

China's water–energy nexus

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Abstract

As China continues to sustain high rates of economic growth, it is important to better understand patterns of resource use within the Chinese economy and the vulnerability of its growth to resource scarcity. This paper examines relationships between two of China's scarcest resources—energy and water—focusing on the energy implications of water use. Based on an analysis of economy-wide resource flows using China's input-output tables, we draw three overarching conclusions: First, the energy used both directly and indirectly in providing non-agricultural water currently represents only a small fraction of China's total energy consumption. However, this share is set to increase as the country expands its water treatment capacity and hydraulic infrastructure. A lifecycle assessment framework for evaluating these projects would aid policymakers as they choose between more and less energy-intensive modes of water provision. Second, energy-water price interactions are currently of little relevance to policymakers because water prices are low, but the high electricity-intensity of water treatment facilities and their need to recover costs may change this situation. Third, water “migration” from agriculture to non-agricultural uses will have important energy dimensions, which will be important for policymakers to bear in mind as they design water pricing and conservation efforts.

Keywords: China; Energy policy; Input-output analysis; Water policy

1. Introduction

China's recent growth experience has established new standards for economic growth among developing countries. Many low income economies aspire to the Chinese example and, although few are likely to replicate such sustained, rapid expansion, China's precedence for export and resource-intensive growth has given strong impetus to outward-oriented development strategies for industrialization and modernization. Even in China, however, the sustainability of this approach is open to question. Although China has maintained double-digit gross domestic product (GDP) growth over nearly three decades,

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serious constraints on water and energy resources have begun to emerge. A better understanding of these constraints will be essential for China's sustainable growth strategies and for other emerging economies to appraise the relevance of the Chinese example fully.

Water and energy resources are central to concerns over the sustainability of China's economic growth. While both issues have increasingly become prominent in domestic and international policy discourse, much less attention has focused on the water–energy nexus in China. In industrial economies, links between water and energy use are often extensive. For instance, energy is used to move water over distances great and small. Water is an indispensable component of the steam power cycles used in the vast majority of China's power plants. More indirectly, both energy and water are essential inputs in producing steel and cement, which in turn are used in building hydraulic infrastructure.

In this paper, we combine Chinese data on energy and water use with China's national economic input–output tables to examine water–energy linkages across the country's increasingly complex economy. Focusing on the energy implications of water use, we investigate three metrics of China's water–energy nexus: the energy intensity of non-agricultural water provision; energy–water price dynamics for non-agricultural use water; and the energy dimensions of water allocation. Section 2 of the paper provides a general overview of the water–energy nexus in China, focusing on the relationships between energy use and water quantity and quality. Section 3 outlines the methods used in the paper and particularly in analyzing input–output tables. In section 4 we explore the above three metrics in greater detail. A fifth and final section offers concluding remarks.

2. Background: the water–energy nexus in China

Linkages between water and energy use pervade modern economies. Energy is required to move water over distances long and short, to meet the thermal requirements of water users and to improve and maintain water quality. Water is used extensively as a coolant, particularly in power plants and vehicle engines. On a lifecycle basis, the links between water and energy are often complex. For instance, dams and other large-scale hydraulic infrastructure incorporate significant amounts of energy-intensive concrete and steel. Power plants that provide the electricity to operate water treatment facilities similarly require energy embodied in material inputs (e.g. concrete to build cooling towers) that are not captured in the water supply sector's consumption of electricity.

The nexus between water and energy use can be more fully understood in terms of three metrics: physical, monetary and distributive. The first of these relates to energy intensity of water use and, conversely, the water intensity of energy use; the second relates to dynamics interactions between energy and water prices. The third measures the energy implications of water allocation. Water quantity (i.e. intersectoral and interregional allocation) and quality (i.e. treatment) are central to water–energy interactions and the remainder of this section is devoted to an overview of these two issues in China. In this paper our focus is predominantly on the energy implications of water use, rather than vice versa.

Faced with supply constraints, managing energy demand growth has emerged as a key policy goal for China's central government. China's recent energy shortages have been driven largely by economic rather than physical constraints. Rapid economic growth, particularly after China's entry into the World Trade Organization (WTO) in December 2001, contributed to more than 14% annual energy demand growth from 2000–05 (NBS, various years). While China's increasing dependence on imported oil is more widely discussed, the country's abundant coal resources have also been overstretched. Expected

to increase by 220 million tons between 2001–05, with much stronger than expected demand, coal consumption grew instead by 890 million tons during this period (Fang, 2006), pushing up newly liberalized coal prices to more than double 1990 levels (Rosen & Houser, 2007). As a result of domestic supply constraints, China became a net coal importer for the first time in its history in early 2007.

Water scarcity in China, alternatively, has been driven by a combination of both economic and physical scarcity. The country's declining water resource base has been extensively documented elsewhere (Ma, 1999; Economy, 2005; Liu & Diamond, 2005). China's annual water deficit is roughly 40 billion cubic meters (m³) in normal years, about half of its cities are facing some degree of water shortage and the decline in surface and groundwater resources has become an impediment to socio-economic development (NDRC, 2005).

