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Water and Energy Nexus in China: Current Situation and Future Perspective in Energy Industry, Water Industry and Agriculture

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Abstract

Water is needed to generate energy. Energy is required to deliver, clean, and evaporate water. There are extensive linkages between water and energy. Meanwhile, both resources may limit the other, especially in the context of urbanization and industrialization as well as climate change. Due to the large population and fast-growing economy, China is one of the most water and energy shortage countries in the world. Relations between water and energy are particularly strained. Unfortunately, up to now, little attention has been paid to the tension relation between water and energy in China. Studying water and energy nexus can provide more information than investigating them separately because of their concomitant relationship. In this paper, we reviewed the recent situations on these issues in China, mainly focused on the following topics: 1) energy consumption in water industry; 2) water consumption and energy nexus in energy industry and urban; 3) water and energy nexus in agriculture; and 4) Energy consumption by evapotranspiration and its cooling effect on reducing urban temperature. Extensive data are analyzed and reported in this study, which will be useful for policy making by taking account of climate change, urbanization, and population growth.

Keywords: Agriculture; Evapotranspiration; Energy industry; Urban; Water and energy; Water industry

Introduction

Water is needed to generate energy. Energy is required to deliver, clean, and evaporate water. Thus, there are extensive linkages between water and energy use [1-3]. Meanwhile, both resources may limit the other, especially in the context of urbanization and industrialization as well as climate change (Stillwell et al., 2011; Qiu and Li, 2013). Unfortunately, up to now, little attention has been paid to the tension between water and energy in academic institutions, governmental agencies, and industries [4,5]. Water and energy nexus is extremely important for sustainable development and adaptation to global climate change.

China is a developing country with annual GDP growth rate around 8% for nearly thirty years and its total nominal GDP has increased up to US$ 8.227 trillion according to the report of the International Monetary Fund in 2013, which is the second largest country in the world. However, China's 2012 nominal GDP per capita was about US$ 6000 and fell behind around ninety countries in the world (National Statistics Bureau, 2013). To some extent, this means that China still has a great potential of economic growth in the future. A great number of water and energy resources are required to support such economic growth in large scale. Further, China has a population of over 1.35 billion and this huge population also makes great demand on water and energy resources.

China's water deficit have risen up to 40 billion m^3 in normal years, and about half of its cities are facing some degree of water shortage [6]. This has led to an economic loss of about US$ 36.5 billion per year in industry and become an impediment to China's socio-economic development. Meanwhile, China has been the second largest consumer of energy in the world and consumed annually around 3.62 billion tons coal equivalent of energy. This has caused a serious imbalance between growing demand and limited domestic supply. About 20.2% of its total energy consumption is imported in 2012 [7]. Therefore, China is confronting with a serious situation of water and energy shortage and this situation is becoming more severe due to large population and fast-growing economy. It is very necessary and urgent for China to realize optimal allocation and efficient use of limited water and energy resources in socio-economic development [2,8,9]. Current national energy policies fail to adequately address water use issues. Similarly, current water policies do not consider the impact of energy consumption and greenhouse gas emissions [10].

Although water and energy resources are well-recognized concerns regarding economic and social development sustainability, little specific research has focused on water and energy nexus in China, especially local data is scarce. The objectives of this study are to review the recent progress on water versus energy in China to summarize and analysis the available data, mainly focused on the following topics: 1) energy consumption in water industry; 2) water consumption in energy industry; 3) water and energy nexus in agriculture; and 4) Evapotranspiration and its cooling effect on reducing temperature.

Material and Methods

To get the most recent progress trend on this issue, we collected and cited the published papers on this topic. In addition, we organized an international workshop in order to explore the nexus between water and energy in April 2012. More than 30 scientists from different countries were invited to this workshop. In addition, the framework of this paper was discussed in this workshop. After then, we collected

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most of the available publications on this theme and reviewed them. The main results are reported in this study.

Results

Energy consumption in water industry

Rayej [11] reported that the water sector is the largest energy user in California. End-users account for most of the water-related energy use (about 73%), rather than water conveyance and transport (about 20%). Hu et al. [12] indicated that the electricity required for water supply, treatment, utilization, and post-use utilization comprised about 5-7% of total electricity consumption in Beijing in 2009. Thus, efficient use of water by end-users is very important for future water and energy conservation.

