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ISSUE BRIEF

OPPORTUNITIES TO REDUCE WATER USE AND GREENHOUSE GAS EMISSIONS IN THE CHINESE POWER SECTOR

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EXECUTIVE SUMMARY

China’s power sector is its largest source of greenhouse gas emissions and also its biggest industrial water user. As a result, current and future decisions about electricity generation—and energy efficiency—will have profound impacts on both global climate and domestic water resources.

To offer suggestions on how to reduce the environmental impact of this growing industry, the World Resources Institute (WRI) evaluated the climate and water implications of over 20 combinations of power-generating technologies and cooling-systems used or proposed in China and other countries. We developed the Water–Climate Impacts Bubble Chart to communicate potentially complex analytical results in a simple, visual manner to help decisionmakers better understand the trade-offs between water use, climate impacts, and capital investment in the power sector. While this approach was developed with primarily Chinese data, other countries considering power generation technologies might also find it useful.

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Our research offers several key observations:

- Employing energy-efficiency measures and technology is by far the most effective strategy for reducing both greenhouse gas emissions and water impacts. Rather than increasing plant generation capacity, energy efficiency measures leverage consumption efficiency to increase available electricity supply, showing a net positive impact on both greenhouse gas emissions and water use.

  Furthermore, this method is the most cost-effective approach among the options considered.

- Of the renewable power generation technologies, run-of-river hydroelectric and wind power stand out as the alternatives with relatively low cost and low environmental impact. However, not all renewables have a positive impact on water. Concentrated solar power (CSP) plants, for example, while ideal for some of China's sunniest and driest locations, require twice as much water as coal-fired plants equipped with the same closed-loop cooling system.

- Carbon capture and storage (CCS) could cut the greenhouse gas emissions of pulverized-coal-fired power plants by 80 to 90 percent, but it would lead to a 90 percent increase in capital costs, a 15–30 percent decrease in power generation efficiency, and doubled water consumption. When retrofitting or designing new pulverized-coal plants with CCS, water availability should be carefully evaluated.

China's national government has established strict water resource management requirements, setting mandatory limits on water withdrawal, efficiency, as well as water quality. These new limits have signaled China's determination to improve the sustainability of water use. While there is no silver bullet to solve China's water-climate conundrum, we offer several recommendations to help manage the water-energy trade-off in the Chinese power sector:

- China should devise policies to regulate water use in the power generation industry and establish sectoral water withdrawal quotas at the national, regional, and local levels.

- China should continue to promote end-use energy efficiency to reduce greenhouse gas emissions and conserve water.

- Wind and solar is the best option for China's water-scarce areas, while run-of-river hydropower is most suitable for areas where water resources are available.

- Shifting to closed-loop or dry-cooling systems is recommended for China's thermoelectric power plants.

- Policymakers should consider regional water distribution and avoid building low-carbon but water-intensive technologies (e.g. nuclear, CSP, and CCS) in water-stressed areas.

POWER GENERATION IS AT THE CLIMATE AND WATER NEXUS

Reducing greenhouse gas emissions (GHG) and water use are both key targets of China's 12th Five Year Plan (2011 through 2015). The goal to reduce carbon intensity (carbon emissions per unit of gross domestic product [GDP]) by 17 percent over the five-year period is also a major portion of China's Copenhagen commitment to a 40–45 percent greenhouse gas intensity reduction from a 2005 baseline by 2020. Equally critical is the government's goal to reduce water consumption per unit of industrial value-added by 30 percent over the same five-year period.[1]

These goals reflect constraints on China's use of natural resources. China is the world's largest greenhouse gas emitter with CO_2 its most prevalent greenhouse gas.[2] It is expected to face significant adverse impacts from climate change over the coming decades, including increased water supply shortages (State Council, China 2008.)

China's water supply has long been constrained: per capita water availability is one third the world average (World Bank 2014). About 46 percent of China's population lives in North China, where the amount of available water resources is less than 20 percent of China's total (Jiang et al. 2013). Power generation, the largest industrial water user, uses roughly 10 percent of China's total water supply.[3]

Policymakers and power companies will need to consider options to best minimize greenhouse gas emissions, reduce the impacts on China's precious water supplies, and make cost-effective investment decisions.

As a rapidly developing country, China is still building its power generation infrastructure. The nation's generation capacity is expected to increase from 962 gigawatts (GW) in 2010 to 1,490 GW by 2015 (NDRC 2013a), and potentially add another 1,320 GWby 2030 (Bloomberg New Energy Finance 2013) which could significantly increase water and fuel consumption. However, the government's announcement of new water resource management measures—which set mandatory limits on water use, efficiency, and quality—have put water-intensive sectors under intense scrutiny (State Council, China 2012). In the past, fuel availability and transmission infrastructure determined power plant design and location. Now, greenhouse gas emissions, water resources, and pollution control are likely to be factored in the overall planning process.

Given the array of technologies available for power production, policymakers and power companies will need to consider options to best minimize greenhouse gas emissions, reduce the impacts on China's precious water supplies, and make cost-effective investment decisions. WRI and the Chinese Energy Research Institute (ERI) have developed an analytical framework for evaluating the climate, water, and financial implications of major types of power generation technologies and selected energy efficiency measures. This analysis, together with a new visualization, can help decisionmakers understand the trade-offs between power generation and associated impacts on water and other natural resources.