Agriculture remains the dominant water user in China, although its share declined from 88% in 1980 to 65% in 2005 (NDRC, 2005; NBS, 2006). Competition for water among agricultural, industrial and residential users has thus far been tempered by a significant increase in water use productivity in the Chinese economy. As Figure 1 shows, water intensity fell by nearly 50% from 1997–2005, offsetting 2.2% annual growth in non-agricultural water demand over this time period and limiting the decline in agriculture's share of water use to 6 percentage points. However, as China continues its transition from a rural, agriculture-based economy to an urban, industry-based and ultimately service-based economy, intersectoral competition for water will gradually grow. The World Bank (2001) projects that agriculture's share of water use in China will be around 50% of the country's total by 2050.

In addition to intersectoral competition for water resources, China is planning massive inter-basin water transfers that have the potential to create regional water competition. Much of the country's water scarcity is concentrated in the north. Eighty-three percent of China's water resources are located in provinces bordering or south of the Yangtze River, whereas 41% of the country's population, 56% of its cultivated land and 42% of its GDP lie in provinces north of this region (NBS, 2005). Use-availability ratios in the country's northern river basins are distinctly higher than in southern river basins (Table 1).

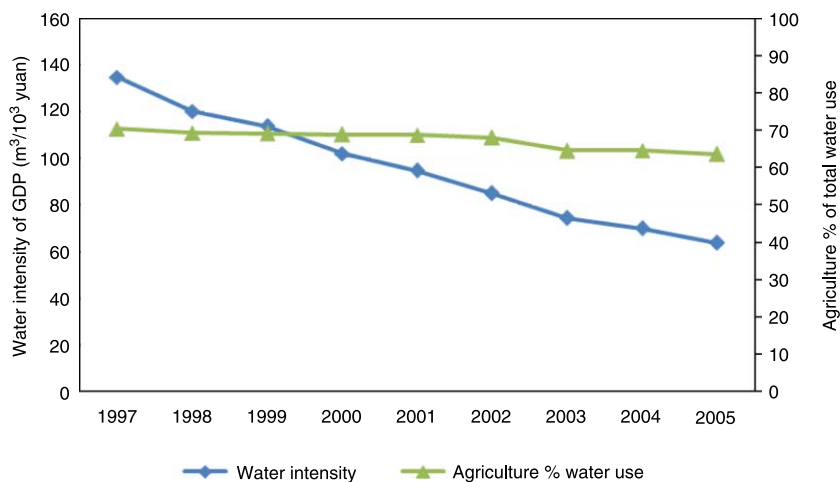


Fig. 1. Water intensity and agriculture's share of water use, 1997–2005, China. Sources: Energy data are from NBS (2006); 2000–2005 water consumption and agricultural water use data are from NBS (2006); 1997–1999 water consumption and agricultural use data are from MWR (various years).

To alleviate regional water scarcity, China's second largest hydraulic engineering project (behind the Three Gorges Dam), the South-North Water Transfer Project, will divert water from the Yangtze River to northern China. By 2050 and at a projected cost of 500 billion yuan (US\$65 billion), the project is expected to transfer 44.8 billion m³ annually, nearly equivalent to the total utilization capacity of the Yellow River (Chen, 2005).

Both at a sectoral and a regional level, water quality poses a constraint for water quantity in China. Roughly one-third of the water in China's monitored rivers has limited or no usability because it does not meet minimum quality standards; in the north this proportion increases to 40–60% (World Bank, 2006a). Indeed, on major rivers water quality is uniformly worse in northern China—and particularly on the Hai and Huai Rivers—than in southern China (World Bank, 2006a). The World Bank estimates the cost of pollution-induced water scarcity to be 1–3% of local GDP in water scarce areas of China (World Bank, 2006b). Water quality is a particularly important constraint on residential water use, as less than half of China's cities have water treatment facilities (MoC, 2005).

Anticipating both quality- and quantity-related pressures on the country's water resources, China's central government set a near-term objective of no growth in agricultural water consumption, negligible growth in industrial consumption and a gradual decrease in total urban per capita water consumption over the term of its 11th Five-Year Plan (2006–2010) (NDRC, 2005). Targets for increasing wastewater treatment are similarly ambitious. In 2007, the Ministry of Construction stipulated that at least 70% of the residential wastewater in towns and cities should be treated by 2010, a significant increase from the 45.7% treated in 2004 (MoC, 2005).

By all three metrics listed above—physical, distributive and monetary—meeting the country's goals for water quantity and quality will have implications for energy use. Increasing collection and treatment rates for wastewater will require higher electricity inputs for the water supply sector and will increase its energy intensity. Hydraulic infrastructure to transfer water over large distances will require significant amounts of concrete and steel, which in turn require large energy inputs and will increase the embodied energy intensity of water provision. Energy price transmission—both directly through electricity prices and indirectly through materials costs—will increase pressure on agricultural, industrial and residential water prices.

