basis of a 100 year time span, i.e., 1 tonne of methane has the same impact on radiative forcing as 25 tonnes of CO_2[23].

	Formula	**Lifetime**	**GWP**
Gas		years	100 years
Carbon dioxide	CO_2	50-200	1
Methane	CH_4	12	25
Nitrous oxide	N_2O	114	298
CFC-12	CCl_2F_2	100	11

Table 2.3.: *Adapted from [57]. Table of the most important anthropogenic greenhouse gases, their chemical formula, atmospheric lifetime and Global Warming Potential (GWP) on a 100 year time scale (see text for a definition of GWP).*

2.3.2. Historic evolution and present state of GHG emissions

High concentration levels in itself are no novelty in earth history: levels of atmospheric CO_2 were several times higher over most of the last 500 million years [58] – the earth was habitable during this time, and brought complex creatures such as the dinosaurs into being. However, it is the rate of increase that is very likely unprecedented, and that can have negative consequences for a densely populated planet.
The concentration of CO_2 has climed from 280 ppm before the start of industrial revolution to about 379 ppm in 2005 and 392 ppm in 2011. Other anthopogenic greenhouse gases

[22] An increasing mean temperature due to higher atmospheric energy content will ultimately increase evaporation rates, thus leading to higher water vapour levels.

[23] Its molecular structure gives methane a higher radiative forcing efficiency than carbon dioxide ($3.7 \cdot 10^{-4}$ $W/(m^2 \cdot ppb)$ versus $1.4 \cdot 10^{-5}$ $W/(m^2 \cdot ppb)$ [57]). However, its shorter lifetime results in a lower GWP for a 100 year time span, decreasing further at longer time spans. Hence, 1 t CH_4 = 25 t CO_2e, or CO_2 equivalents.

have increased as well: methane from about 700 ppb[24] in 1800 to 1,774 ppb in 2005, nitrous oxide from 260 ppb to 319 ppb over the same period [52] [59].

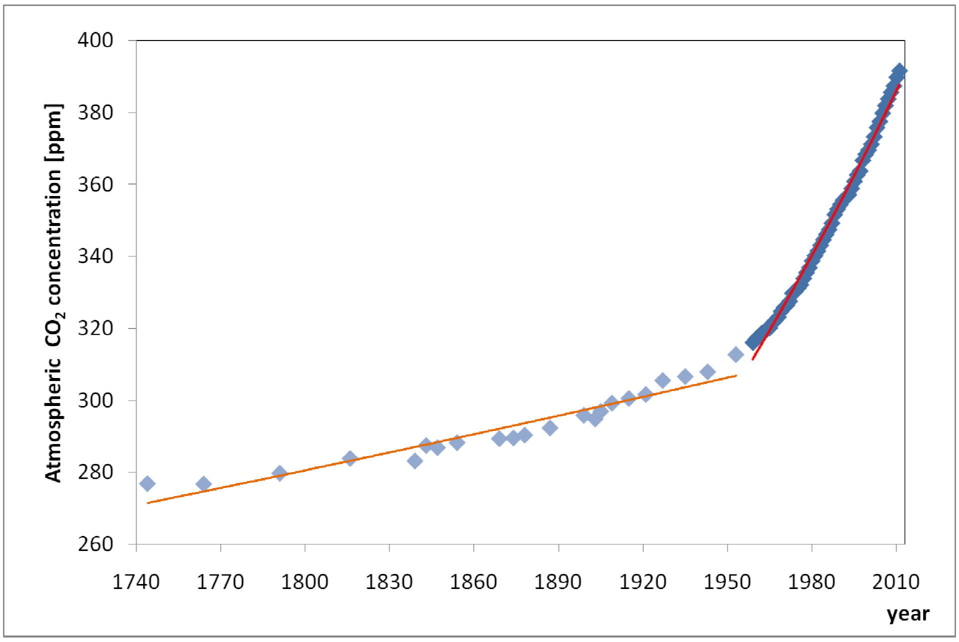

Figure 2.4.: *Historic evolution of atmospheric CO_2 concentrations 1744-2011. Light blue data points (years 1744-1953) are taken from air bubbles trapped in antarctic ice cores [60]. Dark blue data points (1959-2011) are taken from direct measurements of atmospheric CO_2 at Mauna Loa, Hawaii [61].*

Figure 2.4 shows the evolution of CO_2 concentrations levels between 1744 and 2011. It can be seen that concentration levels started to grow since the early 1800s with the beginning of industrialization and the resulting increase in fossil fuel burning. In the 1950s, the growth accelerated. Amongst other, this is likely correlated to a strong increase in population levels: while world population grew from 0.8 billion to 2.5 billion in the 200 years between 1750 and 1950 [62], it grew by a further 4.5 billion to 7 billion in the 51 years until 2011 [30].

Various institutions track greenhouse gas emissions, but large differences in completeness and actuality exist.
The International Energy Agency (IEA) for example publishes its yearly *World Energy Outlook* with data on CO_2 emissions from fossil fuel combustion (e.g., [20]).
The United Nations Framework Convention on Climate Change (UNFCCC) reports

[24]ppb: parts per billion

greenhouse gas emissions for the Annex I countries of the Convention[25], but not for non-Annex I countries [64], while the United Nations Statistics Division publishes holistic greenhouse gas emission data for all countries[26], but the most recent year reported can however be as far back as 1994 for some smaller countries [65].
Other sources report emissions on global scale, but are often restricted to CO_2 only, neglecting CH_4, N_2O and halocarbons, or specific sectors: the U.S. Energy Information Administration for example saw energy-related CO_2 emissions in 2005 and 2008 at 28 Gt and 30 Gt, respectively [66], whereas the World Energy Outlooks 2007 and 2010 estimated 2005 and 2008 emissions at 27 Gt and 29 Gt, respectively [67] [20].
Lastly, a 2006 EPA[27] report on non-CO_2 greenhouse gases estimated 2005 emissions of these to be 10 Gt CO_2e [68].

A database that gives numbers on all greenhouse gas emissions and that is based on a broad set of well-recognized databases is the *Climate Analysis Indicator Tool (CAIT)* provided by the World Resources Institute [69][28].
According to it, total GHG emissions for the latest year with data for all important greenhouse gases – 2005 – were 43 Gigatons of CO_2e; figure 2.5 shows how these emissions split between world regions, sectors and greenhouse gases, and how the regional split has changed between 1990 and 2005:

- *Types of greenhouse gases.* In 2005, CO_2 emissions accounted with 76%, or 33 Gt CO_2e, for the major share of global GHG emissions, followed by methane with 15% (6 Gt CO_2e), and nitrous oxide with 8% (3 Gt CO_2e). Halocarbons accounted for a further percent (0.5 Gt CO_2e) [69].

- *Sectoral split.* As CO_2 emissions arise mostly from the burning of fossil fuels for the production of energy (electrictiy, heat) and for transportation, it is not surprising to see the energy and transportation sectors accounting for 53% (23 Gt CO_2e)[29]

[25] Annex I countries are essentially all OECD countries, plus Russia, the Baltic states and several other Central and Eastern European countries. For a complete list see [63].
[26] Based on UNFCCC and UN Population Division data.
[27] EPA: U.S. Environmental Protection Agency
[28] The CAIT tool builds on data from the U.S. Department of Energy [70] [71], the Emission Database for Global Atmospheric Research (EDGAR) by the European Commission and the Netherlands Environmental Assessment Agency [72], the International Energy Agency [73], the U.S. Energy Information Administration (EIA) [74], the U.S. Environmental Protection Agency (EPA) [68] and the World Bank [75].
[29] This accounts for all energy-related emissions from power (and heat) stations, industry and households. For instance, a part of industrial emissions will be emitted by power stations, while another part is directly emitted from industrial complexes, e.g., for the production of process heat.

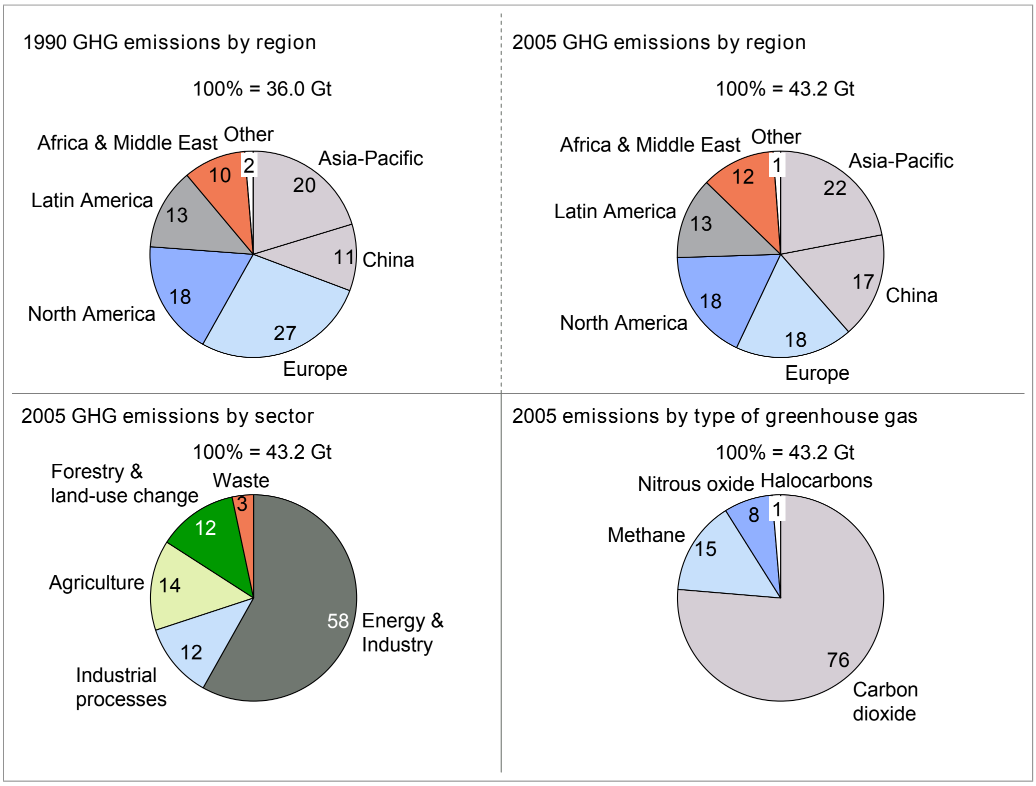

Figure 2.5.: *Split of greenhouse gas emissions by type of greenhouse gas, geography, and sector (2005), and 1990 for the geographic split.*

and 12% (5 Gt CO_2e)[30] of 2005 GHG emissions, respectively. Other industrial processes account for 4% (2 Gt CO_2e)[31], agriculture and forestry including land-use changes for 14% (6 Gt CO_2e) and 12% (5 Gt CO_2e), respectively, and waste for 3% (1 Gt CO_2e)[32].

- *Regional split I.* Asia (without the Middle East) and Oceania accounted for 39% or 17 Gt CO_2e of total emissions in 2005, with China being the single largest emitter (7 Gt CO_2e or 17%). The remainder of emissions is relatively evenly distributed among the other world regions: Europe and North America 18% (8 Gt CO_2e each), Latin America 13% (5 Gt CO_2e), Middle East and Africa 12% (5 Gt CO_2e) and the remaining countries one further percent (0.52 Gt CO_2e).
  However, it needs to be said that the list of main emitters looks differently on a per capita base, as table 2.4 suggests: Middle-Eastern Qatar leads the world with 75 t CO_2e per head. The average Australian still accounted for 28 t CO_2e, and a

[30]Includes private and commercial transport by road, rail, sea, air.
[31]For example, CH_4 and N_2O emissions in chemical plants.
[32]Mainly methane emissions from landfills.

citizen of the European Union for 10 t CO_2e, whereas China had emissions of 6 t CO_2e per capita.

- *Regional split II.* In 1990, overall emissions were 17 % lower than in 2005. Furthermore, the regional distribution looked different: Europe and North America then accounted for 45% (or 16 Gt CO_2e) of global emissions of 36 Gt CO_2e, and Asia (without the Middle East) and Oceania for 31% (or 11 Gt CO_2e). In particular, China's emissions were only 11% or about 4 Gt CO_2e, 52% of the 2005 level. The other world regions (Latin America, Middle East, Africa) roughly maintained their share.

  While emissions in Europe have actually decreased since 1990, emissions in the fast-growing economies of Asia and the Middle East have increased sharply.

Country	**GHG emissions** t CO_2e p.p.	**World rank**
Qatar	75	1
Australia	28	7
USA	23	10
EU 27	10	n/a
China	6	94
Chad	2	144
India	2	152

Table 2.4.: *From [69]. Per capita greenhouse gas emissions for selected countries (and the European Union).*

Another source that gives holistic data on greenhouse gas emissions is the 2009 report *Pathways to a low-carbon economy* by McKinsey & Company [4], and its updates [76], [77][33]. This source is of particular interest for our later purpose, as it gives both projections for GHG emissions until 2030, and mitigation options towards more sustainable emission levels. Similar to the CAIT tool, data on greenhouse gas emissions are based on a range of established sources, namely IEA's World Energy Outlook 2009 [78], but also data from UNFCCC [64] and the IPCC [79].

[33] Albeit published by a private institution, [4] was created with the involvement of an academic review panel and further external experts. See [4], p.139-140 for references. The report is accessible free of charge.

According to it, global GHG emissions in 2005 were 45 Gt of CO_2e. To check the consistency of this data set with other publications, figure 2.6 shows how emissions data from [4] split by region and sector, and how they compare to the CAIT numbers[34]. Reassuringly, the differences between the two sources are small, with the largest deltas in the Asia-Pacifc region and the forestry sector. Regarding the first, this is likely due to the fact that a part of the countries summed in the block *other* in the CAIT are indeed smaller Asian countries, while the delta in the forestry sector is more difficult to explain and likely driven by different assumptions on land-use change.

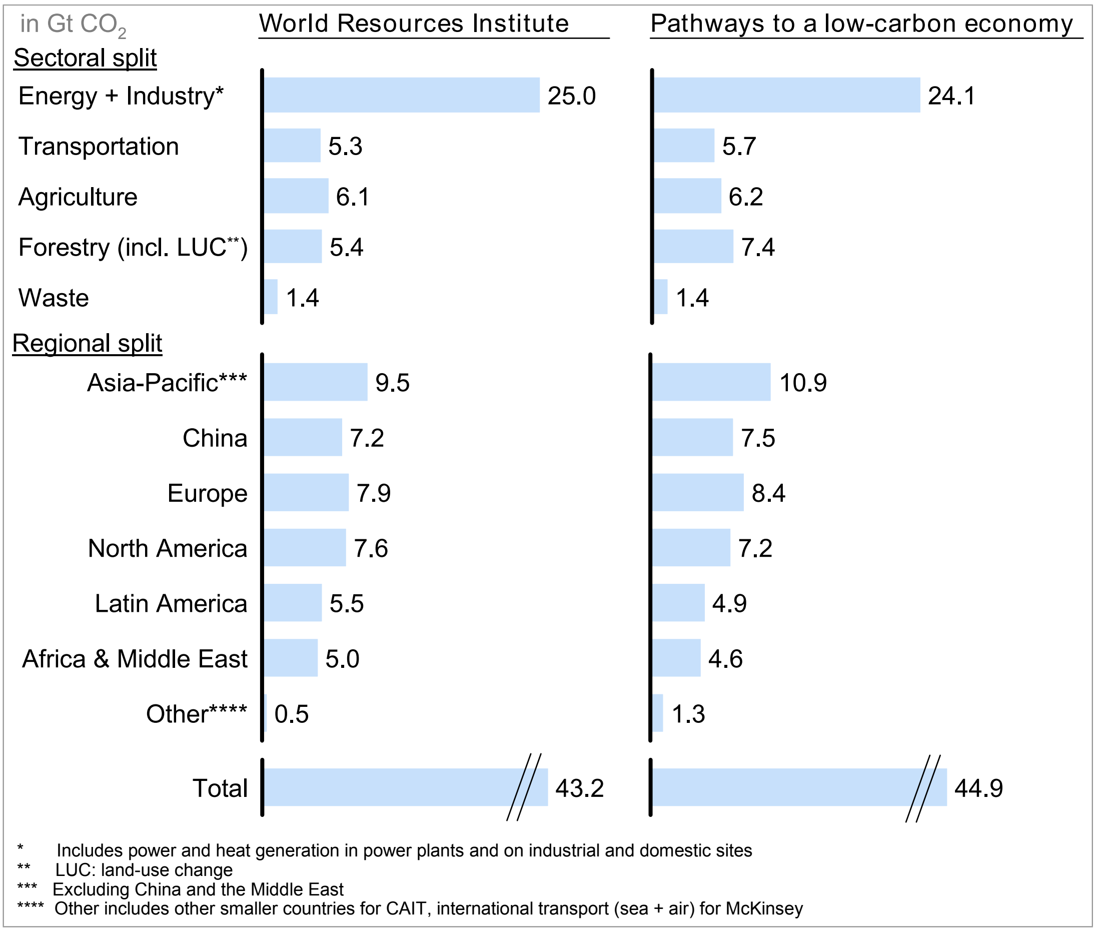

Figure 2.6.: *Comparison of global GHG emissions in 2005 from the World Resource Institute's CAIT tool [69] and the publication* Pathways to a low-carbon economy *[4] [77].*

[34]Please note that emissions in the McKinsey report for transportation and energy (more precisely, domestic emissions) were corrected downwards, by 0.5 Gt CO_2e each, in the 2010 update to the full report [4] ([76]) and [77]. Thus, regional numbers in this graph differ slightly with respect to [4], p. 25.

2.3.3. Projections on GHG emissions

As world population, standards of living and economic wealth grow, greenhouse gas emissions will grow in parallel in the current policy scheme [79] [20]. The following paragraphs will discuss how greenhouse gas emissions are likely to develop in such a "Business-as-Usual" scenario.
The Climate Analysis Indicator Tool [69] cites 2030 projections for global CO_2 emissions from energy of 39–44 Gt CO_2, depending on the scenario[35].
Comparable numbers can be found in the latest issues of the IEA's[36] World Energy Outlooks (WEO): according to the 2010 (2009) issues [78] [20], energy-related CO_2 emissions are expected to rise to 40 Gt CO_2 globally by 2030 under the current climate policy scheme, while the implementation of new environmental policies that are in discussion today would lead to reduced emissions, of 35 Gt CO_2 [20] (see table 2.5).
Non-CO_2 greenhouse gas emissions are expected to reach about 13 Gt CO_2e by 2020, according to the U.S. EPA[37] (no 2030 projection available); simply assuming constant annual growth for a first estimate would yield 2030 emission levels of about 15 Gt CO_2e.
This data, summarized in table 2.5, allows a first estimate of overall 2030 greenhouse gas emissions in the current policy regime, which should rise by about 40–50% between 2005 and 2030. Assuming 45 %, it could be estimated that GHG emissions reach 65 Gt CO_2e by 2030, up from 45 Gt CO_2e in 2005 [76].
GHG emission projections depend on multiple asssumption, with two of the most important being population and economic growth. The EIA reference case assumes that global population will grow by 0.9 %, from 6.5 to 8.2 billion, and the world economy will expand by an average 3.7% (in terms of GDP at purchasing power parity (PPP)) between 2005 and 2030 [80]. The WEO assumes similar trajectories for population, but lower economic growth rates: according to the 2009 edition [78], population growth is at 1.0 % between 2007 and 2030, and GDP growth at PPP 3.1% over the same period[38].

The IPCC[39] Fourth Assessment Report on Climate Change (2007) [79] includes multiple scenarios on global 2030 GHG emissions that cover the solution space in terms of economic and population growth, technological change and convergence of the world community (the level of global interaction), but assume no further climate initiatives beyond current

[35] Based on data from the EIA, U.S. Energy Information Administration

[36] IEA: International Energy Agency

[37] EPA: (U.S.) Environmental Protection Agency

[38] See [78], p. 57 and 62. The 2010 edition includes a projected population growth of 0.9 % and a GDP growth of 3.2 % between 2008 and 2035 (no specific 2030 data available). See [20], p. 65 and 68.

[39] IPCC: International Panel on Climate Change

Organization	Source	2005 emissions Mt CO_2(e)	2030 emissions Mt CO_2(e)	Growth %
CAIT: EIA - reference	[69]	28.2	40.6	44
CAIT: EIA - low	[69]	28.2	38.5	37
CAIT: EIA - high	[69]	28.2	44.4	57
WEO 2007+2009	[67], [78]	26.6	40.2	51
WEO 2007+2010	[67], [20]	26.6	40.0	50
WEO 2007+2010	[67], [20]	26.6	35.1	32
EPA: non-CO_2 gases	[68]	10.2	15.3	50

Table 2.5.: *2005 and 2030 projections on global CO_2 emissions from various sources for the energy sector (EIA, IEA World Energy Outlooks (WEO) 2007, 2009, 2010) and non-CO_2 greenhouse gases (EPA, 2030 numbers own calculation based on 2020 EPA projections).*

policies [81].
According to it, global GHG emissions in 2030 will be in the range of 50–77 Gt CO_2e [82], in accordance with our estimate above[40]. IPCC assumptions on population and GDP growth are comparable to IEA [78] [20] and EIA [80] reports: for 2030, the median of population projections lies at 8 billion [83], and GDP growth projections range from 0.9% to 3.3% [83][41].

Being the only sources that gives a holistic picture for 2030, the updated version of the report *Pathways to a low-carbon economy* [76] [77] estimates global GHG emissions in a "Business-as-Usual" scenario at 66 Gt CO_2e, an increase of 45 % over 2005 levels – a number in line with the range spanned by the IPCC and in well acordance with our estimate based on the EIA and IEA data from table 2.5. Figure 2.7 shows how the 2030 emissions split by region and sector:

- *Regional split.* The trend of rising emissions in Asia is epxected to persist: by

[40] While the high end of this range represents scenarios that involve rapid economic growth powered by fossil fuels, or a less-globalized world with strong population but lower economic development, the low end links to scenarios that see the world move quickly to a global society focused on services, sustainability and clean energy, or towards a world of again high population growth and less globalization, but locally environment-concious communities (see [81] for a detailed description).

[41] However, IPCC GDP growth rates are at market exchange rates, not corrected for purchasing power parity, which tends to understate economic activity in developing countries where the same amount of a given currency buys more goods than in developed economies. Compare for example pages 160 and 161 in [80]: at market exchange rates, world GDP growth falls from 3.4% to 2.8%.

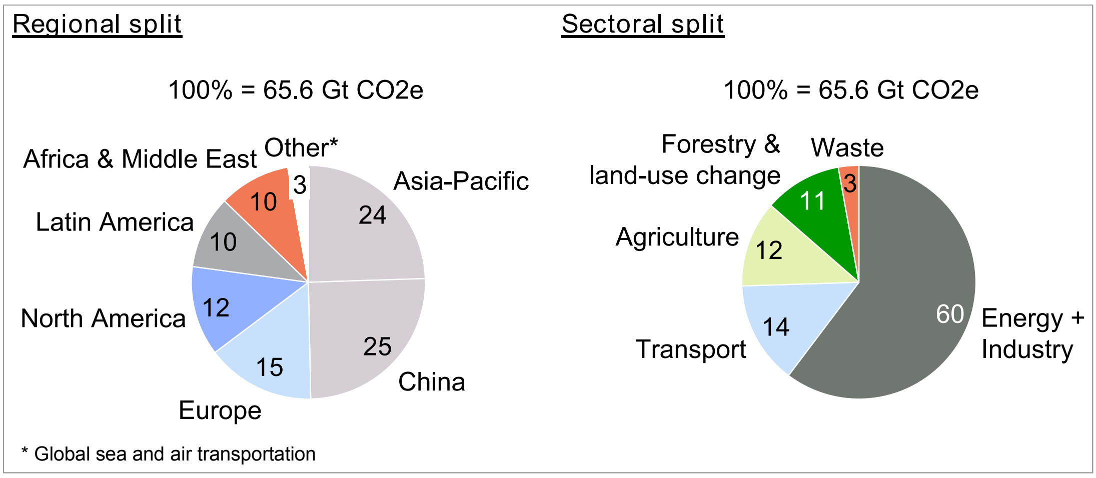

Figure 2.7.: *From [76]. Projections on global GHG emissions 2005 – 2030, and 2030 regional and sectoral split.*

2030, the Asian-Pacific region (without China and the Middle East) is projected to account for 24% (up from 22% in 2005, see figure 2.5), and China for 25% (17% in 2005) of total emissions. All other world regions are expected to have a lower share of global emissions, albeit total levels might still rise.

- *Sectoral split.* Energy and the industrial sectors account for most of emissions in 2030, with 60% (up from 58% in 2005), followed by transportation, agriculture, forestry and waste, which rise in line with global emission levls.

Underlying this data are GDP growth and energy price assumptions from the 2009 edition of the World Energy Outlook [78] (on average 3.1% GDP growth 2005–2030, oil price of 115 USD per barrel ([76], p.7)) and a world population that is expected to grow by 0.9% between 2005 and 2030 from the WEO 2007 [67][42].

To summarize, global GHG emissions are expected to rise in all major sources if no action beyond current policy efforts is undertaken. By 2030, GHG emission levels are estimated to be about 45% higher than 2005, at around 66 Gt CO_2e. This will very likely lead to higher atmospheric concentrations of these gases and increase radiative forcing. Unlike water scarcity, which is a local phenomenon, increasing GHG emissions will have global implications.

[42]The 1997 data differs only slightly from the 2009 and 2010 edition which assume average growth rates of 1.0% and 0.9%, respectively.

2.3.4. Risks and threats of rising GHG emissions

Section 2.3.1 and figure 2.4 (p. 17) showed that atmospheric concentrations of greenhouse gases are rising – CO_2 emissions for example have risen from about 280 ppm to 392 ppm between 1750 and 2011. This is expected to have an influence on global climate, of which global mean temperature is one main parameter. Figure 2.8 shows how it has evolved since 1880: overlying the yearly fluctuations, a move towards higher temperatures is observable [84].

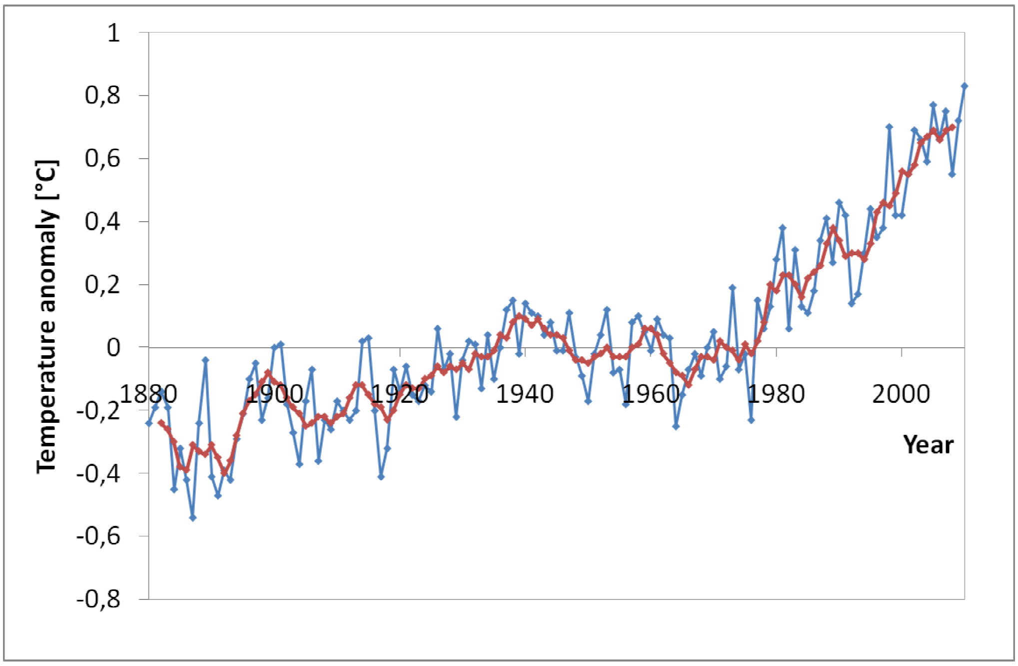

Figure 2.8.: *From [84]. Development of global the mean land-ocean temperature index 1880–2010. The blue line represents the annual mean, the red line the 5-year running mean data.*

Although it cannot be excluded with full certainty that parts or all of the additional GHG emissions will be absorbed in natural processes and emissions levels stabilize, it is assumed more likely that temperatures will continue to rise: according to the IPCC they are estimated to rise by about 0.2°C per decade over the next two decades, based on an assessment of temperature changes over the last half-century [85]. Due to the decade-long atmospheric lifetimes of the most relevant greenhouse gases (see table 2.3), this increase is relatively insensitive to future emission pathways: even if emissions had been kept at 2000 levels, temperature would still rise by 0.1 °C per decade over the next decades [86]. Beyond 2030, the increase in global mean temperature however depends on the chosen pathway. The IPCC high case assumes emissions of 130 Gt CO_2e in 2100, in which case

global mean temperatures are expected to increase by 2.0–6.4°C, with 3.4–4.0°C being the likely range.
In contrast, the temperature could be kept at between 1.8 °C and 2.4 °C if emissions peak by 2030 and decline thereafter [87].
Next to the obvious consequences, rising average temperatures can lead to secondary effects with mostly adverse impacts, such as[43]

- *Rising sea levels.* Melting of glaciers and ice on the (ant-)arctic landmasses, and the expansion of ocean water due to higher mean temperatures will virtually certainly lead to increasing sea levels. This will lead to the inundiation of islands, coastal regions, aggravate damages from floods and reduce water availability through salinization of aquifers. Until 2100, the IPCC scenarios predict a sea level rise of between 0.2 m and 0.6 m, if no corrective climate action is taken [86].

- *Increased frequency of heat waves.* The number of very hot days will very likely increase, reducing quality of life, increasing death risk for older, sick and young persons and leading to reduced agricultural output for some crops due to heat stress.

- *Changing precipitation patterns.* The frequency of heavy rain is very likely to increase over most of the landmass, going along with soil erosion, higher flood risk, decreases in groundwater quality, and increased risk of damages to infrastructure.

- *More and stronger natural disasters.* Both the risk of tropical cyclones and drought are likely to increase, leading, amongst other, to increasing damages to infrastructure, crops, an increased risk of death and injuries and of power outages, an increased risk of food and water scarcity, land degradation and higher migration of populations.

- *Losses in biodiversity.* About 20%–30% of animal and plant species likely face an increased risk of extinction if temperatures increase by 1.5–2.5°C. Beyond 3.5 °C, ecosystems are expected to face major changes with mostly negative consequences on biodiversity: modeling results suggest that 40–70% of species could face extinction under such circumstances.

As mentioned earlier, CO_2 concentration levels and average temperatures have already been much higher than today during the last 500 million years, while the earth stayed habitable [58]. However, these changes occured very slowly compared tp today, leaving

[43] See [49] and [50] for a good overview.

ecosystems time to adapt. Temperature increases of several degree in less than a century most likely never happened before.
Global mean temperatures should not rise by more than 2°C in order to keep the consequences in check, as uncontrollable backcoupling effects might start beyond this threshold [88]: for example, it is expected that the mass balance of the Greenland ice shield becomes negative at a temperature increase greater than 1.9–4.6°C; if that increase persists over longer time spans, the ice shield would disappear, leading to a sea-level rise of about 7 m [87]. Similarly, temperature increases of more than 1–3°C in water temperature will likely lead to bleaching of corals and significant losses in coral reef biodiversity [88].

To keep temperature increases below 2°C, atmospheric CO_2 concentations need to stabilize in the long run at 400 ppm – given that concentrations in 2011 were already 392 ppm (see the graph on page 17), emissions would need to peak before 2015 and subsequently decline. By 2030, CO_2 emissions would then need to be about 20 Gt CO_2 instead of the 40 Gt CO_2 projected in the various "Business-as-Usual" scenarios of table 2.5 [89].
Otherwise, mean temperature increases will be higher: if CO_2 emissions indeed rose to 40 Gt in 2030 and peaked at about 45 Gt in 2050, CO_2 concentration levels would stabilize at 570–660 ppm, likely inducing temperature increases in the range of 4.9–6.1°C [89].

Effors to reduce global GHG emission levels require the concerted action of all nations. While it would certainly not be easy to curb emission levels, chapter 4 will sketch out that sustainable pathways are in principle feasible and overall not more expensive than maintaining conventional patterns.
Before that, however, the following chapter will focus on China and South Africa, the two focus countries of this work, and the projected development of water availability and GHG emissions there.

3. Water and GHG in China and South Africa

After having discussed current and future water availability, water demand and greenhouse gas emissions on a global scale, this chapter aims to give an overview over the specific situation in China and South Africa. Both countries are economies that are expected to experience strong growth over the coming decades. Furthermore, both are major emitters of greenhouse gas emissions, with South Africa being the second-largest African emitter[1] with annual per capita emissions of 9.0 t CO_2e (2005), in the same order as the European Union, and China being the world's largest emitter [4] [69]. On top of this, both already experience water stress today in many of their regions. Thus, the two countries were chosen as case studies as they represent a type of country that faces both challenges in the near future, rising greenhouse gas emissions and increasing risk of water scarcity, and promise to reveal interesting interdependencies.

3.1. Introduction to China

3.1.1. Short country profile

China has the world's largest population with 1.35 billion inhabitants in 2010 [30], and a land area of 9.6 million km^2, the world's fourth-largest [91]. It is divided into 33 provinces, with the largest having populations of more than 100 million – more than any European country except Russia [30].
Due to its size, the Chinese landmass comprises four different climatic zones [92]:

- The South and South-Western parts of the country reaching north to the Yangtze. The mountaineous South-West has a tropical climate in the lowlands and subtropical climate in the highlands and a colder climate on the Tibetean plateau. An almost tropical climate is dominant in the Pearl river basin (comprising cities such as Hong

[1] After Nigeria, which however only has a third of South Africa's per capita emissions (3.2 t CO_2e per capita and year [69]).

Figure 3.1.: *From [90]. Physical and road map of China.*

Kong, Shenzhen and Guangzhou) and the smaller river basins of the South-Eastern coastal region, which are both influenced by monsoon winds. Crossing over to the Yangtze basin, the climate becomes subtropic.
Including the full Yangtze basin, this area includes more than half of China's population [93].

- A large semi-humid zone that stretches north from the Yangtze over the North China plain to the Russian border. It covers a broad band along the East China Sea and the border to North Korea. The climate gradually becomes colder to the North.
- The upper and middle reaches of the Yellow river belong to a semi-arid zone that stretches far into North-Western China.
- The arid western part of China is comprised of the deserts and inland river basins north of the Tibetean plateau.

With respect to its economy, China's real GDP was 3.5 USD trillion in 2010 [43][2], making it the world's third-largest economy [69][3]. GDP growth averaged 9.5% between 2000 and 2010. This strong growth led to an ever-increasing demand for energy: China consumed 2,131 Mt of oil equivalents in 2008, 17% of the world's total [20][4].
Figure 3.2 summarizes population, GDP and energy demand for 2010 and 2030. It is estimated that Chinese population will grow only slightly until 2030, by 0.2% annually, or about 4% in total [30]. In contrast, economic growth is estimated to lead to a more than four-fold increase of real GDP between 2010 and 2030 [43], to 14.5 trillion USD, while energy consumption is seen to increase as well, by 83 % between 2008 and 2030 [20][5].

3.1.2. Water availability in China

China's total renewable water resources are 2,840 km^3 [6], well below the global average of 7,000 m^3 [95] according to FAO-AQUASTAT data[7] [93].

[2] In 2005 USD
[3] In terms of purchasing power parity, China's GDP was 10.1 USD trillion (2010), second only to the United States [94].
[4] See [20], p. 618.
[5] "Current Policies Scenario" of the WEO 2010, i.e., assuming no further (environmental) policies beyond current ones that could lead to reduced energy demand.
[6] Or 2,105 m^3 per capita (2010), using the United Nations population statistics cited above [30].
[7] FAO: Food and Agricultural Organization of the United Nations: AQUASTAT is FAO's information database on water and agriculture.

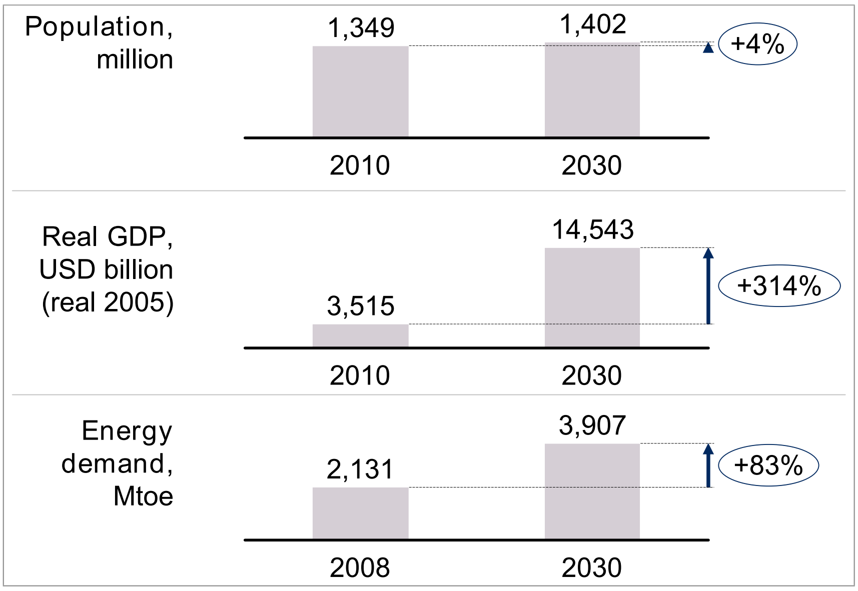

Figure 3.2.: *Projected growth of Chinese population, Gross Domestic Product (GDP) and energy consumption 2005/2008–2030. (See text for sources.)*

Assuming that all this water was available for human use and equally distributed, China would not experience water stress per se according to the Falkenmark index (see Chapter 2.2.1, p. 6), which sees water stress occuring at per capita per year water availabilities of less than 1,700 m^3 [33].

Water availability however varies widely given China's geographic and climatic heterogeneity: while coastal regions in the South receive more than 2,000 mm of precipitation annually, and the areas south of the Yangtze basin still more than 1,000 mm, rainfall is between 400–900 mm in most of the semi-humid zone north of the Yangtze. In the West, precipitation falls below 400 mm per year[8] [93].

As a consequence, river basins in the southern part of the country, including the Pearl and Yangtze and South-Eastern coastal rivers and the Tibetean plateau command internal renewable surface water resources of 2,176 km^3, whereas the basins north of the Yangtze only dispose of 535 km^3 according to the FAO [93][9] [10]. Dividing these resources by the respective population (south: 53.6 %, north: 46.4 % of total [93]) allows to estimate per

[8]For comparison, average precipitation in Germany is 700 mm per year [96].

[9]The sum of China's surface water resource, 2,711 km^3 is lower than the total renewable water resources, which also accounts for groundwater, for which, unfortunately, no basin split was available in the studied sources.

[10]It has to be noted that this data is larger than the 2,376 km^3 of total surface water resources communicated for 2007 in the annual report of the Chinese Ministry of Water Resources [97] which however does not provide more detailed data splits.

capita water availabilities for the two parts of the country, which are 3,010 m^3 in the south and 855 m^3 in the north[11].

2005 and 2030 water supply and demand

Table 3.1 summarizes current and projected data on water withdrawals and renewable water sources for China.
In 2005, it withdrew 554 km^3 of water for human uses according to FAO-AQUASTAT. Of these, 358 km^3 were for agricultural purposes, 68 km^3 for domestic and 129 km^3 for industrial purposes [93]. Other sources give comparable numbers. The Chinese Ministry of Water cites 2007 withdrawals of 579 km^3 in its 2008 report on water resources [97], and an older source, UNESCO's International Hydrological Programme (1999) determined 1995 withdrawals at 526 km^3 [22].

Measure	**Value**, km^3	**Institution**		**Year**
Water resources	2.840	FAO-AQUASTAT	[93]	2010
W. 1995	526	UNESCO IHP	[22]	1999
W. 2005	554	FAO-Aquastat	[93]	2010
W. 2005	555	Water Resources Group	[5]	2009
W. 2007	579	Chinese Water Ministry	[97]	2008
W. 2025	764	UNESCO IHP	[22]	1999
W. 2025	527–740	IWMI	[98]	1998
W. 2030	818	WRG	[5]	2009
Potential S.	873	IWMI	[99], [95]	2001
S. 2030	619	WRG	[5]	2009

Table 3.1.: *China's renewable water resources, withdrawals (W) and supply (S) between 1995 and 2030 according to various sources, and year of publication.*

The 2009 report by the Water Resources Group estimates 2005 water withdrawals at 555 km^3 [5] (p. 57). This report will be of special importance for our purposes: next to projecting China's withdrawals until 2030, aggregated from more detailed data sets of China's ten major river basins, it quantifies the incremental water availability potential and cost of a whole set of options to increase water availability.
Chinese water withdrawals will increase by 1.6% annually and reach 818 km^3 in 2030 according to this report. Of these, 420 km^3 will be used in the agricultural, 265 km^3 in

[11] Please note that these numbers neglect renewable underground water supplies and should thus only be considered as order-of-magnitude estimates.

the industrial, and 133 km^3 in the domestic sector[12].
Forecasts from other sources for comparison are difficult to find. UNESCO's International Hydrological Programme [22] (1999) estimated 2025 withdrawals of 764 km^3, while a 1998 report by the International Water Management Institute (IWMI) projected 2025 withdrawals of between 527 km^3 and 740 km^3 [98] (p. 33), lower than the other sources. However, industrial and domestic withdrawals were assumed to be 128 km^3 combined in 2025, a value already achieved in 2005 according to [5], [93].

The left part of figure 3.3 follows the same logic as the global water supply-demand graph (figure 2.2, page 12) and contrasts projected withdrawals for 2005 and 2030 from [5] with the *sustainable, renewable* and *accessible* water supply for 2030.
It can be seen that a national water gap of 201 km^3 opens until 2030, with eight out of ten basins running a deficit (see right part in fig. 3.3); the relative size of the gap varies in dependence of the local value of the climatic and social drivers described above: the gap is estimated to be largest in the dry but densely populated Hai basin around Beijing, the Yellow river (Huang) basin, the Yangtze basin, and along the south-eastern coast, wheras the humid South-West and the cold Song basin are not expected to experience water gaps by 2030.

In addition to the looming gap in the supply of bulk water, China faces water quality issues. The 2008 report of the Ministry of Water on the state of domestic water resources acknowledged that 40% of rivers, 51% of lakes and 63% of the monitored groundwater wells were not fit for drinking even after treatment [97]. Furthermore, 11% of the population did not have access to safe drinking water, and 45% could not use improved sanitation facilities in 2008[13] [25]. The low levels of water quality and availability are furthermore threatened through environmental accidents. In 2011 alone, Circle of Blue, an international network of water journalists and researchers, counted 11 reports on water pollution events large enough to receive international attention [100]. Amongst these were cases of water contamination from chemical plants and textile mills, or rice poisoned with heavy metals from mining and industrial sewage[14].

[12]Underlying this projection is a population increase from 1.28 billion in 2005 to 1.46 billion in 2030, which lies between the 2030 UN medium case projection of 1.40 billion and its high case estimate of 1.48 billion [30]. GDP is estimated to grow to 13.8 USD trillion, slightly less than 14.5 USD trillion cited in figure 3.2.

[13]Access to safe drinking water is defined as a protected water supply, e.g., a household connection, protected spring or well (see [25], p. 230). Improved sanitation requires the connection to a public sewer or septic system, or at least a simple pit latrine (see [25], p. 241).

[14]Reports on incidents can also be found in [101].

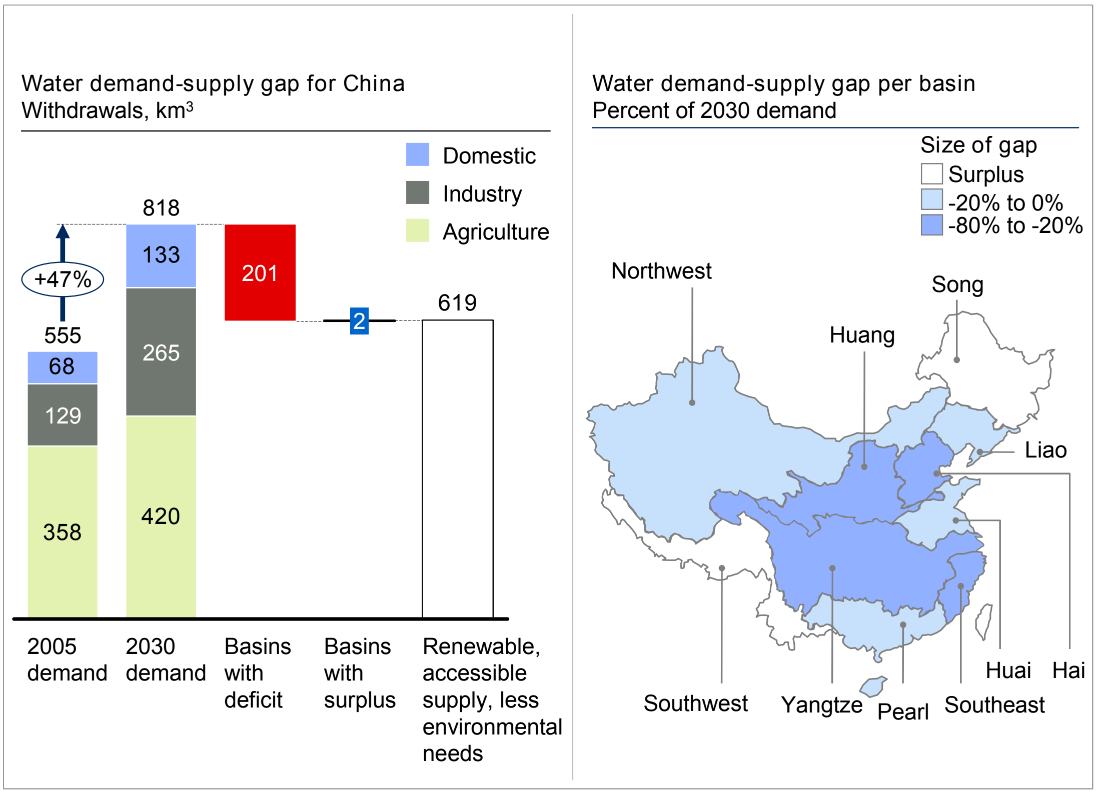

Figure 3.3.: *From [5]. Left part: Chinese water demand-supply in a Business-as-Usual scenario for 2030. Right side: Chinese map showing the ten basins differentiated in [5] along with their relative gap (ratio of unsatisfied demand to total demand in 2030).*

3.1.3. Evolution of greenhouse gas emissions

2005 emissions

In 2008, China still needed more than five times as much energy per unit of GDP than the United States, and about ten times more than Japan[15] [69] – given that China received 83% of its energy from from coal and oil in 2008, compared to 61% for the United States and 52% for the European Union [20], it is not surprising that it became the world's largest emitter of greenhouse gases in 2005 [69].

According to data assembled by the World Resources Institute [69], China emitted 7.2 Gt of CO_2e in 2005[16], 17% of the global total (see figure 2.5, page 19). Similar numbers are provided by the 2010 update of the report *Pathways to a low Carbon Economy* [4],

[15] Tonnes of CO_2 emissions per 1 million of GDP.

[16] As already discussed in section 2.3, 2005 is to our knowledge the latest year of publicly data available for holistic data covering all greenhouse gases and sectors.

according to which 2005 emissions reached 7.5 Gt CO_2e [76].
Figure 3.4 compares the two sources and gives a sectoral split which shows that numbers are in good accordance: total emissions for example differ by only 4%. Compared to the global average, energy and industry account for a larger share of emissions (78%/5.6 Gt CO_2e [69] and 76%/5.7 CO_2e [76], respectively, versus 58% globally), followed by agriculture. Transportation in contrast accounts for less than half the share of global emissions (5% in China, vs. 12–13% globally), whereas the waste sector is only slightly smaller than in the global case. Emissions from forestry and land-use change only play a negligible role in China (versus 16% on global scale [76]) – according to [69], emissions from this sector are in fact negative in China, very likely driven by afforestation programs that act as a carbon sink [102] [103].

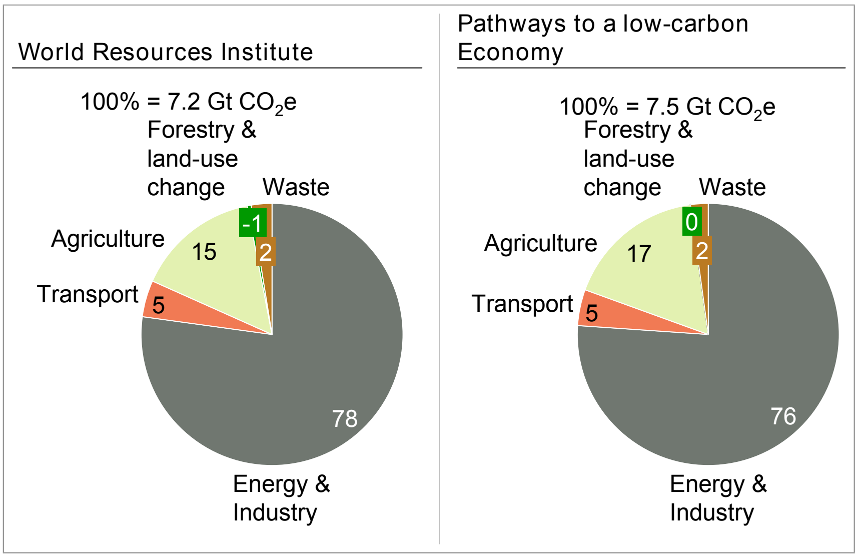

Figure 3.4.: *2005 Chinese GHG emissions by sector based on two sources [69], [76].*

Other sources confirm these numbers. For example, energy-related emissions in 2005 were 5.1 Gt CO_2, according to the 2007 World Energy Outlook [67], 5.5 Gt CO_2 according to the EIA's International Energy Statistics [66], and 5.9 Gt according to a recent study by the Lawrence Berkeley National Laboratory [104].

2030 emissions

The estimates for China's 2030 energy demand in figure 3.2 already indicate that GHG emissions can be expected to rise if no corrective action is undertaken. Indeed, the 2010 World Energy Outlook estimates energy-related CO_2 emissions of 11.7 Gt CO_2

by 2030e [20][17], up from 5.1 Gt CO_2 in 2005 in its *Current Policies* scenario[18], while the EPA report on anthropogenic non-CO_2 Greenhouse Gas Emissions 1990-2020 [68] projects 1.6 Gt in 2005 and 2.0 Gt CO_2e in 2020 for China[19] – extrapolating this number under the assumption of constant growth rates would yield 2.3 Gt CO_2e for 2030.

This data allows to give a first back-of-the-envelope estimate of China's 2030 GHG emissions for a Business-as-Usual scenario:
At about 12 Gt CO_2 of energy-related emissions, about 2 Gt CO_2e of non-CO_2 emissions, and one additional Gigaton of CO_2 emissions from non-energy sources[20], China's 2030 GHG emissions should be in the order of 15 Gt CO_2e[21].
The 2010 update of the report *Pathways to a low-carbon economy* projects 2030 GHG emissions for China, in a Business-as-Usual scenario, of 16.7 Gt CO_2e [76][22] – an increase of 122% over 2005 levels. Figure 3.5 shows how emissions develop for the different sectors: by 2030, the energy and industrial sector still account for the largest share, with 13.1 Gt CO_2e (or 79%), followed by the transportation sector (11%), agriculture (9%) and waste (1%). Again, emissions from forestry and land-use changes are projected to be negligible. Figure 3.5 also shows that transportation is the fastest-growing sector, followed by energy. This seems plausible given China has the potential for a lot of catching up: passenger car density was only 27 per 1,000 inhabitants in 2008, compared to 451 for the United States [105]. Similarly, per capita power consumption was only 2.6 MWh in 2009, versus 12.9 MWh in the United States[23] [106]. Given China's high growth rates, these differences can be expected to become smaller over the next two decades, leading to increased emissions from these sectors.

To conclude, it seems likely that China will have cemented its position as the world's

[17]See pages 672-673.

[18]The 2005 number is from the WEO 2007, as not reported in the 2010 edition. 2030 numbers assuming an annual average GDP growth of 5.7%, and a population growth of 0.3% between 2008 and 2030 for China [20] (See page 65).

[19]Assuming a GDP growth of 7.0% 2001–2020 [68], p. 7-29, or 1.4 % annually.

[20]IEA and EPA neglect non-energy CO_2 emissions, which were 485 Mt CO_2e in 2005 [69]; extrapolating these in proportion to energy-related CO_2 emissions 2005–2030 based on the [20] yields 1.1 Gt CO_2.

[21]One of the main drivers are of course the underlying assumptions on economic growth: given that Chinese GDP has grown by 9.5% between 2000 and 2010, and is projected in some sources to grow by 7.4 % until 2030 [43] (see figure 3.2, page 31), a 5.7% growth rate as used in the WEO might be regarded as conservative. An alternative high-growth (7.5 % annual GDP increase 2005–2030) emission scenario is given in the 2007 edition of the WEO, estimating energy-related CO_2 emissions of 14.5 Gt in 2030 (instead of 11.7 Gt) [67].

[22] [76] uses the slightly higher annual GDP growth rate of 5.9% from the 2009 World Energy Outlook [78].

[23]Including also industrial uses.