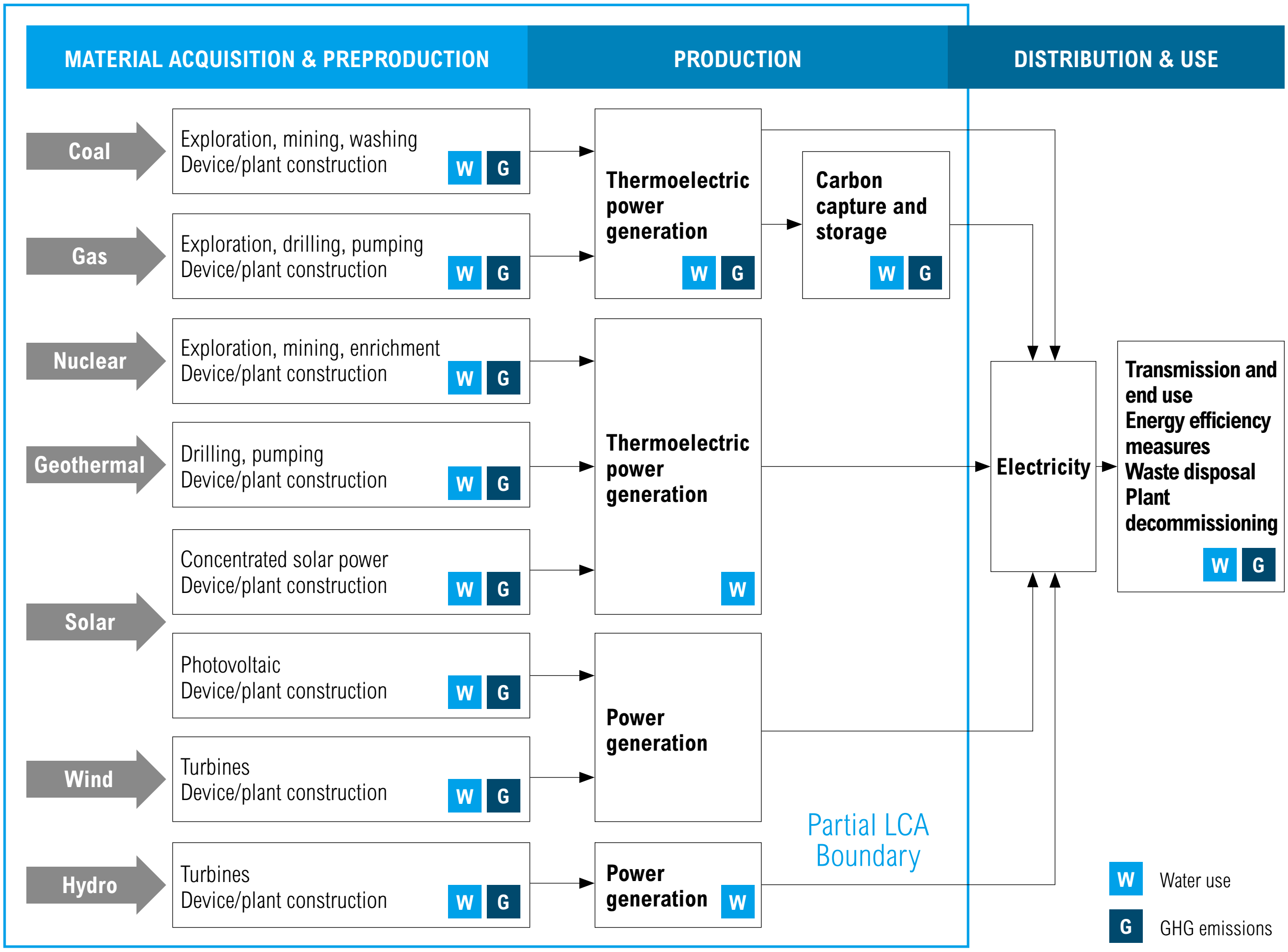
METHODOLOGY

When considered from a lifecycle perspective, all power generation technologies emit greenhouse gases. Fossil-fuel-fired power plants release large amounts of CO_2 from the combustion of coal, natural gas, and oil. Nuclear, wind, and solar power do not emit CO_2 directly; however, uranium enrichment, wind turbine manufacturing, and solar cell construction require fossil-based energy inputs and therefore indirectly involve greenhouse gas emissions. Similarly, hydropower's emissions can be significant if a large amount of vegetation accumulates in a reservoir, because underwater decay of this vegetation will release methane, a potent greenhouse gas (World Commission on Dams 2000).

Most power generation plants, particularly thermoelectric power plants, are water intensive. For the power sector, water use is described in terms of consumption and withdrawal. Water consumption is the amount of water evaporated, transpired, lost to leakage, incorporated into products, or otherwise removed from the immediate water environment. Withdrawal is the water lost to consumption plus any water that was withdrawn but then returned to its source. Consumption matters because it reduces the amount of water available for other uses,

FIGURE 1

POWER GENERATION LIFE CYCLE PROCESS MAP



Source: World Resources Institute

while withdrawal is critical because it often removes large amounts of water for cooling but returns to the environment at a higher temperature, potentially harming fish and other wildlife. Wastewater discharged at the end of power generation processes is another dimension of water impacts.

Life cycle assessment (LCA) is an effective method to assess the environmental aspects associated with all stages of power generation. In this study, WRI's *Greenhouse Gas Protocol Product Life Cycle Accounting and Reporting Standard* (product standard) was used to define the life cycle boundary of power generation. The product standard builds on the framework and requirements of the International Organization for Standardization (ISO) 14044 standard for life cycle assessments and provides additional specifications and guidance (WRI and WBCSD 2011). Because the environmental impacts of electricity distribution and consumption depend on the efficiency of the grid and the end users, which are not included in this study of power generation technologies, we used a partial LCA or "cradle to gate" approach to avoid double counting.[4] Our approach included material acquisition and preproduction and production of power, but not distribution and use (Figure 1). We also excluded downstream processes such as waste disposal and plant decommissioning, which generally have small impacts on water and the environment.

We followed four steps to evaluate the climate and water impacts of power generation. Based on expert

TABLE 1

POWER GENERATION TECHNOLOGIES AND ENERGY EFFICIENCY MEASURES

	Technologies/measures[a]	Abbreviations used in bubble charts	Plant/measure lifespan[b] (years)	Power generation capacity factor[c] (percent)
1	Subcritical coal with closed-loop cooling	CL SubCritical	30	56
2	Subcritical coal with dry cooling	Dry SubCritical	30	56
3	Supercritical coal with closed-loop cooling	CL SC	30	56
4	Supercritical coal with dry cooling	Dry SC	30	56
5	Integrated gasification combined cycle with closed-loop cooling	CL IGCC	30	56
6	Natural gas combined cycle with closed-loop cooling	CL NGCC	25	40
7	Natural gas combined cycle with dry cooling	Dry NGCC	25	40
8	Subcritical coal with closed-loop cooling and carbon capture and storage	CL SubCritical w/CCS	30	56
9	Subcritical coal with dry cooling and carbon capture and storage	Dry SubCritical w/CCS	30	56
10	Supercritical coal with closed-loop cooling and carbon capture and storage	CL SC w/CCS	30	56
11	Supercritical coal with dry cooling and carbon capture and storage[5]	Dry SC w/CCS	30	56
12	Integrated gasification combined cycle with closed-loop cooling and carbon capture and storage	CL IGCC w/CCS	30	56
13	Natural gas combined cycle with closed-loop cooling and carbon capture and storage	CL NGCC w/CCS	25	40
14	Natural gas combined cycle with dry cooling and carbon capture and storage	Dry NGCC w/CCS	25	40
15	Nuclear with closed-loop cooling	CL nuclear	40	88
16	Nuclear with open-loop cooling	OL nuclear	40	88
17	Run-of-river hydro	Hydro (run-of-river)	30	41
18	Hydroelectric dam	Hydro (dam)	40	41
19	Solar photovoltaic	Solar PV	25	15
20	Concentrated solar power with closed-loop cooling	CL CSP	30	38
21	Concentrated solar power with dry cooling	Dry CSP	30	38
22	Geothermal	Geothermal	30	68
23	Wind power	Wind	20	18
24	Energy efficient building		50	
25	Energy efficient lighting		See Appendix 1	
26	Energy efficient air conditioner	Energy efficient AC	See Appendix 1	