Table 1. Water availability and use in China's 10 main river basins and river groupings, 2004.

| River basin (north/south) | Water availability (billion m ³) | Total use (billion m ³) | Use-availability ratio |
|---------------------------|--|-------------------------------------|------------------------|
| Songhua (N) | 118.99 | 36.96 | 0.31 |
| Liao (N) | 41.90 | 18.90 | 0.45 |
| Hai (N) | 29.96 | 37.00 | 1.23 |
| Huang (N) | 62.80 | 37.21 | 0.59 |
| Huai (N) | 75.22 | 55.64 | 0.74 |
| Northwest (N) | 130.04 | 59.97 | 0.46 |
| Yangtze (S) | 873.46 | 181.54 | 0.21 |
| Pearl (S) | 351.29 | 86.23 | 0.25 |
| Southeast (S) | 132.38 | 31.63 | 0.24 |
| Southwest (S) | 596.93 | 9.69 | 0.02 |
| National | 2,412.96 | 554.78 | 0.23 |

Southeast, Southwest and Northwest include smaller river systems in those regions; all data from MWR (2004).

3. Methods: estimating conjoint water and energy requirements

This section provides an overview of three key methodological issues in the analysis: data sources and disaggregation; quantifying embodied water, energy and costs; and direct and indirect water and energy use.

3.1. Data sources and disaggregation

Quantifying water and energy use at a sectoral level, both from an economic (e.g. costs) and a material (e.g. joules or m³) perspective, is an essential component of this analysis. While China's National Bureau of Statistics (NBS) publishes detailed annual data on sectoral physical energy inputs in its *China Statistical Yearbook*, data on sectoral physical water inputs are not publicly available and must be estimated. This subsection discusses both the methods we use for estimation and the data sources on which our estimates are based.

For both water and energy, we use the NBS national economic-input–output (I/O) tables as a distributional structure for converting from monetary to physical flows across economic activities and to some extent vice versa. The NBS publishes national I/O tables every five years (1992, 1997, 2002) and updates these every two to three years based on the underlying structure of the five-year tables. To obtain a sense of both structure and change, we use aggregated, 39-sector versions of the 1997, 2002, and 2004 tables here, referring to the 122-sector version of the 2002 table when this provides insights that the aggregated tables do not.

China's Ministry of Water Resources (MWR) publishes annual physical water use data (in m³), broken down by "Agricultural", "Production", "Consumption" and "Biological protection" uses. More recent data is available in the *China Statistical Yearbook*; pre-2000 data are available in the MWR's *China Water Resources Report* (中国水资源公报) series. Using the I/O tables to disaggregate these three categories by I/O sector is not entirely straightforward because "Water production and supply" in the I/O tables does not include agricultural use water. This is evidenced by the significant discrepancy between the share of physical agricultural water use (65–70%) in the MWR data and the share of agricultural expenditures for water production and supply (just over 1%).

Indeed, it is not entirely clear where agricultural use water is included in the I/O tables. The 122-sector 2002 I/O table contains the sector "water conservancy", but "crop cultivation" comprises only 11% of the economy-wide expenditures for this sector, suggesting either that irrigation prices are orders of magnitude lower than for non-agricultural sectors or that irrigation is located in another sector. For most other purposes (e.g. in the energy tables), the NBS includes agriculture-specific water within a broad definition of agriculture that includes conventional agriculture, forestry, livestock and fisheries. For these reasons, we include agricultural use water in the agricultural sector's own purchases (e.g. the livestock sector's purchases from itself).

The share of irrigation water use within agricultural water use is not available for all years in MWR *Water Resources Reports*. Based on what data is available from 1997–2002, which range from 91–92%, we use an estimate of 92% for all three years that we examine. Shares for livestock and forestry water use are based on their shares of own expenditures. We assume that water use in inland fisheries is negligible relative to the other three categories. In many instances we aggregate the agricultural sector and these assumptions thus do not have a significant bearing on our results.

Converting from I/O table expenditures on energy to physical energy units is more complex because of the many different kinds of energy carriers and double counting issues with primary and secondary energy. For calculating embodied energy, we use primary energy inputs by fuel type (i.e. coal, crude oil, natural gas and hydro, nuclear and wind). These are converted from mass (tons) to energy (MJ) units using the lower heating values in IPCC (2006). In cases where sectoring in the energy input tables is different from the I/O table, we disaggregate based on sectoral primary energy expenditures.

3.2. Quantifying embodied energy, water and costs

As noted above, the primary data source for the results reported in this paper is the NBS national I/O tables and our analysis is based on a structural assessment of these tables. For the sake of brevity, we assume that the reader has a basic familiarity with Leontief methods. The basic approach is based on the commonly used intensity-based approach to input–output analysis¹, where the multiplier matrix imputes a flow of normalized physical quantities across structural chains of intermediate transactions. More formally, this allocation takes the form:

$$\varepsilon = \alpha'(I - A)^{-1} \quad (1)$$

where α is an intensity coefficient (e.g. MJ/unit output for energy), ε is a row vector of embodied intensity with its denominator in units of final demand value, I is the identity matrix and A is the matrix of direct expenditure coefficients. Intuitively, multiplying the transpose of the vector α by the multiplier matrix takes each sector's energy intensity, multiplies it down the column of inputs and then sums the column. The result is an embodied intensity that is essentially a sum of the sectoral intensities of a given sector's inputs scaled by the multiplier distribution.

This approach can also be applied to costs within the transactions matrix. In this case, each entry a_{ij} in the i th row of a given sector is normalized by gross output plus imports. The resulting row vector is multiplied by the multiplier matrix to produce an ε value with units of sectoral costs per unit final demand. Since both quantities share the same units, this measure is technically unit free and can be interpreted as a cost or expenditure elasticity of final demand for a given year. To compare results across years, we deflate all years to 2000 yuan using the IMF's deflator for China.