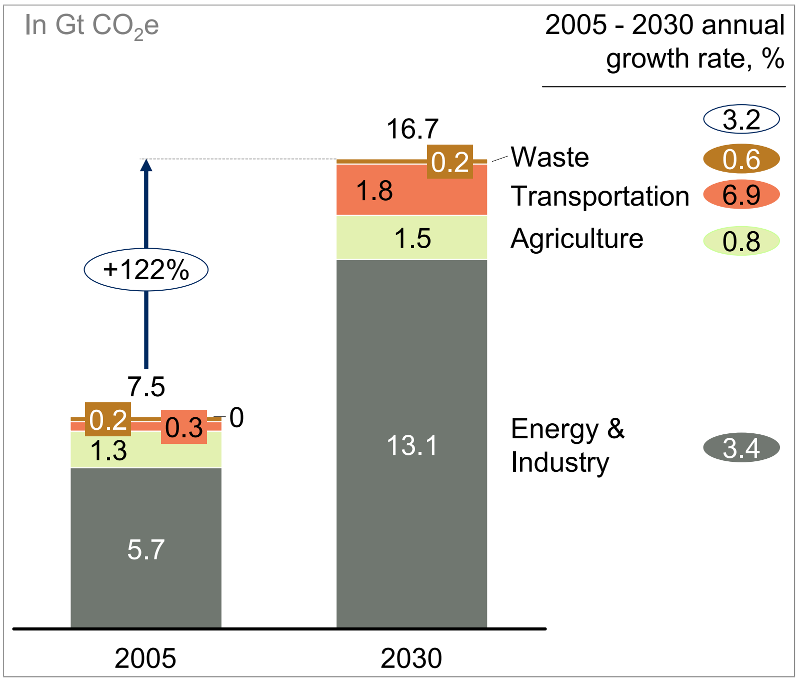

Figure 3.5.: *From [76]. 2005 and projected 2030 GHG emissions for China by sector.*

leading producer of greenhouse gases by 2030. A stabilization of atmosheric concentrations of greenhouse gases at levels low enough to avoid an increase in global mean temperature beyond 2°C will then be difficult to achieve without China's participation.
On the other hand, substantial efforts and investment will be needed to improve China's water quality and to close the water gap.
Reassuringly, enough solutions to address these issues already exist today. After a discussion of South Africa on the following pages, which will show that this country faces the same challenges as China, Chapter 4 will show that increased water availability and lower GHG emissions can indeed be achieved at controllable cost.

3.2. Introduction to South Africa

3.2.1. Short country profile

South Africa's modern history is influenced by the concurrence of its indigenous population and European settlers from mainly Dutch and English background from the late 1600s on. With formal independence from the United Kingdom in 1948, a system of Apartheid was successively implemented that aimed at separating ethnic groups, and that lasted

Figure 3.6.: *From [90]. Physical and road map of South Africa.*

until 1994.
South Africa is the southermost and with 1.2 million km^2 the eigth-largest country on the African continent [91]. In 2010, it had a population of about 50 million [30]. The largest share of the land area is covered by a high plateau with heights of 2,400 m in the east, and dropping to 600 m in the Kalahari desert in the west. The southern end of this plateau is marked by a mountain ridge that reaches heights of more than 3,300 m and runs from the border with Mozambique in south-westward (and later westward) direction, leaving only a narrow coastal plain along the Indian Ocean [107]. Based on this topography, South Africa can be divided into three climatic zones [107]:

- The eastern part of the country on the plateau. Annual precipitation reaches 500 mm and more, and vegetation ranges from grassland in the higher reaches to forest at altitudes.
- The dry western parts of the plateau. Here, precipitation levels are 100–500 mm annually, and vegetation is dominated by meager grassland or short shrubs.
- The coastal region around the Cape and along the Indian Ocean coast, with a Mediterranean climate and annual rainfalls of 300–900 mm.

Due to the low rainfall levels, 65% of the land can only be used as grazing land or need irrigation for growing crops.
About half of the land area and most of the country's central parts are drained by the Orange river, which joins the Atlantic Ocean on the border to Namibia. Amongst its tributaries is the Vaal river system, which drains parts of the densely populated region around Johannesburg. The Limpopo system drains the northern part of the country (14 % of land area) to the Indian Ocean, and smaller rivers that join the Indian and Atlantic Ocean on direct path from the mountain ridge drain further 38% of the country [107].

South Africa is the largest economy in Africa, with a GDP of 279 USD billion in 2010[24] [108] and one of the world's largest mining nations [109]. Partly because these industries require large amounts of energy, South Africa has one of the highest per-capita energy and GHG intensities of Africa – per-capita GHG emissions were 9.2 t CO_2e in 2005, in the same order as in France or Italy [69].
Figure 3.7 summarizes 2010 data on population [30], real GDP [108] and energy demand [110], and contrasts it with projections for 2030 (from the same sources): while population levels will increase only slightly, both GDP and energy demand are expected to more

[24] At market exchange rates and in 2005 dollars.

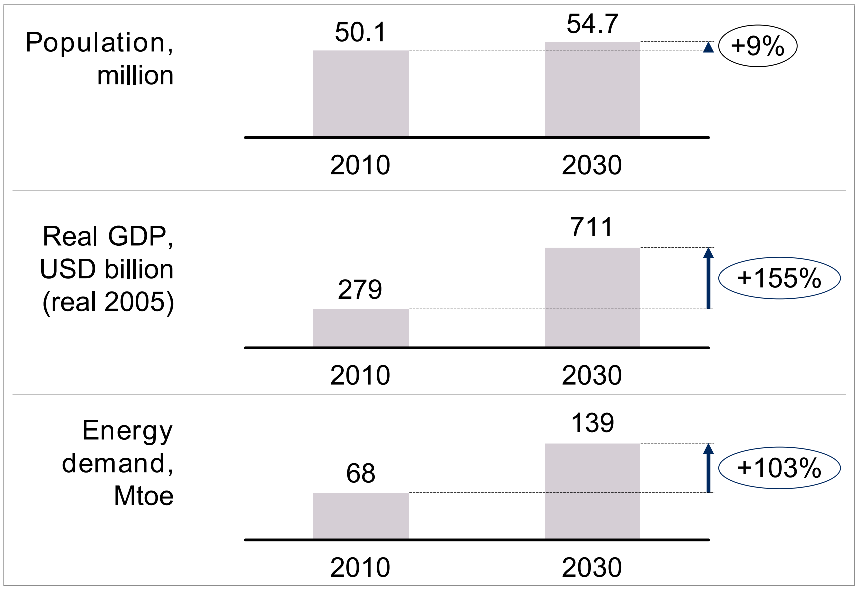

Figure 3.7.: *Projected growth of South African population, real Gross Domestic Product (GDP) and energy consumption 2010–2030. (See text for sources of data.)*

than double. For the latter, a Business-as-Usual scenario without major policy changes is again taken as basis[25].

3.2.2. Water availability in South Africa

South Africa has annual renewable water resources of 50 km^3 according to FAO-AQUASTAT [111] – at a population of 50 million, this gives 1,000 m^3 per capita and year, at the border to physical water scarcity according to the Falkenmark index [33], and well below the global average of 7,000 m^3 [95].

2005 water supply and demand

About 5 km^3 of the 50 km^3 are groundwater, and 45 km^3 surface water; FAO estimates that the majority of these resources is lost to human uses through evaporation and flood spillage, and that 10 km^3 are required for environmental needs – all in all, only 13.9 km^3 are estimated to be available for human use [111], of which 13.3 km^3 were indeed used in 2000 across the different sectors.

[25] Termed *Current Development Plans* in the 2007 report on South Africa's long term mitigation potential in GHG emissions for the Department of the Environment [110]. This report is still South Africa's most comprehensive and accepted data source in climate/energy research.

Comparable numbers come from the 2004 *National Water Resources Strategy* published by the Department of Water Affairs [112], which gives a water demand for 2000 of 12.9 km^3 [26], while the Water Resources Group report [5] estimates 2005 water withdrawals at 13.4 km^3.
Table 3.2 gives the sectoral split of water requirements for all three sources, which shows that the data are in good accordance.

Source	**FAO [111]**	**DWAF** [112]	**WRG** [5]
Year of data/report	2000/2012	2000/2004	2005/2009
Irrigation	7.8	7.9	7.9
Municipal	3.9	3.5	3.5
Power gen. + industry	1.1	1.1	1.5
Afforestation	0.5	0.4	0.5
Total	13.3	12.9	13.4

Table 3.2.: *All data in* km^3. *2000 and 2005 water withdrawals for South Africa by sector from three sources.* Municipal *includes water requirements in commercial buildings and non-bulk industry, e.g., manufacturing, in [111] and [112].*

2030 water supply and demand

Two sources provide estimates on future water withdrawals for South Africa.
UNESCO's International Hydrological Programme [22] gives 2025 withdrawals of 18.6 km^3, but already dates back to 1998. The Water Resources Group report [5] projects 2030 withdrawals to reach 17.7 km^3. As in the case of China, [5] estimates demand for a hypothetic Business-as-Usual scenario under the assumption that adequate water resources are available for unconstrained growth (of GDP, population, standards of living), and contrasts this number with an estimate of the accessible, reliable and sustainable supply (less environmental requirements) for 2030, which is estimated at 15.0 km^3, slightly higher than the 13.9 km^3 mentioned in [107]. Therefore, a national water gap can be expected to open over the coming two decades, similar to the China case[27].
The water gap will again not be distributed evenly across the country, as the right part of figure 3.8 indicates: albeit its higher precipitation levels, the eastern part of the country

[26] Unfortunately, no newer data is available in the established literature. E.g., [25] (2011) also cites the FAO 2000 number, as does the World Bank, which states that 2009 withdrawals remained unchanged at 12.5 km^3 [113].

[27] Looking back at equation (2.1) (page 8), this means that South Africa will have a Water Stress Indicator > 1 in 2030.

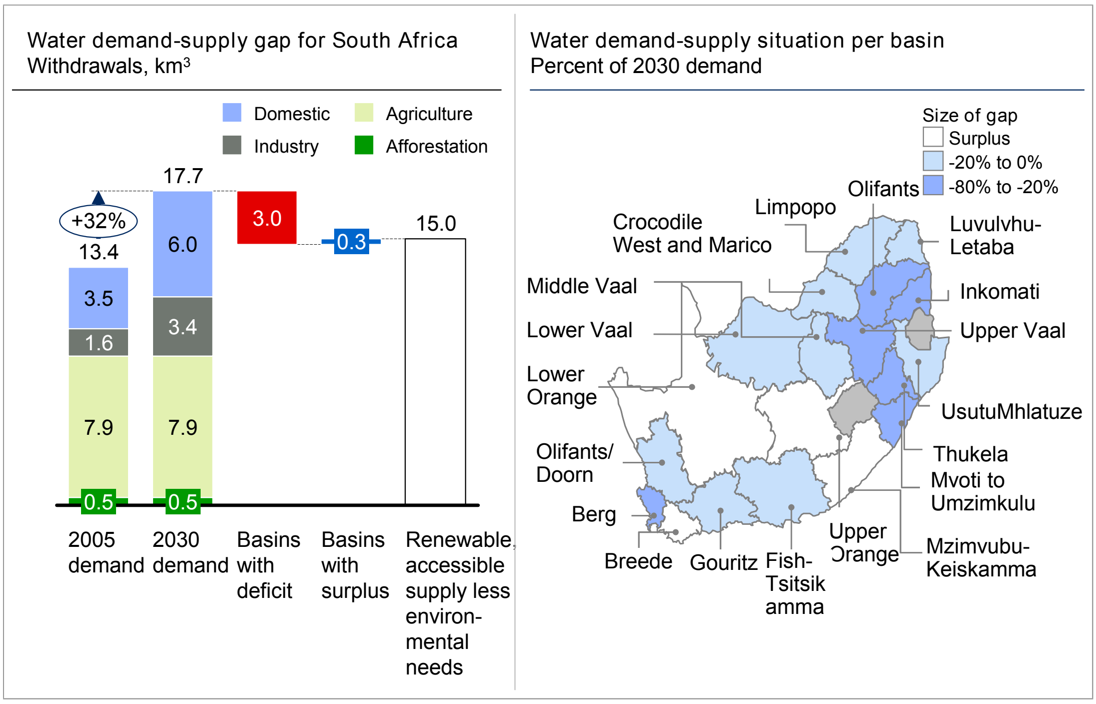

Figure 3.8.: *From [5]. Left part: 2005 and 2030 water demand for South Africa in a* Business-as-Usual *scenario, available supply today, and the national demand-supply gap. The right side shows the water gaps for the 19 Water Management Areas (WMAs).*

and the Cape region is expected to experience higher levels of water stress than other regions. One reason is the higher population density in the agglomerations of Cape Town (situated in the *Berg* area in figure 3.8), Durban (Thukela) and Johannesburg (Olifants and Upper Vaal) compared to the rest of the country. Moreover, the majority of South Africa's power plants and industrial sites is located in these regions, driving up water demand further[28].

Compared to China, which is subdivided into the ten river basins (see figure 3.3), South Africa is divided more granuarly into 19 *Water Management Areas* (WMAs) shown on the right side of figure 3.8. These were established by the government in 1999 in order to simplify the management of the national water resources [114]. The Water Resources Group report [5] and this work follow this division.

[28]See figure 7.14, 137, which gives a map of South Africa, showing the distribution of industrial activities.

3.2.3. Evolution of greenhouse gas emissions

As mentioned above, South Africa is Africa's leading economy and one of the world's largest mining nations: it is world leader in platinum mining, hosts the world's largest gold reserves [115] and is the 7th largest coal miner[29]; however, it exports only 27% of that coal, using the remainder for its own market. It is thus not surprising that South Africa receives 77% of its energy from coal [74].

2005 emissions

Energy-related CO_2 emissions were 331 Mt in 2005, and 337 Mt in 2008, according to the World Resources Institute [69]. As in China, the energy sector accounts for the majority of South Africa's overall greenhouse gas emissions, as figure 3.4 shows: according to both the World Resources Institute [69] and the report *Pathways to a low-carbon economy* [76], it was responsible for about three quarters of emissions, followed by transportation and agriculture with roughly a tenth of total emissions each, and the waste sector with 5% – total 2005 GHG emissions are given at 423 Mt CO_2e [69] and 416 Mt CO_2e [76] respectively. South Africa's Energy Research Centre on Long-Term Mitigation Scenarios [110] confirms this order, and gives GHG emissions of 450 Mt CO_2e for 2005.

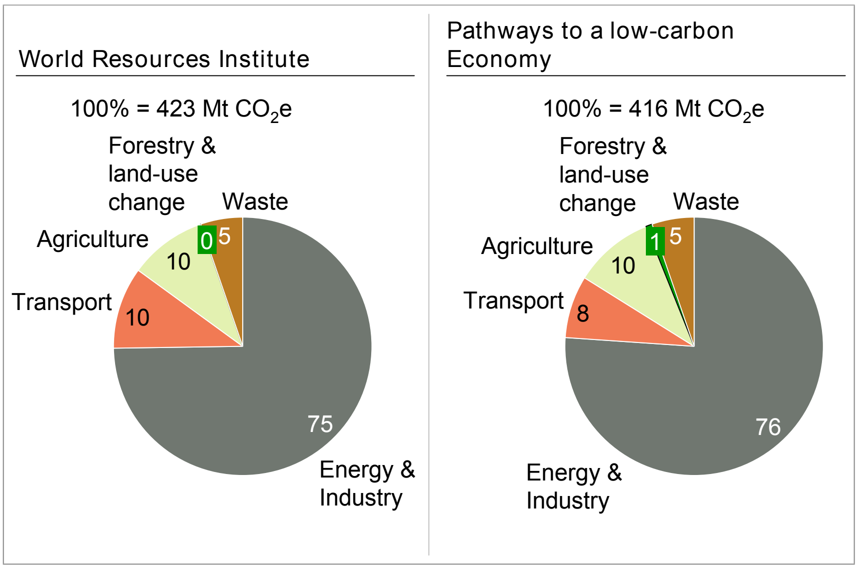

Figure 3.9.: *Comparison of 2005 South African GHG emissions from [69] and [76].*

[29]With a production of 280 million tons in 2009 [74].

While the share of energy-related emissions is roughly the same as in China, differences arise for example in the transport sector, which was notably smaller in China (5 % in 2005, see figure 3.4, p. 35). This is not surprising, given a passenger car density of 98 vehicles per 1,000 people in South Africa's versus 15 in China (2005) [105].

2030 emissions

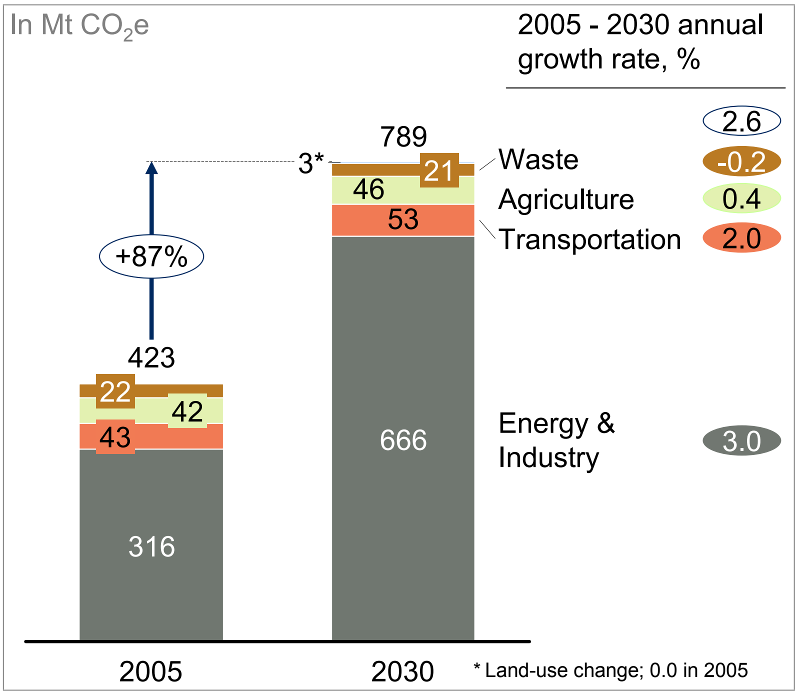

Figure 3.10.: *2005 and projected 2030 GHG emissions for South Africa by sector.*

Regarding overall GHG emissions, figure 3.7 (page 40) indicated that South Africa's energy demand is expected to double between 2010 and 2030, which is expected to lead to an almost doubling of energy-related GHG emissions, from 330 Mt CO_2 in 2005 to 640 Mt CO_2e in 2030 according to a report by the Stockholm Institute [116].
South Africa's Energy Research Centre Long Term Mitigation Scenario (LTMS) report provides two Business-as-Usual scenarios: one, which assumes unconstrained growth (*Growth Without Constraints*), gives 2030 emissions of about 950 Mt CO_2e [110] (p. 49 f), whereas a regulation according to current policies (*Current Development Plan*) leads to emissions of 885 Mt CO_2e in 2030 [110] (p. 53 f)[30].
Based on these sources, the report *Pathways to a low-carbon economy* [76] and further data points [117], this thesis estimates 2030 GHG emissions of 789 Mt CO_2e, an increase

[30] Underlying this estimate is an average GDP growth of about 5% (see p. 25 of the report [110]).

of 89% over 2005 levels (or 2.6 % annually)[31]. Appendix B gives a full derivation for these emissions. To summarize shortly the reasons and adjustments: [76] gives notably lower 2030 emission levels for the Business-as-Usual scenarios than the LTMS report [110]. In particular, emission data for the power and industry sector seemed too low compared to other sources [110], [117] and were adjusted upwards.
Figure 3.10 shows how emissions split up between sectors: energy and industrial emissions are expected to grow strongest, to 666 Mt CO_2e or 84% of the 2030 total. Transportation is estimated to overtake agriculture as the second-largest emitter, accounting for 53 Mt CO_2e (7% of total), while emissions from the waste sector are projected to decrease over the next two decades.

All of the consulted sources estimate that South Africa's GHG emissions will increase steeply in the current policy regime, with most of the increase expected to come from the burning of fossil fuels in power generation, industry and transportation. However, such a correlation does not need to be imperative: the examples of Japan or Switzerland show that high GDP levels can also be achieved (and sustained) with significantly lower emissions, as both countries have a GDP emissions intensity which is only one tenth South Africa's [69].
South Africa therefore faces similar challenges as China: it needs to close a water gap and – ideally – reduce its relative GHG emissions simultaneously. Options to address both problems without a loss of wealth exist, and are often even profitable from indivdual standpoints. The following chapter focuses on these mitigation options.

[31] Of the major sources used, [76] and [117] assumes a growth rate of 3.7 %, whereas [110] estimate a rate of about 5% annually.

4. Towards increased water availability and reduced greenhouse gas emissions

The preceding two chapters described how water demand and greenhouse gas emissions are likely to evolve in so-called *Business-as-usual* scenarios, i.e. under the assumption that current policies rest in place and no additional efforts are undertaken. In this case, both water demand and GHG emissions are very likely to grow over the next decades on a global scale as well as in our two focus countries China and South Africa.
While a water gap will have an immediate impact only on the affected region, rising concentrations of greenhouse gases are a problem of global scale. Their consequences, such as rising sea levels or an increased frequency of natural disasters, materialize over time spans of several decades and will eventually affect most of the world's regions.
It is likely that both China and South Africa will be among the countries that experience both the consequences of increasing water scarcity and climate change. The two countries should thus start to implement strategies that mitigate both problems.
This chapter will discuss options for both increased water availability and reduced GHG emissions. As will be seen, solutions exist and range across all sectors, from the accelerated implementation of high-technology options as well as changes in agronomy practices, and from ones with a net economic benefit to relatively expensive solutions.

4.1. Mitigating water stress

The water gaps discussed in the last chapter took as a basis on the one hand that demand developed at historic rates, without additional efficiency improvements, and on the other hand that supply stayed at current levels. This is of course a hypothetical picture: water stress will ultimately lead to more efficient water uses, more water re-use, and increasing supply infrastructure.
Efforts to secure water availability are already under way. The Three Gorges Dam on the

upper reaches of the Yangtze river in China not only produces electricity with its 18 GW installed capacity, but also regulates water levels and availability downstream [118]. In the arid north, companies that want to tap into water resources are required to become as water-efficient as possible, and procure remaining needs through a water trading program that frees water resources from agriculture through increased irrigation efficiency [119]. Such efficiency increases indeed led to reduced per capita water withdrawals in China, which fell from 490 m^3 in 1960 to 433 m^3 in 1960 [22] [5]. In parallel, China participated – and continues to do so – in extending supply: between 1950 and 2000, half of the world's large dams[1] have been built in China [48]. Other major infrastructure projects include the North-South transfer scheme, which, upon full completion (by 2050), will pipe almost 45 km^3 of water per year in three branches from the Yangtze to the Yellow and Hai river basins [92][2].

For South Africa, the Food and Agricultural Organization of the UN estimates that supply from surface water could be increased by 5.6 km^3, from 13.9 km^3 today[3] [107]. By this, the country's dam capacity would likely grow beyond the 30.5 km^3 installed today [107], already more than twice 2005 withdrawals[4]. In contrast, 1.0 km^3, or 7 % of withdrawals, were lost in 2005 due to leakage [5] – fixing these could increase water availability in a presumably cheaper and environmentally less invasive way than new dams.
Other means to increase water availability are under exploration, such as mine water treatment in the Olifants basin [121] [122] or desalination of industrial wastewater for use in power stations [123]. Furthermore, Eskom, South Africa's state-owned power utility, only plans with dry-cooled coal power stations for the future [117]. These require only a fraction of the water of wet-cooled units[5]

The options to close a water supply–demand gap can generally be arranged in four groups:

- *Increase supply.* Infrastructure that either increases accessible supply in absolute terms, or makes it more predictable. Includes for example dams, water transfer schemes, pumping stations, desalination.

[1] With dam heights exceeding 15 m.
[2] The question remains, though, whether the transfer scheme will solve the water availability problem and not only move water from one water-scarce basin to another: figure 3.3 (page 34) showed that both the Yangtze, Hai and Yellow river basins are expected to experience a substantial water gap by 2030.
[3] Note that [5] cites a accessible, renewable and environmentally sustainable supply of 15.0 km ^{3}.
[4] Which is above the global average: in 2010, the world's dam capacity was about 6,000 km^3 [120], versus withdrawals of 4,500 km^3 [5]
[5] See also section 5.2.1, page 68ff.

- *Reduce demand.* Technologies, appliances or solutions in industry or the municipal space that reduce water demand for a given task. This includes, for example showers that are equipped with water-saving spray nozzles or power plants that are cooled with air instead of water. In agriculture, drip irrigation reduces water needs while preserving crop output.

- *Increase yield (in agriculture).* Higher crop yields with the same amount of water. For example, planting of sorts of rice that give the same yield per area with less water.

- *Reduce losses.* Infrastructure improvements that avoid loss of water on its way from source to consumer such as the repair of leaks in water networks or the revetting of irrigation channels with a watertight material to reduce seepage.

In both China and South Africa efforts were made to recommend actions and develop priority lists towards the mitigation of water stress: the Chinese Ministry of Water Resources published its perspective on the current and projected water situation and development priorities in its latest Annual Report (2007-2008) [97]. In South Africa, the National Water Resources Strategy from 2004 [112] provided a comprehensive picture on the country's water situation and asked for specific sectoral strategies.
Reports that quantify all options with respect to their cost and potential (to increase water availability) are however scarce. The only contribution on this topic to our knowledge was provided by the Water Resources Group report of 2009 [5] already referred to in the preceding chapter.

Given the unfavourable weight to price ratio of water, an approach to mitigate water scarcity has to be a local one[6]. For this reason, the Water Resources Group report provideed individual *water availability cost curves* for several focus countries, amongst them China and South Africa. Its purpose is to give a potential set of solutions to close the water demand-supply gap in 2030, and the respective cost.
In short, the approach was such that, based on the water gaps on basin/WMA[7] level (see figure 3.3, p. 34 and fig. 3.8, p. 42), locally applicable solutions along the four dimensions sketched out above (increase supply, reduce demand, increase yield, reduce waste) were defined and their potential to increase water availability above the Business-as-usual case,

[6] International water transfers are still a rare case – one recent example is the planned shipping of about 11 million m^3 of freshwater from an Alaskan reservoir to India [124].
[7] WMA: South Africa's (19) Water Management Areas.

plus associated net cost[8] were determined.
Then, all solutions were added from the cheapest to the most expensive (in terms of cost per incremental cubic meter of water availability), producing a *Water Availability Cost Curve* on basin level. The sum of the basin cost curves give the national cost curve that represents the mix of mitigation options with lowest full cost in 2030.
The following aspects were considered for determining the potential of a solution:

- *Availability.* Only technologies should be considered which are commercially available today, or will become so with high certainty soon.
- *Local potential.* Very few solution have unlimited potential. For example, new dams can only be built to the extent suitable terrain is available. Savings from more efficient irrigation for example are limited by the maximal level of applicability to the local agricultural sector.
- *Penetration rate.* It is unlikely that a solution will gain 100% market share over a short time span. Historic market share evolution of comparable technologies can give a hint on how a new solution might spread until 2030.

4.1.1. The water availability cost curve for China

Figure 4.1 gives the national water cost curve for China. More than 50 individual solutions were combined to "close" the supply-demand gap of about 201 km^3 (see figure 3.3, p. 34). The solutions become more expensive in terms of full cost per incremental cubic meter of water. The full cost for a solution are defined as

$$\text{Full cost} = \frac{\text{Full cost of mitigation option} - \text{Full cost of Business-as-Usual}}{\text{Incremental water availability of option}}, \qquad (4.1)$$

where the full cost of in one year are the sum of depreciated investments[9] and the operational cost/savings. The full cost can be considered as the (shadow) cost of water that would be required so that the implementation makes economic sense.
The colour coding in figure 4.1 highlights the fact that water availability solutions stretch across all sectors, i.e., industry, municipalities, agriculture and supply:

[8] The cost and potentials for individual solutions were determined by local researchers on the basis of literature reviews, case studies, and interviews with individuals working in the respective areas.
[9] I.e., the annuity from the depreciation of the investments over the lifetime of a mitigation option with a given cost of capital.

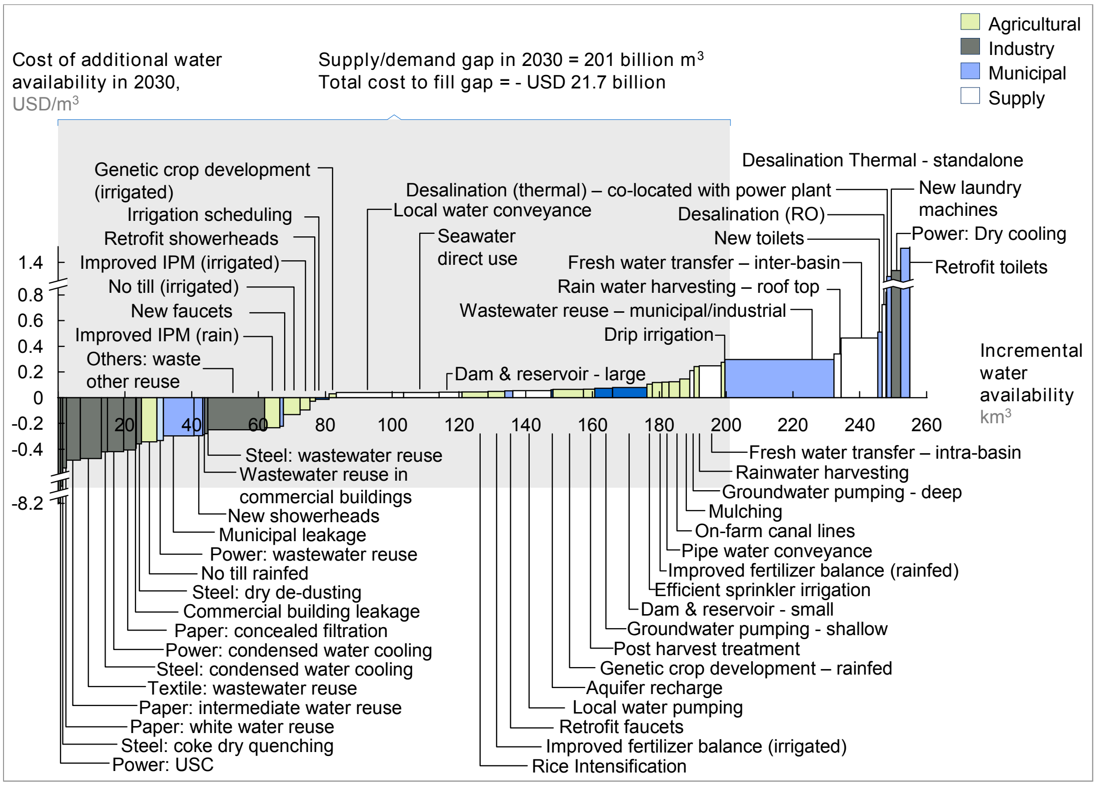

Figure 4.1.: *From [5]. Aggregated water availability cost curve for China. Each option to increase water availability is represented by a rectangle. Its width gives the national potential to increase water availability over the* Business-as-usual *scenario (in km^3); its height gives the full cost per m^3 of increased water availability in 2030.*

- *Industry.* Increasing water efficiency in industry makes up a large share of the cost-negative solutions[10]. Approaches involve on-site re-use of water or a switch to less water-intensive (or even water-free) processes, such as dry dedusting of exhaust fumes. Such measures often also save energy, sometimes reducing operational expenses to the extent that they exceed the initial investments.

- *Municipal sector.* Includes leakage reduction in water networks and improved sanitary facilities such as less water-intensive showerheads or toilets. Little savings other than water, plus high investment make especially the latter options relatively costly. A further large option is the increased penetration of wastewater treatment[11].

[10] Cost negativity means that the new solution is chapter than the Business-as-Usual alternative in terms of full cost.

[11] Although wastewater treatment does not increase the amount of available water, it does increase the availability of *reusable* water, i.e., water that is fit for further withdrawals.

- *Agriculture.* As mentioned, the agricultural sector includes (*i*) solutions that allow the same crop yield with less water, e.g., through introduction of drip irrigation, and (*ii*) such solutions that increase crop yield at a given amount of water, e.g., through planting of less water-demanding species[12]. These solutions generally require low investments, but also enable only low operational savings.

- *Supply.* Supply-side options are found mostly on the right part of the curve, such as new dams or desalination facilities. Requiring high investments and sometimes high operational expenditures, they come at a relatively high net cost.

A detailed list of all mitigation options can be found in appendix C and in [5], p. 147 ff.

It can be seen that closing the water gap in the least-cost configuration as sketched out in figure 4.1 comes at cost that seem low with respect to municipal water fees: the last (and most expensive) option in this solution mix that just closes the gap costs 0.3 USD per m^3. On average, cost are - 0.11 USD per m^3 [13], which means that the least-cost solutions mix comes at a net economic benefit: integrating the curve until the water gap closes gives annual full cost of -21.7 USD billion in 2030[14].
Closing the water gap can thus save money, but this depends on the right allocation mechanisms, sufficient levels of financing, and committment of all stakeholders.

Cost curves differ between basins. Not only are the water gaps of different size, but so are the solutions: industry and the municipal sector will have more weight in densely populated than in rural basins, where increased agricultural efficiency solutions might dominate. Figure 4.2 shows the cost curves for China's South Eastern coastal river basins and the Northwestern inland region.
The industrial and municipal sector dominate in the densly populated and industrialized South East as expected: increased penetration of wastewater treatment for example lifts water availability by more than 4 km^3 annually, while this option accounts for less than 1 km^3 of incremental water availability in the Northwestern basin. The humid climate furthermore allows for an extension of dam infrastructure in the South East, while this is again of lesser importance in the Northwest.

[12] This does however not assume a change in the crop mix, i.e., substitution of water-intensive crops for less-water intensive alternatives.

[13] Weighted average of the full cost of all solutions that are required to close the gap in the least-cost aproach, and their respective potentials.

[14] However, it has to be noted that this cost figure depreciates investments over the lifetime of the assets, and that total expenditures on increased water availability can thus be higher in some years.

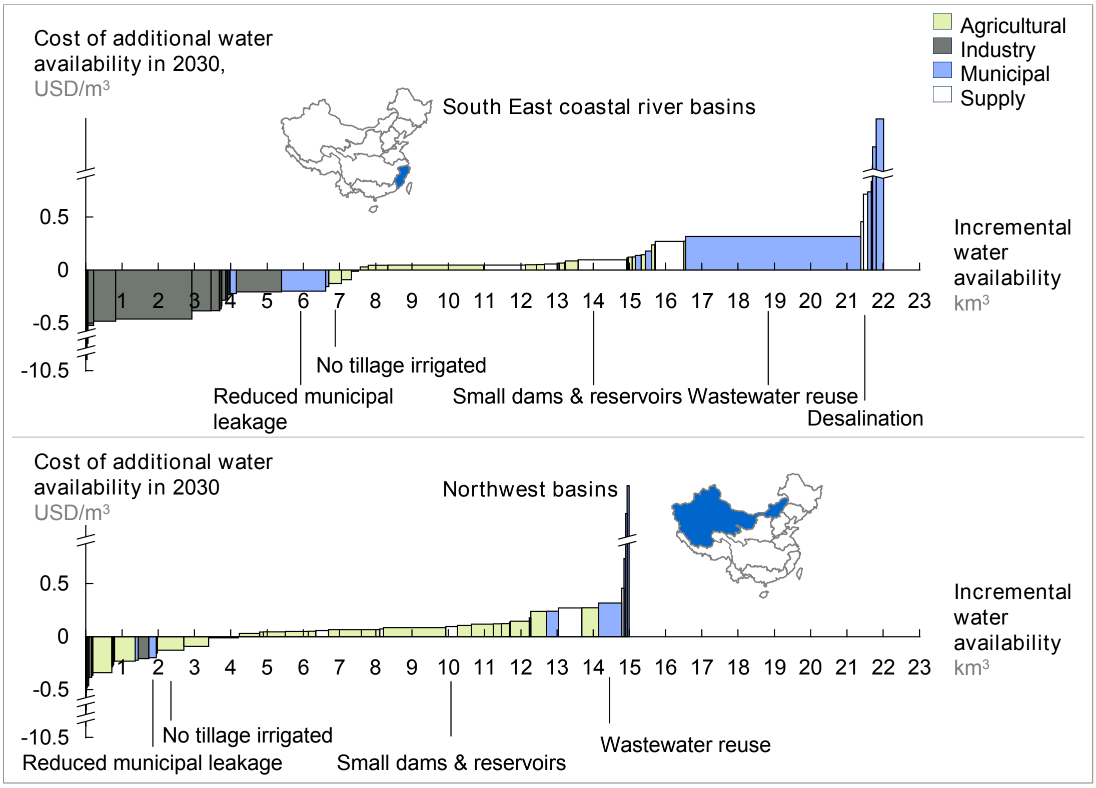

Figure 4.2.: *From [5]. Water availability cost curve for China's South eastern coastal and Nortwestern inland basins. Next to the varying incremental availability, the colour coding shows differences in the locally available solutions.*

The rural and arid North Western parts of the country will in contrast mostly need to rely on efficiency improvements in agriculture, with industrial and municipal solutions being of little importance. Low precipitation levels leave only small potentials for new dam constructions, and the inland location (obviously) makes seawater desalination obsolete, while operational improvements in (irrigated) agriculture, such as reduced/no tillage[15], are more important than in the South East[16].

4.1.2. The water availability cost curve for South Africa

A similar picture can be drawn for South Africa. Figure 4.3 shows its aggregated cost curve, which reveals the same overall structure as its Chinese counterpart: while industrial

[15]Reduced tillage means that the soil on the fields is ploughed less extensively or not at all, and crop residues cover the fields, preserving soil moisture. See also section 7.2.3, page 126.

[16]In relative terms, due to the lack of mitigation options from other sectors, but also in absolute terms, as irrigated approaches matter more in the arid North West, where most agricultural activity is based on it, than in the South East, where a higher share of agriculture is rainfed.

solutions dominate the cost-negative part and agricultural solutions the middle, supply-side options are found more towards the high-cost end. Cost per incremental cubic meter are again to the most part in the range of -1 to 0.3 USD/m^3, with the weighted average being - 0.05 USD/m^3 – integrated full cost for 2030 are therefore again negative on average, at -150 million USD.

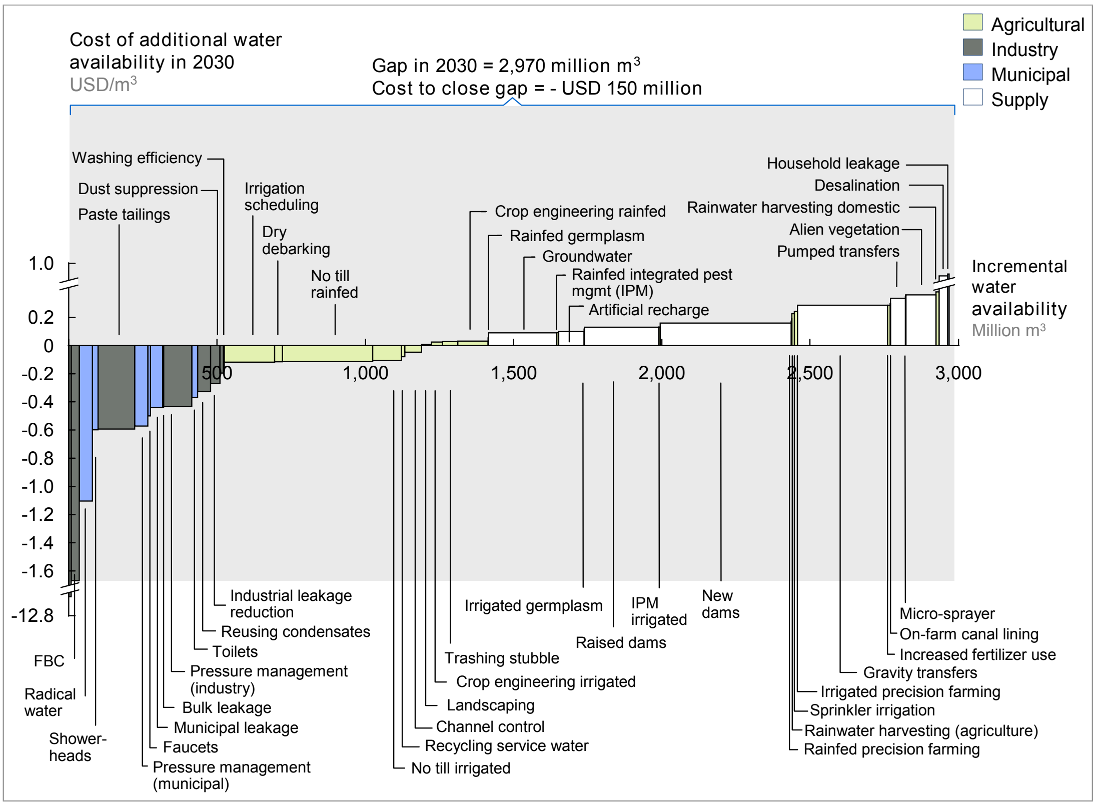

Figure 4.3.: *From [5]. Aggregated water availability cost curve for South Africa.*

The water availability curves so far represented the solution mix with the lowest full cost in 2030 and included solutions from all sectors. In designing a holistic country road map, other key factors would however need to be assessed for each option: among them would probably be scalability, the number of stakeholders involved, the time needed for implementation, risk of failure, organizational requirements, and the impacts on local communities, other critical resources, or ecosystems.

Considering these, solutions that were labelled as low-cost can prove to be much more difficult to implement than a presumably higher-cost alternative. This is also the reason why the past has seen – on average – a stronger focus on increased supply versus agricultural efficiency: building a desalination plant presumably comes faster and involves less stakeholders than convincing thousands of farmers to change from one plant species

to its less water-demanding relative.
Table 4.1 shows three water curve scenarios at the example of South Africa: while the first is the least-cost option already seen in figure 4.3, and the second shows what can be achieved with supply-side options only – presumably among the easier options to get initiated – the third option focuses on agricultural efficiency only.

Solution mix	**Full cost 2030** USD million	**% of gap closed**
Least-cost, mixed approach	-150	100 %
Supply-side approach	545	84 %
Agricultural approach	249	46 %

Table 4.1.: *Adapted from [5]. The least-cost approach and alternatitve pathways for South Africa.*

According to the underlying data, neither of the alternative pathways can close the national water gap. Furthermore, both are more expensive than the least-cost solution mix, with the supply-side options costing almost USD 700 million more per year, about 0.1% of the GDP projected for 2030[17].

4.2. Efforts in mitigating greenhouse gas emissions

Chapter 3 showed that GHG emissions will rise over the next two decades, and global emissions could reach 66 Gt CO_2e by 2030 in a Business-as-Usual scenario[18]. If this trajectory is followed, global mean temperatures will likely rise, by between 3.4–4.0 °C until 2100, according to the IPCC [89]. In order to limit this rise to below 2°C, GHG emissions will need to start falling soon: by 2030, CO_2 emissions of only 20 Gt CO_2e by 2030 would be required [89], instead of the 40 Gt CO_2e projected as the Business-as-Usual scenario[19] in various publications .

4.2.1. Mitigation of global GHG emissions

Given that one tonne of greenhouse gas has the same long-term effect, independent of the emitter's location, mitigation options can be developed and implemented on global scale: as the saving a ton of methane emissions from South-East Asian rice paddies might be

[17]See figure 3.7, p. 40
[18]See section 2.3.3, p. 22 f.
[19]See section 2.3.4, p. 25f and section 2.3.3, p. 22.

cheaper and/or easier to realize than saving 25 tonnes of CO_2 emissions from a European power plant[20], this approach would also make sense from a cost perspective.
In order to define a technically feasible solution mix for mitigating GHG emissions, it is of importance to consider the same constraints that were applied for the water availability options, *availability, the size of local potential, and realistic penetration rates* for each option.

The IPCC Fourth Assessment on Climate Change (2007) includes a report on the *Mitigation of Climate Change* that gives a detailed picture of technical mitigation options [125] [126] – overall, it sees the potential to curb global GHG emissions with respect to the Business-as-Usual scenario by 31 Gt CO_2e by only considering solutions that have a full cost of less than 100 USD per t CO_2e saved.
A major part of the report *Pathways to a low-carbon economy* [4] [76] deals with the determination of a 2030 mitigation potential. There, the mitgation potential of a specific solution is first determined on regional level; the sum of all regional potentials then define the global potential. Sorting all options – as was done in constructing the water availability cost curve – from cheapest to most expensive[21] yields a *GHG abatement cost curve*. Overall, an integrated mitigation potential of 38 Gt CO_2e was assessed in [4] and [76], based on global Business-as-Usual emissions of 66 Gt CO_2e and sustainable emissions levels of 28 Gt CO_2e in 2030 (see section 2.3.3, page 22f).

Figure 4.4 shows the 2010 update of the Global Greenhouse Gas Abatement Cost Curve [76]. Given the high share of the energy sector in global business-as-usual emissions, it seems plausible that the majority of options either reduce energy demand through increased efficiency in the transport, domestic or industrial sectors – accounting for 40% of all abatement opportunities – or aims at less GHG-intensive energy provision through alternative power sources, which are responsible for further 27% of the potential.
Agriculture, forestry and land-use changes account for a third of global abatement potential – proportionally higher than their projected share of 2030 BAU emissions of together 23% (see figure 2.7, p. 24)[22].

Table 4.2 gives the split of the 2030 BAU emissions by world region[23] and contrasts it

[20] Given that methane has 25 times the GWP of CO_2 (see table 2.3, page 16), the two volumes have the same climatic impact.

[21] In terms of full cost per mitigates tonne of CO_2e. The full cost are defined again according to equation (4.1) as the difference betweeen the mitigation option and its Business-as-Usual alternative.

[22] A detailed comparison of these numbers with the IPCC data (from [125]) is given in the appendix of [4], pages 150 – 153.

[23] From figure 2.7, page 2.7.

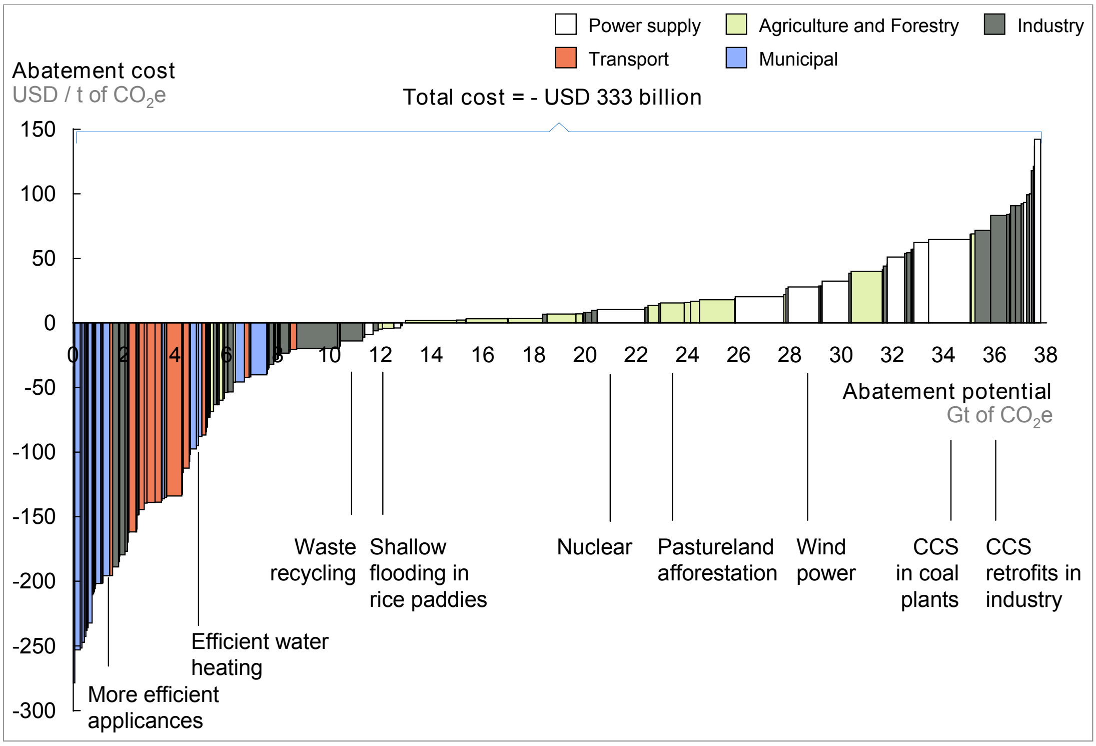

Figure 4.4.: *From [76] and [77]. Global greenhouse gas abatement cost curve 2030.*

with the respective abatement potential: it can be seen that all regions would need to cut emissions roughly in proportion to their 2030 BAU emissions in order to come to sustainable emission levels.
As was the case for the water availability curves, integration of the full cost curve in figure 4.4 would in fact lead to *savings*, of USD 333 billion annually in 2030 in this case. However, this only applies if resources are allocated efficiently, sufficient capital is available for financing investments, and savings from cost-negative solutions are used to finance those with a net cost.

Although greenhouse gases emissions are a global issue, implementation of the most effective solutions mix has to be supported by *national* policy schemes. For this reason, national curves – in essence subsets of the global curve – are of interest, as they can give a quantitative guideline for the design of such policy schemes.

	BAU		Abatement	
Region	Gt CO_2e	% of total	Gt CO_2e	% of total
Asia-Pacific	16,002	25	9,950	27
China	16,666	26	9,143	24
Europe	9,787	15	5,111	14
North America	8,189	13	4,566	12
Latin America	6,517	10	4,547	12
Africa and Middle East	6,580	10	4,035	11

Table 4.2.: *Regional split of Business-as-Usual (BAU) emissions and abatement potential according to [76] and [77].*

4.2.2. GHG abatement cost curve for China

The left-hand column of figure 4.5 shows the 2030 Business-as-Usual emissions for China[24] – according to it, Chinese GHG enmissions reach 16.7 Gt CO_2e in 2030. To the right of it, figure 4.5 shows what can be referred to as *Abatement case* emissions from several sources – i.e., the emissions China could achieve if it contributed to a pathway towards a long-term stabilization of atmospheric GHG concentrations such that the temperature rise is likely kept below 2°C.
Some projections focus on energy-related emissions only: according to the International Energy Agency[25] and the Stockholm Institute [116], energy-related emissions in an Abatement Case would be 5.2 Gt CO_2e and 6.0 Gt CO_2e, respectively. In comparison, [4] and [77] projected energy-related emissions including transportation, at 6.3 Gt CO_2e, slightly more conservative than the Stockholm Institute. A local GHG abatement cost curve report specifically designed for China [127], which sees overall abatement case emissions at 7.8 Gt CO_2e.

The difference between the Business-as-Usual and the Abatement Case emissions yield China's contribution to the global mitigation potential of 38 Gt CO_2e, 9.1 Gt CO_2e. Looked at from the other end, the sum of all China's abatement options sums up to 9.1 Gt CO_2e. If sorted from cheapest to most expensive, these can be represented again in the form of a cost curve, shown in figure 4.6[26].
Compared to the global curve, mitigation options from the energy sector play a larger

[24] Data consistent with figure 3.5, page 37.
[25] *450 ppm scenario* in the World Energy Outlook 2010 [20].
[26] For better readability, not all mitigation options are labelled. See appendix D for a list of all GHG abatement options.

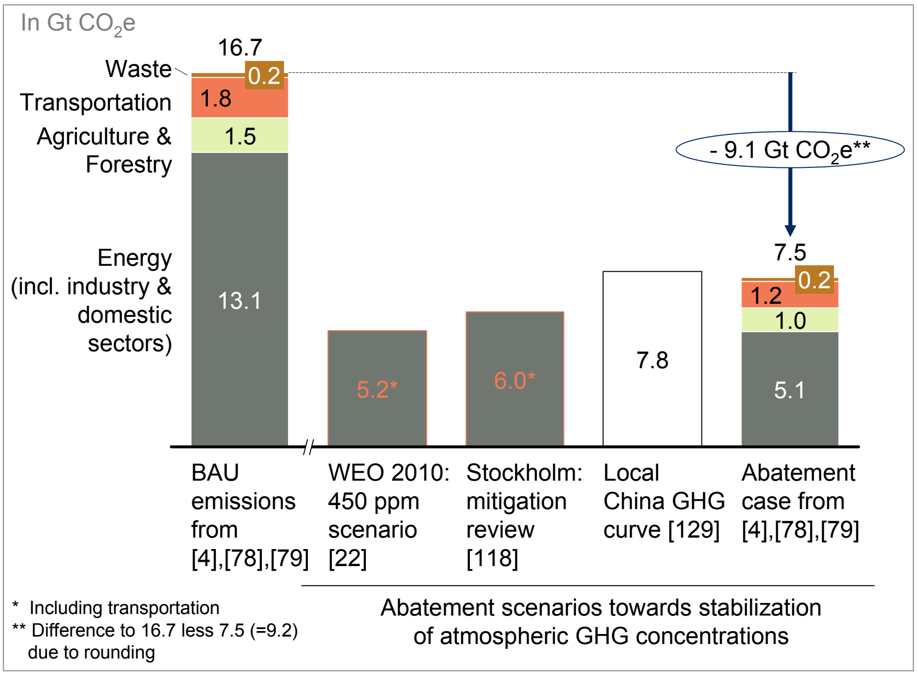

Figure 4.5.: *China's Business-as-Usual and Abatement Case emissions from various sources for the year 2030.*

role in China – not surprisingly, given that energy is also expected to account for a higher share of emissions than in the global average (76% versus 60%, respectively[27]): energy-efficiency options from the the transport, industry and domestic sector account for 44% of China's mitigation potential, while increased use of clean power sources accounts for further 47%. Agriculture and forestry make up the remaining 9%, less than the global number of 33%.

In terms of cost, achieving an abatement of 9 Gt CO_2e will produce net cost of USD 62 billion in 2030, or USD 7 per ton of CO_2e in China.

4.2.3. GHG abatement cost curve for South Africa

Figure 4.7 gives South Africa's 2030 BAU emissions[28] and contrasts it with Abatement Case projections from various sources, amongst them the Long Term Mitigation Scenario (LTMS) report [110], the Stockholm Institute report [116] and the South African part of the global abatement potential from *Pathways to a low-carbon economy* [76].

The LTMS report reports that 2030 emissions levels of about 430 Mt CO_2e are "required

[27]See figure 2.7, page 24, and figure 3.5, page 37.

[28]From figure 3.10, p. 44. Please note that 2030 BAU emissions for South Africa were adjusted based on a comparison of [76] with various other sources (namely, [110], [116], [117]). See also appendix B.