Notes and sources:
a. Definitions of the technologies can be found in Appendix 2.
b. World Bank 2005.
c. China Electricity Council 2010.

> Energy efficiency by end-users is by far the most effective strategy in terms of its net positive impact on both greenhouse gas emissions and water consumption.

consultation and a literature review, we first identified the leading power generation and efficiency technologies under consideration in China. This included power plant fuel types (coal, gas, nuclear, hydro, wind, solar, geothermal) and their cooling system types (open-loop, closed-loop, and dry cooling). Outdated technologies, such as open-loop coal-based technology, were not included because they are unlikely to be used for new plants, even in China's water-abundant south (Zhang 2012). Because the Chinese government has mandated desulfurization in coal-based power plants, water use and greenhouse gas emissions associated with the flue-gas desulfurization (FGD) process were considered. In addition, we looked into three energy-efficiency applications on the end-user side: energy-efficient air conditioners (NDRC 2011), energy-efficient lighting (NDRC 2010), and energy efficiency in buildings (He 2010). Detailed information including power plant lifespans and capacity factors (the ratio of actual net electricity generation to potential energy generation at continuous full-power operation) is listed in Table 1.

Second, using available Chinese data, we quantified the climate, water, and electricity implications for each power plant type along the following metrics:

- greenhouse gas emissions per megawatt-hour (MWh) of electricity produced;
- amount of water withdrawn, consumed, and polluted per megawatt hour (MWh) of electricity produced;[6]
- the potential amount of power generated per 1 billion renminbi (RMB), of capital investment.[7]

To quantify the environmental impacts of energy-efficiency measures, we used Chinese thermoelectric power generation as a proxy to calculate and show their possible avoidance in greenhouse gas emissions and water use (see Appendix 1 for detailed calculations and assumptions).

Third, WRI and ERI surveyed a range of reports for lifecycle greenhouse gas emissions and water use for each power generation technology, taking into account upstream processes such as fuel extraction, preprocessing, and facility construction. Appendix 2 summarizes the data sources.

While hydropower is included in this analysis, we acknowledge that the analysis of its environmental impacts is limited. Greenhouse gas emissions of hydropower facilities are often site specific and vary considerably because of local climate and vegetation, and in some cases are quite high (Mäkinen and Kahen 2010).

COMPARING THE WATER AND GREENHOUSE GAS IMPLICATIONS OF POWER TECHNOLOGIES

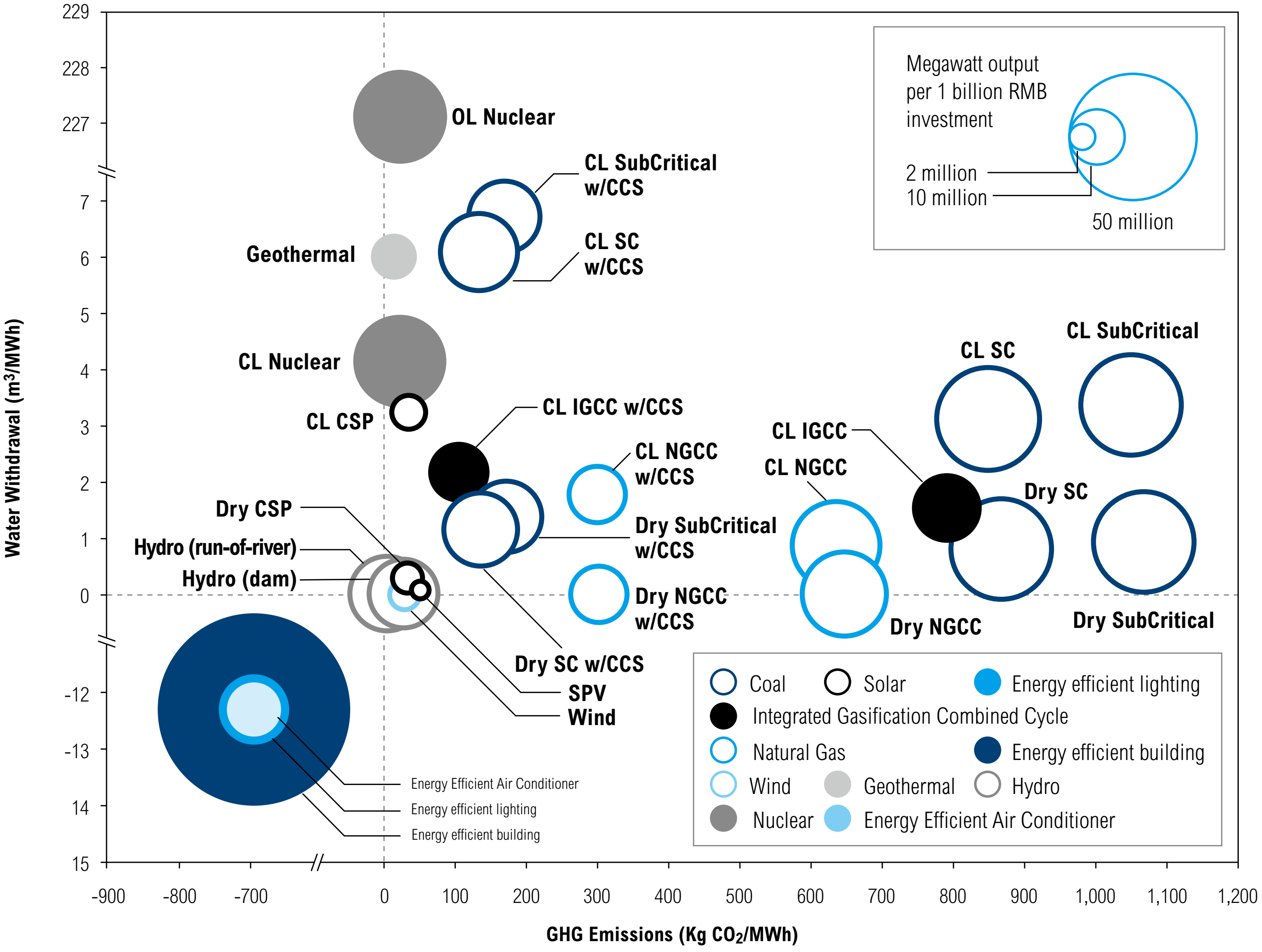
Three Water-Climate Impacts Bubble Charts (Figures 2, 3, and 4) illustrate China's power generation options in the context of climate and water challenges. Bubble charts offer a unique way to present the three dimensions of power generation technology: capital costs, greenhouse gas emissions, and water impacts. The three figures depict the greenhouse gas and financial cost impacts in relation to freshwater withdrawal (Figure 2), freshwater consumption (Figure 3), and wastewater discharge (Figure 4). As industrial water withdrawal is closely regulated in China, Figure 2 is particularly important for the dry provinces.