Total embodied use or cost can be found by multiplying ε by a final demand, or more specifically here household consumption (C), government expenditure (G), capital investment (I) and foreign exports (EX);

$$E(C + G + I + EX) \quad (2)$$

Because we are interested in domestically consumed resources, we remove the energy and water embodied in imports from our embodied energy and water totals. China's published I/O tables are consolidated on the commodity account, and thus both interindustry transactions and final demands include import values. Because the NBS does not publish detailed sectoral data on imports, we assume that imports

¹ See, for example, Hendrickson *et al.* (1998) for the general methodology for environmental flows; see Casler & Wilber (1984) for the energy-specific case.

are homogeneous components of commodities; for example, each agricultural commodity includes 4% imports using this approach. Embodied energy and water in imports can thus be removed by netting out imports from final demand sources and multiplying by embodied coefficients for energy and water.

3.3. *Direct and embodied energy in water use and allocation*

For productive water and energy requirements, we are interested in both direct and total embodied use. Direct use refers to the water or energy directly consumed by a given sector. Embodied use refers to direct use plus the water or energy consumed upstream of a given sector in the production and delivery of intermediate inputs in that sector. For example, direct energy use in the construction sector would include diesel fuel used to operate cranes; embodied energy use in the construction sector would include the energy used to produce steel used in buildings.

For water, direct use is simply equal to the water input into a given sector. For energy, the task is complicated by the distinction between primary energy (e.g. coal) and secondary energy (e.g. electricity). We calculate direct energy use from NBS estimates for total sectoral energy consumption in their energy input tables, which include secondary energy estimates². The NBS data includes conversion efficiencies for non-fossil fuel electricity generation; we do not include these in our primary energy intensity calculations for α values. Although this discrepancy is less than 10% for the economy as a whole, for water production and supply it is somewhat larger because electricity comprises the bulk of energy input into the water production and supply sector. Thus we compare embodied and direct energy calculations with caution.

4. Results: intensity, price dynamics and the energy dimensions of water allocation

In this section we examine three broad trends at the nexus of water and energy use in China: the energy intensity of water provision; the interrelationships between energy and water prices; and the energy implications of water allocation.

We make extensive use of MWR aggregate water consumption data (Table 2) throughout this section and make frequent reference to the MWR water use categories (column headings in Table 2). When we do make reference to these categories, we use capitalization.

4.1. *Energy intensity of water production and supply*

Because of the difficulty of isolating agricultural use water in the NBS I/O tables, the tables do not permit a reasonable estimate of the energy intensity of water use in agriculture. However, the I/O tables do include a “Production and supply of water” sector, which represents water utilities’ production and distribution of water and which we assume includes water in both the MWR’s “Production” and “Consumption” use categories. In reality, only part of the former is provided by water utilities, as industrial users in some cases have their own water supply. We thus assume that these extractions are

² By using NBS secondary energy data we thereby commit to a small discrepancy between our embodied use and direct use calculations.

Table 2. Water consumption by aggregate sector (billion m³), 1997, 2002, 2004, China.

| | Agriculture | Production | Consumption | Biological protection |
|------|-------------|-------------|-------------|-----------------------|
| 1997 | 392.0 (70%) | 112.1 (20%) | 52.2 (9%) | n/a |
| 2002 | 373.6 (68%) | 114.2 (21%) | 61.9 (11%) | n/a |
| 2004 | 358.6 (65%) | 122.9 (22%) | 65.1 (12%) | 8.2 (1%) |

Source: 2002 and 2004 data are from NBS (2006); 1997 data are from MWR (1998).

small, or, in comparing intertemporal intensities, that they comprise a uniform share of total water use. Table 3 examines the energy intensity of water production and supply using three different metrics: direct energy intensity, embodied energy intensity and volumetric energy intensity.

As described in more detail in the methods section, “direct energy consumption” in Table 3 is the energy used directly in the production and supply of water. The direct energy intensity of water production and supply is the amount of energy (primary and secondary) that the sector uses in per unit output. Embodied energy in Table 3 is the energy used throughout the total process of producing and supplying water, which includes, for instance, the energy produced to make concrete for hydraulic infrastructure or plastic for pipes.

Table 3 illustrates two trends in the energy intensity of water production and distribution in China. First, direct energy intensity of sectoral output declined substantially from 1997 to 2004, consistent with declines in the aggregate energy intensity of gross output in the Chinese economy over the same time period. Second, from 2002–2004 the embodied and volumetric energy intensities of water provision increased, driven at least in part by higher per cubic meter electricity inputs. On a lifecycle basis, electricity is the second most energy intensive commodity produced in China, behind coke. As Table 3

Table 3. Energy intensity of water production and supply, 1997, 2002 and 2004, China.