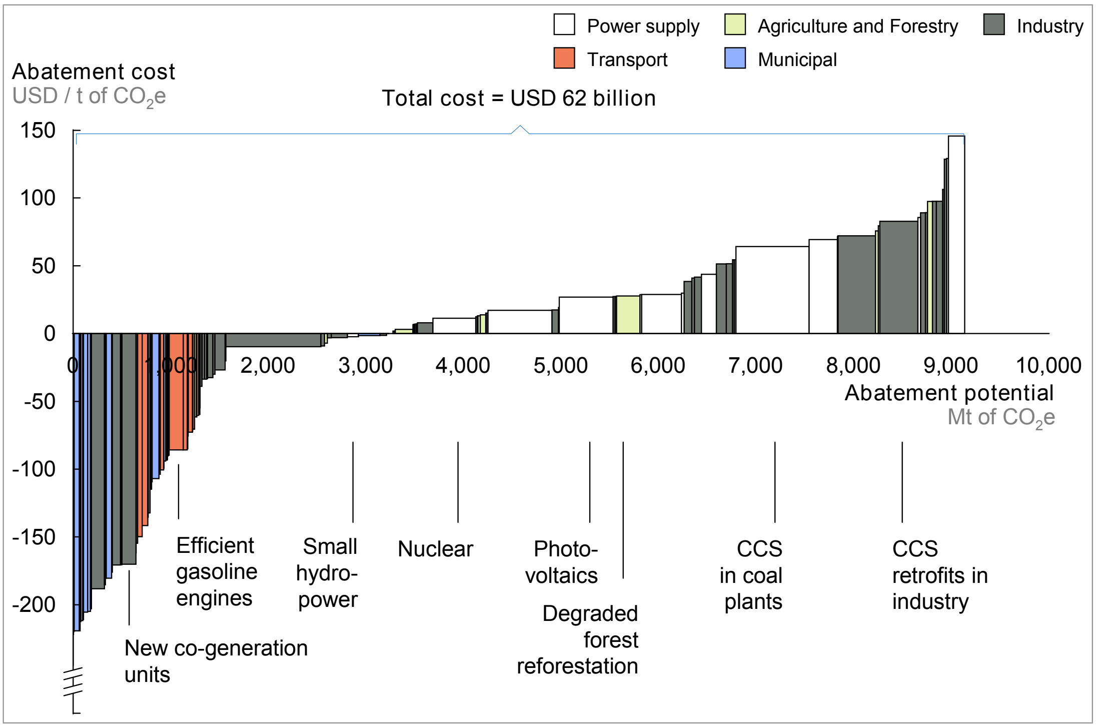

Figure 4.6.: *From [77]. China's GHG abatement cost curve for the year 2030.*

by [climate] science", i.e., at this level South Africa would contribute its share to stabilizing CO_2 emissions at 435–490 ppm (see [110], p. 115). The report also describes mitigation options, their expected mitigation potential and integrated cost in detail[29].

The Stockholm review [116], already consulted as reference in the China case, also gives an abatement case for South Africa, albeit based on the LTMS scenarios. Given its focus on energy-related emissions, it might be interesting to compare this specific number nevertheless: according to it, emissions could be reduced from Business-as-Usual levels of 640 Mt CO_2e to 295 Mt CO_2e by 2030.

Our estimate for Business-as-Usual emissions of 789 Mt CO_2e can be reduced by 341 Mt CO_2e – taken as such from the report *Pathways to a low-carbon economy* [76] and slightly more conservative than [116][30] – to 448 Mt CO_2e, consistent wih the *Required by Science* scenario in [110] (which gives about 430 Mt CO_2e). Energy-related emissions in our abatement case would contain 234 Mt CO_2e directly related to the power sector, which is in good accordance with the most ambitious projections from Eskom, South Africa's state-owned utility, that projects emissions of 220 Mt CO_2e for that scenario [117].

[29] See [110], p. 39 ff.

[30] The energy and transportation sector mitigation potential in [116] is given at 345 Mt CO_2e, versus 290 Mt CO_2e (out of 341 Mt CO_2e in our case).

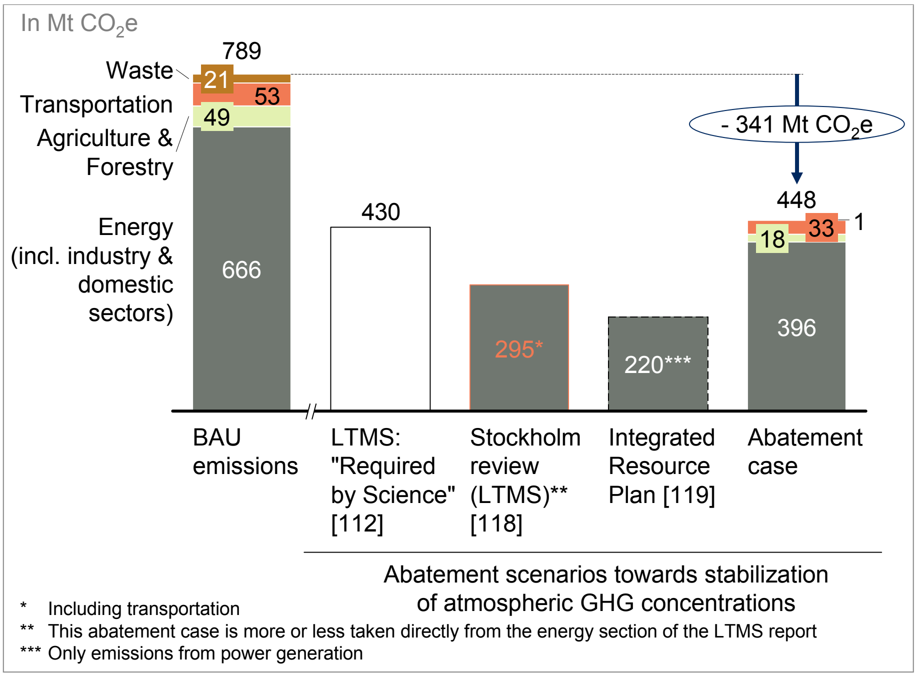

Figure 4.7.: *South Africa's BAU and Abatement Case emissions from various sources for the year 2030.*

Figure 4.8 shows the South African subset of the global GHG abatement cost curve[31]. Similar to the China curve, all sectors contribute to the mitigation potential: given its fossil-dominated power sector in the Business-as-Usual case, a shift to nuclear and renewable power sources accounts for 61% of it, while the transport, domestic and industrial sectors (again dominated by efficiency improvements) contribute further 26%, and agriculture, forestry and land-use change the remaining 13%.
Integration of the curve gives a total cost of USD 3 billion in 2030, with an average cost of carbon of 8 USD per t CO_2e. This is certainly more than in the global curve, which had overall negative cost, but would still be less than 0.5% of the projected 2030 GDP.

The water availability and GHG abatement cost curves in this chapter show that enough mitigation options exist to close the water gaps and reduce GHG emissions to more sustainable levels in both China and South Africa. Morever, such pathways would come at manageable cost, if implemented in the least-cost way.
The two dimensions – water and GHG emissions – were however still studied separately so far, but a look at the mitigation options already suggests that interdependencies between the two curves should exist: a new desalination unit for example will increase

[31]See again appendix D for a list of all GHG abatement options.

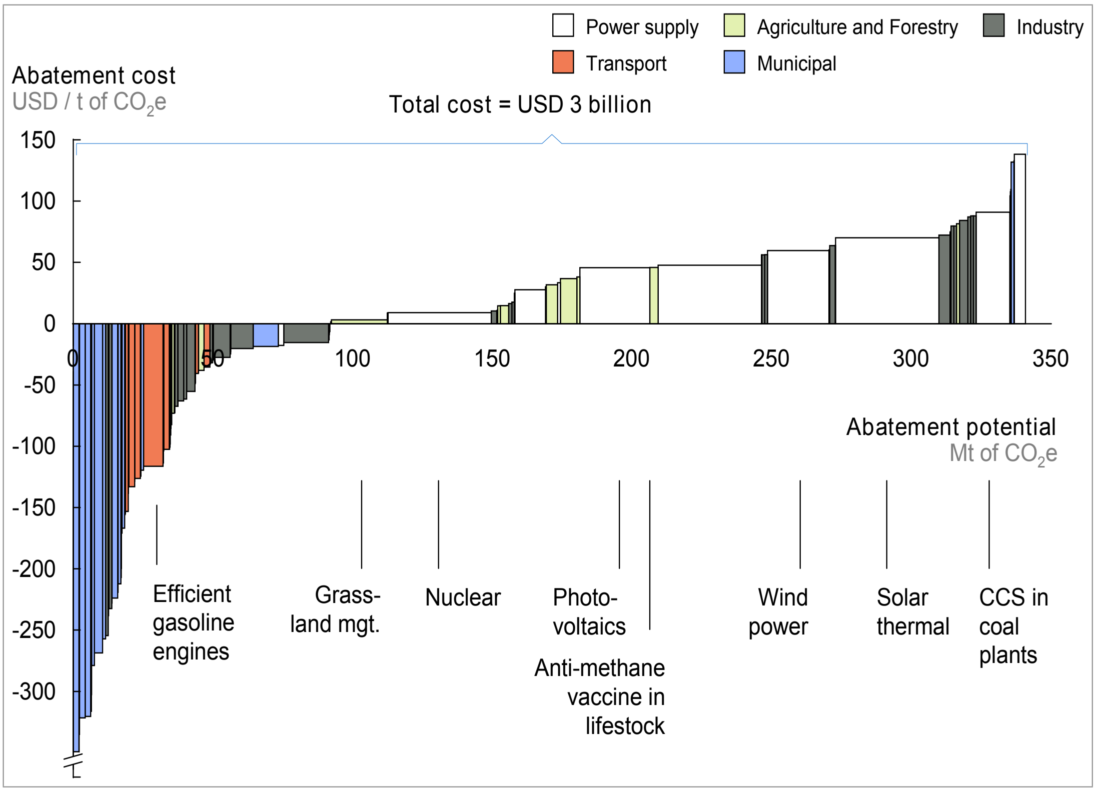

Figure 4.8.: *From [77]. South Africa's GHG abatement cost curve for the year 2030*

power demand, thereby increasing GHG emissions.
The second part of this work will now investigate these dependencies in detail at the example of China and South Africa.

Part II.

Towards an integrated assessment of water and greenhouse gas emissions

5. Interdependencies of water and greenhouse gas emissions so far

Part I introduced to the issues of water scarcity and rising greenhouse gas emissions and approaches to mitigate both. The cost curves showed that a concerted effort across sectors and regions is required in order to come to a sustainable state.
Water scarcity and greenhouse gas emissions were however still considered as two seperate problems in the discussed mitigation pathways, although these two are interlinked on two dimensions.

- *The high-level interlinkage.* One very likely consequence of climate change is a change in precipitation patterns[1], which will influence the available water supply and thus change the size of water supply-demand gaps.
- *Many small interlinkage.* Most of the water or GHG mitigation options discussed in the previous chapter have in fact an impact on the other "resource". For example, building a wind farm not only reduces GHG emissions by making a fossil-fired power station obsolete, but it thereby also reduces water demand, as wind power requires negligible amounts of water – in contrast to thermal power plants. Following the same logic, all energy efficiency measures save water in addition to reducing GHG emissions[2]. In agriculture, reduced tillage does not only preserve soil moisture, but also keeps bound CO_2 in the ground.

It is therefore not intuitively clear whether the water gap could be closed under these circumstances even if all mitigation options were deployed, or from a more optimistic standpoint, whether for example the most expensive solutions to increase water availability are after all needed, as enough water might have already been made available as a side effect of the implementation of GHG mititgation options.

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[1]See also chapter 2.3.4, page 25ff.
[2]Except of course for the case that all power is generated in power plants that do not require water.

This Chapter will discuss the current state of research on interdependencies. Section 5.1 focuses on how climate change is likely to influence water availability overall. Section 5.2 then looks at interlinkages on a technology and sector level.

5.1. Impact of climate change on water resources

Rising sea levels and changing precipitation patterns were mentioned quite generally as one of the risks and threats of climate change in the 2007 IPCC fourth assessment report on Climate Change [79][3], but not further specified therein. A separate IPCC report however specifically dealt with *Climate Change and Water* (2008) [3].
Therein, it is said that rising average mean temperatures in the past have increased the amount of water vapour in the atmoshpere, reduced snow cover and the size of glaciers, and changed soil moisture. Climate modeling suggests that these trends will continue.

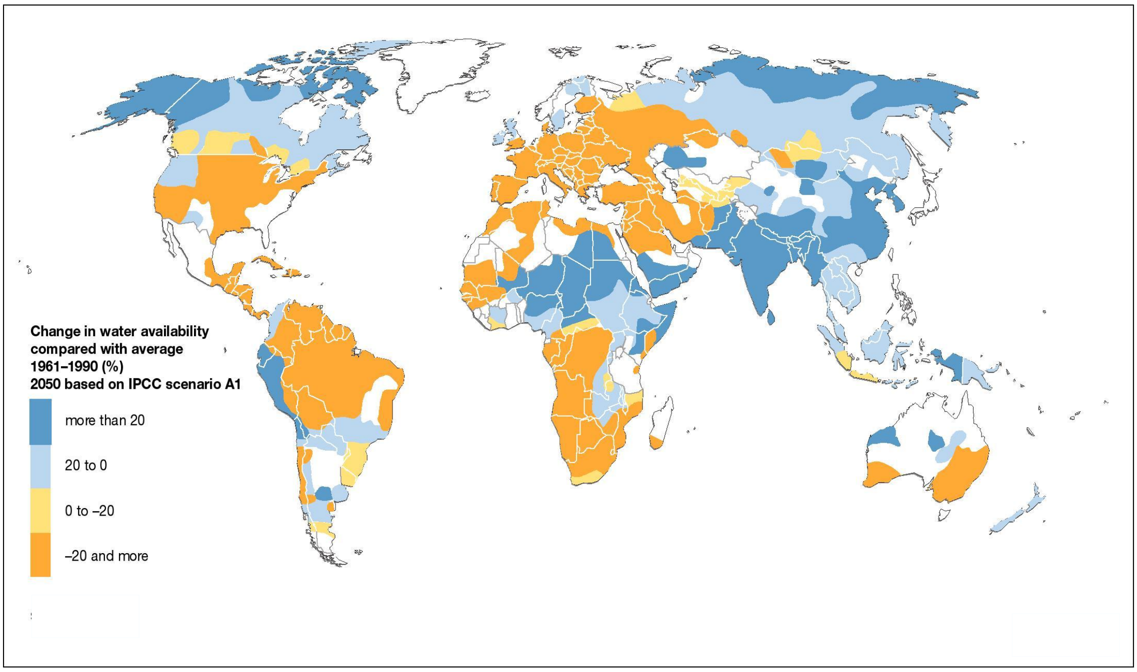

Figure 5.1.: *From [34]. Percent change in overall water availability between 1961-1990 average and 2050, based on IPCC scenario A1. For scenario definition see [16], chapter 10.*

As a consequence, heavy precipitation events will likely occur more regularly, leading to higher flood risk and river runoffs with stronger seasonal fluctuations.

[3]See also section 2.3.4, p. 25.

Overall, precipitation is expected to increase in high latitude and some tropical regions, leading to a likely increase in water availability in these regions. In contrast, semi-arid and arid regions at mid-latitudes, regions that are vulnerable to water stress and scarcity already today, will likely experience a decrease in water availability. Furthermore, the reduced snowcover will imperil water supply during the summer in basins that are fed by snowmelt and glaciers – already today, over 1 billion people live in such basins, and the next decades will see populations grow there in particular[4].
Figure 5.1 shows how water availability is expected to develop until 2050[5]. It can be seen that large areas of Europe, Africa, the Middle East, South America, Australia and the United States could experience a serious decrease by the middle of the 21st century, amongst them regions that already experience water stress today, as a comparison with figure 2.1 (p. 8, the world map showing the Water Stress Indicator today) shows. On top of such changes in precipitation patterns, rising sea levels will lead to saltwater intrusion in coastal areas, contaminating groundwater sources, reducing water availability further.

This trend can however turn out differently on a regional level:

Impact of climate change on China's water resources
Figure 5.1 indicates that average water availability is expected to *increase* in China. According to local modeling results [128], increases in river runoff are expected to be strong in the South East and the westernmost regions, and smaller to negligible in the Yellow river, Hai and Song basins. A further source [129] argues that the overall impact of climate change on Chinese water resources cannot be clearly assessed yet, which is however partly due to opposing trends within the country: while for example the Yangtze basin saw an increase in average runoff over the last decades, the Yellow river basin saw a decrease.

Impact of climate change on South Africa's water resources
Figure 5.1 suggests that South Africa will see a *decrease* in water availability over the coming decades. This picture is confirmed by the short chapter dedicated to climate change in the National Water Resources Strategy [130]: according to it, stream flows in the western part of the country could decrease by up to 10% already by 2015, and

[4]For example, much of Northern India, Pakistan and Bangladesh rely to a sizeable part on snowmelt water from the Himalayas.

[5]The trends shown in this map are overall consistent with the map shown in the IPCC report on water and climate change [3] (page 30), which shows the modeled change in *annual runoff* for the periods 2090-2099 versus 1980-1999; assuming the data behind the two maps is the same, an increase in annual water availability does not yet say that more water is also available in a given month – regions experiencing an increase can still have more droughts, as heavy precipitation events can concentrate the (surplus) runoffs in a short period.

this effect could then move eastwards to the Mozambiquan border until 2060. Modeling results also suggest a reduction in average precipitation of 5–10%, while increases in heavy precipitation events need to be expected as well.

The IPCC report [79] sums up that the adverse consequences of climate change on water resources will likely outweigh benefits. It also states that the current approach to water management might not be sufficient to secure water availability under the additional pressure of climate change in the coming decades, and advocates for the implementation of suitable adaption and mitigation options.
The report also gives an overview over a range of climate change mitigation measures and their impact on water quantity and quality[6], albeit on a rather qualitative level: it for example argues that reduced tillage in agriculture and wastewater treatment can benefit water resources, while hydro dams have both positive and negative impacts, as they produce CO_2-free electricity and can increase water availability, but can also lead to increased methane emissions from algae in the water body and disruptions of local water systems.

5.2. Water impact of GHG measures, GHG impact of water measures

As just indicated, mitigation options related to GHG emissions or water availability can have an impact on the other resource. As energy usage is one of the main sources of greenhouse gases[7], a large part of the these interlinkages are essentially water–energy interlinkages.
And these are not small: in the United States, GHG emissions related to water use were estimated at 290 Mt CO_2e, or about 4–5% of 2005 emissions [131][8], which originate from power consumption of 521 TWh, 13% of the national total that can be attributed to the power sector [131][9]. In India, where high amounts of water withdrawals are used in irrigation, 6% of national GHG emissions are estimated to come from groundwater

[6]See [34], chapter 6.
[7]See figures 2.5, 2.7, 3.5, 3.10: energy accounts for about 60% of global emissions, and around three quarters in China and South Africa.
[8]The percentage range comes from differeing values for total U.S. GHG emissions: using [76], the value is 4%, and 5% when using the same number as in [131].
[9]It has to be noted that these numbers do not only include the energy requirements for water provision, i.e., abstraction, purification, distribution, wastewater treatment, but also for end-use, i.e., water heating, washing etc.

pumping [132].
Inversely, GHG emitting sources also use large volumes of water: thermal power plants in the U.S., most of them fossil-fueled, required 49% of total water withdrawals (in 2005)[10], while mining activities, of which a high proportion is mining of oil, gas and coal, accounted for a further percent [133]. Numbers in China were lower, but (thermal) power generation nevertheless accounted for 41% of 2005 *industrial* withdrawals, according to the Water Resources Group [5].
Interlinkages also exist in agriculture, which makes up for two thirds of water withdrawals and one seventh of China's 2005 GHG emissions[11]: for example, the flooding of rice fields requires water, but also leads to the production of large amounts of methane from bacteria that prosper in the swampy environment.

5.2.1. The water–GHG nexus in energy, industry and agriculture

Most of the literature on water–GHG interlinkages focuses on the water–energy part, often referred to as the *water–energy nexus*. The size of these interdependencies is well assessed.

Water for energy extraction

Coal mining and processing.[12] Underground mining of coal requires water mostly for dust suppression and avoiding of friction-induced ignition of coal seams; 3–20 m^3 of water is consumed per Terajoule of mined coal.
In surface mining, water is mostly required for dust suppression, and potentially for landscape re-vegetation after mine the mine is depleted (2–5 m^3/TJ).
Benefication of coal, e.g. washing to extract impurities, requires on average further 5 m^3/TJ.

Oil and gas exploration and refining. Oil exploration is estimated to require about 2–5 m^3/TJ, mainly for the drilling process and initial treatment.
One of the methods to increase oil field yields is the injection steam in the reservoir to push fuel to the surface. Depending on the depletation state, exact process and geological conditions, this *Enhanced Oil Recovery* requires between 100 and 9,000 m^3/TJ. Oil production from tar sands is similarly water-intensive, requiring an average of 180 m^3/TJ. Lastly, oil refinieries have a water footprint that is related to their need of process

[10]Fossil-fueled power plants accounted for 72% of U.S. power generation in 2005 [20].
[11]See figures 3.3 (p. 34) and 3.4 (p. 3.4).
[12]All numbers in this section are from [1], except for biofuels (from [2]).

steam, consuming 25–65 m^3/TJ, but withdrawing considerably higher amounts, in the order of 325 m^3/TJ.
Conventional *gas* exploration in contrast requires negligible amounts of water.

Uranium mining and processing. Depending on the mining method, water requirements in uranium extraction vary between 0.2 m^3/ TJ for underground and up to 20 m^3/ TJ for surface mining. The whole fuel processing cycle, including milling, conversion and enrichment of the raw uranium can require up to about 40 m^3/TJ, depending mostly on the enrichment method[13].

Biofuels and biomass. Processing of corn to ethanol for example requires 47 – 530 m^3/TJ [134], while biodiesel refining is less water-intensive, requiring about 16 m^3/TJ. The water-intensity of biofuels is however mainly driven by the water-intensity of the crop cultivation. While rain-fed does not require water-withdrawals in the conventional sense[14], irrigation does so and enhances the water footprint: based on U.S. numbers, corn irrigation requires between 9,000 m^3/TJ and 90,000 m^3/TJ; water withdrawals for soy production (for biodiesel) are even higher, 50,000–270,000 m^3/TJ [134][15].
The water footprint becomes smaller if the crop is used for heat or power generation: refining or processing can be omitted, and the energy content of the whole biomass can be used, instead of only using the fruits or oil extracts.

Water for electricity

Thermal power plants.[16] All fossil-powered, as well as nuclear, biomass, solar thermal and geothermal power plants operate according to the same principle: combustion of a fuel in a boiler produces steam that is expanded over a steam turbine. Before returing to the boiler (closing the *primary water cycle*), the steam has to be cooled down as much as possible, as the overall plant efficiency depends on the temperature difference before and after the boiler. Three principle systems can be employed for cooling, which different amounts of water:

[13] Centrifugation is less water-intensive than gaseous diffusion.
[14] I.e., withdrawals that could not be put to other uses.
[15] Irrigation needs vary of course with climatic conditions, and the crop used as feedstock. A detailed perspective on water requirements for ten relevant crops and regional variability can for example be found in [134].
[16] All water requirements for electricity (not only thermal power plants) from [135]. The water requirements mentioned here referred to a coal-fired power plant with an efficiency of 35%. Athough state-of-the art coal power plants achieve efficiencies of up to 45%, the global average of installed capacity lies around 35% [136] (p. 58-59).

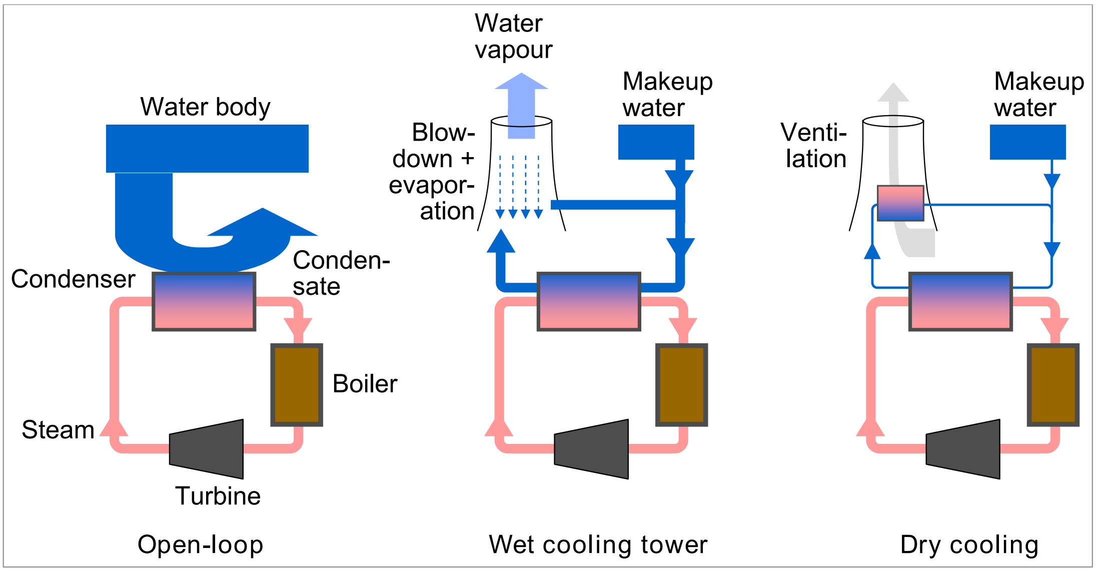

Figure 5.2.: *Schematic sketch of the three principle thermal power plant cooling technologies.*

Open-cycle cooling withdraws water from a nearby river, lake, or the sea and uses it to cool the steam. The water takes up energy from the steam, and is returned to the river/lake/sea at higher temperature. This technology consumes negligible amounts of water, but requires withdrawals in the range of 76–189 m^3/MWh. Open-cycle cooling is especially used in older power plants that are located in proximity of large water bodies.

Wet cooling tower sytems. A *secondary water cycle* takes up heat from the steam and releases it through evaporative cooling in a cooling tower: in most cases, the water is sprayed down and parts of it evaporate and cool the remaining water that is collected and re-used. This technology typically withdraws less than 4.0 m^3/MWh, but also "consumes" most of it through evaporation.

Dry cooling further reduces water requirements by avoiding the evaporative losses in the cooling tower. Instead, water remains in pipes and is conductively cooled by the circulating air in the cooling tower. This reduces withdrawals to typically less than 0.2 m^3/MWh. However, as the water can only be cooled down to ambient temperature instead of the lower dew point of water, dry cooling efficiencies are lower, and the more so, the drier and warmer the climate[17]: it is estimated that plant output can decrease by up to 25% under hot and dry conditions [137].

[17] Ambient temperature and the dew point are the same when relative humidity reaches 100%, and diverge in drier climates.

The water intensities per MWh mentioned here can be translated into water–GHG intensities by applying a carbon intensity, which typically lies at 1,000 kg/MWh [136] for an average coal-fired power plant with 35% efficiency.
Power plants that are fueled by other sources typically operate at lower temperatures, and thus have lower efficiencies and higher water requirements per MWh of output: water withdrawals in a wet-cooled nuclear power plant for example are given at 4.4 m^3/MWh, about 10% higher than for coal-fired units [135].

Combined-cycle gas turbine (CCGT) plants. About two-thirds of the electricity in these plants is produced by burning gas and expanding it directly over a gas turbine. The residual heat is used to produce steam that powers a steam turbine, providing the remaining third of electricity. As only the steam cycle requires exterior cooling, water withdrawals generally are about two thirds lower, 0.9 m^3/MWh.

Hydro power. Power production with water does not consume water directly. Run-of-river installations also have withdrawals which are effectively zero: they use the water in the river and return it seconds later unchanged. Dams in contrast often store large volumes of water – depending on the climate, a measurable part of it can get lost through evaporation, which can reach more than 200 m^3/MWh[18].

Photovoltaics and wind require negligible amount of water. At most, water is needed to wash the solar panels or wind blades occasionally.

Energy for water

The provision of water inversely requires energy[19].
Water supply. Water *abstraction* from nearby surface water sources such as lakes or rivers requires negligible amounts of energy. Pumping of groundwater in contrast requires energy in dependence on the pumping depth: merely overcoming gravitation requires 0.27 kWh of energy per 100 m^3 of water per meter of height difference. Measured numbers are around 0.5 kWh/m^3 for depths of 120m[20]. If water needs to be *desalinated*, energy needs increase, but exact numbers differ depending on the technology: for reverse osmosis, about 4.5 kWh/m^3 are required, while thermal distillation methods use less electric energy, around 2 kWh/m^3, but require larger amounts of thermal energy, in the order of 50–75 kWh/m^3 [21].

[18]Numbers for California from [135]. Section 7.1.4, page 118 estimates evaporation rates for China and South Africa based on this data.
[19]All data in this paragraph from [2] if not otherwise stated.
[20]I.e., the efficiencies are rather 61 % in this (Californian) case example.
[21]See the Master thesis from Stefanos Angelousis on cost and potentials of different desalination

Water treatment and distribution. Depending on the quality of supplied water, treatment to drinking water standards can require up to 0.4 kWh/m^3, and distribution through local networks 0.2 – 0.3 kWh/m^3. These numbers apply to an average system: depending on geographic conditions and the condition of the network (e.g., leakage rates), this number can vary widely.

Wastewater treatment. Cleaning the used water such that it can be discharged safely to the environment typically requires about 0.7 kWh/m^3, which are used for aeration, to operate sewers and filters, and for drying of the sludge. Section 7.2.1 (p. 122) will give more detail, and also discuss how wastewater treatment can actually be turned into a net energy source.

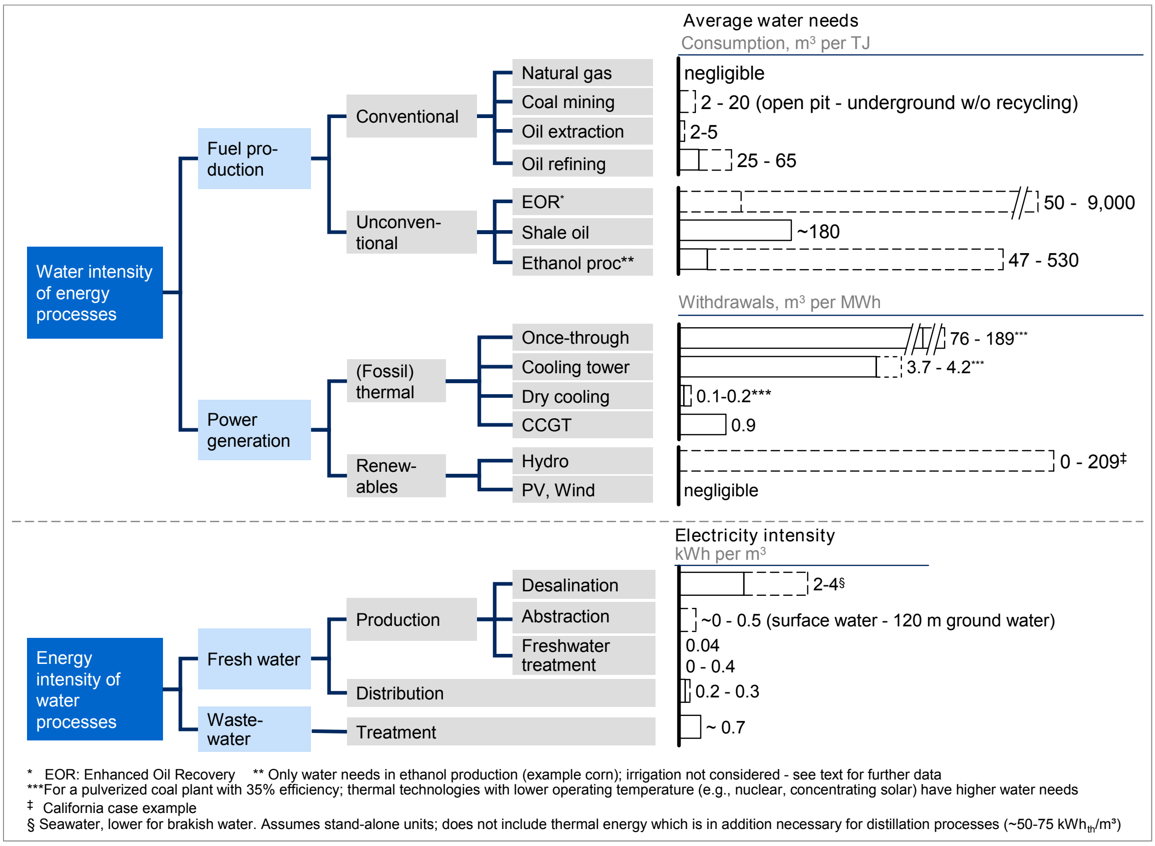

Figure 5.3.: *Water intensity of various fuel and power production processes, and electrictiy intensity along the water provision chain. From [1] (fuel production), [135] (power generation), [2] (water supply and treatment incl. desalination).*

technologies, prepared in the context of this thesis, for further details and reference [138]. Section 7.2.2, p. 124 gives a brief summary of it.

Figure 5.3 summarizes most of the cross-intensities discussed[22].

To put these numbers again into perspective: given a per-capita power consumption of 2.6 MWh (2009) [106], and given a power mix dominated by coal, every Chinese citizen requires about 10 m^3 of water withdrawals for power generation alone[23] – a number that is not negligible compared to average domestic per capita withdrawals of 52 m^3 [25]. The provision of water for domestic purposes on the other hand requires on average 1.4 kWh per m^3, according to figure 5.3, summing up to 73 kWh per person and year. Taking into account water requirements for industry and agriculture (together 365 m^3 per capita) increases this number to almost 400 kWh, producing 32 kg of CO_2[24].
These estimates still assume conventional power production and water provision processes. However, more extreme cases exist, also on large scale: Southern California for example is supplied with water through an aqueduct from the northern parts of the state. Due to geographic barriers, the water has an electricity footprint of 4.2 kWh per m^3 when it reaches the south [2]. At a population of 9.8 million [139], water supply to the county of Los Angeles therefore requires the year-round operation of a large coal or nuclear power station[25].
Similar electricity (and by this GHG) footprints of water provision could be discussed for the Middle East, where a sizeable portion of water is supplied through desalination plants, which partly explains why for example Qatar ranks as the country with the highest per capita GHG emissions globally[26].

Industrial processes. The chemical and steel sector for example accounted for 16% of China's 2005 GHG emissions [77] and 1% of total water withdrawals [5]. In the chemical industry, a lot of these emissions and the largest share of water requirements [140] come from the production of process steam. In the iron and steel industry, the smelting of iron ore in furnaces emits large volumes of greenhouse gases; scrubbing of the furnace exhausts fumes is conventionally done by washing, which requires 3.0–3.7 m^3 per ton of molten iron [140].
The petroleum industry – accounting for 1.5% of China's 2005 GHG emissions – was already mentioned with respect to water needs for oil refining in figure 5.3. Indeed, about

[22] The sources used here and for figure 5.3 ([1], [135], [2]) provide further information on the various technologies and on further (sub-)technologies.
[23] If only powered by coal plants (wet cooling tower). As China receives 86% of its energy from this source [20], the truth it not so far behind this number.
[24] At average Chinese carbon intensity of power generation of 790 gCO_2 per kWh [69]
[25] Assuming: $9.8 \text{ million} \cdot 4.2 \text{ kWh/m}^3 \cdot 193 \text{ m}^3\text{/capita} = 7.9$ TWh, the electricity a 1 GW power plant produces if it runs during 90% of the year.
[26] See table 2.4, page 20.

half of the water requirements of a refinery are needed as make-up water for the cooling system [140] – again closely linked to production of heat and (process) steam and energy consumption.

Interdependencies of water and greenhouse gas emissions in *agriculture* are less intense and more indirect in most cases. In 2005, agriculture accounted for about 70% of global withdrawals[27], but for only 14% of global GHG emissions[28] and 2% of energy needs ([141] (p. 36)). A review of the available literature on energy-use in agriculture was provided by Rothausen *et al.* [142]: according to it, agricultural energy consumption is in the order of 1,000–20,000 MJ per hectar. Water intensities per hectar vary and depend on crop and geographic conditions; the average water duty for Egypt for example is given at 8,400 m^3/ha (see section 9.2, p. 172ff.), which would yield water–energy (and by this water–GHG) intensities in the order of 1–10 m^3/MJ.

The production of energy – or industrial goods – does not only require large quantities of water, but also has an impact on *water quality.* A by-product of oil extraction is in fact impaired water, which can be saline or contain high concentrations of heavy metals and thus pose a risk to nearby reservoirs or aquifers if not properly treated. To give another example, the warm backflow from open cycle power stations can have adverse impacts on aquatic ecosystems[29].

5.2.2. Towards integrated abatement options

This chapter has shown that water and GHG emissions are indeed interconnected. Looking back at the mitigation pathways discussed in chapter 4, it seems clear that many GHG mitigation and water availability options will have a cross-intensity with the other "resource". These can be divided into three types:

- **Win-win: reducing GHG emissions and increasing water availability.** All thermal power-generating technologies use water. Thus, installation of solar PV and wind power not only abates GHG emissions, but also saves water. All solutions that increase energy efficiency therefore increase water availability according to the same logic[30]. In agriculture, reduced tillage not only preserves soil moisture, but also carbon in the ground, reducing both water requirements and CO_2 emissions.

[27] See figure 2.2, page 12.
[28] See figure 2.5, page 19.
[29] A detailed and systematic discussion of such water quality impairements from energy production can for example be found in [25], page 73 ff.
[30] Unless all power is produced in "zero-water" generation units (wind and photovoltaic).

- **Win-lose I: reducing GHG emissions but decreasing water availability.** Biofuels can require huge amounts of water if crops need irrigation, but reduce GHG emissions in transportation and increase energy security in oil-scarce regions. Another technology in this category is *Carbon Capute and Sequestration* (CCS), i.e., the segregation and subsequent underground storage of CO_2 from fossil power plant exhaust fumes: CCS reduces GHG emissions to the atmosphere, but requires substantial amounts of energy, increasing in turn the amount of water needed to maintain constant electric output. Similarly, solar thermal plants avoid GHG emissions but typically have higher water needs than coal-fired units due to lower operating temperatures.

- **Win-lose II: increasing GHG emissions and water availability.** Desalination plants increase water availability, but require energy, which in almost all regions has a non-zero carbon footprint. Another example is dry cooling, where water savings are traded for reduced plant efficiency.

6. Methodology of an integrated assessment

The last chapter discussed the current state of research on interdependencies between water and greenhouse gas emissions. It showed that there exist both a high-level interconnection – climate change will likely alter overall and seasonal water availability –, and many small interlinkages or cross-dependencies between certain technologies, which can be synergetic or can have adverse impacts. It is thus not intuitively clear whether the water availability or GHG abatement cost curves discussed in chapter 4 will have an overall positive or negative impact on the other "resource".

One approach to answer this question is to first assess the cross-dependencies of all water/GHG mitigation options. The mitigation options can then be integrated with their respective cost, mitigation potentials and cross-dependencies into one model which allows to find optimal solution mixes under multiple constraints: it could for example assess the least-cost solution under the boundary conditions of a closed water gap and achieved GHG abatement goals. Determining these cross-dependencies and building of such a model were the main tasks of this thesis.

This chapter will discuss what data sets were used (and why), how the cross-dependencies for the specific mitigation options were assessed, what the boundaries of the model are, and how the integrated model was set up.

6.1. Notes on the main data sources used

This work builds mainly on two sources that were already discussed in Part I: for water availability options, it uses the data underlying the report *Chartering Our Water Future - Economic frameworks to inform decision making* by the Water Resources Group (2009) [5]. For greenhouse gas abatement solutions, it refers to the data sets developed in the context of the report *"Pathways to a low carbon economy - Version 2 of the global greenhouse gas abatement cost curve"* (2009) [4] and its 2010 update [76][1].

[1] The underlying data is available online in the tool *Climate Desk* [77].

Although being (partly) the work of a private institution, both reports are publicly available and the underlying data is thus, at least on an aggregated level, shareable. Furthermore, a scientific or expert panel supervised both working groups[2] in a similar way than comparable non-governmental reports are supported.
Several reasons commend that this work draws its data from these two sources [5] [4]:

- *Completeness.* Both reports have a holistic perspective on a Business-as-Usual development and mitigation options in the given geographies. In both cases, they include all sectors and, in the case of [4], all major greenhouse gases.

- *Data quality.* Part I discussed the data and underlying assumptions from the two sources and compared them to data sets from institutions such as the IPCC, International Energy Agency or the United Nations Food and Agricultural Organization. In general, the overlap of data was good, and differences could be attributed clearly to different (but explainable) assumptions. Adjustments to the basic data set were only carried out in the case of South Africa's projected Business-as-Usual GHG emissions for 2030 (discussed in detail in appendix B).

- *Granularity.* Both reports quantify mitigation potentials and associated cost for each mitigation options separatedly. While the Water Resources Group report [5] typically includes a set of around 50 solutions for each focus country, the GHG abatement cost curve [4] includes up to 160. Although some of these quantifications might only be informed estimates, they still provide one of the more detailed assessments of mititgation potentials to our knowledge.

- *Methodical consistency.* Both reports follow the same approach: they define a 2030 Business-as-Usual case and a sustainable alternative. The "gap" between both is bridged with a solution mix considered as technically feasible[3]

- *Temporal consistency.* Both reports use the year 2010 as reference year[4] and study mitigation options until 2030. Moreover, both were compiled in 2009/10 – yielding comparatively novel data sets[5]; the small time lapse also left little room for changes in the public or scientific debate, presumably leading to similarly ambitious calculations of mitigation potentials.

[2]See p. 139–140 in [4] and p. 176–184 in [5] for a list of persons involved in these expert panels.
[3]Please note that this does not yet take socio-economic or regulatory boundary conditions into consideration.
[4]I.e., for 2010, projected GHG emissions or water availability does not differ between Business-as-Usual and the alternative scenario.
[5]E.g., the last IPCC report on climate change dates back to 2007 [79].

- *Geographic overlap.* Given that water is a local resource, [5] quantifies water availability options only for three countries and one region (India, China, South Africa, and the state of Sao Paulo, Brazil). For all three countries, [4] and [77] can provide national GHG abatement cost curves (based on the global curve). This is particularly important, as otherwise an integration into one model would be become very difficult.

None of the two reports provides information on the overall impact, or the impact of specific mitigation options, on the other "resource". The contribution of this thesis therefore started with the determination of all relevant interlinkages, i.e., the determination of the water itensities of the GHG abatement options, and the GHG intensities of the water availability measures[6], and continued with the setup of an integrated model that included all mitigation options, and the development, run and interpretation of integrated scenarios.

6.2. Notes on water and greenhouse gas definitions

Water

A differentiation is made between *blue* and *green* water[7]. *Blue* water is the water from river runoff, aquifers and groundwater and by this the water that can be accessed by humans and diverted to consumptive uses. Water from unconventional sources, such as treated wastewater or desalinated seawater can be added to this[8]. *Green* water refers to the water from precipitation that is consumed by natural systems, e.g., forests, pastures, lakes. Beyond maintaining ecosystems, it only links to human use insofar as that it includes the water used in rainfed agriculture.

It is the blue water cycle that is studied in [5] and that will be referred to in the remainder of this thesis. This however means that the impact of certain mitigation options on the overall hydrological cycle were not further considered in this work. As an example, one option to reduce GHG emissions is to afforest fallow land. If this happens at sufficient scale, it will likely have an impact on local groundwater levels, evapotranspiration and river runoffs. Quantifying this effect however requires distinct climatic modeling knowledge, beyond the scope this work.

[6]Detailed information on the assessment of the interlinkages will be presented in section 6.4 of this chapter.

[7]See for example [143] (from the FAO) as reference for a definition of blue and green water

[8]Occassionally, the concept of *gray* water is heard. This is blue water of impaired quality after anthopogenic uses. Wastewater treatment converts grey water again to blue water.

Within the blue water cycle, the focus here is on the availability of *raw* water for consumptive anthropogenic uses. This means that water management efforts that either do not change the amount of available raw water such as flood control, navigation and recreation, or efforts that increase water quality beyond basic quality requirements, e.g., treatment to drinking water standards, are not further investigated[9]. This does of course not imply that these efforts are of lesser importance; however, sufficient raw water availability is a prerequisite for fulfilling the other goals.

Numbers regarding water demand in this work consider water *withdrawals* as opposed to water *consumption*. After brought to use, withdrawn water can be returned to the water body, either unchanged or at impaired quality. The accessible supply in this work therefore includes these return flows – the longer a river, the higher this corrective factor. Withdrawals are the metric of choice in this work (and in [5], plus in most other sources), as they are a more complete measure of water demand: an open cycle power plant does not consume any water, but withdraws large quantities, as seen in the last chapter. Looking at consumption would conceal that these plants might need to be shut down at low supply levels.

Greenhouse gases

All anthropogenic greenhouse gases discussed in section 2.3.1 (p. 14 f.), i.e. carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and halocarbons, are considered. For this reason, all GHG-related potential is given in CO_2 equivalents (CO_2e) which takes into account the different lifetimes and warming potentials.
Furthermore, GHG emissions are accounted for in the region where they are emitted, even if finished products which result from these emissions are installed, used or consumed in another region. This also means that emissions from the burning of fossil fuels are attributed to the country where they are used, and not to the country where they are mined. This approach however overemphasizes emissions from regions that export large quantities of finished goods and should be considered when studying the results of this work.

Both water availability and greenhouse gases abatement potentials are only considered so far as they are related to the operations of a particular solution – i.e., water availability/emissions from the manufacturing of this solutions are not accounted for. Potentials thus do not follow a life cycle assessment (LCA) approach.

[9]However, wastewater treatment to levels that the water can be recharged at a similar quality at which it was withdrawn is included as an option to effectively increase water availability.

6.3. Notes on timelines

This work considers the time span between 2010 and 2030 and assesses the cost and potential of mitigation options that could technically be implemented within this span. Most of the GHG and water availability data cited from [4] and [5] referred to the year 2005, as this is the last year of which real data were available at the time of print of [4] and [5]; it is also the last year of which holistic data on GHG emissions or water availability were available from other sources (such as [69]). Still, the gap between the Business-as-Usual and Abatement Case only opens up after 2010 in both [4] and [5][10].
Although both reports only discuss the total mitigation potential between BAU and Abatement Cases in 2030, the underlying data in both cases contains information for each five-year period between 2010 and 2030. This allowed to evaluate a mid-point, the year 2020, in this work, which required the split of all measures from [4] and [5] in two, a 2010–2020 and a 2020–2030 branch, with a respective cost and potential for each. The potential mentioned in [4] and [5] is then the sum of the two decade potentials. The mitigation cost for the two decades are the same only if no cost degression was assumed in [4] and [5]; otherwise, they might differ.

6.4. Assessment of cross-dependencies

The first step towards an integrated assessment is to determine the cross-dependencies of the respective options, i.e. the greenhouse gas impact of the water availability options and the water impact of the greenhouse gas mitigtation options.
As mentioned above, this work focuses on cross-dependencies that can be attributed to the *operation* of a mitigation option and therefore ignores cross-dependencies related to the manufacturing of a specific solution. The following two sections sketch out how the cross-dependencies were determined in principle.

6.4.1. GHG impact of water availability options

Water availability options can be subdivided into a group that has a direct impact on GHG emissions and those that indirectly influence GHG emissions.
If a water availability option has a direct GHG impact and that impact is quantified in [5], no further work is required. If it impacts energy requirements, these are translated into GHG emissions depending on the source of energy: for coal, gas, oil, respective

[10] To describe the evolution between 2005 and 2010, it is for example assumed in [5] that infrastructure projects planned to be finidhed by 2010 are indeed finished by then.

CO_2-intensities are employed; for electricity, the GHG-intensity of the same power mix that is used in determining the water impact of electricity efficiency options is employed (see section 6.4.2 below).

Measures that have no explicit energy/GHG impact in the data from [5] can still be assessed: for example, drip irrigation saves water and thereby reduces energy demand as less water needs to be pumped from deep wells. Similarly, water-efficient toilets reduce domestic water demand and thereby lead to reduced electricity demand for water provision and treatment. These cross-intensities were calculated based on the sources discussed in section 5.2 and, if necessary, further literature search. Appendix C contains a list of all water measures, a short description of the type of the cross-dependency, and a source based on which it was quantified.

6.4.2. Water impact of GHG mitigation options

Most GHG mititgation options, and in particular those from the power, industry, transport or domestic sectors derive their mitigation potential either directly from a reduction in fossil fuel combustion or indirectly through reduced power consumption. The saved quantity of fossil fuels (or electric power) and their respective water intensities, discussed in the last chapter, then allow to determine the water intensity of a mitigation option. Options that immediately reduce GHG emissions are mainly found in the agriculture, forestry and waste sectors[11].

Methodical differences exist between options that impact GHG emissions directly, those that influence them through changes in fossil fuel use, and those options that influence them through reduced electric power consumption.

Measures with a direct impact on GHG emissions

The impact on water resources of those measures was mainly determined from specific literature. In a few cases, an option was part of both the water availability and the low-GHG cost curve, in which case the water intensity of the GHG abatement option (or the GHG intensity of the water availability option) was determined by "merging" the two. A literature search was however still required to check whether the two measures are really based on the same principles[12]. One example is reduced tillage: in South

[11] A list of all GHG mitigation measures can be found in appendix D.

[12] This is also important to know for the determination of cost: these can only be averaged if the water availability and GHG abatement option require (almost) indentical implementation steps.

Africa, its GHG mitigation potential is estimated at 2.2 Mt (according to [77][13]), and its incremental water availability potential 943 million cubic meters (according to [5]). The farmland changed to no-till, a main driver in determining the water availability or GHG potential, was comparable in both data sources, and the two mitigation options were therefore integrated into one.

Measures with an indirect impact on GHG emissions: reduction of fossil fuel use

The water impact in that case is related to reduced water requirements for fossil fuel extraction, and can be assessed based on the data and literature mentioned in section 5.2 – coal mining for example requires 2–20 m^3/TJ – a GHG abatement option that reduces coal demand by 1 TJ would therefore increase water availability by 2–20 m^3.

In order to assess the water impact properly, it is important to determine the employed mining method, and the import-export balance for the respective fossil fuel, as reducing the demand of a good that is imported will not change the local water balance.

Import-export balances for coal, gas and oil between 2010 and 2030 were determined based on the IEA's World Energy Outlooks 2007–2010 for China[14] and databases on local coal mine capacities and locations for South Africa [145], coal [146] and oil production and refining [147]. In contrast to coal and gas, which are readily useable after basic cleaning steps, oil requires refining before it is fit for use – therefore the balance of refining capacities required equal assessment.

To give an example, more efficient cars reduce gasoline, and therefore also oil demand. Given that South Africa's refining capacity is estimated to be roughly equal to its oil consumption until 2030 [147], but it is projected to import virtually all of its crude oil [67], it can be assumed that reduced gasoline demand through more fuel-efficient cars will impact water resources from refining only, decreasing water withdrawals by on average $33m^3$ per TJ[15].

Measures with an indirect impact on GHG emissions: change of electric power consumption

Measures that reduce electricity demand increase water availability if the saved electricity would otherwise be produced in power plants that require water for cooling.

[13] This number is also consistent with the mitigation potential in the LTMS scenario, 2.1 Mt CO_2e ([110] p. 95).

[14] See [20], [67], [78], [144].

[15] This value is taken from [5], but nevertheless lies well within the range of 25–65 m^3/TJ given by other reports (e.g., [1], see section 5.2).

In our case, the water impact is calculated based on the power plant mix that is *avoided* through such efficiency options[16]. The water intensity of the avoided power mix depends on the types of power plants and the cooling technologies within the various types.
In China and South Africa, 72% and 93%, respectively, of the power generation that is avoided if all energy efficiency options from the GHG abatement cost curve were implemented is coal-based[17]. The water intensity for these coal power plants was calculated based on the projected 2030 water intensity of *all* coal power plants, which again was determined from the existing power plant fleet, the plants under construction and those in planning: Platt's power plant database contains a list of virtually all of China's and South Africa's power plants, including location and – in about half the cases – information about the cooling type. For China, the list comprises 6,624 operating units with a total capacity of 888 GW, and for South Africa, 311 operating units and 45.4 GW. Given that the IEA estimates China's 2008 generation capacity at 780 GW [20] and Eskom sees South Africa's at 45.5 GW [117], Platt's seems to give an holistic list; the overshoot in China is probably due to smaller industrial on-site or municipal plants not comprised in the IEA data. Including plants under construction, in planning, retired, in revision or on standby, the databases include 8,894 units with 1,498 GW for China, and 533 units with 845 GW in South Africa. Figure 6.1 gives a snaphsot for China.
In order to determine the likely cooling technology for plants where this information was not further specified, an estimate was performed on the basis of the plant's location: if the power plant is located in close proximity to the sea, it was assumed to be cooled in an open cycle with sea water; if it is located close to a river and clearly has cooling towers, it was assumed to be cooled in a closed-cycle wet cooling configuration. The power plants were furthermore allocated to the different basins/WMAs based on their location – this allowed to determine the water intensity not only on national level, but

[16]This approach is consistent with the logic employed in [4] and [77] for the assessment of the GHG abatement potential of such efficiency options.

Another approach would be to calculate the water intensity of the existing power generation mix for each year and take this as the relevant water intensity. In this case, the marginal utility of energy efficiency measures with regard to water would decrease with increased penetration of low-water power sources such as wind or photovoltaics, in contrast to the approach sketched out above, where the marginal utility stays constant between 2010 and 2030. Both approaches have their justification: while the "fixed" approach allows to properly assess a "what-if" scenario ("Taking the Business-as-Usual case as the starting point, what would be the impact on water availability of an efficiency measure"), the dynamic aproach allows to determine the water availability impact of an efficiency option at the time of its implementation.

[17]With the remainder being gas, in the case of South Africa, and a mixture of biomass, gas, small hydro and small local generation units summarized as "other" in the case of China (in [4]).

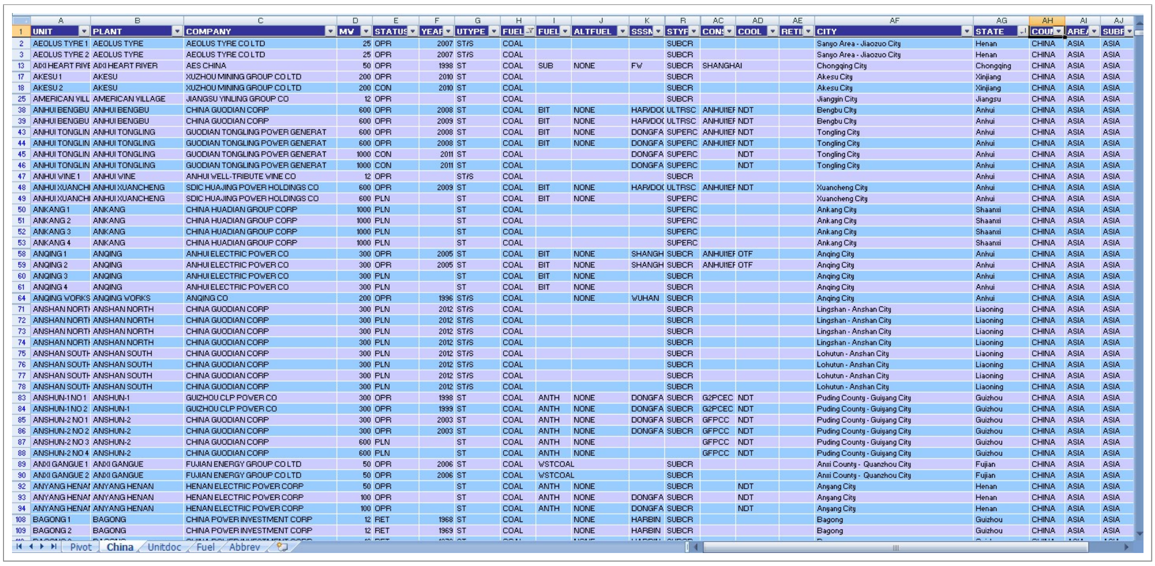

Figure 6.1.: *Snaphot of the Platt's power plant database for China, used to determine the water intensity of the conventional power mix.*

also for each river basin/WMA individually, which is important for the localization of the water impact of (national) GHG mititgation options.