To interpret each bubble chart, consider freshwater withdrawal (Figure 2). The vertical axis shows the amount of freshwater withdrawal per MWh of power generation and the horizontal axis shows the amount of greenhouse gases emitted per MWh of power generation. Each bubble represents a power generation or energy-efficiency technology; see Table 1 for the abbreviations used for each technology in the figures. The size of the bubble reflects the electricity produced or saved over the lifetime of the technology divided by its capital costs, using 2010 technology costs. Thus the larger bubbles indicate power generated more cheaply (more power per unit of investment). Large bubbles in the lower left area of the right quadrant show technologies that produce the most power at the least cost with the least water use and greenhouse gas emissions.

In each chart, greenhouse gas emissions and water impact are either positive or negative. In Figure 2, positive numbers refer to the incremental greenhouse gas

FIGURE 2

WATER WITHDRAWAL AND GREENHOUSE GAS EMISSIONS OF POWER GENERATION TECHNOLOGIES AND ENERGY EFFICIENCY MEASURES



Source: World Resources Institute

emissions or water withdrawal arising from power production. Negative numbers represent reductions in greenhouse gas emissions or water withdrawal due to energy efficiency.

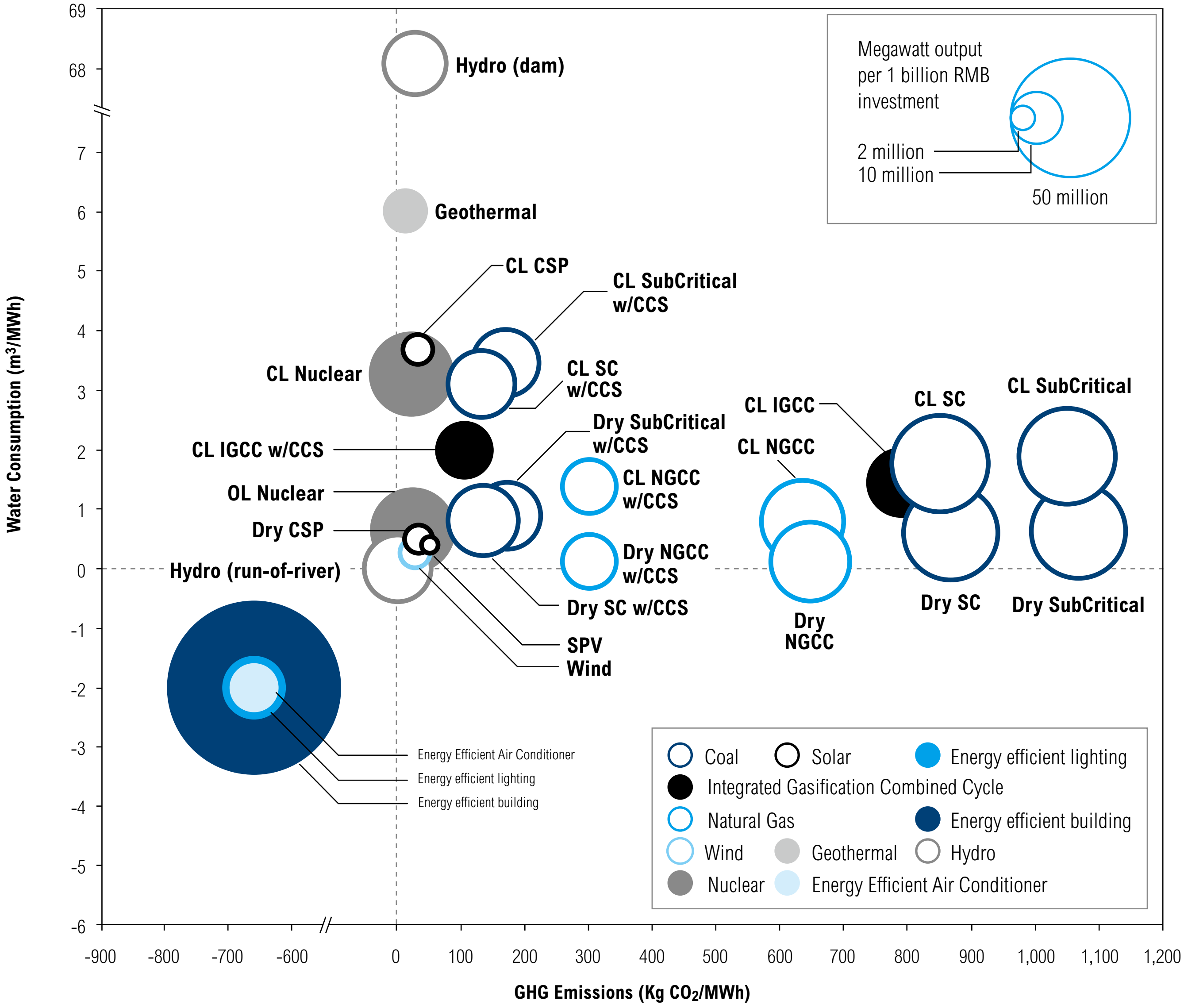
The bubbles are placed on a Cartesian plane with four quadrants. Since most power generation technologies both use water and emit greenhouse gases, most technologies lie in the upper right-hand quadrant, where there are trade-offs. For example, coal-based power generation systems emit more greenhouse gases but use less water than nuclear systems, while geothermal technology uses more water but emit fewer greenhouse gases.