| | 2004 | 2002 | 1997 |
|--|------------------------|------------------------|------------------------|
| <i>Direct energy consumption in water production and supply (WPS)</i> | | | |
| Direct energy intensity of WPS | 2.3 MJ/yuan | 2.8 MJ/yuan | 4.5 MJ/yuan |
| Economy-wide average energy intensity | 1.2 MJ/yuan | 1.2 MJ/yuan | 1.8 MJ/yuan |
| WPS energy consumption as a percentage of total energy consumption | 0.3% | 0.4% | 0.4% |
| <i>Embodied energy consumption in water production and supply (WPS)</i> | | | |
| Embodied energy intensity of WPS | 6.6 MJ/yuan | 5.6 MJ/yuan | 9.5 MJ/yuan |
| Economy-wide average embodied energy intensity of demand | 3.7 MJ/yuan | 3.1 MJ/yuan | 5.0 MJ/yuan |
| WPS induced energy demand as a percentage of total induced energy demand | 0.4% | 0.1% | 0.2% |
| <i>Volumetric energy intensity of water production and supply (WPS)</i> | | | |
| Volumetric direct energy intensity of WPS | 1.0 MJ/m ³ | 0.9 MJ/m ³ | 1.0 MJ/m ³ |
| Volumetric electricity intensity of WPS | 93.1 Wh/m ³ | 79.4 Wh/m ³ | 79.4 Wh/m ³ |

Energy data used in calculating direct energy intensities are from the Production and Supply of Water’s “total energy consumption” column in NBS (1999, 2004, 2006) energy input tables; the denominator in energy intensity calculations is based on Production and Supply of Water output from the I/O tables. To be consistent, “economy-wide average energy intensity” is calculated as the total energy consumption for the entire economy divided by the sum of our sectoral outputs; note that this is not equivalent to energy intensity measured as energy per unit GDP. Embodied energy intensities (ϵ) are calculated using the methods described above; induced energy demands simply ϵ multiplied by total final demand excluding imports. Physical energy intensity is sectoral energy consumption divided by total “Production” and “Consumption” water use from MWR (1998) and NBS (2006).

shows and as documented elsewhere (e.g. Rosen & Houser, 2007), this 2002 upswing in the energy intensity of GDP is consistent with broader trends in the Chinese economy.

Higher volumetric electricity intensity of water provision after 2002 may have been driven by the build out of water treatment facilities to meet rising national standards for water quality. By 2005, China's 661 cities had 708 treatment facilities with a combined capacity of 49.12 million m³/day, a more than doubling of 2000 capacity (MoC, 2005). However, many water treatment facilities are not being used because municipal governments do not have the funds to operate them (MoC, 2005), which means that energy requirements for treatment could increase relatively rapidly. As Figure 2 shows, the electricity intensity of water provision appears to have experienced a stepwise increase from 2003/04.

Both volumetric energy intensity and embodied energy intensity look set to increase. Even with the large expansion in water treatment capacity noted above, more than half of urban residential wastewater in China remained untreated and 297 cities had no treatment facilities by 2004 (MoC, 2005). Without energy efficiency improvements either upstream of or in water treatment facilities, meeting medium-term goals for treatment capacity would result in an increase in the volumetric and embodied energy intensity of both existing and future water supply.

In addition, the need for increasingly energy-intensive and materials-intensive hydraulic projects to alleviate regional water scarcity will raise both the volumetric and embodied energy intensity of water production and supply. The South-North Water Diversion project, for instance, will require massive amounts of concrete to build its three main canals, as well as large quantities of electricity to run the pumps that move water along these canals. The energy and materials requirements of large-scale hydraulic infrastructure are likely to be captured under "construction" in the I/O tables, but are unlikely to show up in the water sector's costs because they are financed by the central government. Adding more detailed lifecycle assessment for these projects regarding the energy requirements for water supply could substantially increase water energy's share of the Chinese economy's total energy consumption. By our estimates, construction sector embodied energy accounted for 25% of China's total domestic energy consumption in 2004.

As it stands, although both the direct and embodied energy intensity of the water supply sector are roughly twice the economy-wide average, the total amount of energy required to supply water—again both directly and on a lifecycle basis³—is less than one half of a percent of China's total energy consumption. Despite 14% growth in its electricity consumption from 2003–2005, the water supply sector accounted for less than 1% of the growth in China's electricity consumption over the same period (NBS, various years; EBCEPY, various years). Including the energy embodied in agricultural use water would only raise this share by at most, and most likely less than, three percentage points (agricultural embodied energy's share of total energy consumption).

4.2. *Energy costs and water prices*

Through its use in powering pumps and running water treatment equipment, electricity represents a significant share of the cost of water provision. At a national level, electricity costs ranged from 33%

³ Note here that the embodied energy share is lower than direct energy share because of the discrepancy in methods between NBS secondary energy calculations and our embodied energy calculations.

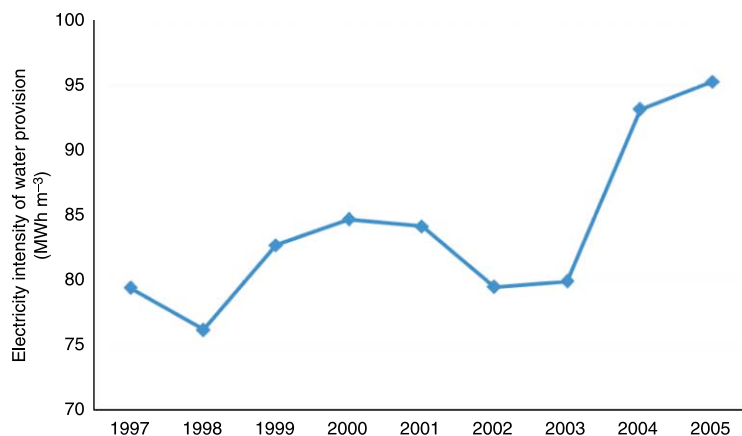


Fig. 2. Electricity intensity of water production and supply, 1997–2005, China. Sources: Electricity data is from NBS (1997–2005) energy input tables; electricity input data for 1998 were not available and we estimated this quantity based on the 1997 ratio of electricity to total energy inputs; 2000–2005 water use data is from NBS (2006); 1997–1999 water use data is from MWR (1997–1999).