The water intensities of generation technologies other than coal in the avoided power mix, accounting for 28% (China) and 7% (South Africa), are taken from the values discussed in section 5.2, and the split by basin or WMA was assumed to follow the distribution of the coal-fired power plants.

Table 6.1 gives an overview of the water intensities used for the calculation of the BAU power mix (in this work).

Cooling technology	m^3/MWh	*Source*
Subcritical, wet cooling tower	2.1	[2], [148]
Supercritical, wet cooling tower	1.8	[149]
Once-through cooling freshwater	133	[148], [150]
Once-through cooling seawater	1.1	[135], [148]
Dry cooling	0.2	[135]
CCGT (wet cooling)	0.9	[135], [148]
Dedicated biomass (wet cooling)	2.5	[135], [148]

Table 6.1.: *Water intensities (withdrawals) of fossil-thermal power plants. These values were used to determine the average water intensity of the power mix that is avoided through energy efficiency measures or alternative power sources.*

Measures with an indirect impact on GHG emissions: alternative power sources

The water intensities of alternative power sources such as nuclear, solar, wind, biomass, geothermal and carbon capture and sequestration (CCS) – which make up 40% of China's and 56% of South Africa's GHG mitigation potential – differ, and the respective impact on water availability can be positive or negative. Section 5.2 discussed that thermal power plants that operate at lower temperatures than coal-fired units require more withdrawals per MWh, all other things being equal. Of the alternative sources, nuclear, solar thermal, geothermal and biomass, but also coal plants equiped with CCS belong into this category, while wind and photovoltaic power require negligible water amounts.
The reference water intensity for alternative power sources is that part of the Business-as-Usual power mix that is avoided through the increased penetration of alternative power sources[18]. The water intensity of this mix was determined based on the same logic and sources as sketched out in the preceding section.
The delta between the water intensity of the avoided mix and the water intensity of the alternative power source give the net water impact per mitigation option, whereby the latter was determined based on the literature values discussed in section 5.2.
One exception is nuclear power, for which a similar approach was followed as for coal-fired power plants in China: based on single-site data from the Platts power plant database, the cooling type of each existing, contructed and planned power plant was determined. From this, a weighted average nuclear (fresh-)water intensity could be determined. In South Africa, the site (and cooling technology) of a potential nuclear power station are under discussion – therefore, not only the cooling type, but also the regional water impact of this GHG mitigation option could be assessed with relative precision.
Table 6.2 shows the values used for the water intensities of alternative power sources.

Lastly, the water intensity of gas CCS was simply calculated based on an assumed efficiency penalty of 20%. Coal CCS water intensity values were – for new builds – put in relation to the water intensities of the coal power plants in planning and under construction. For retrofits, they were set in relation to the water intensity of the existing coal power plant fleet.

[18] Again consistent with the logic followed in [4] and [77] for calculating the GHG abatement potential of the alternative power sources. This mix differs from slightly the Business-as-Usual power mix that is avoided through the increased penetration of energy efficiency options as mentioned above, with the share of coal-fired generation being slightly higher (97% in China, 93% in South Africa).

Technology	m^3/MWh	*Source*
Coal CCS, new built	1.2/1.5	[2], [135], [148]
Coal CCS, new built	12.7/1.7	[2], [135], [148]
Gas CCS, new built	1.0	[2], [135], [148]
Gas CCS, retrofit	1.1	[2], [135], [148]
Geothermal	5.3	[2]
Hydro	0.04-0.18	[135]
Nuclear	2.0/0.4	[2], [135], [148]
Solar thermal	3.0	[135]
Photovoltaics	0.1	[135]
Wind	0	[135]

Table 6.2.: *Water intensities (withdrawals) of alternative power sources. If two values are separated by a slash, the first value stands for China, the second for South Africa.*

Regionalization

As it makes no difference for the overall balance where greenhouse gases are emitted within a country, the national subdivision is the most granular data available in the GHG abatement curve report [4] [77]. Water in contrast is a local resource, and it well makes a difference where availability is increased.

To get a meaningful picture, GHG mitigation options and their impact on water availability therefore needed to be broken down to the 10 Chinese river basins or 19 South African Water Management Areas.

The suitable metric for this breakdown depends on the respective GHG mititgation option: for options with a direct impact on water availability, the regionalization should correlate with the distribution of respective activities. Water requirements for biofuels for example should be accounted for in those basins/WMAs that plant relevant energy crops.

Mitigation options with an indirect impact on water availability need to be assessed differently. In this case, it is not necessarily the location of the mitigation option that is important:

- Measures that reduce GHG emissions through reduced use of fossil fuels save water in those basins where the fuel is mined, extracted or refined[19]. As three quarters

[19] After taking account for the respective import-export balance.

of China's coal is mined in the Song, Huang (Yellow) and Hai river basins, saving one TJ of coal *somewhere* increases water availability mostly in those basins – on average by 1.1 m^3 in the Song, 1.9 m^3 in the Hai, and 3.9 m^3 in the Huang/Yellow river basin (see page 102).

- Measures that reduce electricity demand in one of *China's* basins are assumed to impact water availability also in this basin, under the the assumption that its not yet fully interlinked national transmission grids will remain at least partially decoupled until 2030[20].
  The regional distribution of electricity efficiency measures from industry was obtained from [5][21]. Road transport, commercial and residential sector measures were allocated to basins based on the basin population split.
  The impact on water availability of energy-efficiency measures in *South Africa* was allocated to Water Management Areas based on their share of the avoided power mix, which are not necessarily those where the measures are implemented. This approach seemed valid, as a single transmission grid spans the whole country. The allocation of measures that impact fossil fuel use followed the same logic as for China.

- For *solar and wind* power, solar irradiation and wind speed maps as well as national buildup plans were consulted in order to determine the distribution of capacities (given in [4] [77]) across basins/WMAs. For *China*, it was then assumed that power plants were cut off first in proximity to the new power sources and thus reduce water withdrawals in the respective basin, assuming again independent transmission grids[22]. In *South Africa*, wind and photovoltaics were assumed to reduce water demand by the (national) average water intensity of the avoided power mix[23].

- If no clear regional prefernces could be derived for an alternative power sources

[20] Recent information on the state of the Chinese transmission network are rather difficult to find. Of the information available, [151], an official site, and [152] date back several years and argue that China consists of six more or less independent power grids.

[21] The underlying data of the Water Resources Group report [5] includes data on per-basin water withdrawals of the major branches of industry, which were used also as a proxy for the per-basin breakdown of these industries.

[22] In the case that solar and wind installations outstripped thermal power capacity in a basin, it was assumed that it substituted generation capacity in neighboring basins.

[23] First, wind and photovoltaics require no water themselves and therefore do not change demand in the WMA where they are installed. Second, the national transmission grid was assumed to allow a feed of the produced power no matter where it is produced – wind and photovoltaics therefore increase water availability by the national average water intensity of the avoided power mix.

(e.g., *biomass*), the local distribution was kept in check with the current distribution for power generation capacities. The local distribution of *nuclear* power stations followed the single-site assessment based on Platt's power plant database that was discussed in the preceding section.

To be complete, it needs to be noted that all GHG mitigation options that reduce the output of fossil-fired power plants also reduce coal, gas and oil demand – the water savings associated with the thereby reduced mining, refining and extraction were accounted for as sketched out above, i.e., in the basins with respective mining or production capacities.

6.5. Notes on cost

A key metric to assess in our context are cost (or savings) that result from the implementation of a specific set mitigation options. After all, it is not so much the question whether a water gap can be closed or GHG emissions can be reduced in principle – most problems of this sort can be resolved if money was not the limiting factor – but what the financial consequences of an envisioned solution mix are. For this reason, *cost curves* were at the core of both reports [4] and [5]. The following sections give an overview of the various cost terms used.

6.5.1. Investment, operational, societal cost and the cost of capital

The cost depicted in the cost curves of chapter 4 show the *incremental full cost in 2030 relative to the Business-as-Usual (or reference)* case for each measure. As given in equation (4.1), they are defined as

$$\text{Mitigation cost} = \frac{\text{Cost of mitigation} - \text{Cost of reference}}{\text{GHG emissions of reference} - \text{GHG emissions of mitigation}} .^{24} \quad (6.1)$$

I.e., all cost are put in perspective to the reference, or Business-as-Usual, case.
Equation (6.1) gives what is termed *full cost*, which are composed of investment cost and operational cost, and depend on the assumed cost of capital.

[24] Adapted from [4], p. 147. For the case of GHG mitigation options; for options increasing water availability, the denominator simply includes the delta of water availability between the reference and the mitigation options instead of GHG emissions.

Investments and cost of capital

The investments required for each measure (and its reference case equivalent) were determined in [4] and [5]. Investments for a mitigation option can be higher or smaller than in the reference scenario.
To make different years comparable, the investments were annualized over the lifetime of the mitigation option assuming a certain cost of capital, which is equivalent to the standpoint that the investments are financed by a credit at certain interest. The annualized investments then represent the annuity (principal plus interest) that the debtor pays over the lifetime of the asset.
Let C be an investment, n the asset lifetime in years and i the cost of capital. The annualized investment c is then given by

$$c \,=\, C\,i\,\frac{(1+i)^n}{(1+i)^n-1}\,. \tag{6.2}$$

The cost of capital i depend on how the investment is considered. A private houshold would likely have an interest rate in the order of 4–6%, reflecting the average interest a private person would need to accept to receive money from a bank, or – equivalently – reflecting the opportunity cost of capital he/she has for investing the money and not putting it in a bank account.
For corporations, i could be even higher, if it is considered from the standpoint of a required profit margin for a planned investment.
For countries, i could be linked to a the long-term government bond rate which should be in the order of 2–6%.
Pathways to a low carbon economy [4] used a 4% rate for all mitigation options, whereas *Chartering Our Water Future* [5] assumed different cost of capital for the different sectors.
For this work, i was set at 4% for all options to reflect government bond rates, for two reasons:

- Many mitigation options indeed require governmental involvement or support. Especially large-scale infrastructure projects such as new hydro dams or large power stations are often built directly by the government, or by an entity that is backed by the government. If mitigation options are of smaller scale and implemented by private persons (or corporations), such as energy-efficient building, many examples exist of a government providing for low-interest loans that have an i closer to its cost of capital than to what private households would receive otherwise.
- Using one interest rate judges all measures by their economic cost only, making a comparison easier from a societal standpoint. It has to be noted, however, that

this approach likely underestimates the real cost of a mitigation pathway, as profits margins for businesses, who will need to play a big role in the tranformation, are not yet factored in.

Operational cost

Most mitigation options incur different operational cost for labor, electricity, fossil fuels, or other input factors, than the Business-as-Usual alternative. As an example, consider the switching from incandescent lamps to light-emitting diodes (LEDs) of equal luminosity: LEDs require less electricity than incandescent lamps; the operational cost delta between the mitigation option (LED) and the Business-as-Usual solution (incandescent light bulbs) can then be determined for a given electricity price. Finally, knowing the GHG-footprint of the saved electricity[25] allows to express the operational cost difference expressed in terms of *USD per* tCO_2e.
Adding the difference of the annualized investments to the operational cost difference gives the full cost.

6.5.2. Integrated cost 2010–2030

The full cost, which were at the core of our reference reports [4] and [5], give the cost for a specific year. However, it seems equally important to evaluate the *integrated* cost of a certain GHG abatement or water availability mitigation option mix between 2010 and 2030, as such a transformative effort, which involves large-scale investments in all sectors and spans two decades, will certainly require a solid long-term financial planning.
In order to properly acccount for the cost of capital and make installations in different years comparable, a useful approach seems to be to discount all investment and operational costs[26] to one common year – 2030 – and then add them up.
The mitigation options need to be differentiated based on implementation date and asset lifetime in order to properly determine integrated cost:

- *Implementation date.* Measures that are implemented before 2020 require investments and operational cost (or savings) already in the first decade. These options are then assumed to stay put for the second decade (2020–2030), resulting in ongoing operational cost/savings. In contrast, measures that are implemented after 2020 only incur cost during the second decade.

[25] Which depends – as described in the preceding section on cross-dependencies – on the power mix that is avoided through increased energy efficiency.
[26] Again, considered relative to the reference case.

- *Lifetime.* Measures with a lifetime l greater than 20 years do not require replacement investments before 2030, and neither do measures with $l > 10$ years if implemented after 2020. All other measures need to be replaced at least partly between 2010 and 2030 for the combined potential of all measures to unfold in 2030.
  This makes the early implementation of a measure with net-positive cost unattractive and pushes them back as far as possible – something which could not be investigated by only studying the full cost in 2030. In contrast, measures where operational savings exceed investments will be implemented as early as possible.

Given this, five cases of distinction for the integrated cost can be made:

1. $l > 20$, *implementation 2010–2020.* No replacement investments necessary. The measure is gradually implemented between 2010 and 2020[27].

2. $l > 10$, *implementation 2020–2030.* Similar to the preceding case. No replacement investments necessary; implementation is spread between 2020 and 2030.

3. $l < 10$, *implementation 2020–2030.* No replacements necessary, assumed that implementation is started l years before 2030[28].

4. $l < 10$, *implementation 2010–2020.* Under the assumption that implementation is started l years before 2020, the first decade is the same as in the preceding case. However, replacement investments are required over the course of the second decade – for each year, $1/l$.

5. $10 < l < 20$, *implementation 2010–2020.* Similar to the last case, with the differentiation that replacement investments are only required over part of the decade 2020–2030. Initial implementation of the measure takes place between 2010 and 2030, with equal parts implemented each year.

The integrated cost are composed of investments and operational cost/savings; the following sketches out the formula for the first of the above cases.

Discounted investments

Let i again be the cost of capital and C the investment for a given mitigation option relative to the reference. As $l > 10$ years, it is assumed that the implementation of the

[27] It is assumed that the measures can be implmented gradually and that cost incur proportionally: in year 1, a tenth of the investment and operational cost incur. In year 2, a further tenth of the investments incur, whereas the operational cost/savings increase to two tenths, and so forth.

[28] It is assumed that a share of $1/l$ is implemented each year.

solution is spread evenly over the ten years between 2010 and 2020. The 2020 (future) value of the investment is then given by

$$FV_C(2020) = \frac{C}{10}\sum_{k=1}^{10}(1+i)^k \underset{i=4\%}{=} 1.25\,C \tag{6.3}$$

As no replacement investments are necessary between 2020 and 2030 ($l > 20$), this value just needs to be discounted to 2030 in order to receive the final future value:

$$FV_C(2030) = FV_C(2020)\,(1+i)^{10} \underset{i=4\%}{=} 1.48\,FV_C(2020)\ . \tag{6.4}$$

Discounted operational cost

Let O be the operational cost/savings per year for the mitigation option relative to the reference. The integrated operational cost/savings that are incurred between 2010 and 2020, discounted to 2020, are then

$$\begin{aligned} FV_O(2020) &= \frac{O}{10}(1+i)^{10} + \frac{2\cdot O}{10}(1+i)^9 + \ldots + \frac{10\cdot O}{10}(1+i) \\ &= \frac{O}{10}\sum_{k=1}^{10}(11-k)(1+i)^k \underset{i=4\%}{=} 6.46\,O\ , \end{aligned} \tag{6.5}$$

with the term $\frac{2O}{10}(1+i)^9$ for example meaning that the operational cost/savings of year 2 (=2021) are double the amount of the first year, as already two tenths of the option are implemented.

The future value of the operational cost/savings in 2030 is now composed of two parts: the term $FV_O(2020)$ discounted to 2030 ($FV_{O1}(2030)$), and the sum of all operational cost/savings between 2020 and 2030, discounted to 2030 ($FV_{O2}(2030)$):

$$FV_{O1}(2030) = (1+i)^{10} FV_O(2020) \tag{6.6}$$

$$FV_{O2}(2030) = O\left((1+i)^{10} + (1+i)^9 + \ldots + (1+i)\right) \tag{6.7}$$

$$\begin{aligned} FV_O(2030) &= FV_{O1}(2030) + FV_{O2}(2030) \\ &= \frac{O}{10}\left((1+i)^{10}\sum_{k=1}^{10}(11-k)(1+i)^k\right) + O\sum_{k=1}^{10}(1+i)^k\ . \end{aligned} \tag{6.8}$$

The sum of $FV_O(2030)$ and $FV_C(2030)$ gives the integrated cost of the measure (again relative to the reference), discounted to 2030. It needs to be noted that this cost term neglects operational cost/savings after 2030, which should incur for some time even if no replacement investments were made.

Appendix E contains the formulas for the other four cases.

6.6. Modeling of integrated water–GHG pathways

So far, we discussed how cross-intensities for water and GHG mitigation options can be determined and what cost parameters can be considered.
The goal of an integrated modeling of all options now is to determine the optimal set of water/GHG mitigation options, given one objective function and a number of contraints, such as a water availability and a GHG reduction goal. The Simplex method, a specific numerical approach to the general linear programming problem, can perform this task.

6.6.1. Linear programming

A linear programming problem can generally be described as the *task of finding the maximum (or minimum) of a linear function subject to a set of linear constraints.*
A linear problem can be small enough that the solution can be found by hand. However, most problems – including the ones discussed in this thesis – include many more variables and constraints and are therefore best solved with a dedicated calculation routine.

The standard maximum and minimum problem

Consider the following example: Find the combination of x_1 and x_2 ($x_1, x_2 \in \mathbb{R}$), that maximize $x_1 + x_2$, subject to $x_1 \geq 0$, $x_2 \geq 0$, and

$$\begin{aligned} 5x_1 + 3x_2 &\leq 9 \\ -3x_1 + x_2 &\leq 1 \\ 5x_1 + x_2 &\leq 5 \end{aligned} \tag{6.9}$$

This problem contains two variables (x_1 , x_2), a linear *objective function* that is to be maximized ($x_1 + x_2$) and five linear contraints that are all inequalities: the three equations in (6.9), plus the two nonnegativity constraints $x_1 \geq 0$, $x_2 \geq 0$.
Given that the problem contains only two variables, it can be solved graphically. Starting from the unbounded x_1x_2-plane, each inequality restricts possible combinations of x_1 and x_2 to a half plane. The area that lies within all five possible half planes defines the set of *feasible* solutions.
The shaded area in figure 6.2 shows all feasible combinations for the constraints given above. The objective function $x_1 + x_2$ can be represented by a line with slope -1. The value of the objective increases by progressing away from the origin, in top-right direction in figure 6.2. The maximal value of the problem will thus be reached at that corner of the shaded plane that is the furthest to the top right for a line with slope -1. In

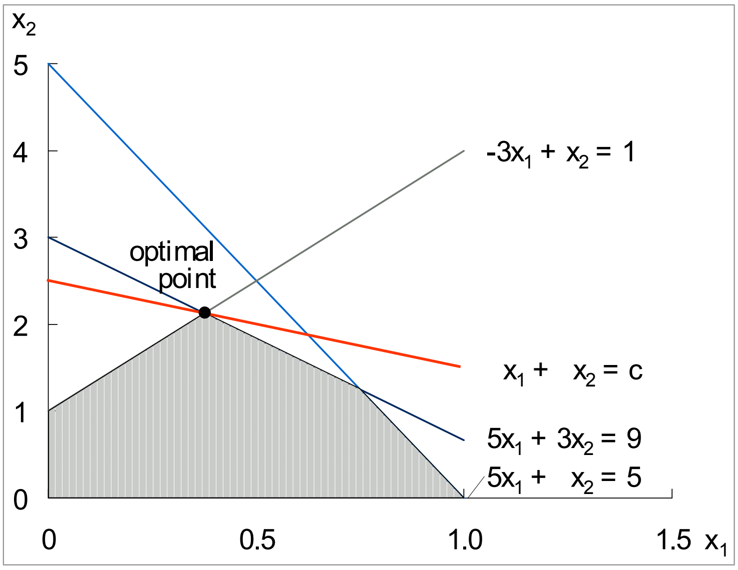

Figure 6.2.: *Grahpical illustration of the linear problem of equation* (6.9).

our case, this is the intersection of the lines $5x_1 + 3x_2 \leq 9$ and $-3x_1 + x_2 \leq 1$, yielding $x_1 = 3/7$, $x_2 = 16/7$ and $x_1 + x_2 = 19/7$.

More generally, a linear programming problem is defined as follows:

Find an n-dimensional vector $\vec{x} = (x_1, \ldots, x_n)$ to maximize

$$\vec{c}^{\,T}\vec{x}\,,$$

where $\vec{c}$ is also n-dimensional. The problem shall be subject to the contraints

$$\begin{aligned}
a_{11}x_1 + a_{12}x_2 + \ldots + a_{1n}x_n &\leq b_1\\
a_{21}x_1 + a_{22}x_2 + \ldots + a_{2n}x_n &\leq b_2\\
&\vdots\\
a_{m1}x_1 + a_{m2}x_2 + \ldots + a_{mn}x_n &\leq b_m
\end{aligned} \tag{6.10}$$

and

$$x_1 \geq 0,\ x_2 \geq 0, \ldots, x_n \geq 0\ .$$

The terms in (6.10) can be expressed in matrix form, with A an $m \times n$-matrix,

$$\begin{pmatrix}
a_{11} & a_{12} & \ldots & a_{1n}\\
a_{21} & a_{22} & \ldots & a_{2n}\\
\vdots & \vdots & \ddots & \vdots\\
a_{m1} & a_{m2} & \ldots & a_{mn}
\end{pmatrix}$$

The linear programming problem can then be reformulated to the following:

Maximize $\vec{c}^{\,T}\,\vec{x}$ *, subject to*

$$\begin{aligned} A\,\vec{x} &\leq \vec{b} \quad \text{and} \\ \vec{x} &\geq \vec{0}\,. \end{aligned} \tag{6.11}$$

This problem is called the *Standard Maximum Problem.* Conversely, the *Standard Minimum Problem* is defined as the search for an m-dimensional vector $\vec{y}$ that minimizes

$$\vec{y}^{\,T}\vec{b} = y_1 b_1 + \ldots + y_m b_m\,,$$

subject to the contraints

$$\begin{aligned} \vec{y}^{\,T} A &\geq \vec{c}^{\,T} \\ \vec{y} &\geq 0\,. \end{aligned} \tag{6.12}$$

Equations (6.11) and (6.12) show that the main constraints of the standard maximum (minimum) problem are "$\leq$" ("$\geq$"). It can be shown that all linear programming problems can be converted to the standard form. For example, if an unrestricted variable x_i exists, it can be replaced by the difference of two restricted variables, $x_i = w_i - z_i$, $w_i, z_i \geq 0$, adding one new variable and to new contraints to the problem.

A linear programming problem is *feasible* if a solution vector $\vec{x}$ or $\vec{y}$ exists that satisfies the constraints. Otherwise, the problem is called *infeasible.* It is *bounded* if the objective function can only obtain finitely large values and is otherwise said to be *unbounded.*

The Simplex method

The preceding section described the general form of a linear programming problem, and how a two-dimensional example can be solved graphically. Larger problems with a multitude of variables and constraints require specific algorithms – one widely spread is the Simplex method.

Technically, it is easier to solve a problem that contains only equalities. For this, a *slack variable* $\vec{s}^{\,T}$ is included in the term $\vec{y}^{\,T} A \geq \vec{c}^{\,T}$ of the standard minimum problem: $\vec{s}^{\,T} = \vec{y}^{\,T} A - \vec{c}^{\,T}$. The problem thus becomes:

Find vectors $\vec{y}$ *and* $\vec{s}$ *to minimize* $\vec{y}^{\,T}\vec{b}$*, subject to* $\vec{y}^{\,T} A - \vec{c}^{\,T} = \vec{s}^{\,T}$*, and* $\vec{s}$*,* $\vec{y} \geq 0$*.*

The problem can now be re-written in a Simplex tableau, where the first and last columns represent the vectors of the objective function that need to be minimized,

$$
\begin{array}{c|cccc|c}
 & s_1 & s_2 & \dots & s_n & \\
\hline
y_1 & a_{11} & a_{12} & \dots & a_{1n} & b_1 \\
y_2 & a_{21} & a_{22} & \dots & a_{2n} & b_2 \\
\vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\
y_m & a_{m1} & a_{m2} & \dots & a_{mn} & b_m \\
\hline
1 & -c_1 & -c_2 & \dots & -c_n & 0
\end{array}
\tag{6.13}
$$

If $-\vec{c} \geq 0$ and $\vec{b} \geq 0$, a solution is $\vec{y} = 0$, $\vec{s} = -\vec{c}$ and $\vec{y}^{\,T}\vec{b} = 0$[29].

The solution for this minimization problem could be read from the Simplex tableau. But the method also holds true for the general case – the task of finding the minimum therefore is to transform a problem with initially negative entries in $\vec{-c}$ and $\vec{b}$ into such a form that the lowest row and rightmost column of the Simplex tableau only contain nonnegative numbers.

Successive *pivot operations* perform this task. Pivoting about one entry a_{ij} of the constraints matrix A means that a y_i of the left column of (6.13) is expressed in terms of the other y_j and s_j. Taking for example a_{11} gives the following Simplex tableau

$$
\begin{array}{c|cccc|c}
 & y_1 & s_2 & \dots & s_n & \\
\hline
s_1 & \hat{a}_{11} & \hat{a}_{12} & \dots & \hat{a}_{1n} & \hat{b}_1 \\
y_2 & \hat{a}_{21} & \hat{a}_{22} & \dots & \hat{a}_{2n} & \hat{b}_2 \\
\vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\
y_m & \hat{a}_{m1} & \hat{a}_{m2} & \dots & \hat{a}_{mn} & \hat{b}_m \\
\hline
1 & -\hat{c}_1 & -\hat{c}_2 & \dots & -\hat{c}_n & \hat{k}
\end{array}
\tag{6.14}
$$

If the vectors in the upper row are now termed $\vec{u} = (y_1, s_2, \dots, s_n)$ and in the left column $\vec{w} = (s_1, y_2, \dots, y_m)$, the minimization problem can be restated as the task to find vectors $\vec{y}$ and $\vec{s}$ that minimize $\vec{u}^{\,T}\vec{\hat{b}}$, subject to $\vec{u}^{\,T}\hat{A} - \vec{\hat{c}}^{\,T} = \vec{w}^{\,T}$ and $\vec{\hat{s}}$, $\vec{\hat{y}} \geq 0$. The solution to this problem is then $\vec{w} = 0$ and $\vec{u} = -\vec{\hat{c}}$ given that $-\vec{\hat{c}}$, $\vec{\hat{b}} \geq 0$.

The lower-right corner of the simplex tableau that contained the value of $\vec{y}^{\,T}\vec{b}$, is transformed accordingly by replacing y_1,

$$
\begin{aligned}
\sum_{i=1}^{m} y_i b_i &= \frac{b_1}{a_{11}} s_1 + \left(b_2 - \frac{a_{21} b_1}{a_{11}}\right) + \ldots + \left(b_m - \frac{a_{m1} b_1}{a_{11}}\right) + \frac{c_1 b_1}{a_{11}} \\
&= \vec{w}^{\,T}\vec{\hat{b}} + \hat{k}\ ,
\end{aligned}
$$

[29]This is feasible, as the conditions $\vec{y}^{\,T}A - \vec{c}^{\,T} = \vec{s}^{\,T}$ and $\vec{s}$, $\vec{y} \geq 0$ are fulfilled, but $\vec{y}^{\,T}\vec{b}$ cannot made smaller, given that $\vec{s}$, $\vec{y} \geq 0$.

where $\hat{k}$ is the minimum value of the objective function.

The solution to an arbitrary minimization problem can now be found by randomly pivoting about entries $\hat{a}_{ij}$ until $-\hat{\vec{c}}$, $\hat{\vec{b}} \geq 0$. In larger problems, this approach would however require huge computational power. The Simplex method therefore introduces some rules on what elements $\hat{a}_{ij}$ to choose for pivoting: for example, if entries in $\vec{b}$ are negative, one of these is chosen (yielding a row i_1 in the Simplex tableau). A negative entry a_{i1j1} in row i_1 is then chosen for pivoting, such that the ratio b_{i1}/a_{i1j1} is smallest with respect to the ratio b_i/a_{ij1} with $b_i, a_{ij1} \geq 0$. Similarly, if all b_i are (already) positive, an $a_{i1j1} > 0$ in column j_1 with $-c_{j1} < 0$ is chosen such that the ratio b_1/a_{i1j1} is smallest. Such rules in general help to increase computation efficiency.

6.6.2. Linear optimization applied to water-GHG patwhays

Objective functions and constraints

The goal of this work is to assess integrated water-GHG mitigation pathways. Admittedly, this is a broad definition and still allows many different objective functions and boundary conditions. There are however some concurrent properties: if $\vec{x}$ is the vector of the potentials[30] of our water/GHG mitigation options, two constraints for our linear optimization problem should hold true in all cases,

$$\begin{aligned} x_j &> 0 \;\; \forall\, j = 1 \ldots n \\ x_j &\leq x_{j,max} \;\; \forall\, j = 1 \ldots n \end{aligned} \tag{6.15}$$

The *nonnegativity constraints* keep hold of the fact that the original mitigation potentials shall not be negative, i.e., have an adverse impact, while the second equation restricts each option to a maximum potential (as determined in [4] or [5]).

The other parameters besides the potential x_j of a mitigation option j are its cost (investment, operational cost, full cost in a given year, or integrated cost) and water and carbon intensity[31]. Furthemore, global constraints such as a GHG abatement goal, water availability goals, or a cost cap can be included[32].

[30] Potentials in terms of incremental water availability (in million cubic meter) or reduced GHG emissions (in t CO_2e).

[31] Section 6.4 discussed how cross-dependencies are determined. In our linear model, each GHG mitigation option now has a distinct water intensity (which can also be zero, in the case of no cross-dependency within the boundaries of this effort) and a GHG-intensity of 1. Inversely, each water availability option has a distinct GHG intensity and a water intensity of 1.

[32] These global constraints are linear combinations of the individual potentials x_j, of the form $a_1x_1 + a_2x_2 + \ldots + a_nx_n \leq A$, where the a_j are for example the full cost of a mitigation option.

Multiple optimization problems can now be defined, which however are similar in structure: in each case, either a cost or intensity parameter a_j factors into the objective function, with the other parameters being part of the boundary conditions.
The following optimization problems were investigated in the course of this work:

1. **Increase water availability and reduce GHG abatement to a given goal at minimal integrated cost.**
   In this case, the integrated cost per measure $c_{j,int}$ build the objective function together with the potentials x_j,
   $$\min \vec{c}_{int}^{\,T}\,\vec{x}\,,$$
   subject to the boundary conditions, in addition to those mentioned in (6.15),
   $$\begin{aligned} \vec{i}_{GHG}^{\,T}\,\vec{x} &\geq G_{GHG} \\ I_{H_2O}\,\vec{x} &\geq \vec{g}_{H_2O}\,, \end{aligned}$$
   where $\vec{i}_{GHG}$ is the vector of the GHG-intensities of mitigation option j, and G_{GHG} the overall GHG emission reduction goal. I_{H_2O} is a $m \times j$ matrix, where each i_{mj} is the water intensity of a mitigation option in the n-th river basin/WMA[33] and $\vec{g}_{H_2O}$ the vector of the basin/WMA water availability goals[34]. Following the orginal reports [4] and [5], G_{GHG} and $\vec{g}_{H_2O}$ could for example be the full GHG potentials from the national cost curve subsets (9,143 Mt CO_2e for China, 341 Mt CO_2e for South Africa), and the respective water gaps (201 km^3 for China, 2.9 km^3 for South Africa).

2. **Increase water availability and reduce GHG abatement to a given goal at minimal investments or full cost in 2030.**
   Very similar to the preceding case; the only difference being the cost term in the objective function, which either is $\vec{c}_{invest}$ (investments) or $\vec{c}_{2030}$ (full cost 2030) instead of $\vec{c}_{int}$.

3. **Maximize GHG emission reductions under the constraint of a water availability target and fixed financial volume.**
   The GHG-intensities $i_{j,GHG}$ factor into the objective function, while the cost $c_{j,\ldots}$[35] become a part of the boundary condition:
   $$\max \vec{i}_{GHG}^{\,T}\,\vec{x}\,,$$

[33]The water intensities do not differ between basins in most cases, though.
[34]I.e., each $g_{1\ldots n}$ is the water availability goal for one basin.
[35]Which can be either integrated, investment, operational or full cost for a given year.

subject to

$$\begin{aligned} \vec{c}_{...}\,\vec{x} &\leq C_{...} \\ I_{H_2O}\,\vec{x} &\geq \vec{g}_{H_2O}\,, \end{aligned}$$

where $C_{...}$ is the financial volume (in terms of investments, integrated cost or full cost) available.

4. **Maximize water availability under the constraint of a GHG emission reduction target and fixed financial volume.**
Similar to the preceding case. The water intensities i_{j,H_2O} move into the objective function while the GHG intensities $\vec{i}_{GHG}$ become part of the boundary conditions.

Isoinvestment curves

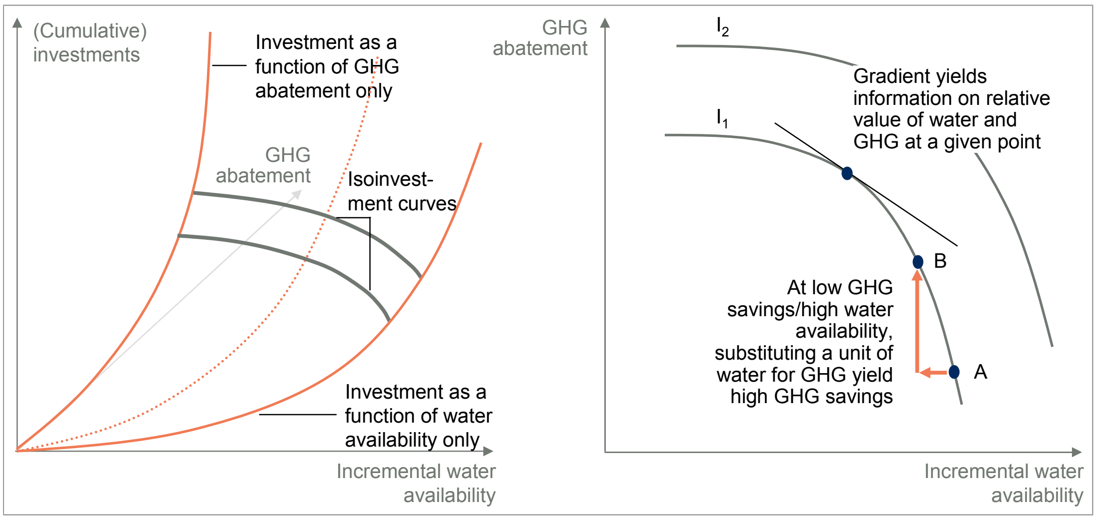

Figure 6.3.: *Concept of the isoinvestment curve. Left, 3d-graph with the position of isoinvestment curves ($x-$axis: incremental water availability; $y-$axis: GHG abatement; $z-$axis: (cumulative) investments. Right, cut parallel to the (x, y) plane showing two isoinvestment curves.*

The last two problems deal with the question of how returns, in terms of increased water availability and/or reduced GHG emissions, can be maximized under financial constraints.
Consider for example investments. Maximizing only one resource, one would expect that total investments increase steadily and at accelerating rate until the given constraint is

satisfied[36]. The left part of figure 6.3 shows this: investments (shown along z axis) grow along the x and y axis in an accelerating way[37].
It seems plausible that investments into combinations of two resources should grow at comparable rates, pictured in the dotted red line in the left graph of figure 6.3. An *isoinvestment curve*, i.e., a function $z(x, y) = C$ that connects all optimal combinations of water and GHG savings with the same total investment needs should therefore be concave with respect to the origin of the (x, y) plane[38].

The right part of figure 6.3 pictures two isoinvestment curves as functions of GHG abatement and incremental water availability, and gives another reason for its concave form: if the objective is for example to maximize water availability, the model chooses mitigation options (mainly) according to their contribution to water availability per unit of investment. At point A, a combination of low GHG emission reduction and high incremental water availability, many and therefore on average expensive water availability measures, but only few and therefore relatively "cheap" GHG mitigation options are implemented. Reducing water availability at fixed investments, i.e., moving to the left on an isoinvement line, will "buy" more GHG abatement than at a point B, where more expensive GHG abatemet options are already implemented, and the cost of an additional tonne of CO_2e emission reduction is higher. If x is the incremental water availability and y stands for GHG abatement it can therefore be said that

The gradient dy/dx of an isoinvestment curve $y(x)$ is the marginal rate of substitution between one cubic meter of increased water availability and one tonne of saved GHG emissions.

The marginal rate of substitution can give information on appropriate price ratios between water and GHG in order to achieve certain combinations of water/GHG savings and investments.

[36] An optimization tool will always move from the cheapest measures (e.g., in terms of investments needed per unit of water availability) to more expensive ones, making each additional unit of water availability more expensive than the previous.

[37] The investment function is shown here as continuous. In reality, investments in many mitigation options are in fact discrete, however (a nuclear power plant for example is either built or not), so a close look at a "real" function would reveal a function that is made up of many small steps (of differing sizes).

[38] Conceptually, isoinvestment lines can be considered as analog to isoquants in production theory. Isoinvestment curves however have a concave curvature while isoquants are typically of convex curvature, due to the fact that the second derivative of our investment functions $I(water, GHG)$ is positive while it is negative for typical functions that measure the output of a good with respect to relevant input factors.

6.6.3. Practical implementation

The linear optimization in this work was done with the solver *lp solve*[39], a mixed integer linear programming solver using the *Simplex* method. The solver was adressed through an Excel add-in.

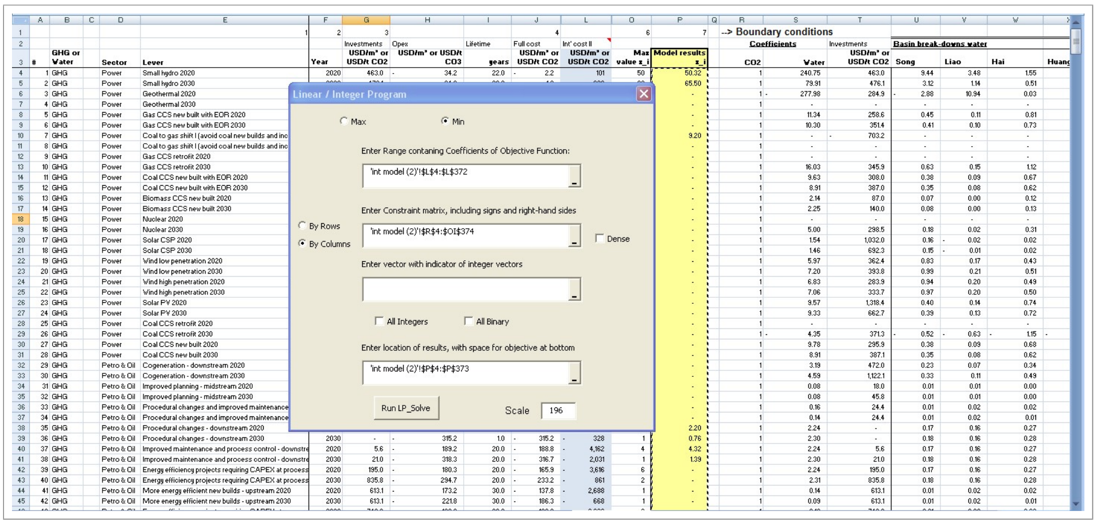

Figure 6.4.: *Snapshot of the Excel link to the linear progamming solver.*

In this environment, the coefficients of the objective function and the vector of variables $\vec{x}$ were given in spreadsheet columns, with each cell or line representing one mitigation option. The boundary conditions consisted of two parts. First, one column each for "global" restrictions on total cost C, total GHG reductions G_{GHG} and incremental water availability by basin g_{k,H_2O}, where $k = 1 \ldots m$ stands for the k-th basin[40]. Second, a $n \times n$ unit matrix that covered the second boundary condition in (6.15), $x_j \leq x_{j,max}$. Figure 6.4 shows a snapshot of the optimization mask. A detailed description of this approach can be found in [153].

[39] For a description and download of the solver, see for example http://lpsolve.sourceforge.net/5.5/.

[40] The individual cells of each column then contain the respective values per measure j: $c_{j,...}$ in the case of C, $i_{j,GHG}$ in the case of G_{GHG} and i_{k,j,H_2O} in the case of g_{k,H_2O}.

7. Interdependencies of water and greenhouse gas pathways

7.1. Water intensity of GHG mitigation options

This chapter will first discuss the water intensities of GHG abatement options, energy carriers and the Business-as-Usual electricity mixes in China and South Africa, which are important inputs for determining the water intensity curves of the GHG abatement options. The GHG impact of water availability options will then be described, and discussed in more detail at the example of three particularly interesting options, desalination, wastewater treatment and no-/reduced tillage in agriculture.
The second part of this chapter then discusses four *intensity curves*: for each of the two countries, a water intensity curve of the GHG abatement options, and a GHG intensity curve of water availability options.

7.1.1. Coal, gas, oil and biofuel provision - China

The preceding chapters mentioned that GHG abatement options can have an indirect impact on water resources through fossil fuel or power demand savings, as both fossil fuel extraction and power generation require considerable amounts of water[1].
Table 7.1 gives the average water requirements for the provision of coal, natural gas, oil and biofuels per unit of energy in China. It furthermore summarizes the percent split of "production" activity by river basin, or, equivalently, by which extent the saving of one unit of energy influences the water availability in a particular river basin: if one Terajoule of coal is saved, the water availability across China increases on average by 9.4 m^3 annually. Of these, 43% are accounted for in the Yangtze basin, 20% in the Hai basin, and so forth[2].
The following paragraphs explain how the water intensities and basin splits in table 7.1 come about.

[1] See section 5.2, page 66.
[2] The import–export balance for a certain fuel is already taken into consideration in table 7.1.

Total/ *basin split*	**Coal** m^3/TJ	**Gas** $m^3/1{,}000\ m^3_{gas}$	**Oil** m^3/TJ	**Biofuels** m^3/MWh
Total	**9.4**	**0.16**	**39.5**	**119**
Song	12%	7%	8%	27%
Liao	5%	7%	17%	0%
Hai	20%	6%	15%	6%
Huang/Yellow	42%	29%	5%	9%
Huai	4%	2%	11%	8%
Yangtze	10%	25%	13%	23%
Southeast	0%	2%	7%	2%
Pearl	1%	2%	11%	23%
Northwest	4%	21%	12%	2%
Southwest	0%	2%	0%	0%

Table 7.1.: *China's domestic water intensity of energy carriers: total demand and percent split by basin (percent values might not add up to 100% due to rounding).*

China: coal mining

According to the IEA, China is expected to produce about 3,300 Mt of coal equivalents by 2030 [67]. Its 2030 demand is estimated at between 3,400 Mtce[3] [67] and 3,500 Mtce [78] – imports thus account for less than 6% of demand. The Water Resource Group [5] estimates average water withdrawals for coal mining in China at 9.4 m^3/TJ[4]. Figure 7.1 gives the total water withdrawals for coal mining and the split by basin according to [5]. It can be seen that three quarters of the coal are mined in just three river basins, the Huang/Yellow,

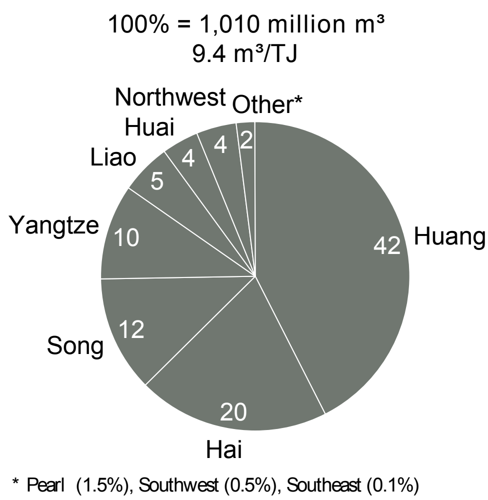

Figure 7.1.: *Water for coal mining.*

[3]Mtce: million ton of coal equivalent.

[4]This is in good agreement with the literature data discussed in section 5.2: according to it, coal mining requires 2–20 m^3/TJ, with surface mining being at the lower, and underground mining at the upper end of this range, 9.4 m^3/TJ seems to be well in range, assumed that coal is mined both via the surface and underground method. (Data on the split of mining methods in China was unfortunately not obtainable from any of the consulted sources.)

Hai and Song. All three are located in the
dry North of the country, and the Hai and Huang basins are expected to experience particularly large water gaps by 2030[5] – this already gives a hint that a cutback in coal demand might be a viable option to relieve water stress in relevant basins beyond conventional options to increase water availability.
Given the low import ratio of coal, it is assumed here that one Terajoule of coal that is saved directly increases China's water availability by 9.4 m^3, with the basin split as given in figure 7.1.

China: oil extraction and refining

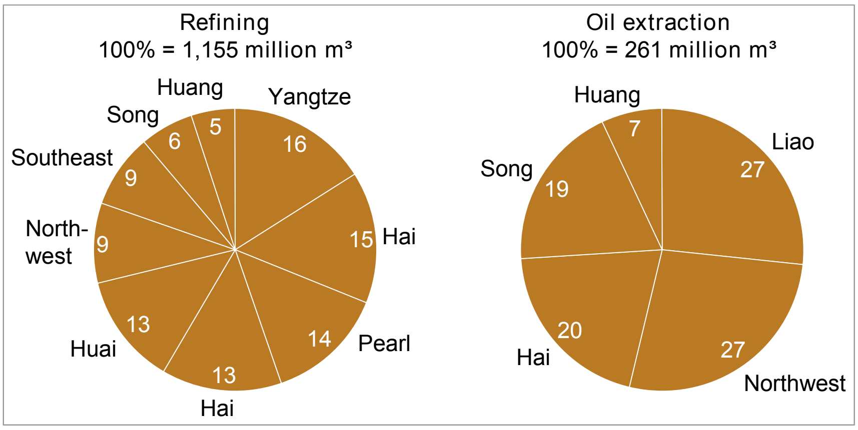

Figure 7.2.: *Water withdrawals for oil refining and extraction in China in the reference scenario, total and split by river basin.*

China is one of the world's largest oil consumers. It imports most of its oil, but has – and is expected to remain so – enough refining capacity to cover domestic demand:

- *Oil production* in China is estimated to decline from 3.7 million barrel per day in 2007 to 3.5 million barrel per day in 2030 day, according to the IEA [144]; translated into yearly figures, production in 2030 is expected to equal 174 Mtoe[6] [144].
- Its *refining capacity* is expected to increase to about 790 Mtoe per year by 2030, from 323 Mtoe in 2006 [144].
- Primary oil demand ist estimated to increase from 360 Mtoe in 2007 [78] to between 760 Mtoe [67] and 810 Mtoe [78]. To cover this demand, imports are expected to reach 650 Mtoe until 2030 [67].

[5]See figure 3.3, page 34.
[6]Mtoe: million tons of oil equivalent.

Based on these numbers, China's oil import ratio lies at around 80% by 2030, up from about 50% in 2006.
The left-hand side of figure 7.2 shows China's water requirements for oil *refining*, as expected for the Business-as-Usual scenario, based on water requirements of 33 m^3/TJ, which were again taken from the Water Resources Group report [5]. The split of refining water needs shows an even distribution between basins, with a slight weight towards basin with sea access. Taking a literature value for conventional oil extraction of 33 m^3/TJ [2], and considering China's high share of imported oil, domestic water withdrawals per Terajoule of oil are estimated at 6.5 m^3/TJ. The special section on China in the IEA's 2007 World Energy Outlook, and the information on the location of Chinese oil reserves therein was used as a base for determining the regional split of water requirements as shown on the right-hand side of figure 7.2.
It is thus assumed that one saved TJ of oil reduces water withdrawals in total by 39.5 m^3/TJ, therefrom 33 m^3 for refining, and 6.5 m^3 for extraction, each split across basins according to figure 7.2[7].

China: natural gas

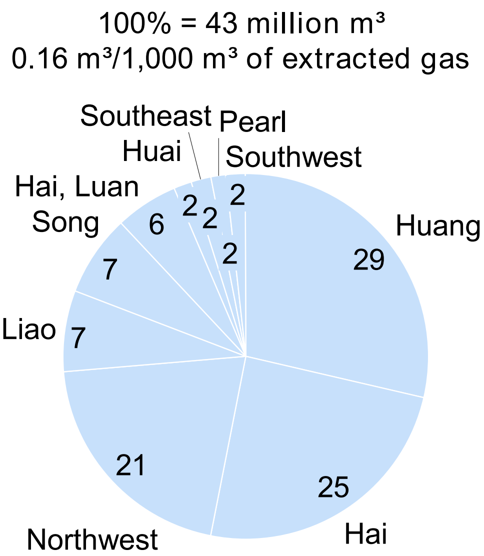

Figure 7.3.: *Water for natural gas.*

The 2007 World Energy Outlook [67] states that natural gas imports were only 0.5 bcm[8] in 2006, but will be 128 bcm by 2030. Over the same time, demand is expected to increase from 59 bcm to 242 bcm[9], while production is estimated to reach 111 bcm in 2030 (vs. 51 bcm in 2005) [67]. Thus, imports will grow continuously, accounting for more about half of China's demand by 2030.
[5] estimates that natural gas extraction and processing requires 9 m^3/TJ. Figure 7.3 gives the overall water requirements for natural gas extraction and processing within China and the split of water requirements by basin (in the Business-as-Usual scenario), under the assumption that half the gas is banked in China. Similar to coal, three drier Northern basins (Huang, Hai, Northwest) account for almost three quarters of total water needs (or estimated gas extraction, respectively).
Overall gas withdrawals are however only about 4% of those for oil and coal, which is consistent with the literature values given in section 5.2.

[7] The overview in table 7.1 in section 7.1.1 gives the sum and weighted distribution of basin oil extraction and refining water requirements.
[8] bcm: billion cubic meter
[9] From the 2009 World Energy Outlook (WEO) [78].

China: biofuels

Biofuels are mainly used as an alternative to oil-based fuels in transportation. They can be subdivided into biodiesel and bioethanol. The "first" generation of biofuels is produced from energy crops: bioethanol mainly from corn, wheat, sugarcane or sugarbeet, and biodiesel from rapeseed or jatropha [134]. Both bioethanol and biodiesel could play a role in China in the future, albeit with very different impacts on water availability.
The water intensities and basin allocations of bioethanol and biodiesel production were derived from data on rainfed and irrigated yields per basin for all crops that are in principle eligible for bioethanol or biodiesel production [5][10]; this information was combined with the water footprint for each crop, taken from literature [5] [134][11], with data on the regional distribution of China's current bioethanol and biodiesel production capacities, and information on the crops that are actually planned to be converted into biofuels [154]. By reason of a lack of better data, it was assumed that this regional allocation will hold true until 2030.

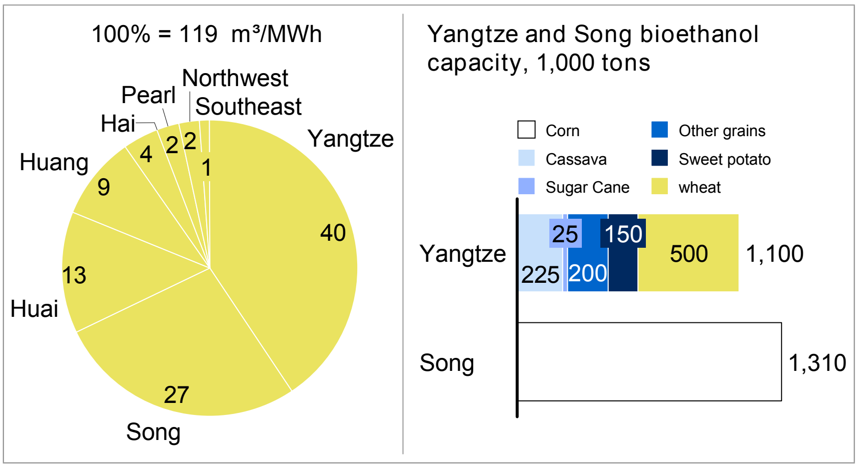

Figure 7.4.: *Water intensity of biofuel production and processing in China, total and split by river basin.*

This allows to calculate the average water footprint for biofuels on a national level, and the weighted average basin contribution, summarized in figure 7.4[12]. According to it, the

[10]The list of relevant crops was taken from [134] and includes the following: for bioethanol, sugar beet, potato, sugar cane, maize/corn, cassava, barley, rye, paddy rice, wheat, sorghum; for biodiesel, soybean and rapeseed.
[11]The average water footprint depends on the crop share that is irrigated (versus rainfed). This information was taken from [5].
[12]Weighted average basin contribution means that the water requirements for sourcing 1 TJ of biofuels from one basin were weighted with the basin's relative share of farmland dedicated to biofuels.

Yangtze and Song basins contribute most to biofuels production, albeit with different crop mixes: while a mixture of cassava, wheat and other crops are used in the Yangtze basin, corn is the virtually only source (for bioethanol) in the Song basin[13].