Technologies clustered at the lower left of the right hand quadrant, such as hydropower, photovoltaics, wind, and dry-cooled concentrated solar power, are low on both water use and emissions.

Because energy efficiency measures have beneficial impacts on both metrics, energy-efficient lighting, energy-efficient air-conditioning, and energy-efficient construction fall into the bottom left-hand quadrant—the “win-win” quadrant. Energy-efficiency measures increase the available market supply of power by leveraging consumption efficiency rather than by

FIGURE 3

WATER CONSUMPTION AND GREENHOUSE GAS EMISSIONS OF POWER GENERATION TECHNOLOGIES AND ENERGY EFFICIENCY MEASURES



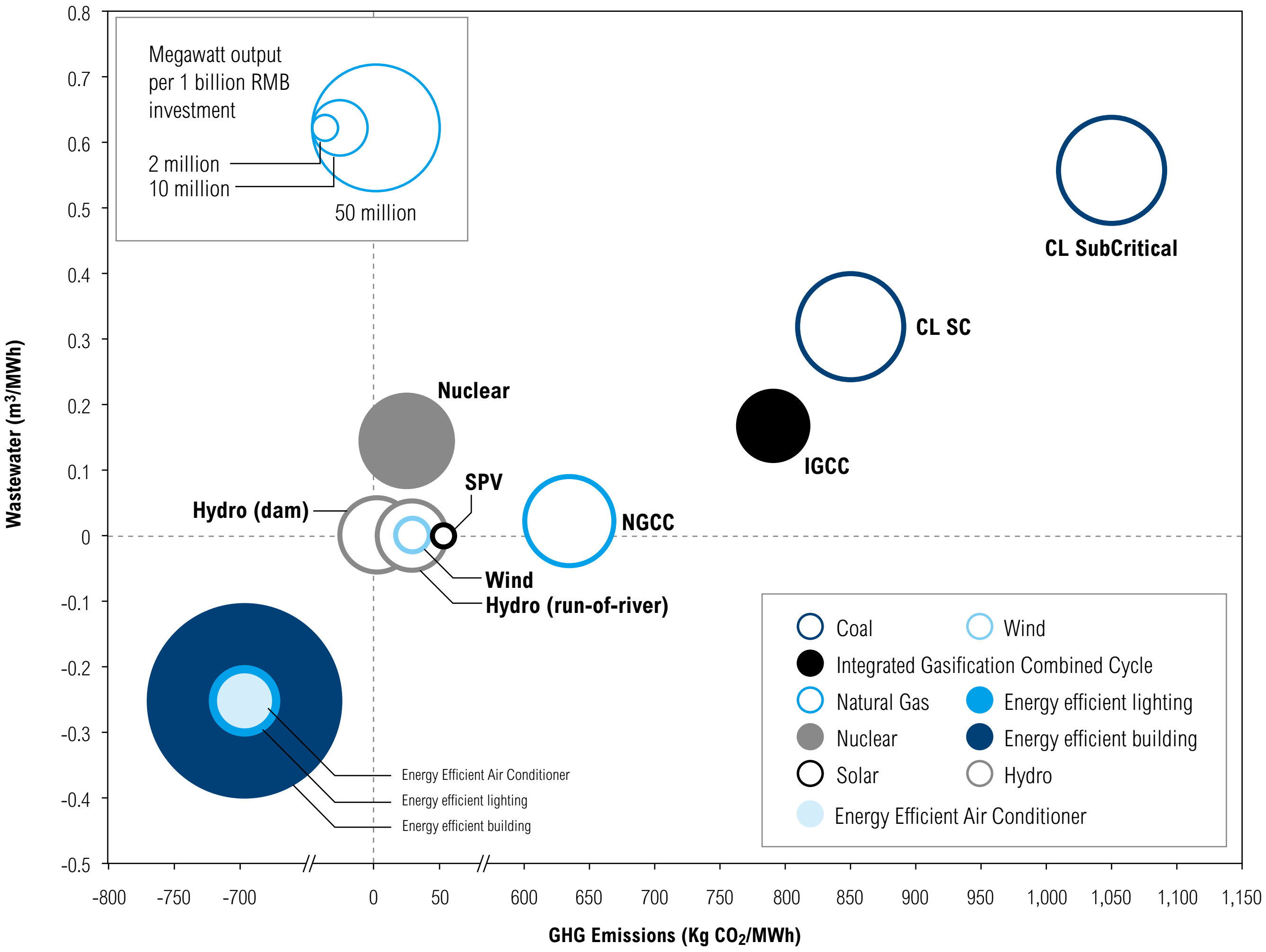
Source: World Resources Institute

increasing plant generation capacity, which in turn effectively reduces water use and greenhouse gas emissions per unit of power.

The sizes of the bubbles indicate how the technologies vary in the amount of power generated per unit of investment. Not surprisingly, coal-fired power is cheaper relative to other generation technologies, thus making the size of coal-fired power bubbles—the total amount of power generated per 1 billion RMB of capital investment—relatively large. However, the environmental and health costs are not internalized into the cost of coal power, thus are borne by society. Newer technologies such as solar and wind are more expensive per unit of power generated, making the bubbles relatively smaller. These figures do not consider how the costs of these technologies will change over time.

FIGURE 4

WASTEWATER DISCHARGE AND GREENHOUSE GAS EMISSIONS OF POWER GENERATION TECHNOLOGIES AND ENERGY EFFICIENCY MEASURES



Note: Not all technologies are displayed here due to data availability.

RESULTS AND IMPLICATIONS FOR POLICY

The bubble charts illustrate that the choices for power generation have implications for climate and water. Given the size of the power sector and rapid increases in electricity and water demand, it is critical that these considerations are factored into decisions made by the power sector. Our bubble chart analysis reveals several important observations.

Energy efficiency by end-users is by far the most effective strategy in terms of its net positive impact on both greenhouse gas emissions and water consumption. By reducing energy demand and subsequently avoiding water use for power generation, energy efficiency measures can free up scarce water resources for other critical purposes, such as agriculture or household use (Ministry of Water Resources 2010). Moreover, it is the most cost-effective approach—it yields the most electricity (or avoided electricity demand) for every 1 billion RMB invested. For instance, China's subsidies for energy-efficient lighting in the 11th Five Year Plan period (2006–10) are estimated to save more than 17,600 GWh of electricity, avoid 12.3 million metric tons of CO_2 emissions, and reduce 35 million cubic meters of water consumption over the lifespan of energy efficient light bulbs (NDRC 2010). Because of these economic and environmental benefits, policymakers should prioritize these options before other power generation technologies.