Future urban water demand will be mainly influenced by population growth, while the agricultural and environmental water demands are mainly affected by climate and weather conditions. Thus, it is important to appropriately allocate water resources for different population and climate conditions. These results can offer much beneficial enlightenment to China.

For example, end-users in urban areas can play a very important role in water and energy saving in China. The water and energy saving can be 10-30% through slightly improving the user's habits and upgrading technology [13,14].

In the water production stage, site specific factors are very important in determining the processes used, and thus the energy consumption in each stage of the water cycle differs by location [15]. The optimization of the water supply system would reduce energy demands and greenhouse gas emissions in the municipal water sector [16].

Yu et al. [17] reported that the average energy consumption of sewage treatment is 0.3 kWh/m^3 in China. By comparing the results with those for Japan (0.45 kWh/m^3) and Iran (0.30 kWh/m^3), we find that the value for China is not high, which is mainly due to the lower treatment level of sewage. China`s energy consumption for sewage treatment will certainly increase with the increment of treatment level. It will be important for China to seek the sewage treatment technologies with high efficiency and low energy consumption. Mo et al. [18] reported that maximizing water reclamation was found to be better than increasing either traditional supplies or seawater desalination in both Tampa Bay and San Diego.

How to effectively use the local water is an important challenge for energy saving. Jiang and Li [19] found that supplemental irrigation using harvested rainwater in the Loess Plateau of China increased crop yield by more than 30% and raised the water use efficiency by 0.7-5.7 kg m^{-3} for spring wheat, corn and flax, and 30-40 kg m^{-3} for vegetables. Moreover, energy consumption per-unit-harvested-rainwater was 25.96 MJ m^{-3}, which was far less (about 42%) than that of the water supply from outside (62.25 MJ m^{-3}) in Baoji city, Shanxi Province of China. This study highlighted the importance and potential of rainwater harvesting and other local water using for water and energy conservation. Vieira et al. [20] indicated that the local characteristics, such as rainwater demand, rainwater harvesting systems (RHS) design, potable water plumbing system design, among other factors that will determine whether or not the environmental and economic performances of RHS are acceptable.

Water resource development should involve not only the optimal allocation and recycling of conventional water resources, such as surface water and groundwater, but also the use of non-conventional water resources, such as brackish water, atmospheric water, sea water and rainwater harvesting. Liu [21] investigated the renewable-energy-driven desalination system developed by the University of Hawaii at Manoa. Test results from a pilot experiment indicated that brackish water consumed significantly less energy to desalinate than the seawater. The system could operate under mild wind speeds of 3 m/s or higher and reduce water salinity (total dissolved solid) from over 3,000 mg/L to 200 mg/L or less. This pilot research indicates that there will be great potential to use the renewable energy (solar energy and wind energy) to clean non-conventional water in the future, including brackish water, seawater, and sewage.

Water and energy nexus in agriculture

The food security will always be one of the major challenges in the long run. Enough water and energy supply is the preconditions for food security. However, global climate change has intensified uneven distribution of water resource in temporal and spatial scales. In addition, population growth and irrigation increase have made water resources even scarce. Thus, it is great urgency to search for technologies or pathways to save water and energy, and promote their efficient use in large-scale agriculture areas. The energy intensities in irrigation also change with the type of crops planted, for example, fruits are more energy intensive than vegetables [15].

Li and Geng [22] reviewed the effects of climate change on water resources and agriculture in China, and investigated some adaptive strategies for water and energy savings, including agricultural water structure optimization, wastewater recycling, and the South-to-North Water Transfer Program. It is concluded that water shortage will become more severe in China's agriculture and more energy will be necessary to overcome this challenge in the future.

Orang et al. [23] used the Cal-SIMETAW model to investigate the potential agricultural water demand and energy use in California. The results showed that California's agriculture used about 20% of the total U.S. agricultural electricity, i.e., about 10,000 gigawatt-hours per year, because of the wide use of pressurized irrigation systems and pumping groundwater. Efficient irrigation water and energy use measures, such as optimum irrigation scheduling, soil water balance method, reduction of unprofitable evapotranspiration, etc., can increase agricultural production and profits-per-unit of water and energy used.