Total/ basin split	**Coal** m^3/TJ	**Oil refining** m^3/TJ	**Biofuels** m^3/MWh
Total	14	33	146
Limpopo	10%	0%	44%
Luvuvhu/Letaba	0%	0%	7%
Crocodile West and Marico	0%	0%	20%
Olifants	46%	0%	1%
Inkomati	0%	0%	12%
Usutu to Mhlathuze	0%	0%	2%
Thukela	0%	0%	0%
Upper Vaal	41%	22%	1%
Middle Vaal	0%	0%	2%
Lower Vaal	0%	0%	2%
Myoti to Umzimkulu	3%	28%	2%
Mzimvubu to Keiskamma	0%	0%	5%
Upper Orange	0%	0%	0%
Lower Orange	0%	0%	1%
Fish to Tsitsikamma	0%	37%	1%
Gouritz	0%	4%	0%
Olifants/Doring	0%	0%	0%
Breede	0%	0%	0%
Berg	0%	9%	0%

Table 7.2.: *Water intensity of important energy carriers in South Africa: total demand and percent split by basin (percent values might not add up to 100% due to rounding).*

[13] Please note that this figure gives only *relative* withdrawals (in m^3/MWh), but no indication on absolute withdrawals (in terms of million m^3) for a reference case (as for oil, coal and gas), due to the fact that biofuels are part of the GHG mitigation solution mix – the extent to which this solution is implemented depends on the contraints chosen in the model.

7.1.2. Coal, gas, oil and biofuel provision - South Africa

Table 7.2 summarizes the water requirements for the provision of important energy carriers, and how these split beween the 19 Water Management Areas (WMAs) in South Africa, as did table 7.1 for China. It thereby also gives information on the overall extent and the WMA where the avoided consumption of one unit of energy would increase water availability.

South Africa: coal mining

The 276 Mt of coal that were mined in South Africa in 2009 required on average 0.33 m^3/ton, or 14 m^3/TJ [155][14] – the fact that domestic coal consumption was only 205 Mt [155] makes South Africa a net exporter of coal. Reduction in coal demand through GHG abatement measures by one Terajoule is therefore assumed to reduce water demand by the full 14 m^3.

A comprehensive list of South Africa's coal mines [145], including the location of each mine, allowed to allocate water withdrawals from coal mining to WMAs; figure 7.5 gives the regional distribution in the reference scenario. Most of the coal is mined in just two WMAs - interestingly (and again similar to the China case), these are both located in parts of the country that are forecasted to experience a particularly large water gap by 2030[15].

Going forward, we assumed that the regional split of coal mining and water requirements will not change in the Business-as-Usual scenario – i.e., saving a unit of coal in our model will increase water availability in the WMAs according to the split given in figure 7.5.

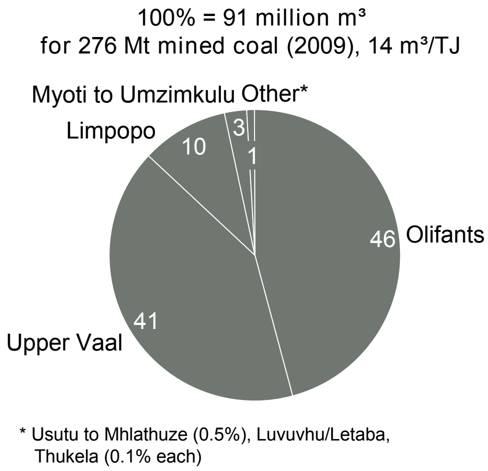

Figure 7.5.: *Water for coal.*

South Africa: oil refining

South Africa consumed 194 million barrel of oil in 2009, and produced about 1 million barrels [155]. It is unlikely that oil production will increase substantially in the foreseeable

[14] Water withdrawals from mining were determined based on the literature data discussed in section 5.2 and data from [5]. The value is in good agreement with data from literature [135], as a rough back-of-the-envelope calculation shows: underground mining requires 12 m^3/TJ, surface mining 4 m^3/TJ and coal washing again 4 m^3/TJ. 60% of South Africa's coal are mined in surface operations [145]; thus: 60%$\cdot$ 12 m^3/TJ + 40%$\cdot$ 4 m^3/TJ + 4 m^3/TJ (most coal is washed) = 12.8 m^3/TJ.

[15] See picture 3.8, page 42.

future[16] – South Africa can therefore be expected to import most of its oil in the future. The country is however home the second largest refining capacity in Africa [155] and is considered self-sufficient in terms refining capacity in some sources [155], or expected to be so by 2015 [157]. Table 7.3 gives an overview of the main refineries (from [147]), including estimated water withdrawals (based on water withdrawals of 33 m^3/TJ, or 0.2 m^3/bbl[17]).
This information led to the assumption that saving one unit of oil will increase water availability due to lower refining requirements, and affect the WMAs in the proportion as mentioned in table 7.3[18].

Refinery	**Basin**	*10^6 bbl*	*10^6 m^3*
Sapref Durban	Mvoti to Umzimkulu	66	13.3
Petronas Durban	Mvoti to Umzimkulu	46	9.2
Calex Capetown	Berg	37	7.4
Natref Sasolburg	Upper Vaal	34	6.8
Sasol I-III	Upper Vaal	55	11.1
Petro SA	Gouritz	16	3.3
Petro SA Mthombo	*Fish-Tsitsikamma*	*146*	*29.6*

Table 7.3.: *Annual production and water withdrawals for South African refineries [147]. The Mthombo refinery (in italic)is not yet in operation, but planned to be so by 2015.*

South Africa: natural gas

Water requirements for natural gas extraction were not further considered in this work: according to the EIA, South Africa consumed 3.6 billion cubic meters (bcm) in 2006 [155], but only produced 1.0 bcm [155], i.e., it imports more than 70% of its gas. Taking the China number for the water intensity of gas extraction (9 m^3/TJ), and assuming that GHG mititgation options reduced domestic gas production would impact total water availability potential by less than 400,000 m^3, or 0.01% of South Africa's water gap.

[16] Proven reserves (in January 2012) were 15 million barrels, the amount Saudi Arabia produces in less than two days [155] [156].

[17] According to section 5.2.

[18] Of course, this approach has its flaws: in reality, a long-term decline in oil demand will most likely lead to the closure of some refineries, and not to a proportional production scale-down in all.

South Africa: biofuels

Local sources [158] [159] indicate that biodiesel will likely play a smaller role than ethanol in South Africa and be produced mainly from waste oils, i.e., putting little stress on water resources. Bioethanol in contrast could become of higher importance with respect to its water requirements, and is expected to originate mainly from two crops, sugarcane and maize [160].
The calculation logic for the water intensity and regional distribution of bioethanol production similar as in China. The Water Resources Group report [5] provides estimates for rainfed and irrigated production of both crops by Water Management Area until 2030; according to it, South African maize and sugarcane production could reach 53 million tons (of which 85% irrigated) and 48 million tons (96% irrigated), respectively[19], with the highest yields expected in the north-eastern part of the country (WMAs Limpopo, Luvuvhu/Letaba, Inkomati). Not all of this will be used for bioethanol production, but it is assumed here that the maize and sugarcane used for bioethanol production will come from the respective WMAs proportionally.
Translating tonnage yields into energy value [134], and combining this data with estimates on water withdrawals for maize and sugarcane irrigation [134] yields the bioethanol water requirements per MWh, per WMA, summarized in table 7.4.

WMA	m^3/MWh	**WMA**	m^3/MWh
Limpopo	144	Mvoti to Umzimkulu	152
Luvuvhu/Letaba	134	Mzimvubu to Keiskamma	150
Crocodile W., Marico	159	Upper Orange	120
Olifants	120	Lower Orange	101
Inkomati	149	Fish to Tsitsikamma	149
Usutu to Mhlathuze	152	Gouritz	-
Thukela	-	Olifants/Doring	57
Upper Vaal	107	Breede	92
Middle Vaal	150	Berg	101
Lower Vaal	153		

Table 7.4.: *Water requirements for bioethanol split by Water Management Area. It can be seen that water requirements are higher in the dry inlands WMAs and lower in the coastal WMAs of the Cape region that have a more humid climate (see section 3.2).*

[19]These numbers build on data from the International Food and Policy Research Institute.

7.1.3. Avoided electricity power mixes - coal power

The preceding chapter mentioned that a large share of GHG mitigation options are directly or indirectly linked to changes in, or reductions of, power production from the Business-as-Usual power mix. This mix is dominated by fossil-fueled thermal plants that typically withdraw considerable amounts of water[20] – changes in power production will therefore impact water resources. Coal power makes up the majority of that Business-as-Usual (BAU) power mix, with 72% in China and 93% in South Africa[21]. It is thus important to determine the water intensities of that generation fleet on a basin/WMA level.

Figure 7.6 shows the regional distribution of coal power plant capacities, and the respective water intensities[22]. It can be seen that China and South Africa differ substantially in that respect:

- **China.** Given the size of the river basins, it is no surprise that generation capacities are distributed across all basins and roughly follow patterns of economic activity and population density. Average withdrawal differ between basins nevertheless: the drier north of the country withdraws less than the south, but the lowest freshwater withdrawal rates are found in the South-East and Pearl river basins, which have long coastlines where power plants are predominantly cooled with seawater. Large differences in water withdrawals also exist between the currently operating fleet, the plants under construction, and those in planning, as the table 7.1.3 shows: the existing fleet has a high share of open loop systems that withdraw large volumes of freshwater, while new plants are predominantly built with closed cycle or air-cooled systems if seawater cannot be put to use.

- **South Africa.** The smaller size of the country and the high number of Water Management Areas provide more granular data than for China. The lower part of figure 7.6 shows that most power plants are located in the north-eastern part of the country, in proximity to the coal mines; these are also the regions with the highest level of population, economic activity, but also water scarcity[23]. Furthermore,

[20]See page 67ff.

[21]See section 6.4.2, page 81.

[22]Water intensities were determined as discussed in section 6.4.2, page 81ff: based on the literature values in table 6.1 (83), average regional water intensities were then determined based on the cooling technology given in the Platts power plant database, supported by a single plant location search if needed. Varying power plant efficiencies (specified in table 6.1) were taken into account as far as noted in Platts. These were then mapped against river basins or Water Management Areas.

[23]See figure 7.14, page 137 for a map of South Africa that shows the regional distribution of economic

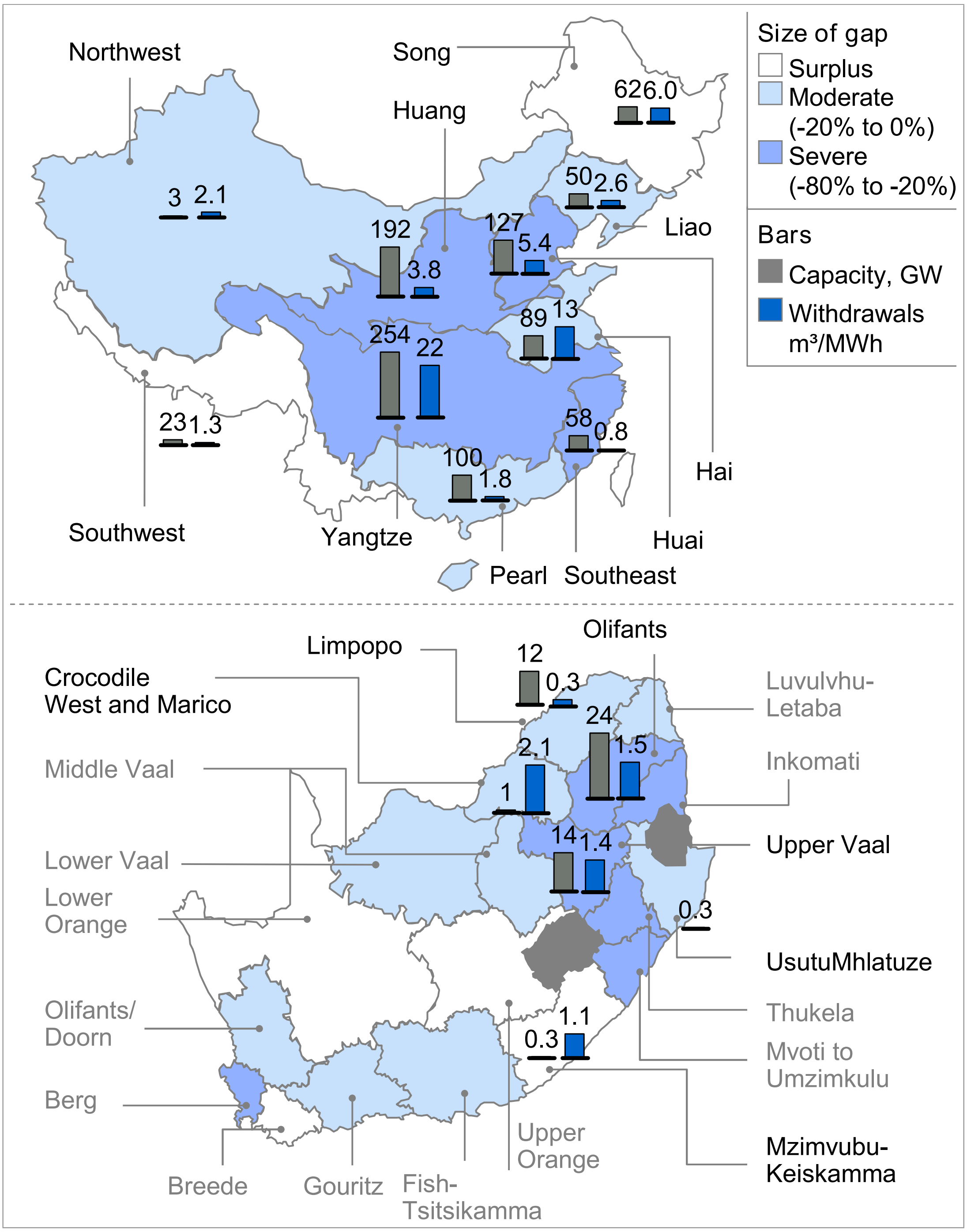

Figure 7.6.: *Coal power plant capacities in operation, planning and under construction for China and South Africa, by river basin/water management area and the respective intensity of water withdrawals.*

	Capacity	**Withdrawals**
	GW	m^3/MWh
In operation	659	13.1
In construction	95	0.9
In planning	213	0.8

Table 7.5.: *Freshwater withdrawal intensity for Chinese coal power plants of different status. Based on the power plant database for China (see page 81).*

average water withdrawals are much lower than in China, even though the power plants are generally located inland and cannot use seawater (see figure 7.6): 43% of considered coal plants[24] are air cooled. Of those under construction or in planning, virtually all will use this technology.

Table **??** shows condensed data on coal plant water withdrawals by operational status. This could be broken down further to provincial level, as table 7.6 shows exemplarily for China's Shaanxi province[25]. It can be seen that average water withdrawals are close to the Yellow river average, to which the province belongs, and are expected to decline in the future as new and more efficient plants come online[26]

The BAU power mixes not only consist of coal power plants, but also include other units, mostly gas-fired plants, local biomass and (in China) small hydro facilities. As described in section 6.4.2, the water intensities of these technologies were taken from literature, and allocated to the basins/WMAs on a pro-rata basis with respect to the coal-fired capacities[27].

Table 7.7 summarizes the water intensities of the BAU power mixes that are avoided through the implementation of energy efficiency measures and alternative energy sources[28] – a comparison with figure 7.6 (p. 111) shows that these water intensities follow the

activities.

[24]The summed capacity of all plants in operation, under construction and in planning.

[25]Located in central China, Shaanxi provinces belongs to the largest part to the Huang-He/Yellow river basin (the southernmost corner is already part of the Yangtze basin). It is a major coal-producing region.

[26]Similar data exist for all other basins or WMAs.

[27]Where appropriate, these numbers were amended with the water requirements for the provision of the respective energy carrier.

[28]This differentiation needed to be made to be consistent with the underlying data source [4] – see section 6.4.2 (81). However, and as table 7.7 shows, the water intensities of the two mixes differ only slightly, particularly for South Africa.

<table>
<tr><th></th><th>Operation</th><th>Construction</th><th>Planning</th></tr>
<tr><td></td><td>GW</td><td>GW</td><td>GW</td></tr>
<tr><td>Air-cooled</td><td>3.6</td><td></td><td>3.8</td></tr>
<tr><td>Cooling tower</td><td>10.3</td><td>2.4</td><td>-</td></tr>
<tr><td>Open cycle freshwater</td><td>0.3</td><td>-</td><td>-</td></tr>
<tr><td>Not specified</td><td>4.0</td><td>1.9</td><td>5.6</td></tr>
<tr><td>- Classified air-cooled</td><td>1.0</td><td>-</td><td rowspan="2">5.6</td></tr>
<tr><td>- Classified wet-cooled</td><td>2.9</td><td>1.9</td></tr>
<tr><td>- Classified open cycle</td><td>0.1</td><td>-</td><td>-</td></tr>
<tr><td>∅ withdrawals, m^3/MWh</td><td>3.9</td><td>2.0</td><td>0.8</td></tr>
</table>

Table 7.6.: *Coal power plant data on provincial level, example of Shaanxi, China: capacity of coal power plant fleet split by status and cooling technology. The data draws from 127 power plants, reaching from 3 MW to 1 GW. The cooling type of those capacities that were not specified in the database was determined pro-rata, based on the classified capacities per operational segment.*

intensities of the coal power plant fleet.

7.1.4. Water intensities and regional distribution of alternative power sources

The water impact of energy efficiency measures is directly given by the respective water intensity of the avoided power plant mix (Δ_1 in table 7.7). Alternative power sources in contrast can have their own water intensities: nuclear power plants generally require more cooling water per unit of output than coal plants, while wind power requires negligible amounts.
The following sections discuss quantity and regional distribution of water intensities for the most relevant alternative power sources, wind, photovoltaics, solar thermal, nuclear and hydro. The difference between the respective water intensity and the intensity of the avoided conventional power mix Δ_2 then determines the net water impact of a given alternative power source.

Wind power

Wind farms themselves do not require water. Wind power can therefore be considered much like energy efficiency measures – it reduces water withdrawals through reduced

China	Δ_1	Δ_2	**South Africa**	Δ_1	Δ_2
Basin	m^3/MWh		**WMA**	m^3/MWh	
Song	4.6	5.9	Limpopo	0.3	0.3
Liao	2.0	2.5	Crocodile West, Marico	2.0	2.0
Hai	4.2	5.3	Olifants	1.5	1.5
Huang	3.0	3.8	Usutu to Mhlathuze	2.0	2.0
Huai	10.0	12.8	Upper Vaal	1.3	1.3
Yangtze	16.6	21.1	Myoti to Umzimkulu	2.0	2.0
Southeast	0.6	0.8	Mzimvubu to Keiskamma	1.0	1.0
Pearl	1.4	1.8	Upper Orange	2.0	2.0
Northwest	1.4	1.8	Lower Orange	2.0	2.0
Southwest	1.0	1.3	Other WMA	n/a	n/a

Table 7.7.: *Water intensities (withdrawals) of the power plant mixes that are avoided through increased energy efficiency (Δ_1) and alternative power sources (Δ_2). "Other WMA, n/a" means that the remaining WMAs have negligible generation capacities.*

needs for fossil-thermal power generation. A differentiation however needs to be made in terms of regionalization between China and South Africa:

Wind generation capacity buildup in **China** in one basin is assumed to reduce water withdrawals in that same basin. This approach seems to make most sense, given the size of the country and the (still) poorly interconnected transmission subgrids[29].
Wind buildup on provincial basis until 2030 was sourced from China's NDRC Energy Research Institute [161][30] and mapped to the ten river basins. According to it, the Yellow, Song, and South West basins receive almost two thirds of wind capacity. The sparsely populated South West would, as the only basin, receive more wind power in this scenario than it is expected to have capacity in the Business-as-Ususal scenario (56 GW) – half of this capacity (28 GW) is therefore assumed to be transported to the neighboring Yangtze and Pearl river basins, and reduce water withdrawals there. Figure 7.7 shows how wind capacities might be distributed across the basins acording to [161], and contrasts this with a wind speed map: wind capacities are low in the coastal eastern basins with little wind potential and increase in north-western direction, which is well reflected in the

[29]See also section 6.4.2, page 85ff.

[30]The values given in [161] correspond well to the data underlying the China cost curve [4]: while [161] gives a span of 220–400 GW installed capacity with a moderate case of 300 GW, [4] assumes 338 GW.

distribution of wind capacities.

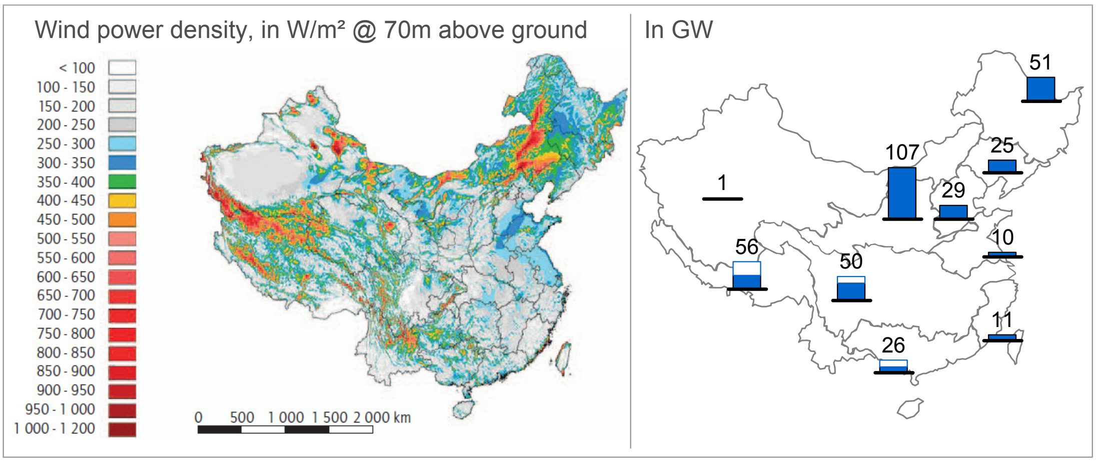

Figure 7.7.: *Left: Land-based wind resource potential of China (from [162]); right: Distribution of potential 2030 wind capacities across river basins after correcting for over-capacities in the South West (see text).*

In contrast, the regional distribution of wind power plants in **South Africa** is assumed to be of lesser importance – it is expected that the installation of wind power reduces water demand from thermal power stations by the national average, independent of its location. This approach should be justified by the fact that South Africa has a well developed transmission grid that covers the whole country[31].

Photovoltaics

Like wind, photovoltaic power require negligible amounts water[32]. A regional differentiation between China and South Africa is again required, given the different structure of the national transmission grids.

Photovoltaics in **China** reduce water withdrawals from thermal stations in those basins where they are installed. The basin distribution of the photovoltaics capacities is assumed

[31] This approach implicitly assumes that South Africa will not run into a congestion of its transmission grid that might arise from the transport of large amounts of wind power through the country. Implemented to full extent, wind capacities of about 18 GW, or 18–24% of South Africa's total expected capacity by 2030 [117] are assumed here. If wind power is not located in one single region, such a share of total capacity is likely manageable: Denmark for example already *generates* 25% of its electricity from wind [163], and installed capacities as a share of the total are still higher (as wind power typically has lower availabilities than conventional power sources).

[32] Some water is needed for washing of the panels. [135] gives a number of 0.055 m^3/MWh, whereas [1] considers the volume negligible.

to follow the currently installed conventional generation capacity[33].

The same argumentation as for wind is assumed to hold for **South Africa**: photovoltaic power should have no impact on the water resources in a given WMA, and reduce withdrawals by the national average water intensity of the avoided power mix.

Concentrating solar thermal power (CSP)

CSP plants require water, as their working principle is a steam cycle that requires a heat sink or cooling element – which is normally provided through evaporating water. A regional allocation of capacities is therefore necessary for both countries.
The regional distribution of the CSP capacity as prognosticated in [4] for **China** is done on the basis of solar irradiation, shown in figure 7.8. Admittedly, this approach differs from photovoltaics. However, photovoltaics is a distributed technique that can well exist in urban areas and owned by individuals, while CSP is a large-scale generation technology that ressembles more a coal power plant and will for this reason also be built based on other criteria[34].
CSP capacity allocation in **South Africa** follows the distribution pattern of the plants announced so far, summarized in table 7.1.4 – due to the lack of better data, it was assumed that the buildup of pilot plants can be considered as an indicator for the future distribution of CSP plants.

Nuclear power

Nuclear power stations also use water, as the principle operating mechanism is the same as in any coal-fired power plants.
Determination of the regional distribution across **China** followed the same logic as for coal: the locations of existing nuclear power plants and those under construction and in planning as well as their cooling types are given by the Platts power plant database.

[33]A point of critique to this approach is that it neglects solar irradiation data. This could be countered German example (little sun, but high installed capacities) or the argument that roof-top installations might predominate, which are rather linked to population density or economic wealth. If the latter argument is followed, the distribution of conventional generation capacity can be used as well, being, in the case of China most likely a good trade-off index between population density, levels of economic activity and existing energy infrastructure.

[34]While both photovoltaics (PV) and CSP use sunlight, the conversion to electricity follows different principles: PV translates sunlight directly into electric power, while CSP rather is a conventional generation technology: sunlight is captured by mirrors that heat a fluid medium which in turn powers a steam turbine (by means of a heat exchanger).

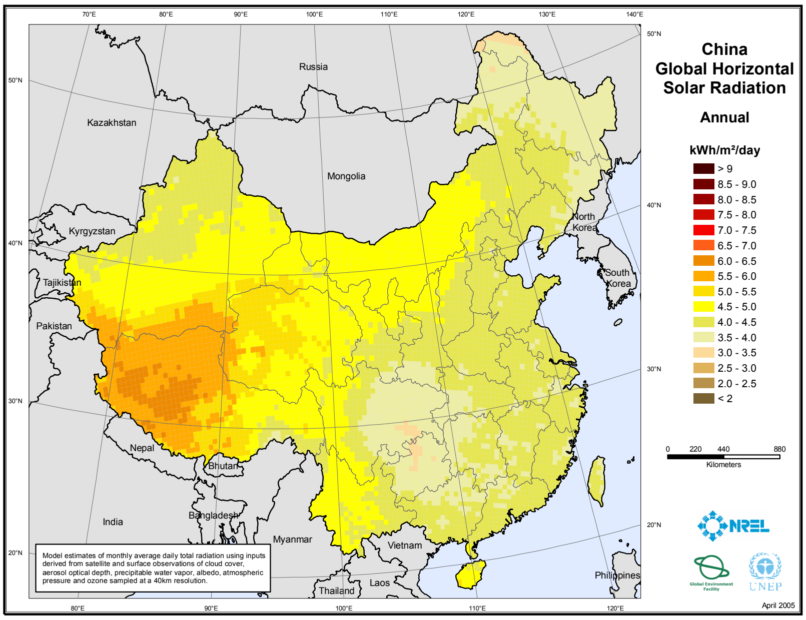

Figure 7.8.: *From [164]. Solar irradiation map for China.*

Company	*Capacity, MW*	*WMA*
Eskom	100	Lower Orange
Concentrix	50	Olifants/Doring
Exxaro	220	Limpopo
Group Five & Sishen Iron Ore	450	Lower Orange/Lower Vaal
Lereko Metier, IDC & Solafrica	75	Lower Orange/Lower Vaal

Table 7.8.: *Announced solar-thermal (pilot) power plants for South Africa.*

Table 7.9 summarizes the results on national level: all plants in operation so far are sea-cooled. Regarding the plants under construction and in planning, an inland move can be observed that effectively increases water withdrawals, as freshwater cooling will increase in importance[35]. Overall, currently operating plants require only 0.38 m^3/MWh[36], while

[35]Regarding overall capacities: the Platts database gives 106 GW of nuclear capacity in operation, under construction or in planning. At a presumed runtime of 85% over one year (nuclear power stations typically serve as baseload; 15% downtime reflects outages due to revision and maintenance), this corresponds to 790 TWh, in good agreement with the 805 TWh mentioned in [4] for the abatement case.

[36]The literature value from [135] for open-cycle-cooled boiling water/pressurized water reactors. This value should also apply to sea-cooled types, as for example make-up water for the primary cycle or for sanitation cannot be provided by seawater.

this value increases to 2.0 m^3/MWh for the plants that are under construction or in planning.

	Open loop sea	*Closed loop river*	*Capacity, GW*
Operating	100%	0%	10.2
In construction	86%	14%	32.3
In planning	68%	32%	64.0

Table 7.9.: *From Platts power plant database: percentage shares of nuclear power plant capacities by cooling type.*

In the case of **South Africa**, it is assumed that the additional nuclear capacity assumed in the abatement case will be installed in the Fish-Tsitsikamma WMA, where Thyspunt is deemed a likely location for new nuclear capacities [165] [166]. As the location will be close to the sea, it is assumed that it will be cooled primarily with sea water, keeping water requirements at 0.38 m^3/MWh[37].

Hydro power

As discussed, water intensities can be significant especially for hydro dams, as they reduce the water flow rate and therefore lead to increased evaporation. The amount of evaporated water strongly depends on the climatic conditions: while effects are presumably small in the cool climate of Norway, a water head of 6mm evaporates daily from Lake Nasser, Egypt, summing up to about 4% of the country's water withdrawals over the course of a year [167].

[135] gives evaporative losses for California of up to 209 m^3/MWh, [1] a range (also for California) of 0.2–160 m^3/MWh, depending mostly on the power station's surface-to volume ratio, with a median of 5.4 m^3/MWh, and 14 m^3/MWh for plants $<$25 MW. As this is the only source found, these values were taken as a basis for determining evaporative losses per river basin/WMA in China and South Africa. Specifically, the value for smaller plants was considered, as the GHG mititgation option is explicitly called "small hydro".

In order to do so, evaporation rates for California were derived from [168]. The same data was obtained for China's river basins [169][38] and South Africa's WMAs [170], and

[37] See last footnote.

[38] The source only allows to draw basin-specific information for the Yangtze, Yellow and Song river basins. Evaporation rates of the other seven river basins were linked to these three data points: for Liao, Hai, Song values were taken; the Huai and North-West basins were linked to the Yellow river

put in relation to California's evaporation rates. Using the data on median evaporation rates per MWh for California as sketched out above allowed to estimate those values for China's river basins and South Africa's WMAs that are summarized in table 7.10. Interestingly, evaporation rates are lower in both China and South Africa than in California: the Yangtze basin for example reaches only 53% of the Californian value (70 cm vs. 130 cm p.a.[39]). The highest value achieved in South Africa is in the Myoti to Umzimkulu WMA, with 70% of the Californian rate.

South African WMA	m^3/MWh	*China river basin*	m^3/MWh
Limpopo	6.4	Song	5.4
Luvuvhu/Letaba	7.6	Liao	5.4
Crocodile W., Marico	6.2	Hai	5.6
Olifants	7.6	Huang	5.8
Inkomati	8.9	Huai	6.6
Usutu to Mhlathuze	9.5	Yangtz	7.5
Thukela	8.7	Southeast	7.5
Upper Vaal	8.1	Pearl	7.5
Middle Vaal	6.5	Northwest	5.8
Lower Vaal	5.2	Southwest	7.5
Mvoti to Umzimkulu	9.8		
Mzimvubu to Keisk.	8.9		
Upper Orange	5.4		
Lower Orange	2.7		
Fish to Tsitsikamma	4.9		
Gouritz	3.3		
Olifants/Doring	2.7		
Breede	6.0		
Berg	5.4		

Table 7.10.: *Evaporation rates for hydropower in China and South Africa.*

basin, and the South-West, Pearl and South-East basins to the Yangtze.

[39]Evaporation rates for California refer to the more humid north of the state, as it was assumed that most of hydro dam capacities is actually installed there.

7.1.5. Waste, agriculture and forestry

Waste

Two mitigation options in the waste sector have an impact on water resources. First, the direct use of *gas from landfills*, i.e., the capturing and processing to further use of methane that would otherwise enter the atmosphere and contribute to the greenhouse effect. This offsets natural gas requirements from fossil sources – its relative water impact is therefore determined by the water intensity of natural gas extraction.
The second option is direct electricity generation from landfill gas, which not only avoids (fossil) natural gas extraction but also power generation from the Business-as-Usual power mix, which can be regarded as another alternative form of power generation; as the electricity will likely be obtained from gas-fired powered plants, the water intensity of CCGT plants, minus the water intensity of avoided gas extraction, was assumed for this option. The regional distribution across basins/WMAs followed the population density, as it was assumed that landfills correlate with this metric.

Agriculture

As mentioned in section 6.2 (p. 77), this work neglects the changes in hydrological cycles from changes in land-cover. Water impacts of measures that affect agronomy practices, land management or degraded land restoration were therefore not considered.
Measures that affect livestocks, antimethanogen vaccine and feed supplements, were considered to have negligible impacts on water resources.
One measure, however, *no-/reduced tillage* sticks out within the boundaries of this research, and is described in more detail in section 7.2.3.

Forestry

Forestry measures in both South Africa and China include afforestation, degraded forest reforestation and improved forest management. Similar to the agriculture measures, their water impact was not further considered here, as a proper evaluation would require hydrological modeling an a regional basis, a task beyond the scope of this work.

7.2. GHG impact of water availability options

Much as GHG mitigation options have a water impact, the implementation of water availability options can influence GHG emission levels. As these options were fewer

in number, and as the differing nature of the mitigation options barred a systematic breakdown to few specific drivers (of GHG emissions), the cost and potential of water availability options were determined on the basis of local case studies and interviews, and so were their GHG intensities.
The case study data in most cases include energy cost or savings, which was translated into a GHG impact in dependence on the implied fuel. The following general observation were made along the sector boundaries:

- **Industrial and agricultural measures.** Water savings either go in hand with energy savings (often in the case of energy efficiency gains) or require additional energy. The GHG impact is determined based on the GHG intensity of the energy source saved. As the majority of energy savings are in fact electricity savings, the GHG intensity is determined by the intensity of the avoided power mix in the same way as discussed in the last section (7.1).

- **Municipal measures.** Efficient toilets or reduced leakage rates reduce energy demand as less water needs to be purified and pumped; their energy savings were taken from literature (see figure 5.3, page 71) and translated into GHG savings by using again the GHG intensity of the avoided power mix. A special case is wastewater treatment, which was considered from a technologically more optimistic standpoint as a net energy producer. This is explained in more detail in section 7.2.1.

- **Supply measures.** Specific literature values were used in order to determine the impact on GHG emissions of concrete infrastructure projects such as the South-North water transfer project in China; more general literature values were used for energy intensities of supply options such as desalination or groundwater pumping. A special case are hydro dams. For these, we first estimated the dam size from the water availability potential (in million m^3). It was then checked whether the dam size stood in a plausible relation to the hydro power capacity as given in the GHG abatement options “small hydro”; as that was the case for both countries, the two measures were combined into one – implying that hydro dams not only store water for dry periods but also produce energy when they release the water.

As each water measure is the result of distinct case studies, interviews, academic publications and technical reports, an in-depth discussion of the GHG intensity of all measures would be beyond the scope of this work. At this point we refer to the appendix of the Water Resources Group report [5] (p.147ff.) that contains an explanation for each option

and to appendix D of this work that contains a comprehensive list of GHG intensities for each water availability option, including comments and references to data and sources that were used for determining it.
The following sections give more detail on three particularly interesting measures, municipal wastewater treatment, reduced tillage, and seawater desalination. Each stands representatively for one sector, and has strong water–GHG interlinkages; in two cases, wastewater treatment and reduced tillage, these create a "win-win-situation", i.e., they reduce GHG emissions and increase water availability, while seawater desalination trades water availability for increased GHG emissions.

7.2.1. Municipal: domestic wastewater treatment

Virtually all wastewater in the developed world is treated today, while developing countries still discharge large parts of their waste streams into the environment in untreated condition [25] (p. 241ff, 254).
Wastewater treatment is energy-intensive – it for example requires 1% of all electricity produced in England and Wales [171]. Disposal of the sludge, an end-product of the treatment process, can also take up high costs and pose a problem in densely populated areas.
This section will discuss the various teatment steps and show that wastewater can for example be considered as an energy carrier.

The wastewater treatment chain

A modern wastewater treatment plant typically has four subsequent treatment steps[40].

- *Pretreatment.* The influent first flows through screens that sort out large parts such as leaves, cans, wood etc. After that, it passes through a grit chamber or some sort of finer screens where larger particles settle down or are filtered out and removed. Modern plants often have a flow equalization stage that allows to effectively store parts of the wastewater stream during peak periods.

- *Primary treatment.* The pretreated wastewater flows into larger basins, primary clarifiers. Here, fat and grease accumulate at the surface and are skimmed off, while sludge, which is made up of previously dissolved matter, settles at the bottom and is separated from the water.

[40]The steps described there are the most typical found in modern plants. However, alternative steps of equal effectiveness exist – for example, wetlands can assume the role of secondary treatment.

- *Secondary treatment.* After these physical steps, the wastewater is mixed with *activated sludge* and passed through an aerator. Activitated sludge contains a mix of bacteria that, with the help of oxygen, consume the dissolved organic matter in the wastewater and bind (parts of) the inorganic matter. From the aerator, the mixture is pumped into a secondary clarifier after a certain retention time, where the sludge settles to the ground and is seperated from the water. The sludge is now called activated, as it contains enough bacteria to start the digestion process in the aeration tank – parts are therefore reused as described above. The remainder is pumped into a tank together with the sludge from primary treatment.

- *Tertiary treatment.* Effluent water quality can be further enhanced through certain final treatment steps: it can be passed through sand or coal filters for mechanical, or wetlands for biological filtration. Nutients such as nitrogen or phosphorus can be removed in order to avoid algae blooming in the effluent water bodies. It can also passed through a chlorine contact basin to kill any remaining bacteria. Tertiary treatment can enhance quality to drinking water standards – as done in Singapore , where the effluent is called *NEWater* and sold as bottled water [172].

- *Sludge treatment.* The sludge from primary a secondary treatment is first dewatered, e.g. in a centrifuge. Its load is then further reduced, which is most commonly done through aerobic or anaerobic digestion by bacteria or incineration. Under aerobic conditions, bacteria consume the organic matter of the sludge and produce CO_2. In an anarobic environment, bacteria digest the biomass under the exclusion of oxygen and produce biogas.

From an energy standpoint, aeration of the wastewater in the secondary treatment typically is the most intensive step, requiring about 50% of the total energy needs [173]. Typical literature values give an overall energy intensity of wastewater treatment of 0.6–0.7 kWh/m^3(e.g., [1] [2] [135]). On the other hand, the energy content of sludge figures at about 12–16 GJ/t of dry solids [174] – about half the energy content of coal, which is on the order of 32 GJ/metric ton [175].

Wastewater to energy

The usefulness of sewage sludge as a source of energy, basic resources such as phophorus, fertilizer pellets, or as a building material has received increasing attention in the last years (see [176], [177]).
The conversion of sludge to energy as one option can take multiple pathways: it can be digested by bacteria in anaerobic conditions to produce biogas as mentioned above, it

can be incinerated in dry form, electricity can be produced directly in microbial fuel cells, or it can be the starting point for the production of syngas[41]. In the following, we focus on anaerobic digestion and subsequent biogas usage, being currently the most widely spread form of energy recovery.

A 2004 article [174] put the sludge energy content in relation to the energy requirements of a large municipal wastewater treatment plant and found that the potential energy in the sludge exceeds energy requirements by more than a factor of nine. Obviously, not all the energy can be transformed into usable form, but it is estimated that the energy content of the produced biogas should still exceed energy needs by a factor of 3.5 – energy self-sufficient treatment plants should therefore be possible after all. However, biogas is still often flared and thus left unused in treatment plants [178].

A recent contribution describes how operational improvements combined with on-site heat and power produciton from biogas can indeed make wastewater treatment plants self-sufficient [173]. It discusses two Austrian plants that produced more electricity over the course of a year than they consumed – one of the plants for example produced 214 kWh of electrical power per person over the course of one year; while the majority was used on-site, overall 1.5 kWh were fed into the external grid.

Put in relation to the amount of treated wastewater, we estimated that the two plants produced on average 0.27 kWh/m^3, of which they required in 0.25 kWh/m^3 internally. The overall energy balance is thus a surplus of **0.02 kWh/m^3**.

If operated well and equipped with biogas recovery (or potentially some other form of energy recovery), wastewater treatment plants should therefore not require the high energy amounts mentioned at the outset of this section. To establish an optimistic point of reference, we used the value of 0.02 kWh/m^3 for the respective lever in China's water availability cost curve[42].

7.2.2. Supply: seawater desalination

All data and information in this section, if not otherwise stated, are taken from the Master thesis of Stefanos Angelousis [138] that was supervised in the context of this work.

The desalination industry is growing fast across the world, in particular in regions that

[41] A good overview of the different processes is for example given in [177].

[42] Please note that the value was not used for the industrial wastewater measure. The composition of industrial wastewater can differ strongly from domestic wastewater, and has in general a lower concentration of organic matter that defines the energy content, we assumed that industrial wastewater treatment will require energy in the order of the literature values mentioned before (e.g., in [1], [2], [135]) if not otherwise stated in the respective case studies.

have limited access to other water resources. The global desalination capacity increased from close to zero around 1950 to more than 30 million m^3 of freshwater per day, or 11 km^3 annually in 2008 [179].

Desalination technologies

Three main technologies account for the bulk of the desalination market. Two of these are based on thermal principles, i.e., the distilling of seawater to freshwater, while one is based on the principle of reverse osmosis:

- *Multi Stage Flash Distillation (MSF)* works in a counter-current principle. Seawater is pumped through a pipe that runs through compartments with increasing ambient temperature. A final amount of heat is added to the seawater in the so-called brine heater after all compartants have been passed. The flow direction then reverses, and the sewater is pumped subsequently through the compartments thenselves[43]. The compartments have pressures such that each temperature lies above the boiling point of the seawater that passes through, which allows part of it to evaporate (or "flash") and condense on the (cooler) pipe that transports the incoming seawater. The freshwater is then collected at the bottom of each compartment.

- *Multi Effect Distillation (MED).* Hot steam is piped through multiple compartments that each have a seawater inflow. The seawater is sprayed into the compartments where parts of it evaporate and condense on the hot steam pipes. The steam itself looses part of its heat energy. Typical temperatures for the entering steam are 70°C and 30–40°C after the final stage.

Both thermal processes are robust, require little seawater pretreatment, and can be coupled with facilities that produce surplus steam[44], such as thermal power plants. In this case, seawater desalination plants act as a heat sink and effectively cool the power plant.

- *Reverse Osmosis (RO).* If two solutions with differing concentrations of the same solvent are separated by a semipermeable membrane, water flows from the low-concentration part to the high-concentration part until the concentrations are

[43] I.e., the first compartment is the hottest, but the still cooler than the entering seawater, due to the presence of the final brine heater stage.

[44] Demands on steam "quality" are low: neither very high pressures nor temperatures are required – MED for example works with steam temperatures of 70°C, as mentioned above.

levelled out. The resulting difference in pressure between the two parts is referred to as *osmotic pressure*.

This process can be reversed if an external pressure larger than the osmotic pressure is applied. Translated to desalination; this means that seawater is pressed at around 60 bar through special filters that retain the salt and thus produce freshwater. Reverse Osmosis requires less energy than thermal processes and can react more flexibly to demand changes. Material deterioration from corrosion and limescale is smaller. On the negative side, it requires more extensive pretreatment of water and cannot eliminate 100% of solvents – in contrast to thermal processes, where the end product is (by definition) distilled water.

Energy requirements

Table 7.2.2 summarizes typical energy requirements for all three desalination processes. For both MSF and MED, a stand-alone and co-location value is given, describing in the first case the isolated operation of the desalination plant, and in the second the operation in combination with a supplier of residual heat such as a thermal power plant. As reverse osmosis only requires electrical power, a co-location will not be beneficial in energetic terms.

Technology	Electrical kWh_e/m^3	Thermal kWh_{th}/m^3	
MSF	4.3	76	46
MED	2.0	51	28
RO	4.5	0	0

Table 7.11.: *Typical energy requirements for desalination processes. From [138] for MSF and MED, [2] for RO.*

7.2.3. Agriculture: no/reduced tillage

Reduced or no-tillage agriculture figures into both low-GHG and increased water availability pathways.
Essentially, reduced tillage means less intense ploughing of the ground and residual biomass kept on the fields. As the name suggests, no tillage agriculture means that planting takes place without disturbing the soil at all[45].

[45] The information used in this section can for example be found in [180].

Reduced/no tillage has multiple benefits. It reduces erosion, avoids the compaction of soil through heavy tractors that plough the field, and retains higher amounts of water and soil carbon in the ground – the latter is decomposed much faster in the case of conventional tillage agriculture and released to the atmosphere as CO_2. N_2O emissions can also be reduced, in the case of no-till agriculture by over 40% [181].
No-/reduced tillage requires equipment that allows to plant seeds through crop residue or into undisturbed soil. Herbicide use increases in most cases and if not combined with diversfied crop rotations or plant associations, as weeds growth is not controlled mechanically through ploughing [182]. As evaporation rates decrease, drainage systems might be needed to avoid in-field backwater in wetter climates.
[4] gives a 2030 GHG mitigation potential of up to 12.1 Mt CO_2e for China from better tillage management; [5] states a potential for increased water availability of 9,620 million m^3 (by 2030), i.e., the water–GHG intensity of tillage measures could be quantified at almost 800 m^3/tCO_2e. In South Africa, potential GHG savings of 2.2 Mt CO_2e face an increase of water availability of 943 million m^3, resulting in a water–GHG intensity of 430 m^3/tCO_2e[46]. The two measures were integrated into one for both countries in this work, as the underlying drivers such as the affected cultivated area correlated well between the two sources.

7.3. GHG intensity curves of the water availability options

This section summarizes the considerations on energy and greenhouse gas intensities of the water availability options in *GHG intensity curves*.
These curves resemble in many ways the water availability cost curves of the previous chapters (figures 4.1 and 4.3), but differ insofar as the they depict the GHG intensity of a given measure instead of its full cost.

GHG intensity curve of China's water availability options

Figure 7.9 shows the GHG intensity curve of the water availability options for China. The x-axis gives the national cumulative water availability, as in the case of the original cost curves, and the y-axis the GHG intensity – a negative intensity means that the

[46]The difference in water intensities can be driven by several factors. Crop mixes differ between the two countries, and so does the split between irrigation and rain-fed agriculture.

option effectively reduces GHG emissions with respect to the Business-as-Usual case. The curve is sorted from lowest to highest GHG intensity.

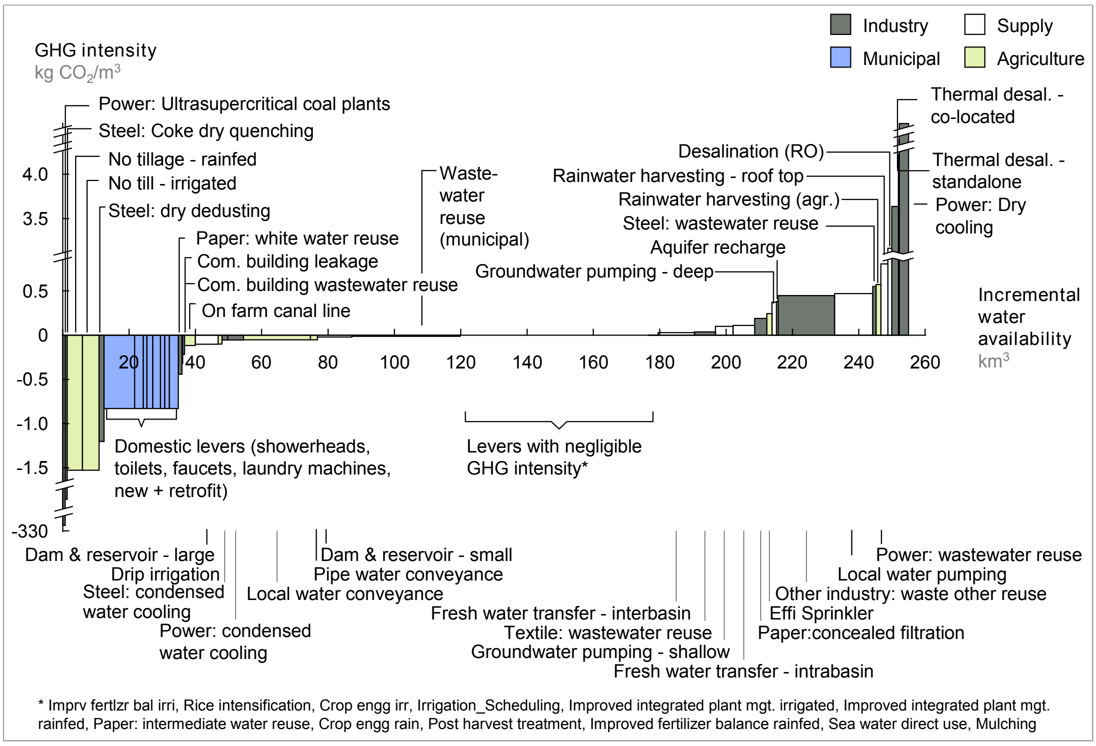

Figure 7.9.: *GHG intensity curve of China's water availability options.*

The structure of the curve does not seem much different than than the original cost curve (figure 4.1, p. 50) at first sight: it contains a mix of measures with negative and positive GHG intensities. Looking more closely, it can be seen that municipal and agricultural options are found in the left part, industrial options spread across the whole curve, and supply-side options only on the right side of the curve.

Integrating the GHG intensity curve as represented in figure 7.9 gives a net savings of greenhouse gases of 238 Mt CO_2e, which means that *the water mitigation options discussed in [5] for China have in sum a reductive effect on GHG emissions*[47].

It is therefore clear that measures with negative GHG-intensity dominate: adding the emissions from all GHG-reducing measures gives 298 Mt CO_2e, versus 60 Mt CO_2e from the GHG-emitting measures.

The cost curve investigated in [5] is based on an ordering according to full mitigation cost. If this ordering is followed here, and only the measures up to an incremental water

[47] Only to mention it again: our approach only considers GHG emissions from the operation of water implementation options; potential emissions from the manufacturing, installation or "disposal" of a measure are neglected here.

availability of 201 km^3 are considered[48], integrated GHG savings are slightly higher, at 268 Mt CO_2e. The fact that this number is higher than the savings of the whole curve indicate that the more expensive measures (which were not required to close the national gap in [5]) also tend to have a positive (i.e., an increasing) impact on GHG emissions.

in Mt CO_2e	**All measures**	**Least-cost closing of water gap**
Total	238	268
- Power + industry	217	245
- Municipal	19	14
- Agriculture	16	16
- Supply	-14	-7
BAU emissions		16,700
Abatement case emissions		7,500

Table 7.12.: *Total and sectoral split of the GHG impact of China's water availability options. Projected Business-as-Usual and Abatement Case GHG emissions for 2030 are shown as reference.*

Table 7.12 summarizes the GHG impacts for both cases and provides a sectoral split which shows that the industry and power sector account for the majority of the GHG impact, while municipal and agricultural measures account for only 5-7% and 6%, respectively; supply measures in contrast have an in sum small elevating effect on GHG emissions. The combined GHG impact of all measures to close the water gap makes up 1.6% of the BAU and 3.6% of the abatement case, about the same order as a larger mitigation option from the GHG abatement cost curve.

GHG intensity curve of South Africa's water availability options

The GHG intensity curve for South Africa's water availability options is shown in figure 7.10. The curve shows the same overall structure as its Chinese counterpart: a mixture of industrial, agricultural and municipal measures dominates the left part, while the right part is filled predominantly with supply measures.

One difference is the lack of industrial measures in the right part, and the overall lower share of options with an elevating impact on GHG emissions, mainly driven by the fact that industrial water reuse options and dry cooling, all part of China's water availability

[48] See figure 4.1: 201 km^3 are required to close China's water gap in 2030, according to [5].

options, play no role in South Africa according to [5][49].

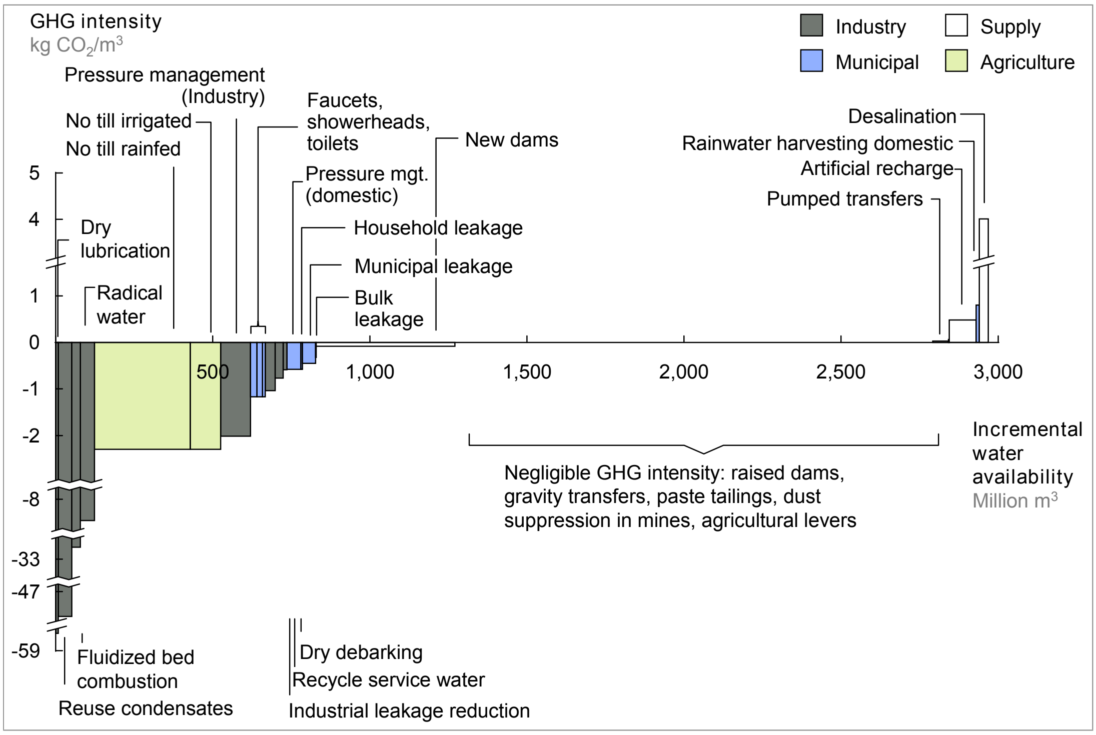

Figure 7.10.: *GHG intensity curve of South Africa's water availability options.*

Options with an elevating effect on GHG emissions produce in sum 0.2 Mt CO_2e of additional GHG emissions annually, while GHG-savings measure have a reductive impact of 5.1 Mt CO_2e. The sum of all South African water availability options therefore reduces GHG emissions by 4.9 Mt CO_ee

Figure 4.3 (p. 53) indicated that the implementation of all measures is required in order to close the water gap. Therefore, the numbers just mentioned also represent the GHG impact for the original water availability cost curve – i.e., the *implementation of the proposed water availability pathway for South Africa, according to [5], would also save GHG emissions.*

Table 7.13 gives again the sectoral split of the GHG impact of the water availability options, and puts it in perspective to the projected GHG emissions for South Africa's Business-as-Usual and Abatement Case, which shows that the GHG impact of its water availability options is slightly smaller than in the China case, making up 0.6–1.1% of its 2030 GHG emissions.