Some experts have suggested that the benefit of energy efficiency will be partly lost through behavioral responses, or the rebound effect (Michaels 2012).The rationale is that greater energy efficiency is partially offset by an increase in energy use since households and companies may increase consumption as the cost of energy decreases. However, a recent study by Yale University revealed that in most cases only 10–30 percent of energy saved was lost to the rebound effect (Gillingham, Kotchen, Rapsom and Wagner 2013). Therefore, energy efficiency measures should continue to be considered as a win-win-win solution for the climate, water, and the Chinese economy.

Of the renewable power generation technologies, run-of-river hydroelectric power stands out for its low cost and low environmental impact. Using the natural elevation of a river to spin the turbines, run-of-river power does not need to drastically change river flow or to flood a large area of land. Therefore, there is negligible water consumption (through evaporation) and negligible greenhouse gas emissions. However, in the absence of a dam or back-up water storage, power generation could be disrupted if water is depleted upstream by droughts or water extraction.

Meanwhile, both wind power and solar photovoltaics have clear advantages in China's water-constrained environment, with neither technology requiring much water input or releasing greenhouse gases during power generation. Based on our life cycle analysis, the water withdrawal of a wind farm is 85–90 percent lower than the most efficient coal-fired power plant. Water is used mostly in upstream processes, such as material processing and plant construction. Compared with wind, photovoltaic cells have slightly higher water requirements because manufacturing the silicon-based panels is more water intensive, and water is used in cleaning the panels (Harto, Meyers, and Williams 2007).

Water requirement is an important consideration when making nuclear power decisions. To date, China has placed its nuclear power plants along the coast, so that seawater rather than freshwater can be used for cooling. This decision has avoided an increase in freshwater consumption in China's coastal areas. However, energy decisionmakers are now discussing inland nuclear power, such as potential sites in Gansu and Henan provinces (NDRC 2007), where water availability is already a critical issue. When equipped with a closed-loop cooling system, a nuclear power plant consumes 70 percent more (and withdraws 130 percent more) freshwater than a coal-fired power plant (NETL 2009). Building nuclear plants in areas with high water risk might further exacerbate water scarcity.

Concentrated solar power (CSP) is a reliable low-carbon but potentially water-intensive technology. Chinese companies started investing in CSP projects in arid Inner Mongolia in 2011.[8] Yet compared with photovoltaics, CSP is more reliable and could be more easily integrated into the current grid. However, it is among the most expensive forms of energy generation today, with initial capital investment 20 percent higher than that of photovoltaic systems. Yet, water usage might pose an even greater concern because CSP is water-intensive, requiring more cooling water than coal-based power generation technologies per MWh of power generated. Dry cooling for CSP can reduce freshwater requirements to a very low level. However, this cooling approach reduces annual electricity production by 7 percent and increases produced electricity costs by roughly 10 percent (IEA 2010). Because China's sunbelt overlaps with its water-scarce region, large water withdrawals and consumption will be a constant challenge for this technology.

Carbon capture and storage (CCS) can cut emissions but at a water cost. CCS is the process by which CO_2 emissions from power plants and other industrial facilities are captured and stored underground. China is considering CCS to reduce carbon emissions in the power sector. In April 2013, the National Development and Reform Commission (NDRC) issued a policy to promote CCS demonstration projects

(NDRC 2013b). At a 90 percent CO_2 capture rate, CCS technology can cut greenhouse gas emissions per MWh by 80–90 percent. Yet, there are other challenges: high costs, a significant decrease in plant efficiency associated with CO_2 separation, as well as increased water supply impacts (Asian Development Bank 2011).

Based on a study by the U.S. National Energy Technology Laboratory (NETL), CCS will increase capital costs of a conventional coal-fired power plant by roughly 90 percent (NETL 2010, NETL 2012). Meanwhile, as the carbon capture process itself requires additional cooling, even for the most efficient ultra-supercritical plant, associated water withdrawal and consumption would increase by about 90 percent. Another concern is that injected CO_2 might affect groundwater quality, releasing toxic inorganic compounds that could jeopardize human health (Newmark 2010).

Therefore, when designing new pulverized coal plants with CCS, water availability should be carefully evaluated. Guidelines and recommendations for the deployment of CCS technologies can be found in *Guidelines for Carbon Dioxide Capture, Transport, and Storage* (WRI 2010).

For thermoelectric power generation technologies, it is important to evaluate both water withdrawal and consumption impacts. Withdrawal and consumption factors vary widely at different plants depending on cooling technologies. In an open-loop cooling system, a large volume of water is used for cooling, and then returned to the environment at a higher temperature. While the level of water consumption is relatively low, the heat added to the recipient water can damage and disrupt aquatic ecosystems. In a closed-loop cooling system, water is recycled through cooling towers, resulting in a much lower withdrawal of water compared with an open-loop system, but higher consumption because of on-site evaporation.

> Power generation has implications for climate and water. Given the size of the power sector and rapid increases in electricity and water demand, it is critical that these considerations are factored into decisions made by the power sector.

Based on our analysis, consumptive water use in an open-loop system is 70–80 percent lower than in a closed-loop system, but water withdrawal in an open-loop system is 30–60 times higher than in a closed-loop one. In China, water withdrawal is particularly critical because tapping a large amount of water could engender competition with other water users, and the discharge of warm cooling water can potentially harm fish and other wildlife.[9] Shifting from outdated open-loop cooling to closed-loop cooling technologies would dramatically reduce power-sector water use and protect China's water resources. Dry cooling, on the other hand, can further improve water efficiency, cutting both water withdrawal and consumption by 70–80 percent. However, this method reduces power plant efficiency and increases greenhouse gas emissions by 3–6 percent compared with a closed-loop system (Wang 2008).

For thermoelectric plants, water efficiency is directly tied to plant thermal efficiency (World Nuclear Association n.d.). More energy efficient forms of coal-based power generation, such as ultra-supercritical and supercritical plants, are also more water efficient than subcritical plants and therefore can help reduce both freshwater withdrawal and consumption.