(2004) to 39% (1997) of the cost of producing and distributing water in China during the three years we examine. As electricity and energy prices in China rise, attendant pressures on water prices will emerge. Assuming that these costs will be passed on at some level, understanding water use and exposure to water prices by final demand source is important for managing energy–water price dynamics.

Table 4 shows water use in the Chinese economy by final demand source and including different water uses. For instance, in 2004 exports accounted for 20.0 billion m³, or 16%, of the Chinese economy’s induced demand for “Production” water (row 1). When “Consumption” water is added to household use (row 2), exports’ share of total water use falls to 11%. Finally, when agricultural use water is included in embodied water use calculations (row 3), exports’ share of total induced water use further decreases to 9%, reflecting the smaller share of exports vis-à-vis household use of agricultural commodities.

Several characteristics of induced water use shown in Table 4 are noteworthy. Although household consumption of embodied production water accounted for only about one-third of total production water use, when residential and agricultural use water are included households accounted for more than 60% China’s total water consumption in 2004. Investment was the largest source of embodied production water demand, with the construction sector accounting for 57% of investment’s embodied water use and thus 21% of total production water use in 2004. Water embodied in household consumption and

Table 4. Embodied water consumption by final demand sector (billion m³ and percentage total), 2004.

| | HH | GOV | INV | EX | Total |
|--|-------------|------------|-------------|------------|-------|
| Embodied water use (production) | 37.4 (31%) | 18.5 (15%) | 45.5 (37%) | 20.0 (16%) | 121.4 |
| Embodied water use (production) and direct residential use | 102.5 (55%) | 18.5 (10%) | 45.5 (25%) | 20.0 (11%) | 188.0 |
| Embodied water use (production and agriculture) and direct residential use | 342.0 (63%) | 47.3 (9%) | 105.6 (19%) | 50.2 (9%) | 546.6 |

Notes: HH is household consumption; GOV is government expenditure; INV is capital investment; EX is foreign exports. Totals do not match total water consumption because of the small (less than 2%) error in the I/O tables.

investment accounted for a combined 82% of China's total water use (excluding biological protection) in 2004. At less than 10% of the country's total water use, exports are a lesser driver of domestic water use in China.

Because each final demand category faced different water prices, shares of embodied water use do not translate into shares of upstream water costs. Table 5 shows production water cost elasticities of final demand (see Section 3, Methods) for each sector and disaggregates households into rural and urban households. As Table 5 indicates, there is no significant difference between any final demand sectors in terms of the upstream increase in production water costs owing to a unit increase in final demand. In other words, all five sectors had roughly the same cost vulnerability to production water price increases in 2004.

In Table 5 we also include electricity cost elasticities to illustrate two points. First, embodied electricity costs exhibit much more variation between sectors than do embodied water costs. Second, a comparison between water and electricity cost elasticities demonstrates how small embodied water costs are relative to embodied electricity costs. A unit increase in rural household demand causes a 0.07 yuan increase in upstream electricity expenditures, but only a 0.003 yuan increase in upstream water expenditures.

Part of the reason for this order of magnitude difference is that, in all intermediate sectors except water production and supply, direct water expenditure is a tiny fraction (less than 0.3% in 2004) of total, average sectoral inputs. Similarly, for final demand sectors (predominantly rural and urban households) water outlays were less than 1% of total direct expenditures in 2004. For both rural and urban households, induced energy demand from the water production and supply sector was 0.5 and 0.7%, respectively, of total induced energy demand in 2004. For production water, at current levels neither water prices nor energy price transmission to water prices have major implications for final demand sectors at a macro level.

Energy implications of water migration. By two orders of magnitude, agriculture has the lowest output per unit of direct water use of any sector in the Chinese economy aside from water production and supply (Table 6). Allowing water to migrate out of agriculture and into higher value added uses will be a necessary condition for sustaining growth in the Chinese economy.

As Table 6 suggests, there is an energy dimension to this water migration. As water transits from agricultural to non-agricultural uses, it moves to sectors that are either more energy intensive (e.g. chemicals) or have similar energy intensities (e.g. services) *vis-à-vis* agriculture. In Table 6, more energy-intensive sectors have higher sectoral energy–water use (MJ/m^3) ratios (e.g. chemicals). Alternatively, sectors with lower energy–water use ratios all have relatively high embodied water intensities (e.g. services).