[49] Dry cooling for example is already assumed to be part of South Africa's Business-as-Usual case (see table 7.7 that showed the water intensities of the avoided Business-as-Usual power mixes and the discussion in section 7.1.3, page 110ff.).

in Mt CO_2e	**All measures**
Total	4.9
- Power + industry	4.1
- Municipal	0.1
- Agriculture	0.9
- Supply	-0.1
BAU emissions	789
Abatement case emissions	448

Table 7.13.: *Total and sectoral split of the GHG impact of South Africa's water availability options, set in persective to its GHG emission BAU and Abatement Case as reference.*

Considerations

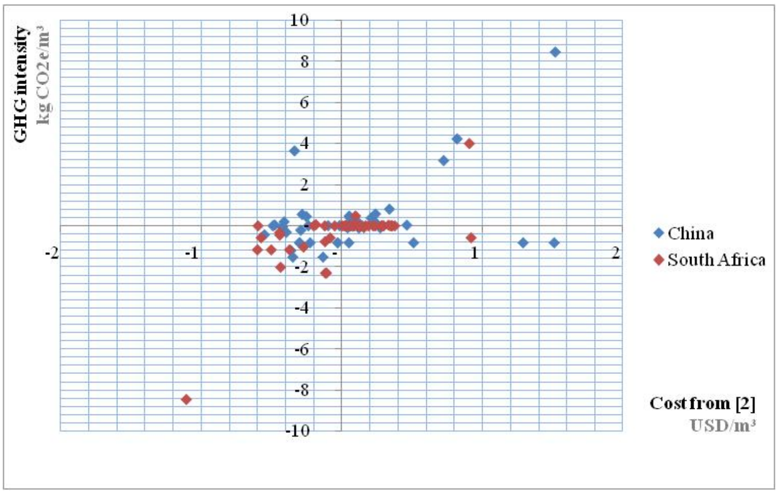

Figure 7.11.: *Correlation between cost per water availability option and GHG intensity.*

Tables 7.12 and 7.13 showed that the largest GHG impact is exerted by water availability options from power and industry[50].
Many of these options have negative full cost, as the original water curves show. As no intrinsic water price was considered in developing these curves, negative cost can only arise from other operational savings, which are often related to energy – a water

[50]This is to some part of course related to the boundary conditions of this research, which neglect GHG emissions from production and the "disposal" of abatement options, as well as more indirect effects that might arise from the introduction of certain agronomy practices.

availability option with negative full cost might therefore have the tendency to also reduce GHG emissions.
Figure 7.11 plots full cost (as reported in [5][51]) against the GHG intensity of the water availability options from both countries. Even though far from perfect, a tendency towards a correlation between low-cost and GHG savings can be observed[52].

7.4. Water intensity curves of the GHG abatement options

This section discusses the impact on water availability of GHG abatement options. The local nature of water requires a more detailed approach: the water impact needs to be broken down to the ten river basins and 19 Water Management Areas, which was based on the findings discussed in section 7.1 (p. 101 ff.).

Water intensity curve of China's abatement options

The left part of figure 7.12 shows the water intensity curve[53] of China's GHG abatement options. The x-axis gives the cumulative GHG abatement potential[54] as for the GHG abatement cost curve (figure 4.6, page 59.), while the y-axis now shows the water intensity for each option instead of the full cost – a negative value means that the particular measure reduces water withdrawals with respect to the Business-as-Usual case, whereas positive values indicate an increase in water requirements.
It can be seen that industrial mitigation options are found at the extremes of the water intensity curve in figure 7.12, while all municipal options have a negative water intensity. The middle of the curve is dominated by power-related options which see a particularly interesting tranformation: while they mostly have a net full cost (i.e., they are more

[51] To be consistent with the original publication, we used the full cost as reported in [5] here and in the rest of this chapter even though it assumes different cost of capital for the four sectors.

[52] Some "outlier" measures with very high/low GHG intensities were neglected for the sake of clear arrangement. However, these typically fit into the general picture of figure 7.11, i.e., low cost correlate with GHG savings and vice versa.

[53] In terms of withdrawals.

[54] The data underlying figure 7.12 lacks about 180 Mt CO_2e abatement potential from the original GHG cost curve, which gave 9.1 Gt CO_2e (see figures 4.5, p. 58, and 4.6, p. 59'). This is due to the fact that the data for our analysis was derived from [77], the latest update to [4], which only includes measures with a cost of less than 100 EUR/CO_2e; two measures, biomass co-firing in thermal power plants and the equipment of gas-fired power plants with CCS, lie above this threshhold. This also holds true for the South African case, reducing the abatement potential by 10 Mt CO_2e there.

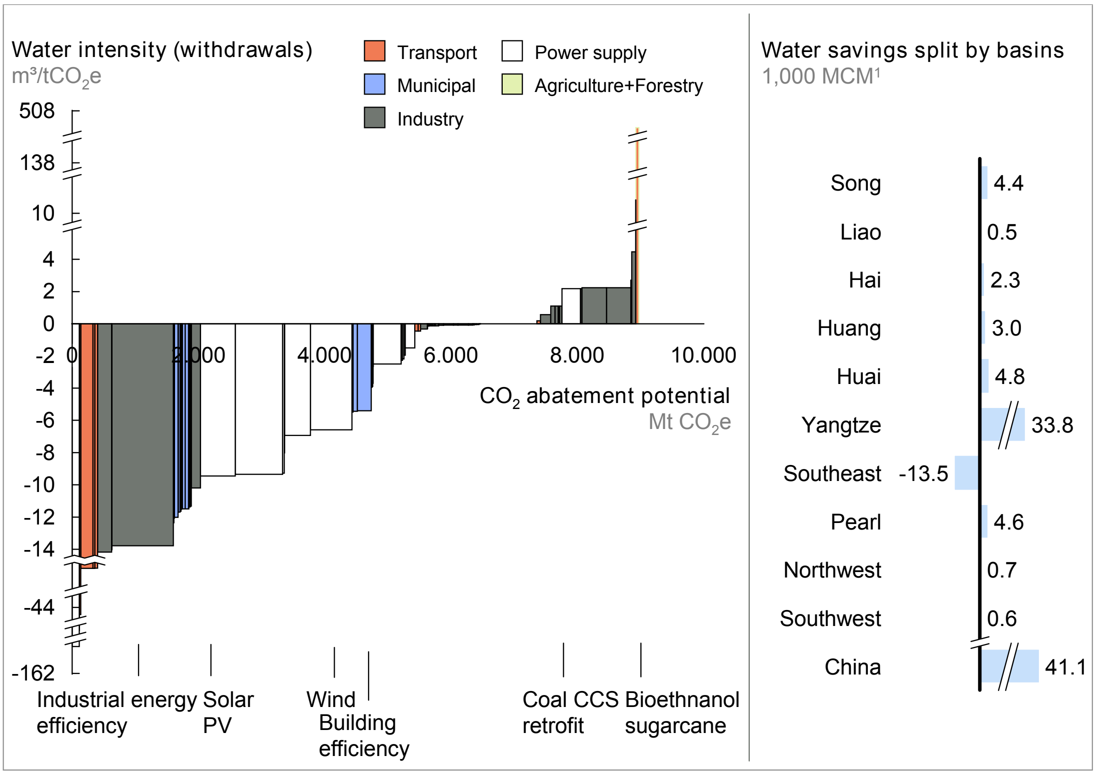

Figure 7.12.: *Water intensity curve of China's GHG abatement options.*

costly than the reference case), they have a negative water intensity and should thus become more attractive if water intensities are taken into consideration – putting a price on water would for example make these options relatively cheaper.

The right part of the curve is populated by biofuels[55] and carbon capture and sequestration (CCS) technologies. Interestingly, both technologies are occasionally mentioned as priority options for reducing GHG emissions across the world.

Small hydro plants are at the very left of the water intensity curve, as we credited the water availability gains from the hydro dam option against it – i.e., small hydro plants are assumed to be built in dams, yielding a very high water availability per ton of CO_2e saved, which offsets the evaporative losses that were equally considered.

Integrating the curve shows that *the implementation of all GHG abatement options increases water availability in China by about 41 km^3, 20% of the national gap.*

Table 7.14 gives an overview how these water availability increases split between sectors: the power sector contributes the majority, 34 km^3, followed by energy efficiency measures that indirectly save water through the reduced consumption of electric power in industry,

[55]Water requirements for irrigation are included in biofuel water intensities – see section 7.1, page 101ff.

transportation and the municipal sector. The agriculture + forestry sector in contrast is a net user of water, driven mainly by the water requirements for biofuels.

in km^3	**All measures**
- Power	34
- Industry	17
- Municipal	5
- Agriculture + Forestry	-22
- Transport	7
Total	41
Water gap	201

Table 7.14.: *Total and sectoral split of the water availability impact of China's GHG abatement options (positive numbers: net increase in water availability). The national water gap as stated in [5] is given as reference.*

The right part of figure 7.12 shows how the overall savings are split across the ten river basins: the water balance in all but the South East basin would benefit from the implementation of all GHG measures, with the by far strongest benefits in the Yangtze basin, for two reasons: first, the Yangtze basin is the largest in terms of population and size[56]; second, the water intensity of the avoided power mixes is highest there, as table 7.7 (page 114) showed – any GHG abatement option that reduces power production from the conventional power mix therefore reduces water withdrawals more than in other basins. The sectoral split of table 7.14 generally holds true for most basins: with the exception of the South East and South West, power accounts for the bulk, or 48–73% of savings, and seems to correlate strongest with the water intensity of the avoided power mix. It is followed by the buildings sector, which accounts for 4–15% of savings, depending on the share of population in a basin, and industry, with 3–35% of water savings, which depends on the size and sectoral composition of the industrial base in a basin[57].
China's *South East* basin has two particularities: first, the fact that many coal fired plants are (or planned to be) sea cooled results in a low water intensity of the avoided power mix – power measures make up only 10% here, and the water availability increases

[56]The Yangtze basin is home to 34% of China's population and has 24% of the arable land [93] (2010).
[57]Water withdrawals per basin were taken from [5] for the industry sectors distinguished in the GHG abatement options (petro & oil, chemicals, steel, cement and the accumulative GHG abatement option "other industry") – water savings from GHG measures in these sectors were distributed across basins on this basis.

from energy efficiency measures are therefore also smaller than in other basins. Second, the basin might become a major producer of energy crops for biofuels according to the sources studied here, pushing the water balance to the negative.
Power measures in contrast make up 99% of the sparsely populated, mountaineous *South West* basin[58] – driven by a large potential for hydro power that has, as discussed, the double-benefit of offsetting coal-fired plants and increasing water availability through the concurrent building of hydro dams[59].

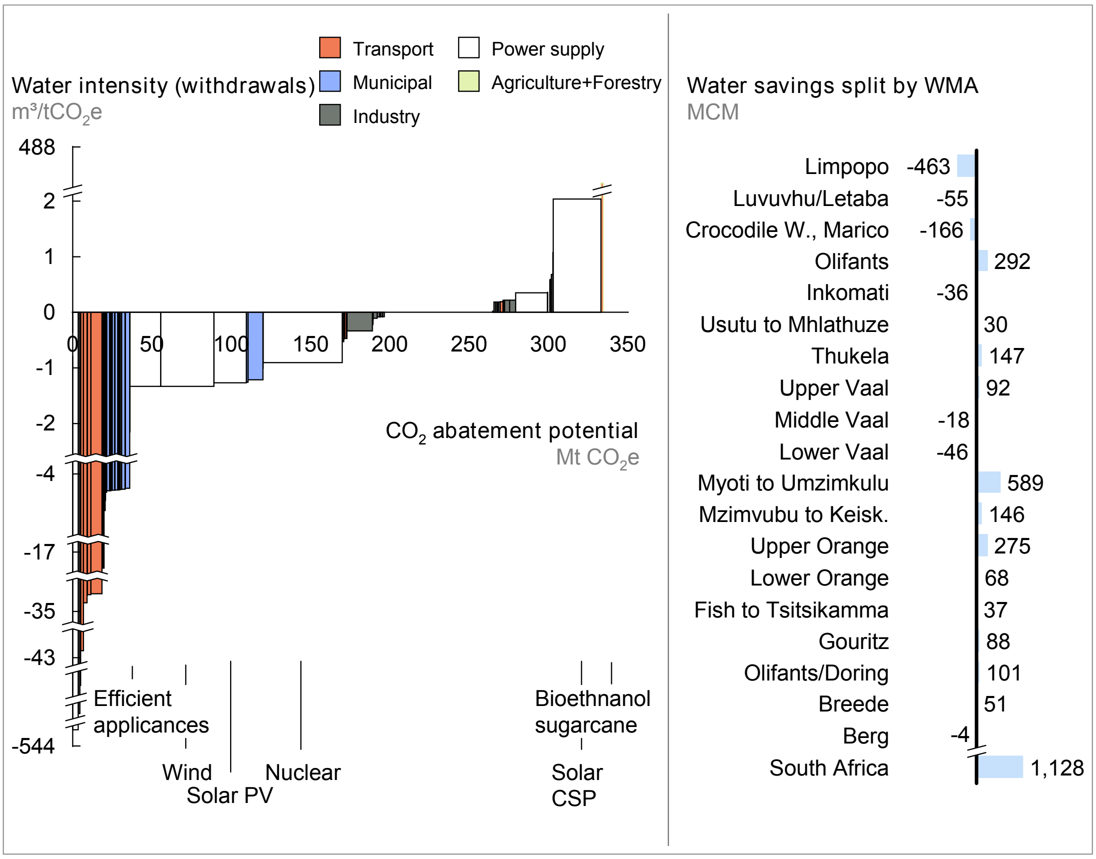

Figure 7.13.: *Water intensity of South Africa's GHG abatement cost curve.*

Water intensity curve of South Africa's GHG abatement options

The left part of figure 7.13 gives the water intensities of South Africa's GHG abatement options. The overall picture is similar to the China case: the left and right ends of

[58]According to the FAO [93] (2010), the South West is home to less than 2% of the population and has less than 2% of the arable land.

[59]A map of China's planned hydropower dams, for example provided by [183], also confirms a large concentration in the South West basin.

the curve are populated by hydro power on the one and biofuels (CCS plays a smaller role than in China) on the other side. Power measures – from wind over photovoltaics to nuclear – account for most of the savings between 30 Mt CO_2e and 170 Mt CO_2e. Concentrationg solar power (CSP) is an exception here and is indeed one of the most water intensive of GHG abatement options[60].

The implementation of all GHG abatement option would increase water availability in South Africa by 1,128 million m^3, 38% of the national water gap, comparable to the China case.

Table 7.15 shows how these savings split across sectors: savings from power account for the largest part, followed by municipal, industry and transport measures, much as in the case of China. Agriculture & forestry again exerts a negative effect on water availability, driven by the planting of energy crops.

in million m^3	**All measures**
- Power	1,989
- Industry	59
- Municipal	79
- Transport	531
- Agriculture + Forestry	-1,532
Total	1,128
Water gap	2,970

Table 7.15.: *Total and sectoral split of the water impact of South Africa's GHG abatement options (positive numbers: net increase of water availability). The national water gap is given as reference.*

It was already mentioned that the regional granularity provided by 19 Water Management Areas (WMAs) in South Africa is higher than for China, where most of the ten river basin are larger in terms of population, GDP and land area than the whole of South Africa. This fine segmentation should therefore yield more information on the impact of structural differences between WMAs.

The right part of figure 7.13 shows how the 1,128 million m^3 of increased water availability split across the 19 Water Management Areas (WMAs), which already highlights larger difference between WMAs than between the ten Chinese river basins (compare to the right part of figure 7.12).

[60] The avoided power plant mix, which includes a large share of air-cooled coal power plants, has a lower water intensity than CSP that is assumed to be wet-cooled (air-cooling would inflict considerable efficiency penalties). See also tables 6.2 (page 85) and 7.7 (page 114).

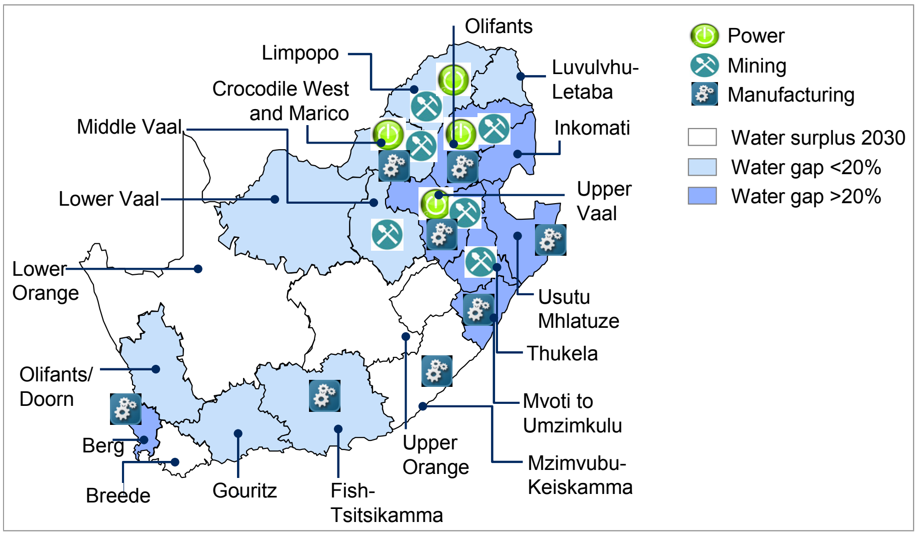

Figure 7.14.: *Distribution of industrial activities across South Africa.*

The distribution of industrial activities across South Africa is given in figure 7.14: it can be seen that a high share of the power generation and mining activity is concentrated in the north-eastern WMAs of Olifants, Upper Vaal, i.e., around the Johannesburg-Pretoria area, and stretches towards the Indian Ocean. Manufacturing activity can be found there, in the Durban area (WMA Thukela), and further along the coast, around Port Elizabeth (WMA Fish-Tsitsikamma) and Cape Town (WMA Berg). This activity, in combination with the assumption that population densities and commerce can be expected to reach equally high levels in these WMAs, might be an explanation for the fact that they figure among those with the highest projected water gaps for 2030, as figure 7.14 also shows.
The water impact of options that reduce power demand is linked to areas with power plant capacities or industrial activity. An implementation of GHG abatement options should therefore increase water availability particularly in WMAs that will likely experience a large water gap by 2030 – which links back to the right part of figure 7.13:

- WMAs with high industrial activities figure among those with the highest water savings from GHG abatement options, among them Olifants, Upper Vaal, Thukela.
- High water savings were also found in the mountaineous WMAs along the coast, Myoti to Umzimkulu, Mzimvubu-Keiskamma or Olifants/Doring. These WMAs have a high potential for new or upgraded hydro dams[61].

[61]The small hydro power (GHG curve) and hydro dam (water availability curve) options were merged into one option for South Africa, as was already the case for China.

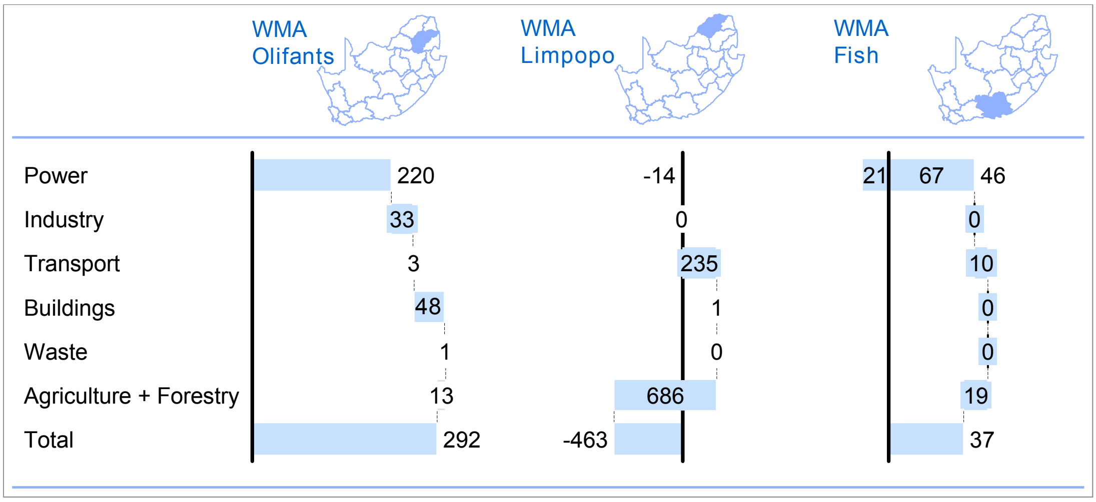

Figure 7.15.: *Sectoral split of the water impact of GHG abatement measures for three of South Africa's Water Management Areas.*

Figure 7.15 shows the sectoral split of the water availability impact of GHG abatement options at the example of three WMAs. The water balance of the WMA *Olifants*, which is home to a large share of South Africa's conventional power plant fleet and also covers a large part of the Johannesburg-Pretoria region, benefits from increased efforts in energy efficiency and a shift towards alternative power sources across South Africa – reflected in the high savings from the power, industry and buildings/domestic sectors.

In contrast, the *Limpopo* WMA might become one of the main growing areas for energy crops, resulting in an overally negative impact on water resources[62].

The impact on water balance in the third WMA, *Fish-Tsitsikamma*, is again dominated by power, albeit in different ways than the Olifants WMA: being the potential site of a new nuclear power plant, this negative impact (-21 million m^3) competes with increased availability from hydro dams installed in the coastal ridge.

7.5. Considerations towards an integrated approach

The last two sections showed that both GHG abatement and water availability options have in sum a positive impact on the other resource. This is already an indication that costs should indeed decrease in an integrated approach towards water and GHG mitigation.

[62]The positive effect of transportation arises from the same logic: transportation measures build on increased motor efficiency. Their implementation reduces gasoline, but also biofuel demand, reliefing again stress in the Limpopo region.

Figure 7.16 shows a matrix with GHG abatement/water availability options that have the strongest impact on the other "resource" at the example of South Africa. Of the six measures in the upper-right corner, i.e., that save both water and GHG emissions, all but wind and solar PV have negative cost. Furthermore, figure 7.11 indicated a correlation between full cost[63] and GHG emissions for water availability options: those that result in higher emissions more often than not also have above-average full cost, and should therefore be among the first ones to become obsolete in a cost-minimization approach, if GHG abatement options already close part of the water gap.

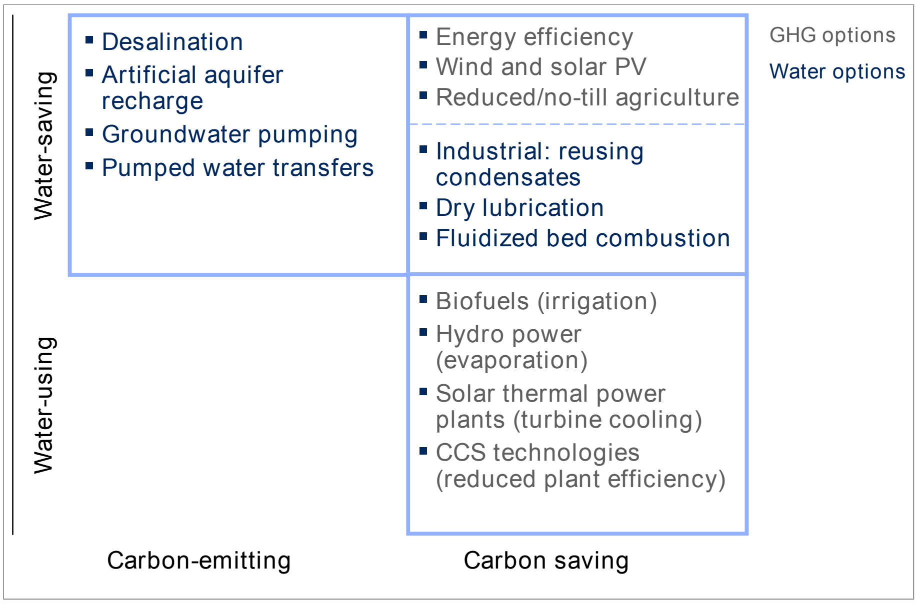

Figure 7.16.: *GHG abatement and water availability options with largest positive or negative impact on the other "resource" (in t $CO2_2e/m^3$ or m^3/t $CO2_2e$).*

[63]We refer here to the full cost as given in equation (6.1). The argument also holds true for integrated cost, which is basically the discounted sum of the full cost.

8. Integrated modeling of water and greenhouse gas mitigation pathways

This chapter finally integrates all mitigation options into one model. It will eventually show that an integrated view does indeed save resources – or achieve higher mitigation targets with the same resources.
The chapter chapter sets out with a description of the considered scenarios. It then discusses those scenarios whose objective was to minimize cost at given water and GHG abatement targets, to afterwards discuss those where the goal was to maximize water/GHG savings at given investment levels.

8.1. Overview of scenarios

While a multitude of potential scenarios could be studied, this work focused on two principle optimization problems:

Minimization of cost. Following the two original reports, it was first investigated how a GHG abatement and water availability target can be achieved at minimal cost. Considered cost terms were full cost, the main focus of [4] and [5][1], and integrated cost[2].
The benefits of an integrated approach can come from a "simple" cross-accounting of water and GHG benefits and the omission of the most expensive mitigation options while maintaining the merit order of the original cost curves, and from a real integrated view; the considered scenarios help to assess both effects:

- *Scenario 1* adds up the water and GHG curves in terms of cost[3], increased water availability and GHG abatement. It assumes that each curve fulfills its target independently.

[1] Please refer to equation (6.1) for a definition of full cost.
[2] I.e., integrated cost 2010–2030, discounted to 2030. See section 6.5.2 (page 89) and appendix E for definitions.
[3] The cost of capital in both original sources [4] [5] were harmonized beforehand.

- *Scenario 2* takes a two-tier approach. It assumes that the water impacts from those GHG abatement options implemented to achieve the emission abatement target are accounted for in the water pathway. This allows to assess the cross-accounting effect mentioned above: assumed that the GHG options increase water availability in sum, less water availability options will be needed. Water and GHG options are however still optimized independently.

- *Scenarios 3* finally integrates water and GHG options and optimizes the solution mix under consideration of both cost and cross-intensities for each option. The (cost) delta to scenario 2 allows to assess the benefit of an integrated approach (versus cross-accounting).

Maximization of water/GHG savings. Policies and development pathways are often constrained by budgets. A second class of scenarios therefore has the objective to maximize GHG emissions savings or water availability under the constraint of fixed investments. We chose integrated investments 2010-2030 as a boundary condition here, for it can serve as a proxy for the financial requirements a society has to raise[4].

<table>
<tr><th>Scenario</th><th>China</th><th>South Africa</th></tr>
<tr><td>1</td><td colspan="2">Achieve water and GHG targets independently and add up cost</td></tr>
<tr><td>2</td><td colspan="2">As 1 + water impact of GHG options accounted for in water pathway</td></tr>
<tr><td>3a</td><td colspan="2">Linear optimization: minimize integrated cost</td></tr>
<tr><td>3b</td><td colspan="2">Lin. opt.: as 3a, but minimize full cost in 2030</td></tr>
<tr><td>4</td><td>Minimize integrated cost without agriculture & forestry</td><td></td></tr>
<tr><td>5</td><td colspan="2">Maximize water/GHG savings under fixed investments</td></tr>
</table>

Table 8.1.: *Scenarios considered in this chapter. See chapter 6 for a definition of the cost parameters.*

8.1.1. GHG and water availability targets in the scenarios

Chapters 3 and 4 discussed possible “Business-as-Usual” projections for GHG emissions and water demand in China and South Africa as well as respective Abatement Cases.

[4]Integrated cost or full cost in contrast also include operational savings that might only materialize after the measure has been implemented. An in these terms beneficial measure can still require, and might be impeded by, large upfront investment needs.

It was shown in this context that the water/GHG targets implied by the cost curves (from [4] and [5]) are consistent with other data sources.

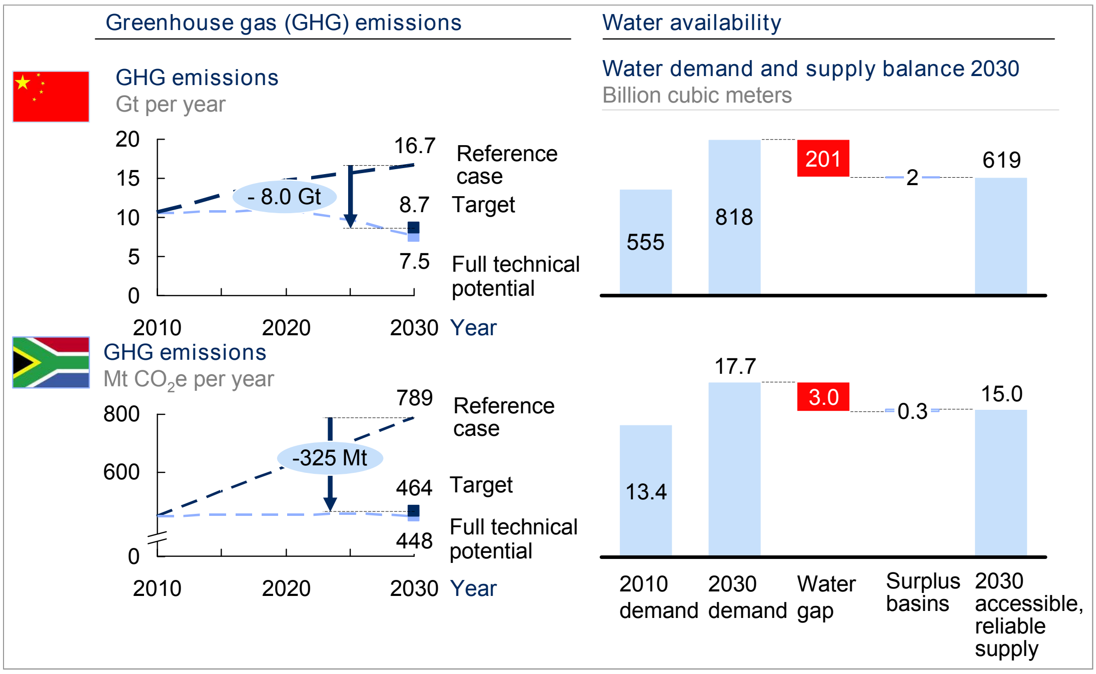

Figure 8.1.: *GHG abatement and water availability targets used in this chapter.*

The water gaps proposed in [5] were therefore adopted without change for scenarios 1–4, but some adjustments were made to the GHG abatement targets:

- For *China*, we chose a 2030 abatement target of 8.0 Gt CO_2e with respect to the reference case, i.e., 1.1 Gt CO_2e lower than the maximum potential of the cost curve, and closer to the abatement potentials in other reports [20] [116] [127].

- For *South Africa*, an abatement target of 325 Mt CO_2e was used, slightly lower than the maximum potential of 341 Mt CO_2e. This adjustment was primarily made to give the linear model more flexibility in chosing the optimal mix and therefore increase stability and reliability of the solution[5].

[5]This avoids that "extreme" measures (in terms of cost or cross-intensities) need to be included in the solution mix.

8.2. Scenarios 1–4: integrating water and GHG at minimal cost

8.2.1. Scenario 1. Water and GHG added up

This scenario is in principle just the sum of the water availability and GHG abatement cost curves given the targets from figure 8.1. Some adjustments have however been made to the mitigation options, notably a split of the 2010–2030 potentials (and cost) into two decades (2010–2020 and 2020–2030), and a harmonization of the cost of capital to 4%. Furthermore, the key metric are the *integrated* cost 2010–2030, a different solution mix than in the original reports can therefore be expected.
Water availability increases and GHG emission reductions can be summarized as follows:

GHG emissions. The GHG abatement targets were overachieved in both China and South Africa. This comes at little surprise, as the two curves were optimized independently, requiring the GHG options to reach their target stand-alone; the (reductive) GHG impact of the water availability options is then added to the already fulfilled target. Table 8.2 summarizes the GHG abatement: both China and South Africa overshoot their GHG abatement target by about 2%.

	China	**South Africa**
	Mt CO_2e	*Mt CO_2e*
- Water measures	185	8
- GHG measures	8,000	325
Total	8,186	333
Target	8,000	325

Table 8.2.: *GHG savings in scenario 1.*

Water availability. The water intensity curves of the GHG abatement options (figures 7.12, p.133 and 7.13, p.135.) in the last chapter showed that the water impact of GHG measures on basin/WMA level can either be positive or negative. Some basins will therefore overachieve their water target in that setting, while others, where the sum of the available water availability options just sufficed to close the projected water gap and the water availability from the GHG measures is negative might come to the point that the gap cannot be closed at all.
Figure 8.2 shows that the sum of water savings from water and GHG mitigation options indeed leads to an overachieving in some basins/WMAs, while the gap cannot be closed

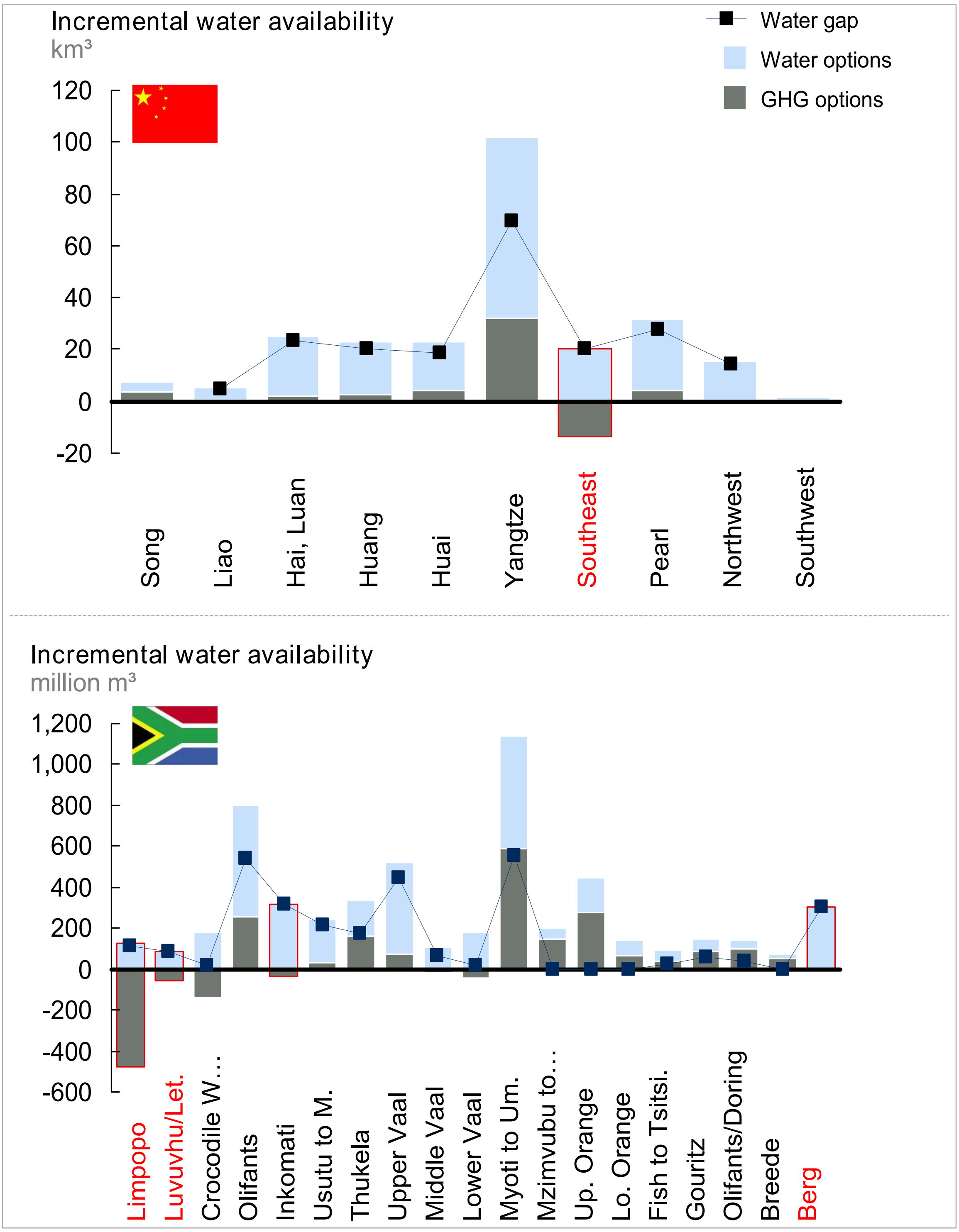

Figure 8.2.: *Scenario 1: basin/WMA water gaps and the impact on water availability of water and GHG abatement options realized under given constraints. Basins/WMAs with a remaining gap are marked in red.*

in others, particularly in those with a negative water impact from GHG options[6].

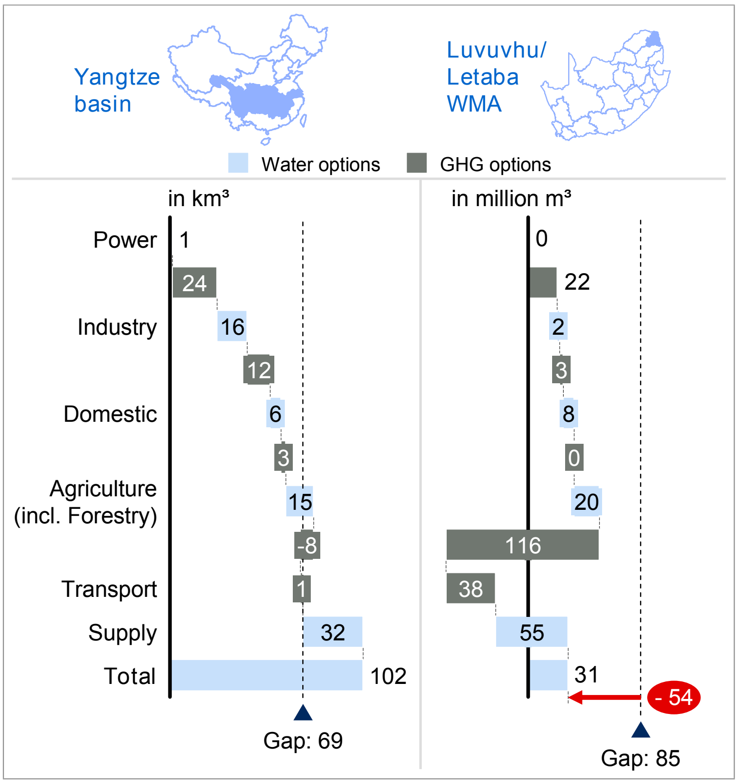

Figure 8.3.: *Scenario 1: water impact of all measures in China's Yangtze basin and South Africa's Luvuvhu/Letaba WMA. As GHG measures that also save water predominate in the Yangtze basin, the water availability target is over-achieved. In the Luvuvhu/Letaba WMA, energy crops for biofuel production lead to a widening of the water gap – the available water availability options cannot compensate for this.*

These considerations lead to one key outcome of this scenario:

Implementing the water availability and GHG abatement pathways independently leads to an overachievement of GHG targets, but does not resolve water availability shortages in all basins/WMAs.

[6]However, not all basins/WMAs with a negative water impact from GHG options have a remaining water gap in this scenario: in South Africa's Crocodile West/Marico, Middle and Lower Vaal WMAs for example, the negative impact of GHG options is (over-)compensated by the fact that more water availavility options than necessary for closing the gap were implemented in the first place. This happened because they all had negative integrated cost, i.e., the integrated operational savings exceeded investments, and were therefore chosen by the optimization tool despite no remaining water gap.

The discrepancies between basins that overachieve their water target and those with a remaining water gap are illustrated at two examples in figure 8.3. The water availability options at hand suffice to close the gaps in both the Yangtze basin and the Luvuvhu/Letaba WMA. Additional water savings arise in both regions from the power sector, industry and domestic sector. The difference stems from agriculture: the Yangtze basin has less (relative) potential for irrigated energy crops than the Luvuvhu/Letaba WMA, where the implementation of all measures leads to a residual water gap.

	Int. cost	**Investments**	**Cost in 2030**
	USD billion	*USD billion*	*USD billion*
China	1,269	3,637	-5
- Water measures	-4	212	-9
- GHG measures	1,273	3,425	4
South Africa	64.2	184.9	-7.4
- Water measures	-5.1	2.9	-0.7
- GHG measures	69.2	182.0	-6.7

Table 8.3.: *Cost figures from scenario 1.*

Table 8.3 summarizes the financial implications of the first scenario:
The GHG abatement options require the larger part of investments and integrated cost in both countries – they for example account for 94% of investments in China, and 98% in South Africa. One explanation for this might be differing solution mixes: the GHG part generally involves technologically more advanced measures that require high investments, while increased water availability relies to a larger part on less investment-intensive agricultural or domestic measures[7].
To put these cost numbers into perspective: China's cumulated GDP 2010–2030 is projected to be about USD 170,000 billion, and USD 9,500 billion for South Africa[8] [108]. The integrated cost/investments according to table 8.3 therefore make up 0.7%/2.1% of China's and 0.7%/1.9% of South Africa's cumulated GDP.
Looking more specifically at investments, China's cumulated 2011–2030 investments are estimated at USD 82,000 billion, and South Africa's gross domestic investment at USD 2.200 billion according to the same source[9] – investments in water–GHG pathways

[7]As indicated in the original cost curves; see figures 4.1 (p. 50), 4.3 (p. 53) for the water availability curves and figures 4.6 (p. 59), 4.8 (p. 61) for the GHG curves as given in [5] and [4] [77].
[8]Figures 3.2 (page 31), and 3.7 (page 40) gave 2010 and 2030 real GDP for both countries. Cumulated GDP is the 2011–2030 sum of the yearly real GDP forecasts from [108].
[9]In real 2005 terms.

according to table 8.3 therefore make up between 4% (China) and 8% (South Africa) of overall investments over that period.

8.2.2. Scenario 2. Cross-accounting of water savings from GHG measures

The GHG solution mix of this scenario is the same as in scenario 1 given the still independent modeling approach. The water availability options solution mix is however different, as the initial basin/WMA water gaps were adjusted so that they reflect the water impact of the GHG solution mix.

The overall **GHG savings**, shown in table 8.4, differ little from scenario 1, as the (unchanged) GHG abatement option mix already achieves the abatement target, and the GHG impact of the realized water availability options adds further savings which however differ from table 8.2

	China	**South Africa**
	Mt CO_2e	*Mt* CO_2e
- Water measures	188	7
- GHG measures	8,000	325
Total	8,188	332
Target	8,000	325

Table 8.4.: *GHG savings in scenario 2.*

Figure 8.4 contrasts the original **water** gaps with the new gaps after accounting for the impact of the GHG measures. The blue bars, which represent the increase in water availability from the water options only, show that the cross-accounting allows for a more precise closing of the water gaps. Still, not all water gaps are closed, as the basin/WMAs marked in red show: the negative water impact of the GHG measures was in particular too large in those basins with high energy crop potential to be compensated by the available water options.

The benefits of the cross-accounting can best be studied at the example of a basin/WMA that experienced a strong overfulfillment of the water gap in scenario 1, such as South Africa's Olifants WMA (figure 8.5):

- In scenario 1, the sum of all water measures would have closed the water gap of

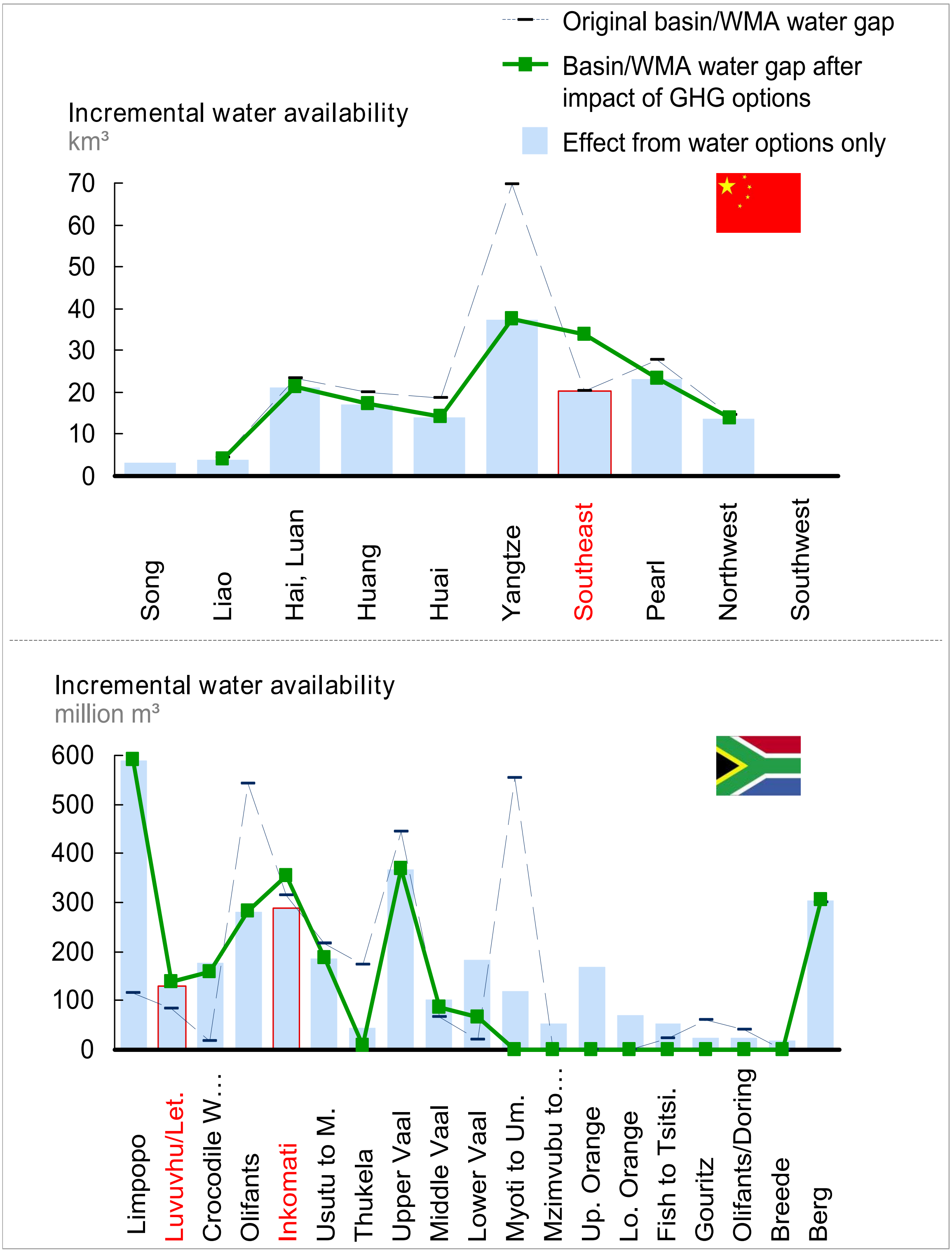

Figure 8.4.: *Scenario 2: basin/WMA water gaps after accounting for the water impact of GHG measures, contrasted with the increase in water availability from the water availability options. Basins/WMAs with a remaining gap are marked in red.*

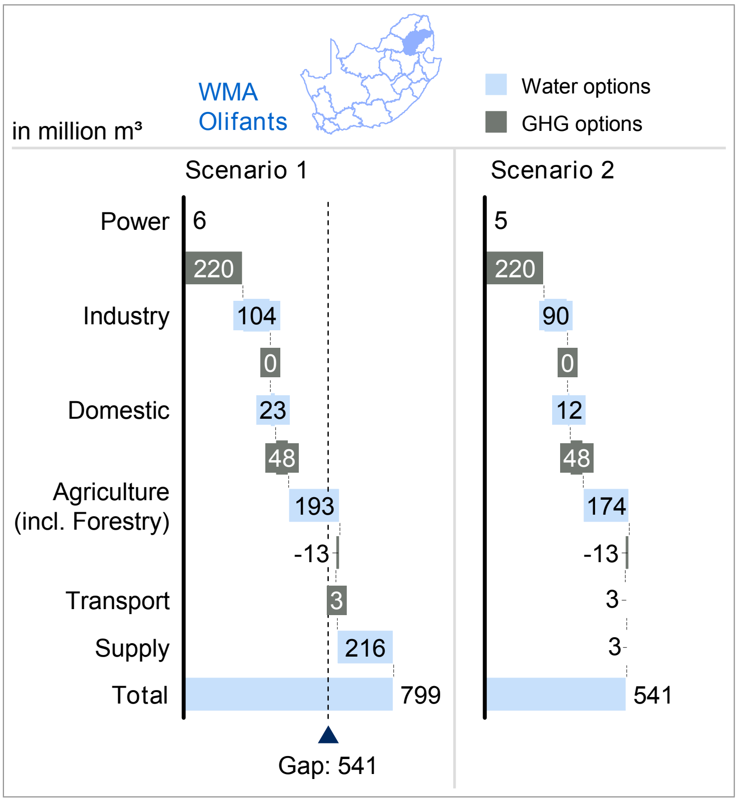

Figure 8.5.: *Scenario 1 and 2 in comparison at the example of South Africa's Olifants WMA: summing up of all water availability increases results in an overachievement (left part). Accounting for water savings from GHG options before closing the remaining water gap (right part) avoids this.*

541 million m^3 alone, but GHG abatement options increased water availability by further 258 million m^3.

- In scenario 2, the effective water gap for the water measures was reduced to 283 million m^3 (541 less 258), under the assumption that the GHG measures cover the remaining 258 million m^3. The sum of all measures now matches the water gap.

Cost parameters for scenario 2 are shown in table 8.5. Integrated cost decreased by 10% in China and 1% (South Africa) compared to scenario 1. As it was not the objective of the optimization, the decrease in investments is lower, 1.4% for China and 0.5% for South Africa[10].

The difference in cost decrease can be explained by the fact that GHG measures have a positive impact on water balances in all but one of China's basins – less potential from

[10] The cost figures for the GHG abatement solution mix has not changed with respect to scenario 1.

	Integrated cost	**Investments**	**Cost in 2030**
	USD billion	*USD billion*	*USD billion*
China	1,137	3,586	-12
- Water measures	-136	161	-16
- GHG measures	1,273	3,425	4
South Africa	63.6	184.1	-7.4
- Water measures	-5.6	2.0	-0.7
- GHG measures	69.2	182.0	-6.7

Table 8.5.: *Integrated cost, investments and full cost of scenario 2.*

water availability options is therefore required in scenario 2 (compared to scenario 1); only China's South East basin has the adverse impact. However, the water measure potential in the basin was already exhausted in scenario 1, so that no further is left to close the (now larger) water gap in scenario 2.

In *South Africa*, four out of 19 WMAs experience a negative impact on water balances from GHG mititgation options (see figure 8.2, page 144). In all, the water savings potential from water availability options could indeed be increased between the two scenarios (compare figures 8.2 and 8.4). This closes the water gap in two them, but offsets cost reductions in other WMAs, leading in sum to smaller savings than in the China case.

8.2.3. Scenario 3. Integrated approach

These scenarios finally integrate all GHG and water mitigation options into one model and optimize the solution mix according to the logic described in section 6.6 (p.92 ff.); scenario 3a minimizes for integrated cost, while scenario 3b minimizes the full cost in 2030.

3a. Minimization of integrated cost

The **GHG savings** in table 8.6 shows that abatement targets are now exactly hit by the combination of water and GHG mititgation options[11].

A similar picture can be drawn for **water availability**. Figure 8.6 shows that the integration of water and GHG mititgation options allows to close the water gaps in *all*

[11] See for comparison tables 8.3 (scenario 1) and 8.5 (scenario 2): the GHG target is achieved by the GHG measures alone, with water measures adding further emission reductions on top.

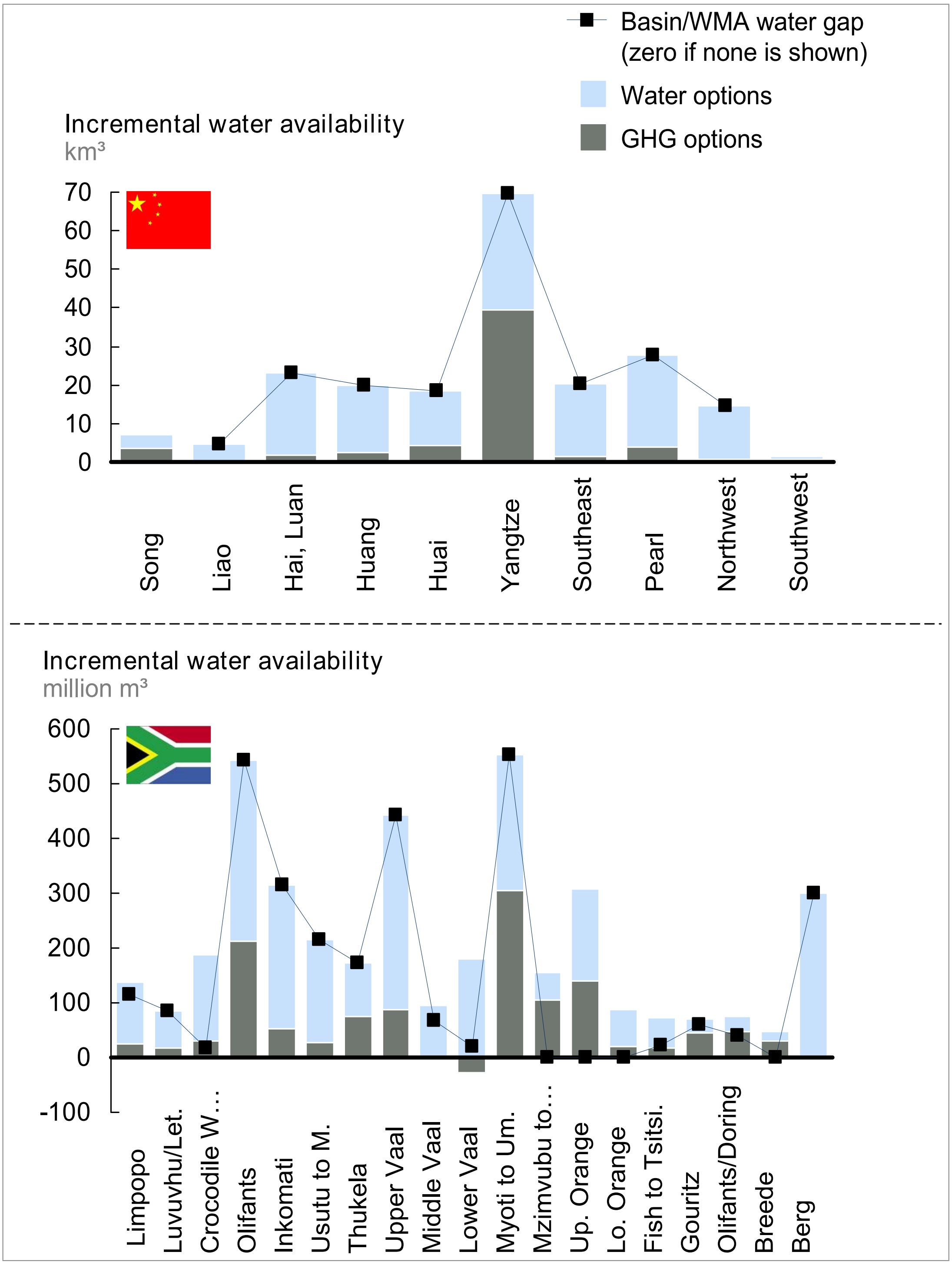

Figure 8.6.: *Scenario 3: again the original basin/WMA water gaps, contrasted with the water impact of both water availability and GHG abatement options in an integrated approach.*

	China	**South Africa**
	Mt CO_2e	*Mt CO_2e*
- Water measures	190	7
- GHG measures	7,810	318
Total	8,000	325
Target	8,000	325

Table 8.6.: *GHG savings in scenario 3a.*

basins/WMAs, and overachievings are at first glance smaller. All basins/WMAs that still overfullfill their water gap do so "on purpose", as the integrated water potential of all cost-negative options is larger than the water gap[12].