Water pollution is an important consideration when adding fossil fuel plant generation capacity. Wastewater from coal-based power plants can contain high levels of suspended solids, metals, and organic compounds. The environmental impacts of this waste can be minimized by appropriate treatment. However, treatment systems add costs. With increasingly stringent environmental standards, such added costs can help make wind and solar increasingly attractive environmentally and economically relative to fossil-fuel-based power generation systems. It is also worth considering that among fossil fuel options, both natural gas combined cycle (NGCC) and integrated gasification combined cycle (IGCC) plants generate less water pollution than traditional pulverized-coal plants, reducing the amount of wastewater by 70–90 percent per MWh of power generated.

RECOMMENDATIONS

China has established strict water resource management requirements, setting mandatory limits on water quantity usage, water efficiency, and water quality. These new limits have clearly signaled China's determination to improve the efficiency and sustainability of the country's water resources. Water demand for energy, therefore, should be carefully factored into China's decisionmaking process for power-sector development. While there is no silver bullet to solve the water-climate conundrum, we offer several recommendations to help manage the trade-off in the Chinese power sector:

China should devise concrete policies to regulate water use in the power generation sector by establishing sectoral water withdrawal quotas at the national, regional, and local level. Under current policy, China's State Council only sets provincial water use targets, with provinces then further allocating quotas to municipalities and industrial sectors. In other words, the amount of water allocated to the power generation sector is unknown. Given the sheer size of China's power industry and its high water demand, it would be beneficial to specify sectoral water use quotas, particularly at the regional and local level. Based on water quotas, China's energy planner would then allocate proposed power generation targets for different regions, ensuring that new plants do not exceed their water limit, or cause water competition with municipalities, farmers, herders, and other industries.

China should continue to promote energy efficiency among end users of electricity. Though energy efficiency is generally considered for its cost savings or avoided greenhouse gas emissions, it generates water savings, as well. In addition to energy efficient electric appliances, China should tap broader industrial sectors for even bigger savings. The nation's top energy-intensive industries are also among its most water intensive. In 2010, thermoelectric, iron and steel, chemical, pulp and paper, and textiles accounted for 60 percent of China's total industrial energy consumption and 80 percent of total industrial freshwater withdrawal (NDRC 2013c). Actions to improve energy efficiency in industries would reduce greenhouse gas emissions and conserve water at the same time.

Renewables (excluding hydropower) are the best choice for China's water-scarce areas, while run-of-river hydropower can be further exploited where water is available. China's arid northwest is particularly rich in wind and solar resources. Costs of power generation from these renewable technologies are also decreasing. Recently, the Chinese National Energy Administration announced that the installed price of solar photovoltaics in 2012 declined by 13 percent compared with the 2009–10 period, and the trends will maintain their downward trajectory in the future (NEA 2014). The levelized cost of energy (LCOE) from wind power is expected to decline by 30–40 percent by 2030 (IEA 2012). Policies encouraging investment and technology innovation would help decarbonize China's power sector and free up scarce water resources. As for run-of-river hydropower, roughly 60 percent of China's small hydropower resources have not been developed. This technology can surely play an important role, particularly in rural China (UNIDO and ICSHP 2013).

A shift to closed-loop or dry-cooling systems should be the future for China's thermoelectric power plants. About 80 percent of China's electricity is produced by thermoelectric units, which rely heavily on water for cooling. Shifting from out-dated open-loop cooling to closed-loop cooling technology would reduce water withdrawals by up to 98 percent. Further reduction could be achieved by dry cooling. Our data indicate that for ultra-supercritical coal-fired power plants, the greenhouse gas emissions difference between dry cooling and closed-loop cooling is quite modest (1.6-3 percent higher for dry cooling systems relative to closed-loop cooling systems), and the investment cost differences are also quite small (2–4 percent higher for dry cooling systems relative to closed-loop cooling systems). Therefore, dry cooling is still an attractive option for many Chinese provinces and for other industrial sectors requiring large amounts of cooling water.

Some technologies reduce greenhouse gas emissions but increase water use. When equipped with the same cooling system, nuclear power and CSP require far more water than a coal-based plant. Deploying CCS will likely see a 90 percent increase in water demand. Policymakers should consider water requirements and avoid placing such technologies in water-stressed areas.

APPENDIX 1 METHODOLOGY USED TO QUANTIFY CLIMATE AND WATER IMPLICATIONS OF ENERGY EFFICIENCY MEASURES

Energy efficiency measures can reduce electricity demand and therefore cut greenhouse gas emissions, water withdrawal, water consumption, and wastewater discharge in generating electricity. In this study, we evaluated three energy efficiency applications that the Chinese government implemented during the 11th Five Year Plan period (2006–10). In an effort to curb its increasing energy demand, China has provided subsidies to buyers of energy efficient air conditioners and light bulbs. The government also financed efficiency retrofits for existing residential buildings in China's northern region. Financial input and estimated energy savings are listed in Table A1.1.

To calculate the above energy savings:

$Q_{GHG} = E \times C \times F \times S$

Q_{GHG} – GHG emissions, in kg CO_{2e};

E – Electricity saved by implementing energy efficiency measures, in kWh;

C – Coal consumption required to generate 1 kWh of electricity. In 2010 Chinese coal-fired plant requires 0.335 kg of coal to generate 1 kWh of electricity (China Electricity Council 2010)

F – CO_2 emission factor of coal. 1 kg coal releases 2.5677 kg CO_{2e} (NDRC 2011b);

S – Share of coal-fired power plant in China's total electricity output. 80.8 percent of China's electricity is generated by coal-fired plants (China Electricity Council 2010). To simplify the calculation, greenhouse gas emissions and water use of non-coal-based electricity are not counted.

$Q_{WW} = E \times A \times S$

Q_{WW} – Water withdrawal, in m^3;

E – Electricity saved by implementing energy efficiency measures, in MWh;

A – Withdrawal factor of Chinese coal-fired power plants. In 2010, including cooling water for open-loop units, water withdrawal factor was 15.2 m^3/MWh (China Electricity Council 2010, Ministry of Water Resources 2010);

S – Share of coal-fired power plant in China's total electricity output.

$Q_{WC} = E \times B \times S$

Q_{WC} – Water consumption, in m^3;

E – Electricity saved by implementing energy efficiency measures, in MWh;

B – Consumption factor of Chinese coal-fired power plants. In 2010, water consumption factor was 2.45 m^3/MWh (China Electricity Council 2010);

S – Share of coal-fired power plant in China's total electricity output.