Table 5. Water and electricity cost elasticities of final demand, 2004.

| | RurHH | UrbHH | GOV | INV | EX |
|--|-------|-------|------|------|------|
| Water cost elasticity of final demand (basis points) | 0.29 | 0.33 | 0.36 | 0.35 | 0.34 |
| Electricity cost elasticity of final demand (basis points) | 7.02 | 8.87 | 7.27 | 9.08 | 7.10 |

Notes: RurHH is rural household consumption; UrbHH is urban household consumption; GOV is government expenditure; INV is capital investment; EX is foreign exports.

Table 6. Characteristics of water and energy use by sector, 2004.

| | Gross output/direct water use (yuan/m ³) | Embodied energy intensity (MJ/yuan) | Embodied water intensity (m ³ /1,000 yuan) | Energy–water use ratio (MJ/m ³) |
|-----------------------------|--|-------------------------------------|---|---|
| Agriculture | 9 | 1.9 | 356.8 | 5 |
| Mining | 100 | 4.6 | 7.0 | 656 |
| Manufacturing | 508 | 3.0 | 6.7 | 510 |
| Chemicals | 276 | 7.1 | 11.4 | 617 |
| Building materials & metals | 357 | 6.5 | 10.6 | 620 |
| Equipment | 484 | 4.7 | 8.2 | 566 |
| Electronics & instruments | 605 | 4.5 | 9.8 | 456 |
| Electricity & gas | 156 | 18.5 | 12.9 | 1,439 |
| Refining & coking | 399 | 20.1 | 7.2 | 2,816 |
| Water | 12 | 6.6 | 94.6 | 69 |
| Construction | 562 | 4.7 | 8.8 | 538 |
| Transport & telecom | 302 | 3.7 | 8.4 | 439 |
| Trade | 286 | 2.5 | 8.1 | 309 |
| Restaurants | 172 | 2.1 | 9.7 | 214 |
| Services | 252 | 3.0 | 11.2 | 267 |
| Average | 87 | 3.7 | 8.5 | 433 |

Notes: Embodied energy and water intensities are calculated as unit energy or water per unit sectoral GDP.

Although these energy–water use ratios do not necessarily reflect the energy intensity of water use *per se*, they do provide insight into some of the trade-offs facing policymakers in energy–water-related decision making. For instance, while the services industry is the least energy intensive non-agricultural sector in the Chinese economy, its water intensity is on par with the building materials and metals industries. Encouraging sector rotation from industry to services might thus lower the Chinese economy's energy intensity, but at the same time raise its water intensity.

Table 6 also illustrates the merit of a lifecycle perspective for evaluating sector resource use. For instance, whereas the construction sector has the second highest gross output/water use ratio in the table, its embodied water intensity exceeds the economy-wide average and, among industry sectors, construction is China's largest water consumer. Induced demand from the construction sector accounted for 14% of China's total non-agricultural water use in 2004.

A final point to add to this discussion is that neither water migration nor its energy implications is strictly a rural–urban issue. A number of industry types in Table 6, including both the light industry commonly found in township village enterprises (TVEs) and heavy industry, operate in rural areas. From an industry perspective, water reallocation is predominantly a transition from agricultural to non-agricultural water use rather than a rural–urban transition. In reality, a significant share of industry is located in cities. In China's contemporary urban planning regime, both light and heavy industry have clustered in urban areas, a phenomenon that may become less prevalent as China's cities evolve.

In addition, as Figure 3 illustrates, agricultural water's migration to urban residential water use does not imply a transition toward higher energy consumption. Figure 3 shows the water and energy intensities of five rural and seven urban income groups based on NBS classifications. Although NBS data does not provide sufficient information to determine how many individuals are within each grouping, energy–water ratios are relatively constant for rural residents and fall for urban residents as income increases. In other words, as water moves from agriculture into the goods and services consumed by rural

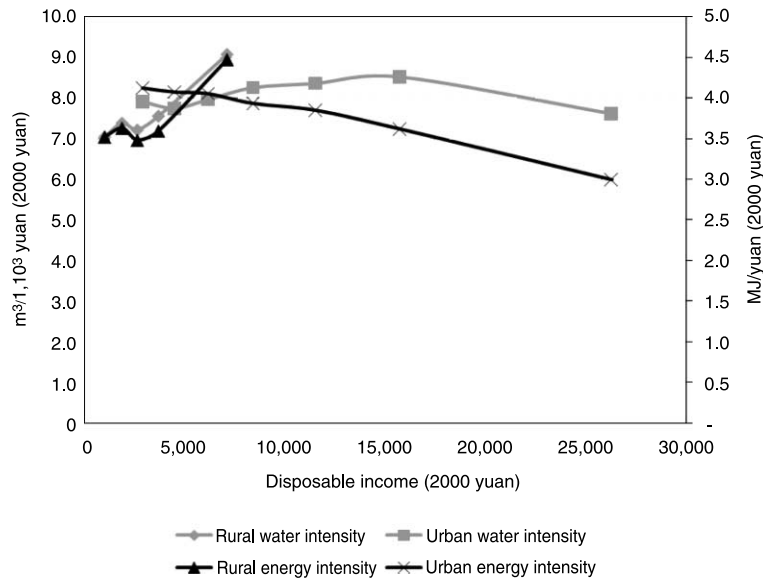


Fig. 3. Rural and urban household embodied water and energy intensity, 2004, China. Sources: Household consumption data are based on 12 NBS household types disaggregated in a social accounting matrix for 2004. For each household type, energy and water consumption are calculated by multiplying commodity consumption by an embodied energy and water coefficient; intensities are then calculated as total embodied energy and water consumption divided by total consumption. The figure above shows these intensities as a function of income level. Disposable income data for each of the 12 household types are from NBS (2006).

and urban households, by moving into urban rather than rural consumption it does not necessarily move into consumption bundles that are more energy intensive.