	Unit	**China**	**S. Africa**
Water savings from GHG options			
- total	million m^3	58,897	1,209
- of which power-related	million m^3	36,335	147
- power related in percent	%	62%	12%
GHG savings from water options			
- total	Mt CO_2e	190	7
- of which power-related	Mt CO_2e	176	3
- power related in percent	%	93%	48%

Table 8.7.: *Contribution of power-related measures to the water impact of GHG measures and the GHG impact of water measures, respectively.*

The role of the power sector

A hypothesis from the last chapter was that the strength of the water-GHG interdependencies is largely influenced by the power sector and the fact that most GHG or water mitigation options with a positive impact on the other resource were related to energy efficiency or renewable power generation.

Table 8.7 gives the water (GHG) impact of GHG (water) mitigation options and shows the share of the impact that is directly related to power generation in scenario 3[13].

[12]Cost-negative options in terms of integrated cost – as the objective function is to minimize integrated cost, these measures will be implemented by the model no matter what the actual water target is.

[13]This includes the water impact from all alternative power generation technologies such as wind, solar,

The majority of cross-intensities in China can indeed be attributed to power related measures, while the share is markedly lower for South Africa. An explanation for this can be found with a look back to table 7.7 (page 114) that gives the water intensities for avoided power mixes: these are higher in China's largest basins (such as the Yangtze, Hai, or Song) than in South Africa's main WMAs (Limpopo, Olifants, Upper Vaal) – an energy efficiency measure will therefore have a proportionately stronger impact on water resources in China.

Omission of options between scenarios 2 and 3 – China example

The high-cost "end" of China's water availability cost curve is dominated by supply and municipal options (see figure 4.1, page 50). Of these, supply-side options mostly have negligible GHG impacts (within the boundaries of this work), while options from the municipal sphere do have a positive GHG impact, but their resource savings come at comparatively high cost: a new toilet requires integrated cost of USD 15, and saves 0.8 kg CO_2e (in the case of China) per cubic meter of incremental water availability. Dry quenching of coke, an industrial process, *saves* in contrast USD 30 and 2.7 kg CO_2e per cubic meter.

In the case of China's GHG abatement cost curve, CCS-related options dominate the high-cost end (see figure 4.6, page 59), which have to the most part a negative impact on water balances.

These options are reduced the most from scenario 2 to scenario 3: omission of CCS abatement options leads to a drop in the integrated cost 2010–2030 for industrial GHG measures drop from USD 12 billion in scenario 2 to USD -110 billion in scenario 3. Similar reduction can be observed for municipal (USD -2 bn $\rightarrow$ USD -9 bn) and supply (USD 124 bn $\rightarrow$ USD 115 bn) water availability options. Changes in most other sectors are negligible in comparison: integrated cost in power, agriculture and transport decreased by a combined USD 37 billion across both water and GHG measures.

Table 8.8 summarizes the cost parameters for scenario 3: integrated cost are in sum 14% (China) and 3.4% (South Africa) lower than in scenario 2 (and 23%/4.3% lower than in scenario 1), while investments decrease by 6% (China) and 5% (South Africa).

3b. Minimization of cost in 2030

As the original curves studied the full cost *in* 2030, it might be worthwhile to investigate how the integrated solution mix changes if optimized along this parameter.

biomass, plus that share of water savings from energy efficiency measures that can be attributed to reduced power consumption. Conversely, for water availability options, it includes the share of GHG savings that can attributed to power savings or cleaner, alternative forms of power generation.

	Integrated cost	**Investments**	**Cost in 2030**
	USD billion	*USD billion*	*USD billion*
China	975	3,385	-8
- Water measures	-153	155	-17
- GHG measures	1,128	3,230	10
South Africa	61.4	175.3	-7.0
- Water measures	-5.2	1.7	-0.6
- GHG measures	66.7	173.7	-6.4

Table 8.8.: *Integrated cost, investments and full cost in scenario 3a.*

	China	**South Africa**
	Mt CO_2e	*Mt CO_2e*
- Water measures	130	7
- GHG measures	7,870	318
Total	8,000	325
Target	8,000	325

Table 8.9.: *GHG savings in scenario 3b (minimization for full cost in 2030).*

To summarize, all boundary conditions are met in this scenario, i.e., all water gaps can be closed, and the GHG abatement targets are met in the same way as was the case for scenario 3a (see table 8.6).

	Integrated cost	**Investments**	**Cost in 2030**
	USD billion	*USD billion*	*USD billion*
China	2,839	5,126	-31
- Water measures	174	243	0
- GHG measures	2,665	4,883	-31
South Africa	78	199	-8
- Water measures	-4	2	-1
- GHG measures	78	197	-7

Table 8.10.: *Integrated cost, investments and full cost of scenario 3b, minimization for cost in 2030.*

The differing objective function can be expected to lead to a change in the cost figures compared to scenario 3a. Table 8.10 shows that the integrated cost for both China and South Africa are higher than in the preceeding scenario, whereas cost in 2030 are – not suprisingly – lowest.

An interesting difference between scenarios 3a and 3b is that the minimization of *integrated* cost 2010–2030, versus cost *in* 2030, leads to a push of measures from the first to the second decade: it can be cheaper from an integrated cost standpoint to avoid the implementation of technologies with cost above the reference case in the first decade, as they would need to be financed over two decades, and instead build a larger share of more expensive technologies (such as CCS) in the second decade that need to be paid for only in one decade[14].

Table 8.11 shows the GHG emission reduction and water availability increases after one decade at the example of China – as expected, both values are lower if the optimization is for integrated cost than for cost in 2030.

In particular, the realized potential of expensive CCS technologies increased by more than 700 Mt CO_2e (all built after 2020) between scenario 3b and 3a, while for example the potential of photovoltaic before 2020 droped by more than 100 Mt CO_2e.

This cost consideration is of course only one aspect of a wider problem:

[14]This argumentation builds on the assumption that it is impossible to scale up the two-decade potential of a measure in one decade.

	GHG savings	**Incr. water av.**
	Mt CO_2e	*km^3*
3a Min. for integrated cost	2,500	104.9
3b Min. for cost in 2030	2,960	107.5

Table 8.11.: *Comparison of 2020 GHG and water savings in scenarios 3a and 3b.*

While it makes sense to optimize an implementation process such that targets are hit in time and not much in advance, stakeholders need to realize that the later they start, the more they need to rely on measures that are then more expensive, riskier, or less easy to implement.

8.2.4. Scenario 4. Integrated approach (infrastructure only)

The scenarios discussed so far assumed that the whole set of mitigation options is at disposal.

A variety of factors might however lead to the situation that certain options face in fact high barriers to implementation. These are for example those options that cannot be decided upon easily by a small group of stakeholders, but rather require the rethinking of millions of people and their access to adequate financing.
Most agricultural mitigation options certainly fall into this category. It seemed therefore interesting to study a scenario into which all agriculture and forestry measures are excluded. The analysis was perfomred at the example of China, and the objective was again to minimize integrated cost.

The GHG abatement target of 8 Gt CO_2e can be achieved in this configuration – this is plausible, as agricultural measures make up less than 0.7 Gt CO_2e of the total potential from all GHG options of 9.1 Gt CO_2e.
Agriculture and forestry options however account for 28% of the water availability potential. Figure 8.7 contrasts the realized increases in basin water availability with the respective water gaps and shows that, by excluding agriculture and forestry options, the potential of the remaining water and GHG mitigation options does not suffice to close the water gap in four out of eight basins with a projected deficit (in 2030).

Moreover, the achieved water and GHG savings are more costly than in previous scenarios.

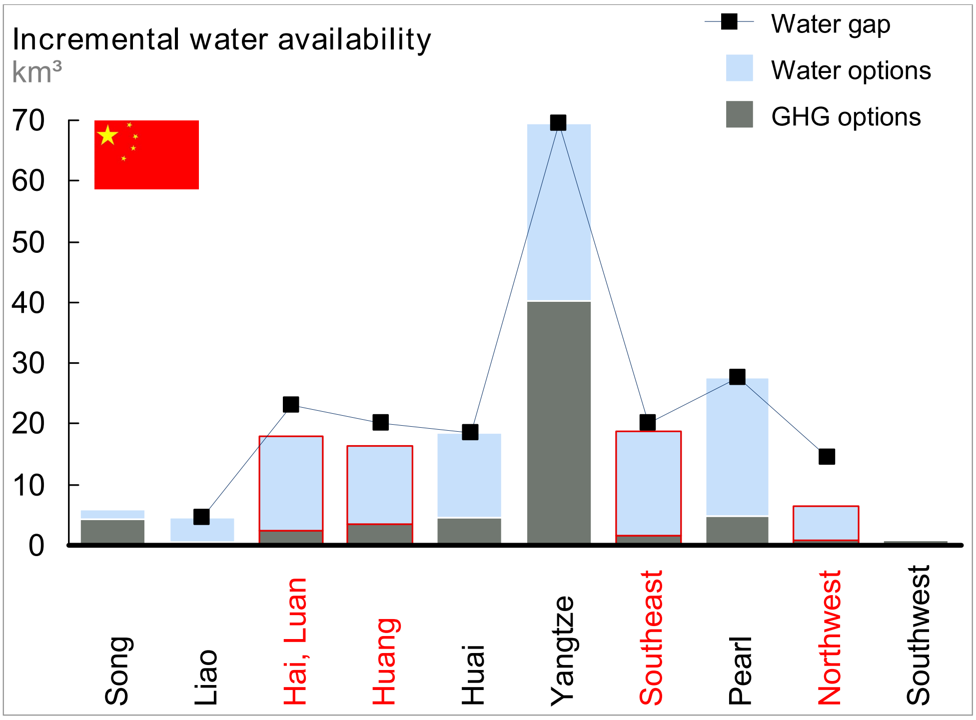

Figure 8.7.: *Scenario 4 – excluding agriculture & forestry options: basin water gaps and the water impact of both water availability and GHG abatement options under an integrated modeling approach. Basins whose water gap could not be closed are marked in red.*

Table 8.12 shows that all cost paramaters are higher than in scenarios 1–3[15], with investments for example being 36% higher than in scenario 3a.
The lessons from this scenario are perhaps as follows: *it is important for a decsision maker such as a government to get all relevant stakeholders involved and committed, and align on the cheapest or most practical solution mix. An integrated pathway can then further reduce cost or stress on resources, but can hardly outweigh the "loss" of important mitigation options.*

8.2.5. Summary of scenarios 1–4

Figure 8.8 summarizes all cost parameters and gives the average water/CO_2e cost on a per cubic meter/ton basis for scenarios 1–4[16].

[15] With the exception of scenario 3b, which however had a different objective function (minimization of full in 2030 cost, instead of integrated cost).

[16] The water (CO_2e) cost were calculated by dividing the integrated cost 2010–2030 of the implemented water (GHG abatement) options by the integrated water (GHG) savings of all measures. This method

	Integrated cost	Investments	Cost in 2030
	USD billion	*USD billion*	*USD billion*
China	2,382	4,610	15
- Water measures	15	200	-7
- GHG measures	2,367	4,411	22

Table 8.12.: *Integrated cost, investments and full cost of scenario 4.*

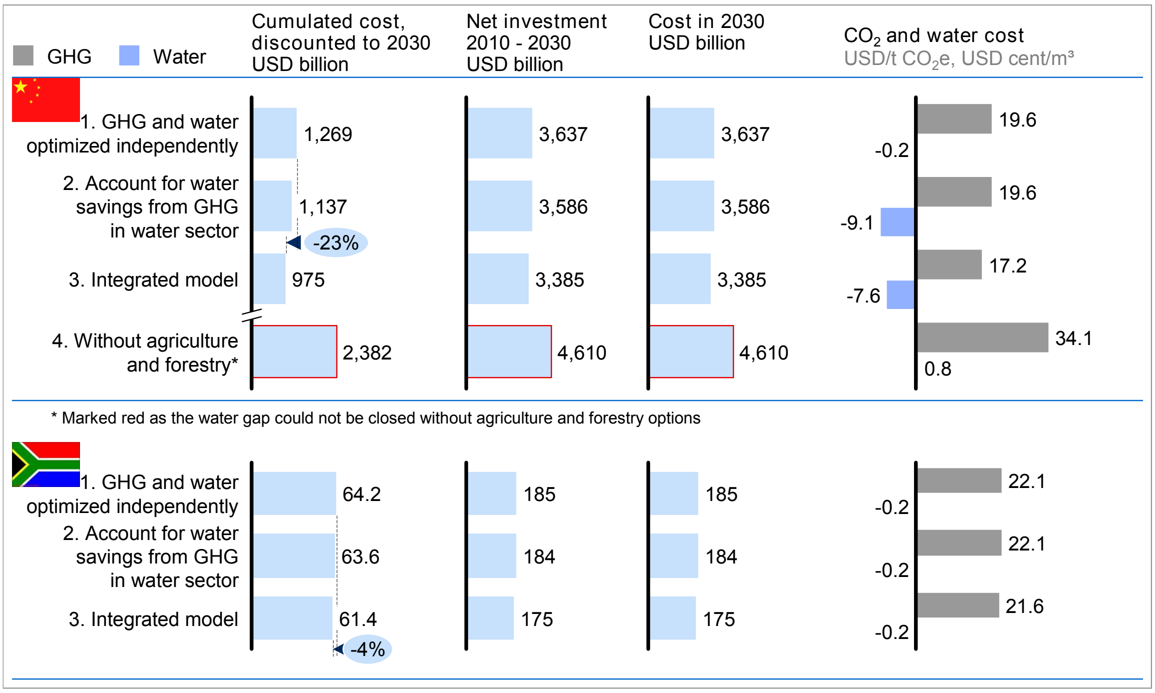

Figure 8.8.: *Comparison of integrated cost, investments, and associated mitigation cost for water and CO_2e for scenarios 1–4.*

As can be seen, the cost figures clearly decrease from scenario 1 to scenario 3 – integrated cost in scenario 3 are for example a full 23% lower for China, and 4% for South Africa. It can furthermore be expected that the cost in figure 8.8 are in line with those mentioned in the original reports [4] [5]:

- The cost figures for **water** measures in China (South Africa), between -7 and -17

has the drawback of using once a subset (cost) and once all measures (resource savings) for the calculation. Alternatives are the division of integrated cost of all measures by total water/GHG savings, which however results in making GHG measures relatively cheaper at the expense of water measures. As disscussed before, the original reports [4] [5] follow a third logic and divide the full cost of one year by the water/GHG savings (of that year). This gives a snapshot, but does not say what cost are in other years.

USD billion (-0.6 to -0.7 USD bn. for South Africa), are in the same order as the -21 (-0.2) USD billion reported in [5][17]. The remaining difference arise from the discussed change in cost of capital and a different approach to basins with a projected surplus in 2030[18].

- Cost for **GHG** measures in China (South Africa) of 4 – 22 (-6.4 to -6.7) USD billion in figure 8.8 compare to 62 (3) USD bn. in [4] [77]; the lower values in our analysis are related to changes in GHG abatement targets (remember that China's USD 62 billion corresponded to GHG savings of 9.1 Gt CO_2e, compared to our target of 8.0 Gt CO_2e).

Costs set in perspective

	Unit	**China**	**S. Africa**
Cumulated GDP 2010 – '30	*USD billion*	170,000	9,500
Integrated cost	*USD billion*	975 – 2,380	62 – 64
	in % of GDP	0.6 – 1.4%	0.7%
Investments	*USD billion*	3,390 – 4,610	175 – 185
	in % of GDP	2.0 – 2.7%	1.8 – 1.9%

Table 8.13.: *2010–2030 integrated investments, integrated cost and GDP in perspective. Numbers for China cover scenarios 1–4, for South Africa scenarios 1–3.*

As the informative value of unrelated cost figures is rather small, table 8.13 puts cumulated investments and integrated cost in perspective to GDP projections for China and South Africa. In both countries, integrated cost[19] are on the order of 1%, and investments about 2–3% of GDP, with the bulk of these cost related to GHG abatement options (see figure 8.8). The following paragraphs therefore mainly aim to set the cost of the GHG abatement options in perspective.

An alternative GHG abatement cost curve for *China* [127] estimates investments for a low carbon pathway at 3,000 – 4,000 USD billion between 2010 and 2030. For 2030, the

[17] See figures 4.1, page 50, and 4.3, page 53.

[18] Our linear optimization model implements all options with negative cost, independent of an existing water gap; integrated cost and cost in 2030 are thus lower than in [5], which implemented only those options necessary to close the gaps.

[19] Please note (yet again) that all cost figures are incremental to the reference case - i.e., the cost in figure 8.8 are on top of what is required in a Business-as-Usual scenario.

report states that this represents 1.5–2.5% of China's GDP[20], in good agreement with our data.
According to the 2010 World Energy Outlook [20], China accounts for 30% of the global GHG emissions reduction potential towards atmospheric CO_2 concentrations of 450 ppm[21]. This scenario is estimated to require global investments of USD 11.4 trillion between 2010 and 2030 – China would then need to invest USD 3.4 trillion if these were split on a pro-rata basis, in good agreement with table 8.13[22].
Lastly, *South Africa's* Long Term Mitigation Scenario report [110] gives total cost (which can best be compared to our integrated cost) for low-carbon pathways as a percentage of GDP: the *Scale-Up* scenario achieves 2030 GHG savings of about 300 Mt CO_2e and requires incremental cost of 0.77% of GDP[23], while the *Use the Market* scenario, mitigating about 400 Mt CO_2e until 2030, increases cost by 0.11% of GDP[24]. These numbers again agree with our data from table 8.13.

	IPCC	**China**	**S. Africa**
Baseline emissions, Gt CO_2e	68	16.7	0.8
Economic pot. @ USD 100/tonne, Gt CO_2e	16 – 31	7.0	0.3
- % of baseline emissions	23 – 46%	42%	35%

Table 8.14.: *Abatement potential of GHG mitigation options with full cost of less than USD 100/tonne according to the IPCC report [184] and the solution mixes of scenario 3a for China and South Africa.*

Lastly, table 8.14 shows that the economic potentials of all measures with a marginal

[20] Under comparable conditions: the integrated curve in [127] yields GHG emission savings of 6.7 Gt CO_2e, slightly lower than our target of 8.0 Gt CO_2e. However, the reference case is also lower, at 14.5 Gt CO_2e.

[21] Based on global and China emission deltas between the *Current Policies* and *450 [ppm]* scenarios (see pages 621 and 673 in [20]).

[22] Even though the WEO only focuses on energy-related measures, the data are comparable, as non-energy investments are small: in scenario 3, investments in agriculture and forestry (accounting for most of the non-energy part) accounted for less than 1% of investments in China.

[23] See pages 119-120 of [110]. From the report, it is not fully clear which period the cost figures refer to, but likely the period 2003–2050. Moreover, the reference scenario in [110] (*Growth Without Constraints*) assumes a steep increase in GHG emissions, reaching about 950 Mt CO_2e in 2030; the comparison should thus be seen as an order-of-magnitude check only.

[24] The LTMS scenarios were not derived from GHG abatement targets, but abatement targets are rather the result of a package of potential regulatory measures. This can lead to cost numbers that are at first sight counterintuitive with respect to the achieved GHG savings.

cost of less than USD 100/tonne CO_2e from our modeling are in the same order as the numbers stated in the IPCC report [79][25].
A look back at figure 8.8 at the beginning of this section shows that the average CO_2 cost in scenarios 3 are about 20 USD/tonne, which again shows that some options come at a negative cost while others cost up to (or even more) than 100 USD/tonne – an indication on how important it will be for decision makers to devise well-functioning redistribution schemes. This argumentation also holds true for water availability measures: while the average cost, in terms of USD/m^3 of incremental water availability, is in fact negative (see fig. 8.8), mitigation options can have much higher specific cost, as a look at the original water cost curves[26] confirms.

To conclude, two main results seem to come out of this section:

1. *An integrated view on water and GHG mitigation options reduces cost and helps to achieve targets.* The comparison between scenarios 1 and 2 showed how a cross-accounting of savings from one pathway (GHG abatement) in the other (increased water availability) already enables synergies and thereby reduces cost and helps to meet targets. The shift from scenario 2 to 3 then demonstrated how an integrated modeling optimizes the solution mix further, beyond what is possible through "manual" cross accounting.

2. *Considering all options is important to fulfilling targets in an optimal way.* Scenario 4 finally showed what can happen if a certain sector, in this case agriculture, is ignored.
   In order to achieve a goal in an optimal way, it is therefore important to convince all stakeholders first – the most holistic and integrated planning will not bear full fruit if decision makers focus on conventional mitigation options such as increased supply, modern power plants or increased industrial efficiency only, and leave out options that need to be anchored deeper in the public.

The findings presented here should however not be considered as the final results on the matter of water–GHG interdependencies, but rather as a first proof of our considerations. The results are sensitive to underlying assumptions on economic growth, reference case development of water and GHG emissions and the assumed potential of the different mitigation options. In particular, assumptions on biofuels growth have a sizeable impact on whether water gaps can be closed in some basins/WMAs. Lastly, the "frozen technology"

[25] Unfortunately, no country-specific data was available to our knowledge.
[26] See pages 49 – 54

approach neglects the benefits of potential new technologies that are not yet feasible today, but might well be so by 2030.
Therefore, these results should not be considered as exact predictions for a China or South Africa of 2030. They are rather sensitivities on the general development direction towards more sustainable water management and reduced GHG emissions that was sketched out independently in [5] and [4]+ [77]. Within this general direction, the sensitivities represent boundaries: it is neither very likely that a country focused on sustainable development neglects all (water/GHG) interactions (scenario 1), nor that such a tight planning process can be established that considers all cross-dependencies in detail (scenario 3).

8.3. Scenario 5: maximizing water/GHG savings

The implementation of water availability and GHG abatement options is often constrained by investments. No public or private stakeholder can borrow indefinitely to finance mitigation options which eventually pay back later. Even if paybacks are larger than investments, it is not always the case that the investor can line his pockets with them[27]. It might therfore be interesting to study scenarios that maximize water/GHG savings under fixed investments.

Isoinvestment curves

Section 6.6.2 (page 98 f) discussed the concept of *isoinvestment curves*. In short, these connect all optimal combinations of water and GHG savings under fixed investments[28]; if the incremental water availability was plotted in a graph along the x-axis, and incremental GHG abatement along the y-axis, isoinvestment curves are concave with respect to the origin, and the gradient dy/dx gives the marginal rate of substitution between one cubic meter of incremental water availability and one tonne of GHG abatement. This can give information on appropriate price ratios between water and GHG in order to achieve certain combinations of water/GHG savings and investments.

[27] Consider for example energy efficient retrofits of appartment buildings: the owner invests in insulation and thereby reduces heating costs for the tenants. As these are normally paid to a different stakeholder (a utility), and given that the rent can often only be increased by small amounts per year, it is difficult for the owner to recoup the investments, even though the measures comes at a net economic benefit. Therefore, owners might only retrofit their appartment buildings if financial incentives are created, which however increases stress on the governmental budget.

[28] *Optimal* hereby means that it is not possible to further increase water availability or GHG abatement at given investments without reducing savings of the other resource.

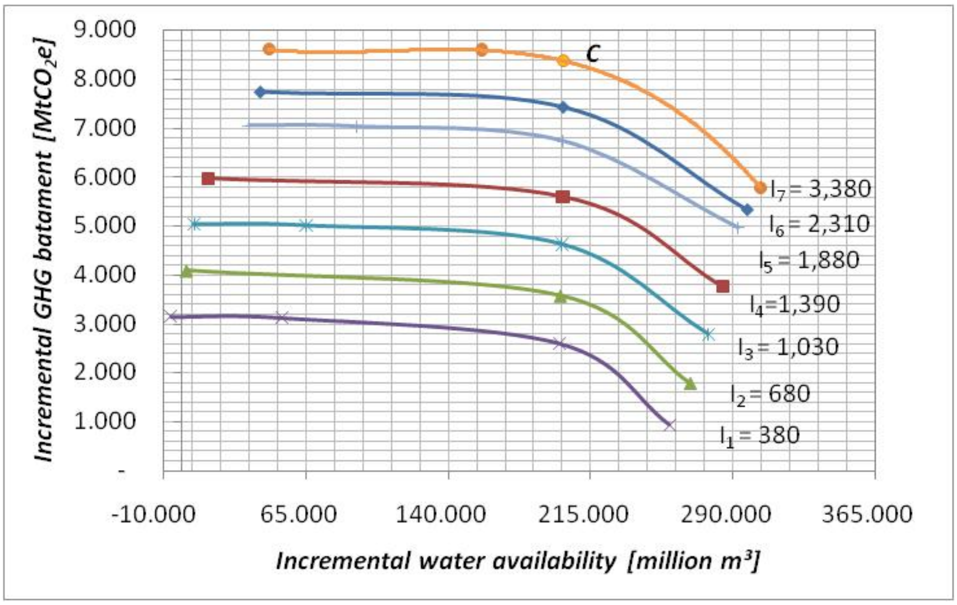

Figure 8.9.: *Isoinvestment curves for China.*

To construct a set of isoinvestment curves for both China and South Africa, we ran the integrated model for seven fixed investment levels per country, with three or four model runs per level. These runs differed in objective function and boundary conditions:

- *Run 1* maximized GHG abatement under the constraint that the water gaps are to be closed in all basins/WMAs.
- *Run 2* maximized GHG abatement without constraints on water availability
- *Run 3* maximized water availability without constraints on GHG abatement
- *Run 4* maximized GHG abatement under the constraint that a fixed percentage of the water gaps are closed

Investment levels were between 400 – 3,400 USD billion for China, and 8 – 153 USD billion for South Africa[29].

Figures 8.9 and 8.10 give the resulting isoinvestment curves. As expected, they are concave with respect to the origin, do not intersect, and increase (in terms of investments) by moving away from the origin.

[29]The maximum level was chosen under consideration of the investment levels from scenario 3: there, China required 3,400 USD billion and South Africa 175 USD billion to fulfill *both* the water and GHG target (see figure 8.8, page 158). As runs 2 and 3 maximize only one resource, higher investment than needed in scenario 3 might have led to the case that the model runs out of measures.

China				
x	75,000	150,000	200,000	250,000
dy/dx (max)	≈ 0	≈ 0	- 0.004	- 0.016
dy/dx (min)	- 0.005	0.010	- 0.021	- 0.038
South Africa				
x	1,500	3,000	5,000	7,000
dy/dx (max)	≈ 0	- 0.001	- 0.003	- 0.005
dy/dx (min)	- 0.010	- 0.012	- 0.019	- 0.027

CO_2 cost	*Water price, USD/m^3*					
USD/tCO_2	0.1	0.3	0.5	0.75	1	2
10	0.010	0.030	0.050	0.075	0.100	0.200
20	0.005	0.015	0.025	0.038	0.050	0.100
30	0.003	0.010	0.017	0.025	0.033	0.067
40	0.003	0.008	0.013	0.019	0.025	0.050
50	0.002	0.006	0.010	0.015	0.020	0.040
60	0.002	0.005	0.008	0.013	0.017	0.033
70	0.001	0.004	0.007	0.011	0.014	0.029
80	0.001	0.004	0.006	0.009	0.013	0.025

Table 8.15.: *Upper part: evaluation of the marginal rate of substitution dy/dx for several values of x, i.e., incremental water availability. Maximal and minimal values reflect the set of seven isoinvestment curves which were fitted by (slightly) different functions. Lower part: matrix of the quotients of water and CO_2e price for selected values.*

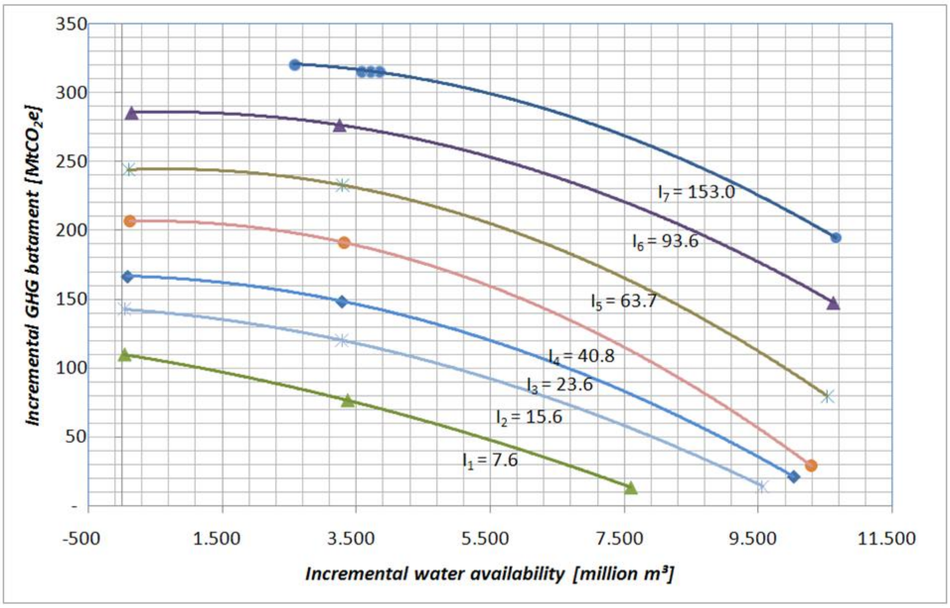

Figure 8.10.: *Isoinvestment curves for South Africa.*

Fitting of the isoinvestment curves. Marginal rate of substitution dy/dx

The isoinvestment curves were fitted with simple polynoms in order to create functions $y(x)$ which allow to determine the marginal rate of substitution dy/dx (appendix F shows the formulas for all functions). The top part of table 8.15 now evaluates the marginal rate of substituion for different values of x, i.e., the incremental water availability, while the lower part of the table shows a matrix with values for the quotient of different water and CO_2e prices.

Matching the values for dy/dx from the upper part of table 8.15 with the lower table allows to determine price ratios between water and CO_2e at a given combination of investments, incremental water availability and GHG emission reduction. To give an example: assume that China is able to invest 3,380 USD billion in water and GHG savings (isoinvestment curve 7 in figure 8.9). If the target combination agreed upon is to close the basin water gaps and invest the remaining budget in GHG abatement, the government should ensure that point C on the isoinvestment curve (in figure 8.9) is achieved. One option to do this is the definition of incremental prices for water availability and GHG abatement: if done so, a price ratio of 0.021 would match the marginal rate of substition at point C[30]; in contratst, price ratio < 0.021 would lead to a drain of investments from water to GHG (and vice versa).

[30] In absolute terms. The marginal rate of substitution is negative by calculation given the curvature of the isoinvestment lines.

Investment functions $I(water, GHG)$

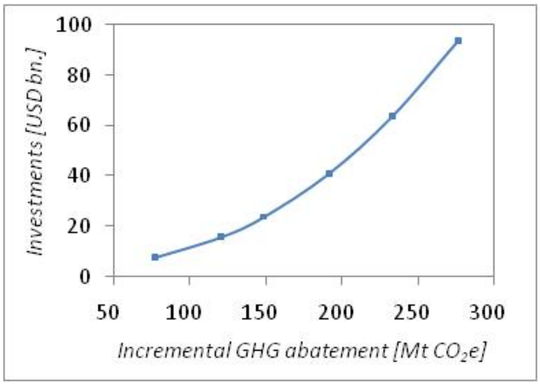

Figure 8.11.: *Investments vs. GHG savings.*

It is difficult to see in figures 8.9 and 8.10 how investments increase between isoinvestment curves. Section 6.6.2 and in particular figure 6.3 (page 98) speculated that the increase must be accelerating with increasing water/GHG savings. This is highlighted in figure 8.11, which plots investments against GHG savings for all *runs 2* of South Africa[31]. The curve is now fitted with a polynom, which gives $I = 1.6y_g^2 - 146y_g + 9359$, where I are the investments and y_g the realized GHG abatement.

The increase in investments along arbitrary combinations of water/GHG savings is plotted for the South African case in figure 8.12, which essentially is a three-dimensional representation of figure 8.10. The data points, where each represents one scenario run, can best be fitted with a fourth-order polynom[32]. If I is again the investment, $y_{(g)}$ the incremental GHG abatement (in Mt CO_2e) and $x_{(w)}$ the incremental water availability (in million m^3), the fit function is given by

$$\begin{aligned} I(x,y) &= 2.1 \cdot 10^{-12}x^4 + 8.2 \cdot 10^{-6}y^4 + 1.3 \cdot 10^{-9}xy^4 + ... \\ &\quad ... + 2.2 \cdot 10^{-8}x^2y^2 + 2.5 \cdot 10^{-15}x^2y - 2.2 \cdot 10^{-4}xy^2 + ... \\ &\quad ... + 1.9 \cdot 10^{-2}xy + 1.3x + 2.0 \cdot 10^{-2}y - 1.5 \cdot 10^4 \ . \end{aligned} \tag{8.1}$$

This now allows to assess parameters for arbitrary combinations of x and y: linear combinations of the directional derivatives $\partial I/\partial x$ and $\partial I/\partial y$ allow to determine the marginal investment required for a combination of incremental water availability and GHG savings (x, y), and the marginal rate of substitution between incremental water availability and GHG abatement is the exact differential of $I(x, y)$,

[31] I.e., the water gap is closed in all WMAs. These are the data points at an incremental water availability of about 3,500 million m^3 in figure 8.10.

[32] We used a fitting tool (available online under *www.zunzun.com*) that tested potential function classes (polynoms, power, exponential, fractional function) on the least-error fit of the provided data points and concluded that a fourth-order polynom provides the closest fit to the data. The fitting target was the lowest sum of squared absolute error (the lowest/final value was 2.802 $\cdot 10^8$).

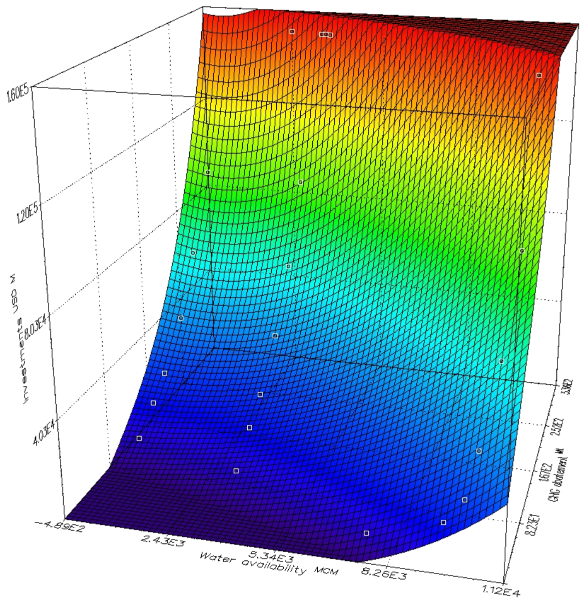

Figure 8.12.: *Plot of investments (z-axis) against GHG abatement (y-axis) and water availability (x-axis) for South Africa. Original data points are shown as small white-blue squares.*

$$dI = \frac{\partial I}{\partial x}dx + \frac{\partial I}{\partial y}dy$$

set to zero.

9. Integration of water and greenhouse gas mitigation pathways in other geographies

The last chapter showed at the example of China and South Africa that an integrated assessment of water and GHG mitigation measures can reduce overall cost. The question remains, though, whether such an approach reaps similar benefits in other geographies.

The first part of this chapter abstracts from our case studies to other regions and develops three prototype regions that are expected to differ in strength and nature of their water-GHG interdependencies. The second part discusses one further – albeit shorter and more qualitative – case study, on Egypt, a country with quite different characteristics than China and South Africa.

9.1. The power sector as a deciding factors in integrated approaches

The intensity curves for China and South Africa in chapter 7 and the discussion of the integrated modeling results in chapter 8 showed that changes in power generation and consumption are responsible for a large part of the water-GHG interdependencies[1]. This is again sumarized in table 9.1 for the results from scenario 3.

It was discussed that the differing importance of power-related measures between China and South Africa originates from China's higher water intensity of the avoided power mixes: it was seen that the same power-related mitigation option, e.g., an energy efficiency option, induces on average higher water savings in China than in South Africa[2].
This can be confirmed by using the basin water savings from GHG abatement measures

[1]Of course and again within the boundaries of our study, which excludes the impact of measures on hydrological cycles that would, if included, likely reduce the relative importance of power measures.
[2]See the analysis of scenario 3, section 8.2.3, page 150 f.

	Unit	***China***	***S. Africa***
Aggregated water savings	*million* m^3	206,400	4,000
Water savings of GHG options	*million* m^3	58,900	1,200
- of which power-related	*million* m^3	36,300	150
- power related as % of GHG options	%	62%	12%
GHG abatement goal in models	$Mt\ CO_2e$	8000	325
GHG savings of water options	$Mt\ CO_2e$	190	7
- of which power-related	$Mt\ CO_2e$	176	3
- power related as % of water options	%	93%	48%

Table 9.1.: *Adapted from table 8.7: contribution of power-related measures to the water impact of GHG measures and the GHG impact of water measures, respectively.*

as an expression for the strength of interdependencies, and assessing its correlation with various factors.

Figure 9.1 puts the incremental water availabilities for China's ten river basins in relation to the basin population, water intensity of the avoided power mix, share of GDP, and basin area. This indicates that the water intensity of a Business-as-Usual power mix is likely one of the factors that influence the strength of water–GHG interdependencies the strongest.

The situation is different in the case of South Africa. Figure 9.2 shows the correlation between South Africa's water management areas and the water intensities of the avoided power mix, which is lower than in China. A first reason is the fact discussed above, i.e., that the water intensity of the avoided power mix is generally lower in South Africa than in China. Secondly, South Africa can be considered as a country with a well-integrated power grid where conventional power plants are located only in some WMAs; WMAs with negligible conventional generation capacity thus have no power-related water savings; other savings dominate and therefore distort the picture. Conventional generation capacity can be found mainly in the Olifants and Upper Vaal WMAs, marked red in figure 9.2.

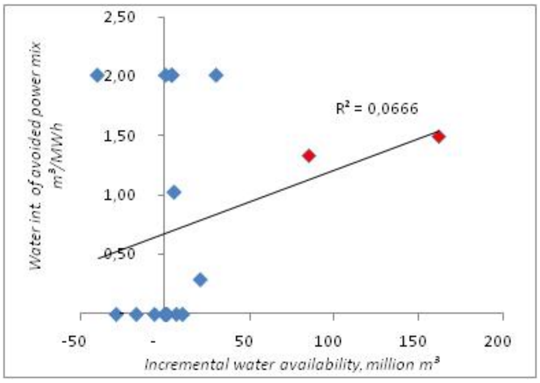

Figure 9.2.: *The South Africa case.*

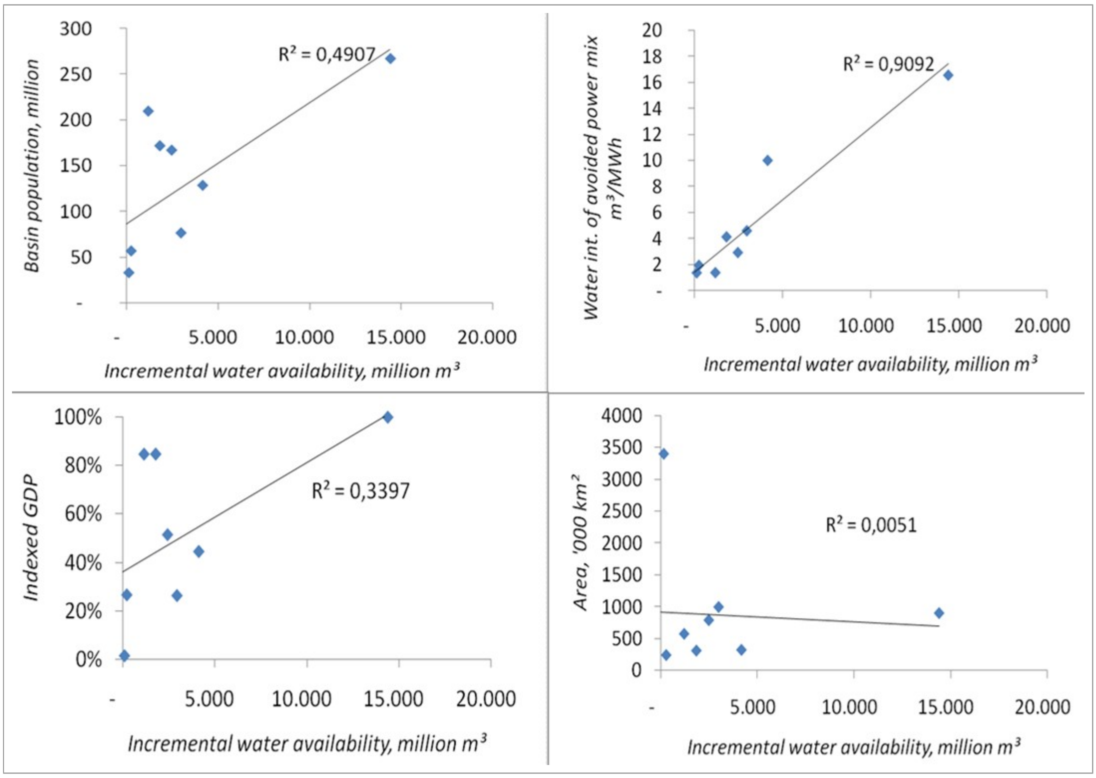

Figure 9.1.: *Incremental water availability from GHG mitigation options in China's ten river basins, in dependence of basin population, water intensity of the avoided power mix, GDP and land area.*

The left part of figure 9.3 now sets the water intensities of the avoided power mixes in perspective to the basin/WMA water gaps as projected for 2030. The regions with high water intensity levels, such as the Yangtze, Huai and Hai basins in China or South Africa's Olifants WMA are those where the water impact of GHG mitigation options was the largest[3]. The WMAs which are marked in green in figure 9.3, i.e., with little conventional generation capacity, in contrast experienced little to no water impacts from power-related GHG abatement options.

From this, three different prototypes of regions, sketched out schematically in the right part of figure 9.3, can be identified, with each having a different characteristic with respect to the interdependencies of water and GHG abatement options:

- *Case I - no (physical) water gap by 2030, such as China's Song or Southwest river basins.* Efforts to increase water availability are less important – the focus might therefore be on the implementation of GHG abatement options. The

[3]See the discussion of the water intensity of GHG abatement options in section 7.4, page 132ff, and the results from the integrated modeling, see section 8.2, page 143ff.

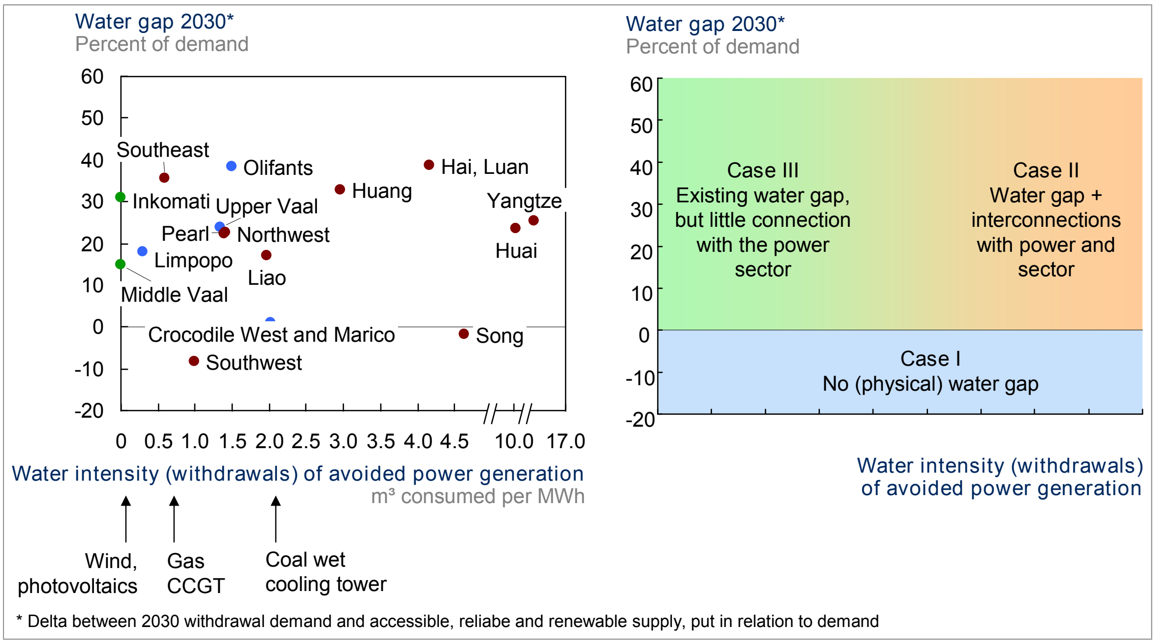

Figure 9.3.: *Left: water intensities of avoided power mixes in relation to 2030 the water gap for China's river basins (red) and South African WMAs with conventional generation capacity >1 GW (blue), and a selection of WMAs with little or no conventional generation capacity (green). Right: the three prototype regions with respect to the nature of their water–GHG intepdendencies.*

optimal pathway is then determined by the GHG abatement cost curve alone, insofar as the implementation of those measures does not increase water demand disproportionately and thereby create a water gap.

Regions that likely also fall in this category are Canada, Japan, New Zealand, or most parts of Northern Europe and Russia – all developed economies with high GHG emissions but no foreseeable physical water scarcity by 2030.

- *Case II - water gap by 2030 & high water intensity of the conventional power mix in Business-as-Usual scenarios, such as China's Yangtze, Huai or Hai river basins, and – to a lesser extent – South Africa's Olifants and Upper Vaal WMAs.* These regions have strong interconnections of water and GHG mitigation options. The results from our case studies apply here: an integrated assessment of water and GHG mitigation options will create synergies, thereby reducing cost and easing the handling of non-economic challenges.

  Other regions in this group likely involve the Southwestern parts of the USA, Australia, or the Middle East – all developed economies with high per capita power consumption and GHG emissions, and a risk of water stress[4].

- *Case III - water gap by 2030, but low water intensity in power generation, such as in South Africa's Middle Vaal or Inkomati WMAs.* The water and GHG mitigation measures investigated in this study are less correlated than in case II. This can have three reasons. First, a region is powered by neighboring region and water savings from increased power efficiency measures bring no local benefit, as is indeed the case in the South African WMAs. Second, a region is economically developed and powered by renewable power sources. And third, a region is still developing and has few thermal power capacities installed.

9.2. The case of Egypt

Many developing regions and countries in dry parts of the world will fall in the third category described above, and one main concern will be to secure water availability over the next decades. Egypt is one example of this last prototype. It is furthermore one of Africa's largest countries in terms of population and economy – the following pages will therefore study this country in more detail and highlight on what basis water availability and GHG emissions interlink there.

The largest part of water-GHG interdependencies in China and South Africa are triggered by power-related measures, while agricultural measures did not play a large role there, with the notable exception of no-till agriculture.

In contrast, plans exist to transform large areas of currently unused land into farmland in Egypt. If done so and conventionally, this will likely put additional stress on the country's already tight water situation. One supply-side option, the constructing of large-scale seawater desalination facilities, is most likely too expensive, while another, the use of fossil aquifers, is not sustainable in the long term.

If the farmland extension was however aligned with water efficiency and conservation measures in other sectors, it might well be possible to gain farmland without additional stress on national water resources. Furthermore, the new farmland could act as a carbon sink, installing agriculture as a win-win sector with respect to water and GHG .

[4]See the water stress for world map on page 8.

9.2.1. Short country profile

In 2010, Egypt had a population of 81 million, which is projected to increase to 95 million until 2030 [30][5]. Over the same period, its per capita GDP is estimated to grow from USD 1,600 to USD 2,200 [40][6]. Of its current GDP, 46% is earned in services, 40% in industry and 14% in agriculture [185], which is a more important sector than in China (10% of GDP [109]) or South Africa (3%, [109]).
The majority of Egypt's population and economic activity is concentrated in the Nile valley and delta. This area however constitutes only 4% of the country's surface [186]; the rest of the country is mostly desert, with the exception of few oasis. Mean rainfall is low, and ranges from 200 mm along the Mediterranean coast to virtually zero in the south of the country [186].

Egypt's water situation today

An exception in this respect, Egypt is a country that can be regarded as one basin. The Nile directly provided for 79% of the country's water supply of 70 km^3 in 2008 [32], while further 9% come from groundwater, about 2% are captured rainwater and another 10% are return flows from wastewater treatment or agriculture. According to the same source, demand already reached 72 km^3 in 2008 – of this, agriculture acounted for 83%, or 60 km^3 [32].
The Food and Agricultural Organization of the U.N. estimates total renewable water resources at 57 km^3; including reuses of wastewater, desalinated water, drainage water and treated wastewater, total available water resources are set at 72 km^3 [186][7].

The Nile water volume of 56 km^3 that is allocated to Egypt is based on a 1959 treaty between Sudan and Egypt that divides most of the Nile's waters between these two countries [187]. It forbids upstream riparian countries (the most important being Ethiopia and Uganda[8]) to extract water in excess of their fixed lots without permission from Egypt and Sudan. The treaty is contested, and increasingly so as the economic output and population rises in the upstream countries. A 2010 effort to find a new agreement between all riperian countries however stalled, as their historical quotas are not subject to negotiation, according to Egypt and Sudan [188] [189] [190]. The fact that South

[5] According to the medium scenario; the range given by the UN numbers spans 100–113 million.

[6] In real 2005 USD. In purchasing power parity and 2010 USD, [185] estimates this number at 6,500 USD.

[7] [186] also includes 0.8 km^3 of water from fossil aquifers that is excluded here under the argument that such withdrawals are not sustainable in the long term.

[8] The other countries being Burundi, the Democratic Republic of Congo, Kenya, Rwanda, Tanzania [188].

Sudan seceded from the North in 2011 and relations between the two states are tense will likely not ease the long-term securing of Egypt's Nile water lot [189].
The secession will also not increase the chances that the Jonglei canal on the territory of South Sudan will be finished soon. The canal, started in 1980 and built until 1983 to within 100 km of completion (out of 360 km), would drain the swamps of Sudd, where large volumes of water evaporate, and thereby increase water availability downstream by an estimated 4.8 km^3 annually, to be distributed between Sudan and Egypt [191][9]. Two other projects in the region could increase Egypt's water availability by an additional 5 km^3.
Lastly, ongoing climate change likely has adverse consequences for Egypt's water balance. It likely leads to higher temperatures over Egypt and Eastern Africa, the Nile's headwater, resulting in higher evaporative losses. Rising sea levels will furthermore increase the chances of saltwater intrusion and loss of land in the Nile delta [192]; a sea-level rise of 0.5 m in the Mediterranean for would destroy 1,800 km^2 of arable land and directly affect a population of 3.8 million (based on today's population) [193].

Egypt's Business-as-Usual water demand 2020

Looking forward, an extrapolation of domestic per capita water withdrawals in line with the population increase would result in a domestic water demand of 10.7 km^3 by 2020[10]; assuming that per capita industrial water demand stays constant as well results in additional withdrawals 0.3 km^3 [11].
The additional water demand from agrciulture was determined under investigation of Egypt's planned famrland extension, as described in the following section.

Egypt's agricultural extension, and its impact on water resources

Egypt's area of cultivated land today is 3.4 million ha (34,000 km^2) [186], almost all of it concentrated in the Nile valley and its delta. Major crops under cultivation are wheat, rice, cotton, maize. Given the very low rainfall levels, 99.8% of the cropland is irrigated, of which 88% use surface irrigation schemes [186].
Going forward, Egypt plans to increase its cultivated land through reclamation projects across the country; on the Sinai peninsula alone, a further 0.5 million hectars are planned

[9] The completion of the canal would however impact the swamps; [191] estimates that total swamp size will decline by 15–25%.
[10] Under the assumption that per capita annual municipal demand of 113 m^3 (based on a 2008 population of 75 million and a demand of 8.5 km^3 [32]) stays constant until 2020.
[11] Based on the same logic and sources.

to be added [186] until 2017, and the total reclaimed land area is projected to increase to 1.4 million hectars by then [194].
The addtional water demand from this extension can be estimated at at least 11 km^3, based on the following assumptions:

- The crop mix on the new farmland is the same as on the currently cultivated area, with wheat, rice, cotton and maize as the dominant crops. Furthermore, the same annual crop sequence applies – which means that the additional cultivated area of 1.38 million ha equals an irrigated area of 1.97 million ha [195]

- Is is assumed that the new farmland is irrigated to 50% by sprinkler irrigation and 50% drip irrigation, as legislation forbids surface irrigation in those areas.