China's arable land area is about 121.7 million hectares, which is about 7.7% of global arable land area. However, relatively old irrigation methods are still widely employed in most part of China, which has caused much unnecessary consumption of water and energy resources. Thus, there is a huge potential of saving water and energy in agriculture in China, by means of improving irrigation technology. Zhang et al. [24] evaluated the water and energy savings of three different irrigation technologies, i.e., improved irrigation management measures (IIMM), low pressure pipeline irrigation (LPPI) and intermittent irrigation (ITI). Compared to traditional irrigation methods, IIMM can save energy by up to 20%. LPPI can save 6.48×10^9 kWh energy per year in 11 surveyed provinces in China and reduce the CO_2 emission by 6.72 metric tons per year. Compared with continuous flooding irrigation, ITI can improve yield and water use efficiency in paddy fields.

Meng et al. [25] illustrated that the surface water shortage could be 5.14% in an Oasis near the Ulan Buh Desert in 2010 and it would keep rising with the increasing population. Since water resource is the key restricting factor for the oasis agriculture, it is essential to develop water conserving agriculture.

For groundwater irrigated agriculture, the situation is more severe. Li et al. [26] found that there has been a severe deficit between water demand and supply for agriculture in Minqin Oasis (located in desert area in northwest China), where irrigation is mainly depended on groundwater. In this area, unit groundwater energy use rose by 76% in 1961-2009 because of a severe decline in groundwater level. In the past ten years, greenhouse gas (GHG) emissions from groundwater pumping accounted for 65-88% of the total emissions from agricultural water. In this area, GHG emissions increased from 0.047 to 0.074 Mt CO_2 (57%) during 2001-2009 due to the increase of diverted water use. In addition, their results also showed that long distance conveyance or high pump lift per unit of diverted water from outside need more energy than per unit of groundwater abstraction. Wang et al. [27] reported that roughly 70% of the irrigated area in northern China is now groundwater-fed. Pumping of water for irrigation is one of the most energy consuming on-farm processes. Groundwater abstraction represents an important source of GHG emissions that has been rapidly increasing and which at present is largely unregulated.

Water and energy nexus in industries

In China, with rapid industrialization, a large amount of water and energy are consumed in industries, including mining, manufacturing, power-generating and waste treatment. Hu et al. [12] found that water used in the energy-related sub-sectors accounted for about one-fourth of the water used in the whole industrial sector and about of 3% of the total fresh water used in Beijing in 2009. To identify and understand the water and energy nexus in industries is crucial for exploring the possible measures for water and energy savings as well as CO_2 emission reduction. Gu et al. [10] reported that energy-saving efforts in industries will result in savings in water consumption. Zhou et al. [16] indicated that four sustainable water management scenarios would bring the cobenefit of reducing the total energy use of the water system by 13.9%, and 77% of the energy savings through indirect water conservation. To promote sustainable water management and reduce greenhouse gas emissions, China would require its water price system, both for freshwater and recycled water, to be reformed.

Lu et al. [28] showed that CO_2 emission reduction, due to the development of hydropower to replace coal, increased rapidly from 1 million tons in 1949 to 502 million tons in 2010, with a total cumulative CO_2 emission reduction of 6221 million tons in China. Feng et al. [29] demonstrated that a shift to low carbon renewable electricity generation technologies, i.e. wind, could potentially save more than 79% of total life-cycle CO_2 emissions and more than 50% water consumption per kWh electricity generation compared to the current fuel mix and technology for electricity generation. If the projected wind farms are built by 2020, Inner Mongolia, one of the water scarce northern provinces, would annually save 179 MT CO_2 (i.e. 44% of Inner Mongolia's total CO2 emissions in 2008) and 418 million m^3 (Mm^3) water (18% of its industrial water use in 2008) compared with the same amount of electricity produced from coal.