5. Conclusions

As China continues to sustain high rates of economic growth, it is important for both the country's own policymakers and those in other developing economies to understand better patterns of resource use within the Chinese economy and the vulnerability of its growth to resource scarcity. Over the last decade, energy and water constraints have indeed emerged as important sustainability issues for China's economy and have become the subject of greater scholarly, policy and media attention, both within China and abroad. Much less attention has focused on the linkages between energy and water use in China. This paper attempts to begin to fill that gap from an economy-wide perspective, focusing on the energy implications of water use.

In examining the energy dimensions of water use in China, we take a lifecycle perspective. That is, our primary interest is in water and energy flows throughout the Chinese economy and embodied in the goods and services that make up final demand, rather than simply the water and energy directly used by economic sectors. To capture these linkages we combine and analyze several different data sets, including China's National Bureau of Statistics (NBS) energy input data, Ministry of Water Resources (MWR) water use data and NBS national input–output (I/O) tables. We examine the energy implications

of water use through three metrics: physical (energy intensity), monetary (energy–water price interactions) and distributive (energy implications of water allocation).

Based on this analysis, we draw three overarching conclusions. First, both direct and embodied energy used to supply non-agricultural water account for less than half of 1% of China's total water use. Adding the direct energy to supply agricultural water might increase this by one to two percentage points at most. However, these shares do not include the energy embodied in large-scale hydraulic infrastructure, such as dams that provide irrigation water or conveyance systems that transfer water from water abundant to water scarce regions. Given China's plans for extensive large dam (e.g. the Three Gorges Dam, scheduled for completion in 2009) and massive inter-basin water transfer projects (e.g. the South-North Water Diversion Project), the embodied energy requirements of hydraulic infrastructure at the margin are likely considerable.

While the I/O tables do not facilitate a direct assessment of the energy requirements of large hydraulic infrastructure, it is noteworthy that, despite its low direct energy input, on a lifecycle basis the construction sector accounted for 25% of energy use in the Chinese economy, as well as 14% of its non-agricultural water consumption, in 2004. As managing energy demand becomes an increasingly urgent task for China's policymakers, more detailed lifecycle analysis is needed to evaluate the total energy and water requirements of large-scale hydraulic infrastructure *vis-à-vis* less resource-intensive alternatives.

Second, although energy is a significant share of the cost of non-agricultural water provision, because water prices are comparatively low as a percentage of aggregate sector input, energy–water price interactions are largely shielded from the broader economy. Even as the water supply sector grows more energy intensive through, for instance, requirements for improved water quality, pressure on water prices through energy price increases will be comparatively modest. As we demonstrate, final demand sectors are an order of magnitude more vulnerable to changes in electricity prices than non-agricultural water prices and two orders of magnitude more vulnerable to changes in direct electricity prices than the electricity costs embodied in these water prices. Nor would there be significant variability in the impact of energy price-driven water prices increases among aggregate final demand sectors. Cost vulnerability to non-agricultural water prices and thus the exposure to energy price transmission through water prices, is roughly uniform across sources of final demand. If and when the need for cost recovery for large hydraulic infrastructure and water treatment facilities arises, water prices in China would presumably experience a sustained increase and the energy–water price relationship would become more important at an economy-wide level.

Third, the “migration” of agricultural water from agriculture to other uses has significant implications for aggregate energy and water use. Agriculture has by a significant measure the lowest output–water use ratio in the Chinese economy and allowing water to continue to transit from agriculture to other uses is important for sustaining economic growth. As water migrates from agriculture to higher value added uses, it moves to sectors that are more (e.g. chemicals) or less (e.g. services) energy intensive. While this migration provides a window of opportunity to influence trajectories of resource use through encouraging and discouraging certain sectors, trade-offs between energy and water intensity are part of this process. Services, for instance, are less energy intensive but more water intensive than the equipment manufacturing industry. Using policy instruments to steer water toward less energy-intensive sectors, such as services, could decrease the Chinese economy's energy intensity while increasing its water intensity.

Nor are the energy implications of water allocation neatly divided along rural–urban grounds. Small-scale industry has been a feature of rural China since the 1980s and larger scale industry may increasingly shift to rural areas as China’s cities evolve. From a household consumption standpoint, as water transits from agriculture to rural and urban residential use it does not necessarily move to more energy-intensive consumption in urban *vis-à-vis* rural areas. In short, addressing the energy implications of water allocation requires attention to both rural and urban water and energy use and not simply the interface between them.

Acknowledgements

This report is part of a series of research studies, entitled Research Papers in Energy, Resources and Economic Sustainability, which examine alternative energy pathways for the global economy. This report is part of a series of research studies into alternative energy pathways for the global economy. In addition to disseminating original research findings, these studies are intended to contribute to policy dialogue and public awareness about environment–economy linkages and sustainable growth. All opinions expressed here are those of the authors and should not be attributed to their affiliated institutions.

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