- Egypt's average water demand for drip and sprinkler irrigation was determined based on the average water duty per hectar on the existing farmland (8,400 m^3/ha) [195], the current split between surface, sprinkler and drip irrigation (88.5%, 5.0% and 6.5%, respectively [186]), and the delta in water requirements between the different irrigation technologies from the water availability cost curve data for China (see appendix D)[12].

To sum up, Egypt will likely be confronted with a water supply-demand gap in the foreseeable future. Its water demand could reach about 86 km^3 by 2020 (see figure 9.4) in a Business-as-Usual scenario, which contrasts with a supply situation that can at best be assumed to stay constant at about 72 km^3 [186].

Egypt's power sector and GHG emissions

Egypt produced 123 TWh of electricity in 2008 [196], of which 88% came from conventional power plants, almost all of which powered by gas, and 11% from hydro power, almost all from the Aswan dam. The remaing percent was contributed by wind power [196].
Depending on the technology, the water intensity (in terms of withdrawals) of gas-fired plants is between 0.7 and 2.0 m^3/MWh[13], which would yield total water withdrawals related to thermal power generation of about 0.1–0.2 km^3 annually, less than 1% the nation's water demand. The water intensity of the hydro part from the Aswan dam is

[12] It has to be noted that the water duty of 8,400 m^3/ha is lower than the water demand estimated "top-down" from total water withdrawals for agriculture of 60 km^3(2008) and the irrigated area of 5.12 million hectars, which is 11,700 m^3/ha. This is most likely due to losses through canal seepage, leaks, evaporation and suboptimal irrigation scheduling, which can also be considered as a potential set of efficiency improvement measures (see text below).

[13] See section 6.4.2, page 81 ff.

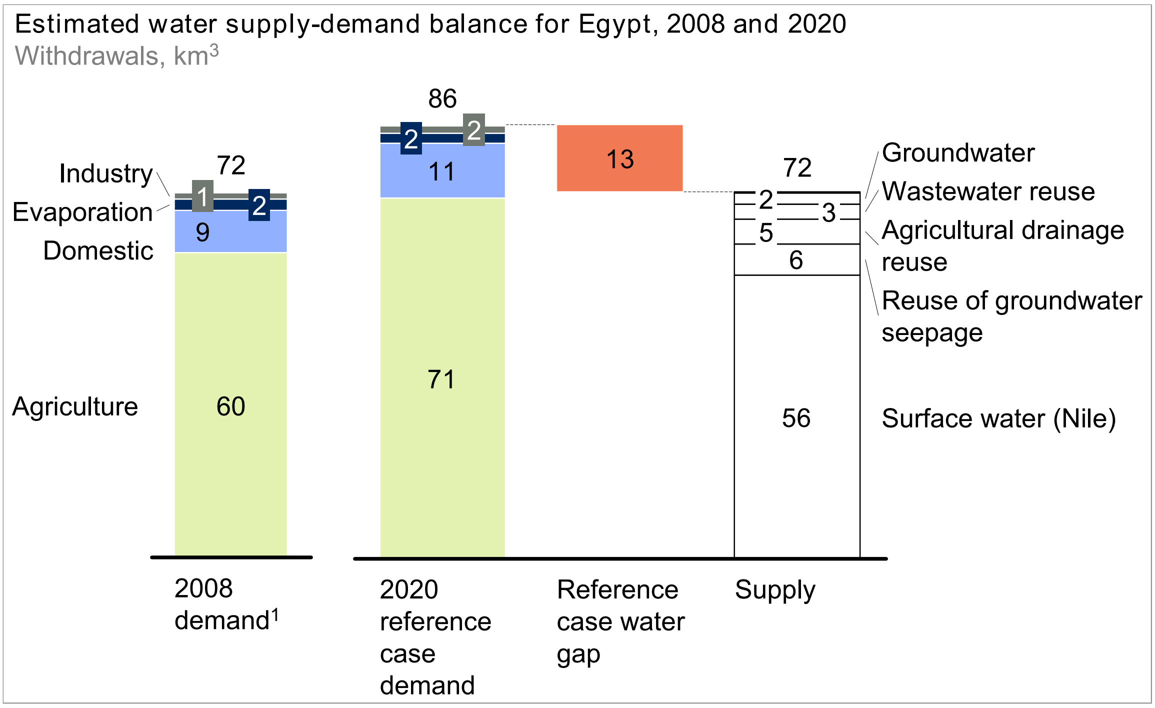

Figure 9.4.: *Estimates on Egypt's potential 2020 water gap.*

a different matter, but certainly a question of definition. A head of water of 6.0 mm evaporates daily from Lake Nasser[14] – over the whole surface, this sums up to evaporative losses of 3 km^3 annually [167]. If all these losses were allocated to the hydro plant, the water intensity would reach 200 m^3/MWh, a hundred times higher than a wet-cooled thermal power plant[15]. Of course, the Aswan dam fulfills other purposes than power generation, such as flood control or water storage; a replacement of the dam for the purpose of increased water availability seems – above all – very unrealistic.

A low CO_2 intensity in the power sector due to the mix of gas and hydro plants contributes to Egypt's comparatively low per capita GHG emission, which are given at 3.2 t of CO_2e for 2005 (234 Mt CO_2e in total) by the World Resources Institute [69].
Forecasts to 2030 are more difficult to obtain; however, there is no evidence that emission levels will rise substantially over the next two decades. Given that a per capita emission level of about 2 t CO_2e is considered sustainable in the long term[16], it can be assumed

[14]Lake Nasser is the artificial lake behind the Aswan dam.
[15]However, 200 m^3/MWh compares well to the high end of water losses mentioned by Gleick [1], 160 m^3/MWh which were given for Californian hydro facilities. Assuming that evaporation rates in Egypt are higher than in California, and that the Aswan dam was presumably not optimized for hydro power generation, it seems plausible that water losses are higher in that case.
[16]See section 2.3.4: total anthropogenic emissions of 20 Gt CO_2e are determined; at a world population

Figure 9.5.: *Physical and road map of Egypt. From [90]*

that the challenges in reducing GHG emission fall back behind the looming water supply-demand gap.

Given the low water intensity of its power sector, small industrial base and relatively low per capita power consumption, little potential to increase water availability through increases in energy efficiency seems to exist, and water-GHG interdependencies as discussed for China and South Africa will therefore play a smaller role[17].

9.2.2. Increasing Egypt's water availability in a sustainable way

Conventional methods of increasing water supply will likely not provide for the required amounts of water in an economic way:

- As seen above, the *Nile's waters* are already fully divided between riparian countries – the question will rather be whether Egypt can sustain its current lot than extend it. Even if the Jonglei canal was finished, the increase of water supply by 4.8 km^3

of about 9 billion, this amounts to 2.2 t CO_2e per capita.

[17] Looking back at figure 9.3, Egypt can thus be considered as a Case III country.

would not all reach Egypt. The other dam projects in the Sudd valley (providing further 5 km^3) are even more speculative today.

- *Additional dams* along the Nile will not increase seasonal supply, as the Egypt's storage volume of 169 km^3 [186] is already more than three times its lot of Nile water, and more than the double of current annual demand.

- *Deep groundwater pumping* from fossil aquifers. Estimates on aquifer yield under some of the agricultural extension areas give potentials of 0.6–3.8 km^3 annually [194]. Tapping into these can mitigate water stress for some years, but will not provide for a sustainable solution in the long term.

  Furthermore, the power demand for such pumping schemes would be high: for depths of 50 m, our China case studies assumed 0.14 kWh/m^3, and 0.53 kWh/m^3 for 135 m – pumping an additional 11 km^3 for irrigation (a hypothetical case, though) would require 1.6–5.9 TWh, or up to 5% of Egypt's power demand (2008).

- *Seawater desalination* is likely a too expensive way to supply water, as already seen in the water availability cost curves for China and South Africa, where it figured along the high cost end. Furthermore, desalination of 11 km^3 annually would require at least 20 TWh of power, or 16% of Egypt's total demand, and more than the power generated by the Aswan dam annually[18].

Furthermore, the options of enforced desalination or groundwater pumping would result in increased GHG emissions levels.
On the other side, given that most of the land is still irrigated with surface schemes, large operational improvement potentials exist, and are already addressed: [194] argues that Egypt's water strategy includes increased efficiency in water use, reduced losses through improved water transportation schemes, and increased levels of water reuse. The same source also gives a list of concrete measures and initiative that are finished, under implementation, or in planning.

Such efficiency improvements and the considerations on supply-side options above already sketch out a prioritization list of water availability measures that would in its structure very likely resemble the China and South Africa cost curves discussed in section 4.1.
The development of a detailed Egypt cost curve and its GHG intensity would require a more thorough assessment than can be performed here. However, it might be interesting

[18]If thermal desalination facilities were co-located with thermal power plants. With reverse osmosis systems, power demand would increase to almost 50 TWh.

to have a first look into whether efficiency and conservation measures can help to sustain Egypt's water balance in the light of a land reclamation project of 1.4 million hectars, and what impact they have on the country's GHG emission balance[19].

Irrigation efficiency improvements in the Nile valley and delta

Egypt requires on average 11,700 m^3 of water per hectar of irrigated farmland[20]. However, the average water duty for the typical crop mix is given at only 8,400 km^3, about 3,000 m^3 per hectar less than stated above. It therefore seems plausible that considerable water resources are lost to evaporation in canals, canal seepage or ill-timed irrigation scheduling – closing only half of that delta in per-hectar water requirements could already increase water availability by 8.6 km^3.

89% of the cultivated are in the Nile valley and delta are surface-irrigated. In China, drip and sprinkler irrigation options reduced water needs by 38% and 32% with respect to the reference case of surface irrigation[21]. If those techniques could be extended to part of the Nile valley and delta[22], 37% of the surface-irrigated farmland would need to be converted to drip or sprinkler irrigation in order to increase water availability by 14 km^3, and thus close the water gap.

The impact on power demand of these efforts is likely negative: drip and sprinkler systems are more energy-intensive than the alternative of surface irrigation in Egypt, as surface water is just diverted from the Nile to the fields, requiring little to no pumping, but general numbers are hard to obtain[23]. By taking the data from the China case example for sprinkler irrigation, 0.33 kWh/m^3, and using the same number for drip irrigation[24], power demand would increase by about 4.4 TWh, resulting in GHG emissions of about

[19] Please note that the following considerations presented here should in all cases be regarded as rough back-of-the-envelope calculations and to not claim to be exact to the digit. Neither are they mutually exclusive insofar as the potentials can be added.

[20] Based on 2008 agriculture withdrawals of 60 km^3 [32] and an cultivated area of effectively 5.1 million hectars [195].

[21] See also for example [197], which gives water savings for sprinkler irrigation: for wheat, cotton and maize, three of Egypt's main crops, these are on average 35%, 36% and 41%; however, the same source says that irrigation efficiencies are lower in desert climates, indicating that a 32% efficiency gain seems an estimate in the right order.

[22] We assume a 50/50 split between both irrigation techniques. The current plit is close to this, with 6.5% (drip) and 5.0% (sprinkler irrigation).

[23] [198] for example discusses a large variety of sprinkler and drip irrigation systems in detail, but only indicates energy demand qualitatively, presumably due to large discrepancies between sub-technologies.

[24] This is clearly an upper boundary – drip irrigation systems typically require less water than sprinkler irrigation [198].

2.0 Mt CO_2e if the power was produced in gas-fired power stations.

Municipal wastewater treatment

A look at the 2008 data indicates that not all of Egypt's domestic wastewater is treated: according to Egypt's State Information Service, treated wastewater accounted for 1.3 km^3 in 2007, about 20% of the 6.5 km^3 of domestic water demand [32].
Domestic demand is estimated to increase to 11 km^3 according to figure 9.4; water availability would increase by 9.4 km^3 if all this treated by 2020 – about 70% of the total gap, or 84% of the additional water needs in agriculture. If on top of this the energy stored in the wastewater sludge could be recovered with a similar efficiency as assumed for the China case example, the additional treatment plants could operate with a slight power surplus and produce up to 0.2 TWh. The remaining sludge from the biogas digesters can be used as a fertilizer in agriculture, which reduces cost and GHG emissions, as the alternative, synthetic fertilizers, accelerate the decomposition of soil organic matter, and thereby produce CO_2 [199].

Conservation and organic agriculture

Agricultural soils are a potential carbon sink and therefore one option to mitigate GHG emissions [200] [201]. Reclaimed desert soils should be no exception, and it can be expected that Egypt's land reclamation project should have a positive impact on GHG emissions. The exact amount of the soil GHG storage potential will depend on the agronomy practices employed; we looked into two reports that assessed this.
Conservation agriculture, which implies minimal to no mechanic soil disturbance, a permanent organic soil cover and diversified crop rotations or plant associations [182] can on average sequester about 0.5 tons of carbon per hectar and year, which corresponds to 1.8 t CO_2e per hectar and year[25].
A report specifically on the carbon sequestration potential of organic agriculture on reclaimed desert lands in Egypt states that 0.9 t of carbon, per hectar and year, or 3.2 t CO_2e/ha/year, can be sequesterted in reclaimed desert land by this method [199] – if this number was applied to all new reclaimed land, GHG sequestration could reach 4.4 Mt CO_2e annually, almost 2% of Egypt's 2005 total emissions.
For comparison, simply (and only indicatively, given different climatic conditions) taking the GHG mitigation potentials and affected areas from no-till agriculture from China

[25] The amount of carbon, C, stored is transformed into the corresponding amount of CO_2 extracted from the atmosphere by the ratio of its molecular weights, (44/12.

and South Africa yields a sequestration potential of 0.9 t CO_2e/ha/year, slightly lower than the numbers given above.
As no-till agriculture also reduces water demand with respect to more conventional approaches, it can furthermore be expected that the above-mentioned techniques could also play a part in reducing the water gap.

Summary of Egypt's options

To sum up this short section, enough potential likely exists to increase water availability in Egypt to the extent that the rising water demand from growing population and an ambitious land reclamation project could be satisfied. As in the China and South Africa cases, the most effective measures are not those that increase supply – these are very likely either unsustainable, very costly, or energy-intensive – but rather measures that increase water efficiency and reuse rates. Beyond simply closing the water gap, such measures could furthermore make the land reclamation project a net carbon sink, improve water quality and increase power production from renewable energy sources. All this comes on top of the obvious benefit of increased food security and therefore provides an example where (even) three resources, food, GHG emissions, or energy, and water interact positively.

10. Conclusions

Starting from a discussion of global water supply and demand, and the likely consequences of water scarcity and rising greenhouse gas emission, this work first demonstrated that many options to mitigate either of these issues are actually interlinked, i.e. that increasing the water availability or reducing greenhouse gas emissions through a certain measure often has an effect on the balance of the other resource. As this work only considers resource savings from the time of implementation onwards, it is likely that further interdependencies exist under full life cycles considerations, or if the impact of certain mitigation options on ecosystems or hydrological cycles was included.

Given this, it was found that the majority of interdependencies are related to the nexus of energy provision and water – water is needed to extract energy carriers from the ground, and to turn them into electric power, where the cooling of steam turbines can again require large quantities of water. On the other hand, energy or electric power is required to pump and distribute freshwater or treat wastewater.

The study of mitigation options in China and South Africa showed that interdependencies are overall positive, i.e., addressing water scarcity or unsustainable levels of greenhouse gas emissions yields in sum savings of the other resource. A more detailed look then showed that in particular those options that promote efficient uses of one resource are among those with the strongest savings on the other resource.

A linear optimization model helped to prove that an integrated consideration of all water availability and greenhouse gas abatement options allows to better achieve overall mitigation goals, in particular with regards to local water availability, and reduce mitigation cost by up to 23% compared to an independent assessment.

The integrated modeling further allowed to study isoinvestment curves and investment functions, which relate investments to arbitrary combinations of water and greenhouse gas savings. These considerations showed interesting parallels to microeconomics, as the example of the marginal rate of substitution between water and greenhouse gas savings demonstrated.

The last chapter brought forward the hypothesis that interdependencies as investigated for China and South Africa are likely also observable in other geographies that are both

water-stressed and dependant on thermal power generation, while countries with little such generation capacities will likely experience less or different interdependencies.
A more qualitative case study on Egypt demonstrated that water–greenhouse gas interdependencies along the energy link are of lesser importance there, but that interdependencies in agriculture might play a role in the future, as reclaimed desert land can act as a sizeable carbon sink. Combined with water conservation efforts and sourcing from secondary sources, such as treated wastewater, the irrigation of reclaimed land could therefore develop into a positive exemplar along the nexus of water, GHG emissions, and food production.

Criticality

Given the positive interlinkages, policy makers should consider the interdependencies between resources, cost, but also societal parameters more when devising mitigation pathways.
Cost certainly are an important aspect, but not necessarily the deciding one, as it often is, for example, of equal importance to convince a multitude of scattered stakeholders. Table 10.1 summarizes various aspects that in our opinion require consideration before a certain set of mitigation options, or more generally, actions, can be judged.

Economic cost	(Potentially) differentiated by different cost parameters, e.g., investments and operational cost
Art of use of a resource	Quality in which a resource is needed (e.g., freshwater vs. wastewater)
Impacts on ecosystems and other resources	– Stress on (other) critical resources – Considerations of external cost
Feasibility	– Political and legal boundary conditions – Advantage of central vs. local implementation – Implementation possible under current practices vs. requirements for new processes
Dynamics	Time frame to implementation

Table 10.1.: *Aspects of criticality.*

How these dimensions are exactly weighted against each other depends on local boundary conditions – an over-populated, cash-constrained region might come to a different conclusion than a region with enough (monetary) resources at hand.

Policy makers should ensure that those options are prioritized that score high along most dimensions. In this work, efficiency measures were mentioned at several occasions as “win-win” options, as they generally increase both water availability, reduce GHG emissions and often save more money than they cost in the first place. It would remain the subject of further research to assess to what extent other criticality parameters can be fulfilled for these options – some technologies for example might require rare or increasingly expensive resources. Furthermore, being the sum of many small efforts and changes in mindsets, the dynamics and feasibility to achieve a given overall target might be lower for these options than in other areas.

In the end, such an assessment could result in a multi-dimensional merit order of options, where each dimension represents one criticality parameter and the different dimensions are interlinked through intensity curves such as the water–GHG curves discussed in this work.

Outlook

The interdependencies of water and greenhouse gases are thus only one example of a resource interlinkage, and the study of other resources and their interdependencies with water or GHG mitigation options, such as metals, rare earths, available land, or food, will be of equal importance.

First research has been devoted to this task. A recent publication, *Materials critical to the energy industry* [202] investigated an important aspect that was neglected in this work, namely the dependency of energy sources on special materials. The results show that for example photovoltaics and wind power, both interesting mitigation options that increase water availability and reduce GHG emissions simultaneously, require Cadmium, Chromium (solar PV) and rare earth elements (wind power) – all materials with a critical supply situation, as figure 10.1 highlights.

Such considerations will become more important in a resource-constrained world. Decision makers that have the choice between multiple (mitigation) options will therefore need to start considering not only the cost of a particular solution, but also the other parameters mentioned in table 10.1 if the practicability of a chosen pathway shall be ensured.

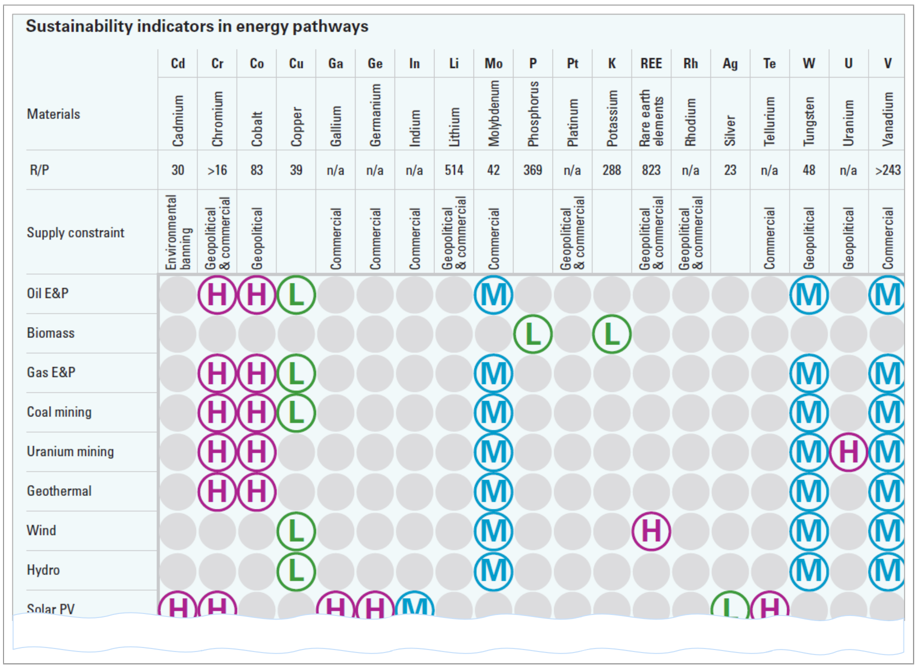

Figure 10.1.: *From [202] (excerpt of graph): Exposure of energy pathways to selected materials and their risks of supply constraints (L = Low, M = Medium, H = High). Such constraints, as well as other criticality dimensions, should be taken into account in addition to the water–GHG interdependencies before deciding on a pathway.*

Part III.

Appendix

A. Glossary

Abatement case	A scenario that achieves a greenhouse gas reduction target that is more ambitious than the reference case
BAU	Business as Usual (scenario); also referred to as reference case
BCM, bcm	Billion cubic meter, equivalent to km^3
CH_4	Methane. Both a greenhouse gas and the main component of natural gas
CO_2	Carbon dioxide, a greenhouse gas
CO_2e	Carbon dioxide equivalents, a unit for comparing different greenhouse gases on the basis of their contribution to global warming
Consumption	Water consumption, i.e., the amount of water that is taken from a water body and cannot be returned locally
DWAF	South Africa's Department of Water Affairs and Forestry
EIA	United States Energy Information Administration
EPA	United States Environmental Protection Agency
EUR	Euro
FAO	Food and Agricultural Organization of the United Nations
Full cost [year]	The sum of the annuity of the required investment plus oper– ational cost/savings in a given year for a mitigation option, incremental to the reference case solution. Investments are discounted over the lifetime of the mitigation option.
GHG	Greenhouse gas
GJ	Gigajoules, 10^9 Joules
Gt	Gigatonnes, 10^9 tonnes
GW	Gigawatt, 10^9 Watt
GWh	Gigawatt hour, 10^9 Watt hours
Halocarbons	An umrella term for organic compounds that contain halogens such as fluroine, chloride or bromide; many

	halocarbons are greenhouse gases
IEA	International Energy Agency
Integrated cost	The sum of all investments and operational cost/savings of a mitigation option that incur between 2010 and 2030, discounted to 2030 and incremental to the reference case solution
IWMI	International Water Management Institute
kW	Kilowatt, 10^3 Watt
kWh	Kilowatt hour, 10^3 Watt hours
LTMS	Long Term Mitigation Scenarios, a set of GHG emissions scenarios for South Africa
MCM, mcm	Million cubic meter
Mitigation measure/ option	A technology, method or process that reduces GHG emissions or increases water availability with respect to the BAU alternative
MJ	Megajoules, 10^6 Joules
Mt	Megatonnes, 10^6 tonnes
Mtoe	Megatonnes of oil equivalents, a unit of energy content
MW	Megawatt, 10^6 Watt
MWh	Megawatt hour, 10^6 Watt hours
N_2O	Nitrous oxide, a greenhouse gas
PJ	Petajoules, 10^{15} Joules
TJ	Terajoules, 10^{12} Joules
USD	United States Dollar
W	Watt, the unit of power
Water gap	The delta between the projected water supply and demand [in a given year]
Withdrawals	Water withdrawals, i.e., the amount of water taken from a river body; parts or all of it can be returned locally
WRG	Water Resources Group

B. South Africa's GHG emissions

Sections 3.2.3 and 6.1 mentioned that South Africa's GHG emission projections for 2030 (and the pathway 2005–2030) needeed adjustement based on the comparison of the main data source employed ([4]) and external data. This chapter explains how this adjustment was performed.

Figure B.1 gives an overview of the projected 2030 "Business-as-Usual" emissions from various sources, showing that [4] gives considerably lower values than the other sources[1]. In particular, energy-related BAU emissions in figure B.1 seem to be lower than in other reports, and this is also where corrective action was undertaken. The energy sector can again be split up in emissions from power generation and a remainder, mostly associated to industry and households.

Adjusted power-related emissions

Looking into the data underlying the 2030 BAU power sector for South Africa already suggests that emissions should actually be higher than presented in [4] and [77]. Even with the assumed power mix, emissions should rather be 460 Mt, instead of 297 Mt CO_2e. A total production of 873 TWh seems however too high, compared with other sources:

- Eskom's Integrated Resource Plan projects 2030 emissions of about 640 TWh in a high-case scenario with no efficiency gains. If these savings are presumed, power demand is forecasted to be around 450 TWh by 2030 [117].
- The Long Term Mitigation Scenarios assume a installed capacity of about 70 GW in 2030 [110] (p. 51), mostly from fossil fuels. Based on this, power generation can be estimated at 500–550 TWh by 2030. This is confirmed by a Greenpeace report on "green" jobs for South Africa, which cites about 520 TWh from the LTMS report [203] (p. 1).
- The Water Resources Group [5] used a power demand of 607 TWh for South Africa.

[1]The reason for this is likely related to the global level of investigation in [4] [77], where South Africa wasonly one of the 21 world regions, as opposed to the other reports that explicitly focus on this country.

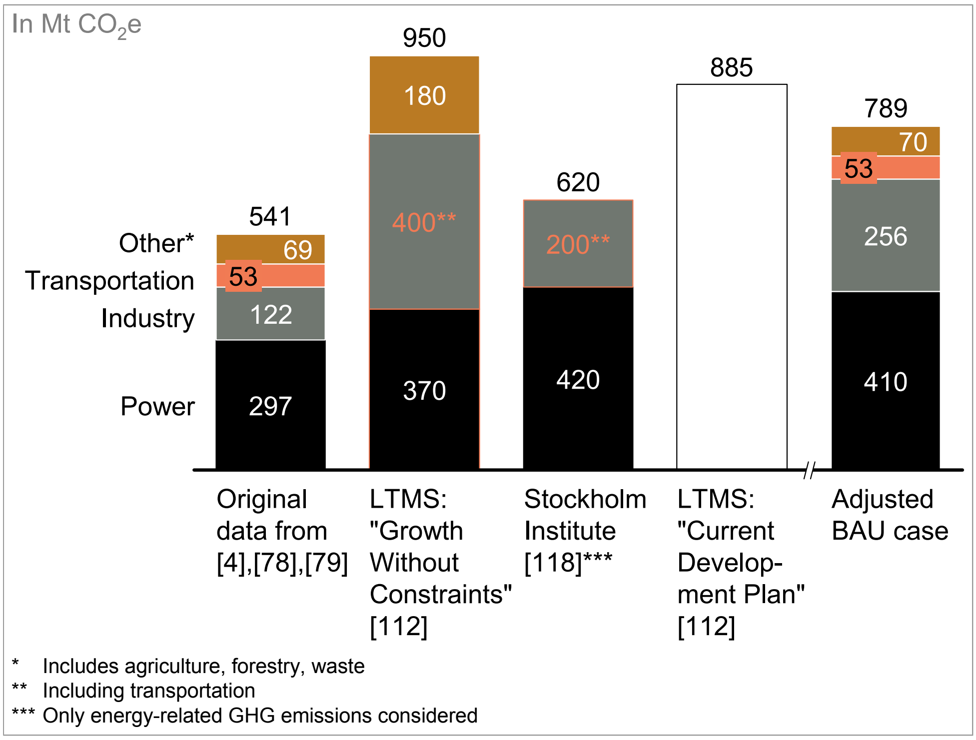

Figure B.1.: *2030 Business-as-Usual GHG emissions from different sources.*

Based on this data, South Africa's BAU power mix was adjusted to generate 550 TWh in 2030 – a value close to the high end of [117] was chosen to reflect little improvements in energy efficiency or sustainability. In particular, the amount of gas-fired power was reduced and unclassified generation was eliminated; the adjusted generation mix builds mainly on 410 TWh of coal, 70 TWh gas, 30 TWh nuclear and about 40 TWh of renewables. Power-related GHG emissions then amount to 410 Mt CO_2(e).

Adjusted emissions from industry

According to [4] [77], direct emissions from the industry and domestic sectors grow by a factor of 1.7 between 2005 and 2030, from 73 to 122 Mt CO_2e. According to the LTMS base-case scenario *Growth Without Constraints*, energy demand in the industrial, commercial and residential sectors (including power) was estimated to grow by a factor of 2.1, from about 800 PJ[2] to 1,700 PJ [110] (p. 50). Adjusting emission growth with this factor results in respective 2030 BAU emissions of additional 135 Mt CO_2e, giving a total of 256 Mt CO_2e.

[2]PJ: Petajoule = 10^{15} Joule.

Adjusted overall emissions for South Africa

Thus, total South African emissions for the Business-as-Usual scenario are as follows:

- Adjustments in power generation add 113 Mt CO_2e (297 $\rightarrow$ 410 Mt CO_2e).
- Adjustments to the industrial, commerical and sector add further 135 Mt CO_2e (225 $\rightarrow$ 360 Mt CO_2e).

Overall emissions are then, in Mt CO_2e: $541 + 113 + 135 = 789$. This is also a value that is in better accordance with the other sources, as the rightmost bar in figure B.1 shows.

C. List of water mitigation options

The following tables list all water availability options, first for China, then for South Africa. All options from the original report *Chartering Our Water Future* [5] (and the underlying data sets) were considered.
Further infomation on the specific options and underlying assumptions can be found in the appendix of [5], page 147 ff.

Table C.1.: Water availability options in **China**.

Sector	***Measure***	***GHG int.*** $kg\ CO_2e/m^3$	***GHG intensity: source and approach***
Agri-culture	No tillage - rainfed	(1.53)	Integration of water and GHG measure
	No till - irrigated	(1.53)	Integration of water and GHG measure
	On farm canal line	(0.12)	interview with Ministry of Water expert and [204]
	Drip irrigation	(0.10)	Based on three case studies: Xinjiang cotton and tomato fields, and orchards in Beijing
	Piped water conveyance	(0.05)	Case study based on interview with expert from Ministry of Water; see also [205]
	Improved integrated plant – management - rainfed	-	No direct GHG impact
	Improved integrated plant – management - irrigated	-	No direct GHG impact
	Irrigation scheduling	-	No apparent GHG impact
	Crop engineering irrigated	-	No direct GHG impact
	Rice intensification	-	No direct GHG impact
	Imprv fertilizer – balance (irrigated)	-	No direct GHG impact
	Crop enigneering rainfed	-	No direct GHG impact
	Post harvest treatment	-	No direct GHG impact
	Improved fertilizer balance – (rainfed)	-	No direct GHG impact
	Mulching	0.00	Case study based on expert interview and [206]
	Effi Sprinkler	0.24	Higher energy needs from pumping
Municipal	Municipal leakage	(0.83)	Reduced energy needs for extraction, distribution
	New showerheads	(0.83)	(see e.g. [2])
	New faucets	(0.83)	Reduced energy needs for extraction, distribution ...

Continued on the following page

Sector	***Measure***	***GHG intensity*** *kg CO_2e/m^3*	***GHG intensity: source and approach***
	Retrofit showerheads	(0.83)	and treatment (see e.g. [2])
	Retrofit faucets	(0.83)	
	Wastewater reuse – (municipal & industrial)	(0.02)	Based on [173]; see section 7.2.1
	New toilets	(0.83)	Reduced energy needs for extraction, distribution
	New laundry machines	(0.83)	
	Retrofit toilets	(0.83)	and treatment (see e.g. [2])
	Commercial building leakage	(0.32)	Reduced energy needs for extraction, distribution (see e.g. [2])
Industry	Steel: Coke dry quenching	(27.32)	Case study: dry-quenched plant of 3 Mt annual output can power 15 MW generator with waste heat [207]
	Steel: dry dedusting	(1.20)	Power savings due to omission of water processing (pumpimg, heating, treatment); see [208]
	Paper: White water reuse	(0.44)	Based on case study; energy savings partly from reduced heating requirements
	Steel:condensed water cooling	(0.06)	Based on data from [209] for reduced energy needs in industrial water
	Paper: intermediate water reuse	(0.00)	Based on interview with industry expert
	Textile: wastewater reuse	0.04	Based on interview with industry expert and [210]
	Paper:concealed filtration	0.19	Based on plant case study
	Other industry: waste other reuse	0.45	Average of energy needs for reuse in steel, power, textile and paper
	Steel: Waste water reuse	0.55	Steel plant case example with 0.86 kWh/m^3 power need for water treatment
Power	Ultrasupercritical coal plants	(329.44)	Based on efficiency gain between supercritical (40% efficiency) and ultrasupercritical (44%)
	Condensed water cooling	(0.06)	Based on data from [209] for reduced energy needs in industrial water

Continued on the following page

Sector	***Measure***	***GHG intensity*** $kg\ CO_2e/m^3$	***GHG intensity: source and approach***
	Wastewater reuse	3.64	Based on zero-discharge coal power plant case study (see [140], p. 4.26ff)
	Dry cooling	10.06	Energy penalty of dry cooling translates into higher GHG intensity. See [137]
Supply	Sea water direct use	-	No apparent GHG impact
	Dam & reservoir - large	(0.10)	Assumes 48 kW generation capacity per MCM additional dam capacity based on case studies
	Dam & reservoir - small	(0.02)	Assumes 11 kW generation capacity per MCM additional dam capacity based on case studies
	Fresh water transfer - interbasin	0.03	Based on South-North transfer scheme. See [1], [211]
	Fresh water transfer - intrabasin	0.11	Based on 4 projects: Luan to Beijing, Yellow to Hebei, Blue to Lian, Huang diversion
	Groundwater pumping (shallow)	0.10	Based on energy requirements for pumping (see e.g., [135], [2])
	Groundwater pumping (deep)	0.37	Based on energy requirements for pumping (see e.g., [135], [2]
	Aquifer recharge	0.38	Energy requirements for double pumping: first into reservoir, then extraction (see e.g. [135], [2])
	Local water pumping	0.47	Based on energy requirements for pumping (see e.g., [135], [2])
	Rainwater harvesting	0.57	Based on case study from the China Irrigation Development Center
	Rainwater harvesting (roof top)	0.80	Based on [212]
	Desal reverse osmosis	3.16	4.5 kWh/m^3 taken. See section 7.2.2
	Thermal desalination – (co-located with power plant)	4.22	6.0 kWh/m^3 taken. See section 7.2.2
	Thermal desalination – (standalone)	8.44	12.0 kWh/m^3 taken. See section 7.2.2

Table C.2.: Water availability options in **South Africa**.

Sector	***Measure***	***GHG int.*** $kg\ CO_2e/m^3$	***GHG intensity: source and approach***
Agri-culture	No till rainfed	(2.30)	Integration of water and GHG measure
	No till irrigated	(2.30)	Integration of water and GHG measure
	Irrigation scheduling	(0.001)	Less pumping energy needs due to
	Micro sprayer	(0.001)	reduced water requirements
	Channel control	-	No direct GHG impact
	Landscaping	-	No direct GHG impact
	Crop engineering irrigated	-	No direct GHG impact
	Trashing stubble	-	No direct GHG impact
	Crop engineering rainfed	-	No direct GHG impact
	Rainfed germplasm	-	No direct GHG impact
	Drainage construction	-	No direct GHG impact
	Groundwater	-	No direct GHG impact
	IPM rainfed	-	No direct GHG impact
	Irrigated germplasm	-	No direct GHG impact
	IPM irrigated	-	No direct GHG impact
	Rainfed precision farming	-	No direct GHG impact
	Rainwater harvesting ag	-	No direct GHG impact
	Sprinkler irrigation	-	No direct GHG impact
	Irrigated precision farming	-	No direct GHG impact
	Drip irrigation	-	No direct GHG impact
	On-farm canal lining	-	No direct GHG impact
	Increase fertilizer use	-	No direct GHG impact
	Alien vegetation	-	No direct GHG impact
Municipal	Toilets	(1.17)	Reduced energy needs for extraction, distribution and
	Showerheads	(1.17)	– treatment (see e.g. [2])

Continued on the following page

Sector	***Measure***	***GHG intensity*** *kg CO_2e/m^3*	***GHG intensity: source and approach***
	Faucets	(1.17)	Reduced energy needs for extraction, distribution, treatment (see e.g. [2])
	Pressure management (domestic)	(0.58)	Reduced energy needs for extraction and
	Household leakage	(0.58)	– distribution (see e.g. [2])
	Municipal leakage	(0.45)	Reduced energy needs for extraction and distribution (see e.g. [2])
	Bulk leakage	(0.32)	Reduced energy needs for extraction (see e.g. [2])
Industry	Dry lubrication	(58.63)	Case study; 10% power savings in conveyor lines. See for example [213]
	Reuse condensates	(47.53)	Case study; heat energy savings: condensate water 70°C warmer than makeup water. See [214], [215]
	Fluidized bed combustion	(32.74)	Burns coal at lower water needs and CO_2 emissions
	Radical water	(8.46)	Interview and case study; power cost for radical water outweighted by reduced pumping needs. See [216]
	Pressure management – (industry)	(2.02)	Case study based on mining industry. Reduced energy needs for pumping, treatment
	Industrial leakage reduction	(1.03)	Mining case study; reduced energy needs for pumping and treatment
	Dry debarking	(0.77)	Requires only 63% of wet debarking energy; see [217]
	Recycle service water	(0.59)	Reuse grey water, saving water treatment cost (for the latter, see e.g. [2])
	Paste Tailings	-	Energy intensity case-specific – can be even positive or negative. Therefore set to zero here. See [218]
	Dust suppression	-	Negligible energy needs
	Washing efficiency	0.06	Energy needs for pulp washing
Supply	New dams	(0.08)	Assumed 30 kW generation capacity per MCM additional dam capacity; based on case studies
	Raised dams	-	No direct energy needs

Continued on the following page

Sector	***Measure***	***GHG intensity*** $kg\ CO_2e/m^3$	***GHG intensity: source and approach***
	Gravity transfers	-	No direct energy needs
	Rainwater harvesting – domestic	-	No direct energy needs
	Pumped transfers	0.03	Energy requirements for pumping (see e.g. [2])
	Artificial recharge	0.48	Energy requirements for pumping: first into reservoir, then extraction (see e.g. [2])
	Desalination	4.01	Assumes energy intensity of reverse osmosis [2], [138]

D. List of GHG mitigation options

The following gives a list of all GHG mitigation options used in the GHG abatement cost curves for China and/or South Africa in the report *Pathways to a low-carbon economy* [4] and the associated online tool and database *Climate Desk* [77]

Sector	***Mitigation measure***	***China***	***S. Africa***
Agriculture	Tillage and residue management practices	x	x
Agriculture	Cropland nutrient management	x	
Agriculture	Grassland nutrient management	x	x
Agriculture	Rice management - nutrient management	x	x
Agriculture	Rice management - shallow flooding		x
Agriculture	Grassland management	x	x
Agriculture	Organic soils restoration	x	
Agriculture	Agronomy practices	x	x
Agriculture	Degraded land restoration	x	x
Agriculture	Livestock feed supplements	x	x
Agriculture	Livestock - antimethanogen vaccine	x	x
Buildings	Water heating - replacement of gas - res.	x	x
Buildings	Water heating - replacement of gas - com.	x	x
Buildings	Lighting - switch incandescents to LEDs - res.	x	x
Buildings	Lighting - switch incandescents to LEDs - com.	x	x
Buildings	Lighting - new build controls - com.	x	x
Buildings	Lighting - switch CFLs to LEDs - res.	x	x
Buildings	Electronics consumer - residential	x	x
Buildings	Electronics office - commercial	x	x
Buildings	Lighting - switch CFLs to LEDs - commercial	x	x
Buildings	Appliances - residential	x	x
Buildings	Appliances - refrigerators - commercial	x	x
Buildings	Retrofit - building envelope - commercial	x	x
Buildings	Retrofit HVAC - controls - commercial	x	x
Buildings	HVAC retrofit to heat pump (residential)	x	x
Buildings	Water heating - replacement of electric - com.	x	x
Buildings	Lighting - T12 to T8/T5 - commercial	x	x
Buildings	Efficiency package - new build, commercial	x	x
Buildings	Retrofit HVAC - gas/oil heating - residential	x	x
Buildings	Water heating - replacement of electric - res.	x	x
Buildings	Lighting - retrofit controls - commercial	x	x

Continued on the following page

Sector	***Mitigation measure***	***China***	***S. Africa***
Buildings	Retrofit HVAC - maintenance - residential	x	x
Buildings	Retrofit HVAC - air conditioning - res.	x	
Buildings	Retrofit HVAC - commercial	x	x
Buildings	Efficiency package - new build, res.	x	x
Buildings	Retrofit - building envelope - res.	x	x
Cement	Waste heat recovery	x	x
Cement	Clinker substitution by fly ash	x	x
Cement	Alternative fuels - bio	x	x
Cement	Clinker substitution by slag	x	x
Cement	Alternative fuels - waste	x	x
Cement	Post combustion CCS- retrofit	x	x
Cement	Post combustion CCS - new capacity		x
Chemicals	Motor systems - new build	x	x
Chemicals	Motor systems - retrofit	x	x
Chemicals	Catalyst optimization - energy - level 1	x	x
Chemicals	Process intensification - energy - level 1	x	x
Chemicals	CHP - new build	x	x
Chemicals	CHP - retrofit	x	x
Chemicals	Catalyst optimization - energy - level 2	x	x
Chemicals	Process intensification - process - level 1	x	x
Chemicals	Catalyst optimization - process - level 1	x	x
Chemicals	N2O decomposition of adipic acid	x	
Chemicals	N2O decomposition of nitric acid	x	
Chemicals	Process intensification - energy - level 3	x	x
Chemicals	Catalyst optimization - energy - level 3	x	x
Chemicals	Ethylene cracking - new build	x	x
Chemicals	N2O decomposition of nitric acid - retrofit	x	
Chemicals	Ethylene cracking - retrofit	x	x
Chemicals	Process intensification - energy - level 2	x	x
Chemicals	Catalyst optimization - process - level 2	x	x
Chemicals	Process intensification - process - level 2	x	x
Chemicals	Fuel shift coal to biomass - new build	x	
Chemicals	Fuel shift coal to biomass - retrofit	x	
Chemicals	Catalyst optimization - process - level 3	x	x
Chemicals	Process intensification - process - level 3	x	x
Chemicals	CCS direct energy - new build	x	x
Chemicals	CCS ammonia - new build	x	x
Chemicals	CCS ammonia - retrofit	x	x
Chemicals	CCS direct energy - retrofit	x	x
Forestry	Degraded forest reforestation	x	x
Forestry	Forest management	x	x
Forestry	Pastureland afforestation		x

Continued on the following page

Sector	***Mitigation measure***	***China***	***S. Africa***
Iron & Steel	Co-generation - retrofit	x	x
Iron & Steel	Co-generation - new build	x	x
Iron & Steel	Direct casting - new build	x	x
Iron & Steel	Smelt reduction - retrofit	x	x
Iron & Steel	Smelt reduction - new build	x	x
Iron & Steel	Energy efficiency general	x	x
Iron & Steel	Coke substitution - new build	x	x
Iron & Steel	Coke substitution - retrofit	x	x
Iron & Steel	CCS - new build	x	x
Iron & Steel	CCS - retrofit	x	x
Other industry	Bundled energy efficiency	x	x
Oil & Gas	Planning	x	
Oil & Gas	”Behavioral” changes in upstream oil and gas	x	
Oil & Gas	”Behavioral” - procedural changes	x	x
Oil & Gas	Improved maintenance & process control	x	x
Oil & Gas	Energy efficiency at process unit level	x	x
Oil & Gas	Energy efficient new builds in upstream	x	
Oil & Gas	Energy efficiency projects [...] upstream	x	
Oil & Gas	Energy efficiency projects at plant level (co-gen)	x	x
Oil & Gas	Reduced flaring	x	x
Oil & Gas	Replace seals	x	
Oil & Gas	Maintain compressors	x	
Oil & Gas	Distribution maintenance	x	
Oil & Gas	CCS in downstream operations	x	x
Power	Small hydro	x	x
Power	Geothermal	x	
Power	Nuclear	x	x
Power	Wind - low penetration	x	x
Power	Shift of coal to increased gas utilization	x	
Power	Solar PV	x	x
Power	Wind - high penetration	x	x
Power	Coal CCS - new build with EOR	x	x
Power	Solar concentrated (CSP)	x	x
Power	Gas CCS - new build with EOR	x	x
Power	Coal CCS - new build	x	x
Power	Coal CCS - retrofit	x	x
Power	Gas CCS - retrofit	x	x
Power	Biomass CCS - new build	x	x
Power	Gas CCS - new build	x	
Power	Biomass - co-firing	x	
Transport	LDV - gasoline bundle	x	x
Transport	LDV - diesel bundle	x	x

Continued on the following page

Sector	***Mitigation measure***	***China***	***S. Africa***
Transport	MDV - gasoline bundle	x	x
Transport	HDV - diesel bundle	x	x
Transport	1st generation bio-fuels	x	x
Transport	2nd generation bio-fuels	x	x
Transport	MDV - diesel bundle	x	x
Transport	LDV - diesel full hybrids	x	x
Transport	LDV - gasoline plug-in hybrids		x
Transport	LDV - gasoline full hybrids	x	x
Transport	LDV - diesel plug-in hybrids	x	x
Transport	LDV - electric vehicles		x
Waste	Landfill gas direct use	x	x
Waste	Landfill gas electricity generation	x	x
Waste	Composting new waste	x	x
Waste	Recycling new waste		x

E. Integrated cost formulas

Section 6.5 discussed the different cost terms used in this work. Amongst other, it discussed at one example how integrated cost, discounted to 2030 can be derived in dependence on the lifetime and "decade" of the mitigation option (see equations (6.4) – (6.8)). This appendix chapter derives the formulas for the four cases that were not yet discussed in section 6.5.
Again, let C be the investment needs for a given mitigation option (relative to the reference case), O be the associated operational cost/ savings (relative to the reference), and i the cost of capital.

Case 2: $l > 10$, implementation 2020–2030

Discounted investments
In this case, no replacement investments are required in the period under consideration. Investments are again spread equally over the decade, i.e., $C/10$ per year. The future value in 2030 is then equivalent to the 2020 future value in case 1, as the implementation occurs a decade later here,

$$FV_C(2030) = \frac{C}{10} \sum_{k=1}^{10} (1+i)^k \underset{i=4\%}{=} 1.25\, C\,. \tag{E.1}$$

Discounted operational cost
Again, the future value of all operational cost/savings in 2030 is the same as the 2020 future value in case 1,

$$\begin{aligned} FV_O(2030) &= \frac{O}{10}(1+i)^{10} + \frac{2\cdot O}{10}(1+i)^9 + \ldots + \frac{10\cdot O}{10}(1+i) \\ &= \frac{O}{10}\sum_{k=1}^{10}(11-k)(1+i)^k \underset{i=4\%}{=} 6.46\, O\,. \end{aligned} \tag{E.2}$$

Case 3: $l < 10$**, implementation 2020–2030**

Discounted investments

As mentioned in 6.5, it is assumed that the implementation of mitigation options with $l < 10$ is spread equally of l years and assumed to be finished by the end of the decade; i.e., implementation starts in the year $2030-l$ and finishes in 2030 here. For this reason, no replacement investments incur. The 2030 value of the investments can then be derived as follows

$$FV_C(2030) = \frac{C}{l} \sum_{k=1}^{l} (1+i)^k \, . \tag{E.3}$$

Discounted operational cost

As the investments only start in the year $2030-l$, operational cost/savings only have an effect from then on. Discounted to 2030 and summed up over the l years, this gives

$$\begin{aligned} FV_O(2030) &= \frac{O}{l}(1+i)^l + \frac{2 \cdot O}{l}(1+i)^{l-1} + \ldots + \frac{l \cdot O}{l}(1+i) \\ &= \frac{O}{l} \sum_{k=1}^{l} (l+1-k)(1+i)^k \, . \end{aligned} \tag{E.4}$$

Case 4: $l < 10$**, implementation 2010–2020**

Discounted investments

First, the same assumptions as in case 3 apply here (investments were spread equally over l years, full potential achieved by the end of the decade, i.e., 2020 in this case). The 2020 future value of the investments in this case follows the same logic as the 2030 value from case 3. For the decade 2020–2030, replacement investments become however necessary to maintain the mitigation potential. Replacements need to occur over the full decade 2020–2030: when the last investment tranche of C/l is finished at the beginning of 2020, the earliest already reaches the end of its lifetime, requiring replacement at the beginning of 2021, and so forth.

Let $FV_C(2020)$ and $FV_{C1}(2030)$ be the 2020 and 2030 values of the original investments, respectively, and $FV_{C2}(2030)$ the 2030 value of the replacement investments between 2020 and 2030.

$$
\begin{aligned}
FV_{C1}(2020) &= \frac{C}{l}\sum_{k=1}^{l}(1+i)^k \\
FV_{C1}(2030) &= (1+i)^{10}\, FV_{C1}(2020) && \text{(E.5)} \\
FV_{C2}(2030) &= \frac{C}{l}\sum_{k=1}^{10}(1+i)^k && \text{(E.6)} \\
FV_C(2030) &= FV_{O1}(2030) + FV_{O2}(2030) \\
&= \frac{C}{l}\left((1+i)^{10}\sum_{k=1}^{l}(1+i)^k \;+\; \sum_{k=1}^{10}(1+i)^k\right). && \text{(E.7)}
\end{aligned}
$$

Discounted operational cost

Operational cost/savings follow the same logic as in case 3: they only take effect from a point within the decades onwards and increase to the end of the decade to full potential. In contrast to case 3, they incur (at full potential) over the whole second decade. The 2020 value $FV_O(2020)$ thus is the same as the 2030 value in equation (E.4),

$$
FV_O(2020) = \frac{O}{l}\sum_{k=1}^{l}(l+1-k)(1+i)^k\ . \qquad \text{(E.8)}
$$

The 2030 value is composed again of two parts, the value from equation (E.8) discounted to 2030 ($FV_{O1}(2030)$) and the operational cost/savings incurred between 2020 and 2030 ($FV_{O1}(2020)$),

$$
\begin{aligned}
FV_{O1}(2030) &= (1+i)^{10}\, FV_{O1}(2020) && \text{(E.9)} \\
FV_{O2}(2030) &= O\left((1+i)^{10} + (1+i)^9 + \ldots + (1+i)\right) && \text{(E.10)} \\
FV_O(2030) &= FV_{O1}(2030) + FV_{O2}(2030) \\
&= \frac{O}{l}(1+i)^{10}\sum_{k=1}^{l}(l+1-k)(1+i)^k \;+\; O\sum_{k=1}^{10}(1+i)^k\ . && \text{(E.11)}
\end{aligned}
$$

Case 5: $10 < l < 20$**, implementation 2010–2020**

Discounted investments

Given the longer lifetime of the asset, replacement investments are only required during a part of the second decade, in contrast to the preceding case. Other than that, this case follows the same logic; if investments are distributed equally over 10 years again, the integrated, discounted 2030 value $FV_C(2030)$ is given as follows:

$$
\begin{aligned}
FV_{C1}(2020) &= \frac{C}{10}\sum_{k=1}^{10}(1+i)^k \\
FV_{C1}(2030) &= (1+i)^{10}\,FV_{C1}(2020) && \text{(E.12)} \\
FV_{C2}(2030) &= \frac{C}{10}\sum_{k=1}^{20-l}(1+i)^k && \text{(E.13)} \\
FV_{C}(2030) &= FV_{O1}(2030) + FV_{O2}(2030) \\
&= \frac{C}{10}\left((1+i)^{10}\sum_{k=1}^{10}(1+i)^k \;+\; \sum_{k=1}^{20-l}(1+i)^k\right)\,. && \text{(E.14)}
\end{aligned}
$$

Discounted operational cost

As operational cost/savings incur from 2020 on, increase to full potential by 2020 and stay at this level through 2030, this case is the same as case 1. The integrated operational cost, discounted to 2030 are given by equation (6.8),

$$
FV_O(2030) \;=\; \frac{O}{10}\left((1+i)^{10}\sum_{k=1}^{10}(11-k)(1+i)^k\right) + O\sum_{k=1}^{10}(1+i)^k\,. \qquad \text{(E.15)}
$$

F. Fit functions for isoinvestment curves

Section 8.3 (page 162 f.) discussed isoinvestment curves, i.e., curves that connect points of varying incremental water availability and GHG abatement, but constant investments. The gradient of these curves can be regarded as the marginal rate of substitution between water availability and GHG abatement.
The isoinvestment curves were fitted with polynoms. If y stands for the GHG abatement and x for water availability, the fits to the isoinvestment curves are as given below. The marginal rate of substitution is then given by dy/dx.

China

We fitted the isoinvestment curves 1, 3, 5, 7 in figure 8.9.

$$\begin{aligned}
1.\ y(x) &= -4 \cdot 10^{-13}x^3 + 9 \cdot 10^{-8}x^2 - 0.0034x + 3124.4 \\
3.\ y(x) &= -3 \cdot 10^{-13}x^3 + 7 \cdot 10^{-8}x^2 - 0.0043x + 5065.5 \\
5.\ y(x) &= -3 \cdot 10^{-13}x^3 + 7 \cdot 10^{-8}x^2 - 0.0063x + 7197.6 \\
7.\ y(x) &= -4 \cdot 10^{-13}x^3 + 1 \cdot 10^{-7}x^2 - 0.0131x + 8968.3
\end{aligned} \tag{F.1}$$

South Africa

We fitted all isoinvestment curves in figure 8.10.

$$\begin{aligned}
1.\ y(x) &= -7 \cdot 10^{-7}x^2 - 0.0077x + 110.23 \\
2.\ y(x) &= -1 \cdot 10^{-6}x^2 - 0.0035x + 142.74 \\
3.\ y(x) &= -1 \cdot 10^{-6}x^2 - 0.0012x + 166.82 \\
4.\ y(x) &= -2 \cdot 10^{-6}x^2 + 0.0014x + 206.52 \\
5.\ y(x) &= -2 \cdot 10^{-6}x^2 + 0.0023x + 244.22 \\
6.\ y(x) &= -1 \cdot 10^{-6}x^2 + 0.0018x + 285.41 \\
7.\ y(x) &= -2 \cdot 10^{-6}x^2 + 0.0055x + 317.12
\end{aligned} \tag{F.2}$$

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