$Q_{WD} = E \times D \times S$

Q_{WD} – Wastewater discharge, in m^3;

E – Electricity saved by implementing energy efficiency measures, in MWh;

D – Wastewater factor of Chinese coal-fired power plants. In 2010, wastewater factor was 0.32 m^3/MWh (China Electricity Council 2010);

S – Share of coal-fired power plant in China's total electricity output.

TABLE A1.1

CHINA'S ENERGY SAVINGS THROUGH GOVERNMENT EFFICIENCY MEASURES, 2006-10

Energy efficient measures	Investment 2006–10 (billion RMB)	Energy savings (million MWh)
Energy efficient lighting	1.207	17.66 (lifespan)
Energy efficient air conditioning	11.54	100 (lifespan)
Energy efficient building	159	333.78 (annual saving, lifespan at 50 years)

Sources: NDRC 2010; NDRC 2011; He 2010

APPENDIX 2 SUMMARY OF DATA SOURCES

The reports and statistics included in this issue brief are summarized in Table A2.1.

TABLE A2.1

SUMMARY OF DATA SOURCES

Topic	References
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APPENDIX 3 GLOSSARY

Capacity factor: A measure of how often an electric generator runs for a specific period of time. It indicates how much electricity a generator actually produces relative to the maximum it could produce at continuous full power operation during the same period.

Carbon dioxide capture and storage (CCS): A process by which carbon dioxide emissions from power plants and other industrial facilities are captured and stored underground.

Closed-loop cooling: Also known as "recirculating cooling," closed-loop cooling withdraws water from a source, circulates it through heat exchangers, cools it, and then re-uses the water in the same process. Recirculating cooling systems may use induced-draft cooling towers, forced-draft cooling towers, cooling ponds, or canals.

Dry cooling: Dry-cooling systems function without allowing water to contact air. Hot condenser water is passed through a liquid-to-air heat exchanger, requiring no water for cooling.

Geothermal: The use of heat generated and stored in the Earth.

Greenhouse gas emissions from hydropower: Greenhouse gas emissions are released from decaying biomass from the landscape flooded when hydro reservoirs are created. The intensity of emissions can vary greatly, depending on site-specific conditions such as topography, the size of the flooded area, the type of ecosystem flooded, and local climatic conditions, among other factors.

Greenhouse gases (GHGs): Greenhouse gases, as defined by the Intergovernmental Panel on Climate Change (IPCC), include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF_6), and nitrogen trifloride (NF_3).

Integrated gasification combined cycle (IGCC): A form of power generation in which hydrocarbons or coal are gasified and the gas is used as a fuel to drive both a gas and a steam turbine.

Levelized cost of energy (LCOE): The LCOE is the total cost of installing and operating a project expressed in dollars per kilowatt-hour of electricity generated by the system over its life.

Life cycle assessment (LCA): A method of quantifying the environmental aspects and potential environmental impacts (e.g., use of natural resources, environmental consequences of pollution) throughout a product's life, from raw material acquisition through production, use, end-of-life treatment recycling, and final disposal.

MWh: Megawatt hour

Natural gas combined cycle (NGCC): A form of natural-gas-fired power plant with gas and steam turbines.

Open-loop cooling: Also known as "once-through cooling," open-loop cooling withdraws water from a source, circulates it through the heat exchangers, and then returns it to a body of water at a higher temperature. The temperature of the water returned depends on whether there are cooling towers, how long the cooling towers hold the water, and the local climatic conditions.

Pounds per square (psi): inch, a unit of pressure or of stress based on avoirdupois units.

Subcritical unit: Pulverized coal unit operated at 550˚C and 22 MPa (1025˚F and 3200 psi). Its overall electrical generation efficiency ranges from 33 to 37 percent (HHV, high heat value).

Supercritical unit: Pulverized coal unit operated at 565˚C and 24 MPa (1050˚F and 3530 psi). Its overall electrical generation efficiency ranges from 37 to 42 percent (HHV, high heat value).

Ultra-supercritical unit: Pulverized-coal unit operated at a temperature higher than 598˚C and pressure higher than 27 MPa (1110˚F and 3916 psi). Its overall electrical generation efficiency ranges from 42 to 45 percent (HHV, high heat value).

Water consumption: The amount of water evaporated, transpired, incorporated into products, or otherwise removed from the immediate water environment.

Water withdrawal: is the water lost to consumption plus any water that was withdrawn but then returned to its source.

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ENDNOTES

1. Industrial value-added includes value added in mining, manufacturing (also reported as a separate subgroup), construction, electricity, water, and gas. China's industrial value-added (percent of GDP) was 47percent in 2010 (http://data.worldbank.org/indicator/NV.IND.TOTL.ZS). Thus, a 30 percent reduction in water-intensity per unit of industrial value-added is equal to an approximately 15 percent reduction in intensity per unit of GDP.

2. In total terms China is not the largest historic greenhouse gas emitter, nor the largest on a per capita basis.

3. According to the China Water Resources Report 2010, available at http://www.mwr.gov.cn/zwzc/hygb/szygb/qgszygb/201204/t20120426_319578.html, industrial water accounts for 24 percent of China's total water withdrawal. The China Electricity Council reports, available at http://www.chinarein.com/ndxx/detail.asp?id=14375, indicated that water used in thermoelectric power plants accounts for about 40 percent of all industrial water withdrawal. Thus, approximately 10 percent of China's water withdrawal goes to the thermoelectric sector.

4. Cradle-to-gate is an assessment of a partial product life cycle from resource extraction to the factory gate (i.e., before electricity is transmitted to the consumer).

5. We assumed the CO_2 capture rate is 90 percent for all CCS-related technologies.

6. By convention, water withdrawal of hydroelectric power plants (dams) is often considered zero (Fthenakis and Kim 2010). Because the water consumption of hydroelectric power plants is not measured in China, we applied the average consumptive factor of U.S. dams in this analysis (NREL 2003).

7. This study did not consider the operating costs of these technologies.

8. According to the Ordos Development and Reform Commission, China Datang Energy Corporation was approved to build the first solar thermoelectric plant in the Ordos desert. See: http://www.ordosfgw.gov.cn/xmdt/xmjz/201109/t20110929_488304.html.

9. According to the North Carolina Division of Water Quality's Annual Report on Fish Kill Events 2010, discharge of hot water from power plants on the Catawba River was linked to mass die-offs of striped bass in 2004, 2005, and 2010.

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