Xue et al. [30] found that water consumption per GDP in China's energy industry decreased rapidly in 2001-2010. The total water consumption in energy industry in China almost did not change in 2001-2010. For example, its water consumption was 3.488 billion tons in 2001 and 3.491 billion tons in 2010. However, the water consumption per unit of GDP decreased by 86%, from 13.16 $m^3/10^4$ CNY in 2001 to 1.85 $m^3/10^4$ CNY in 2010, illustrating a significant increase in energy and water use efficiency. Meanwhile, Xue's results showed that the electricity and heat industries consumed the largest volume of water in the six main energy industries in China, but the water consumption proportion decreased gradually from 63.94% in 2001 to 37.13% in 2010. New technologies could be applied to save more freshwater. Wong [31] contributed a suggestion to use seawater for closed system condenser cooling in power plants that are not near the sea or ocean or any large body of freshwater. The open system seawater condenser cooling has been practiced for years throughout the world. This will definitely reduce the demand for freshwater, which could otherwise be used for human consumption or agriculture. The suggestion is also useful for America. In the U.S., thermoelectric power production comprised 41% of total freshwater withdrawals, surpassing even agriculture [32].

Li et al. [26] analyzed the nexus between water and electricity consumptions in Shenzhen city, one of the fastest urbanization megacities in China. Their results illustrated that industry, construction, residential life and services consumed more than 90% of the water and electricity in 2001-2009 in Shenzhen. However, due to the industry transformation toward advanced materials and manufacturing, both water and energy use per GDP decreased gradually. Water use per GDP decreased by 58% (from 61.1 $m^3/10^4$ CNY in 2001 to 25.6 $m^3/10^4$ CNY in 2009) and electricity use per GDP decreased by 20% (from 692.2 kWh/10^4 CNY in 2001 to 556.4 kWh/10^4 CNY in 2009). Because Shenzhen's water and energy use efficiencies are much higher than the nation's average level, its experience could be an excellent model for other parts of the country.

Energy consumption by evapotranspiration and its cooling effects especially in cities

Evapotranspiration (ET) can consume huge amounts of solar energy (latent heat) and result in a significant temperature reduction to the surrounding environment. Actually, ET of vegetation and water bodies can function as a huge air-conditioner, which can mitigate urban heat island and even global temperature.

Qiu et al. [9] estimated that global terrestrial ET can consume 1.480×10^{23} joules of solar energy per year, which is about 21.74 % of total available solar energy and 300 times of annual human energy use (4.935×10^{20} joules). It means that increase in ET has a great potential to reduce urban and global temperatures. Further, Qiu et al. [9] showed that vegetation ET can reduce urban temperatures by 0.5-4.0°C. Green roof can decrease ambient temperature and roof surface temperature by 0.24-4.0°C and 0.8-60.0°C, respectively. The temperature of a water body can be lower than that of the surrounding built environment by 2.0-6.0°C and a water body with a 16 m^2 surface area can cool up to 2826 $m^3$of nearby space by 1°C. Based on these findings, it is concluded that the increase in ET in urban areas can significantly mitigate urban heat island effects.

Zhu and Zhao [33] showed that forest (*Schima superba* plantation) transpiration in wet season (from April to September) could account for about 58.5% of the annual transpiration. Heat energy absorbed by one individual tree transpiration averaged up to 1.4×10^8 kJ per month and the temperature for a 10 m^3 air could be decreased by 4.3°C. Li et al. [26] used the eddy covariance method to explore the characteristics of ET and energy fluxes over a meadow ecosystem (*Kobresia*) in 2002-2005, to understand the water and energy exchange on the Qinghai-Tibetan Plateau. The results showed that the average annual ET was about 390 mm, of which more than 80% occurred in growing season from May to September. The energy consumed on the ET was about 44% of net radiation during the growing season.

Xiong et al. [34] estimated ET and its energy consumption in an arid river catchment (Shiyanghe River catchment) in Northwest China during 2008-2011. Results showed that the annual mean value of ET was 325 mm in oasis and it decreased significantly from oasis toward the desert. The land surface temperature in the oasis was 8°C lower than that in the desert area, which was caused by the difference in ET. In the vegetated oasis area, ET consumed approximately 39% of net radiation on average, whereas that of the barren or sparsely vegetated desert areas only consumed 30% of net radiation in maximum.

Discussion

No matter how the global climate changes, the total amount of global water resource will not change. However, the temporal and spatial distributions of water resources are largely altered along with the climate change. In order to adapt to climate change, we urgently need to develop and use technologies with high water and/or energy efficiencies. Studies on the water and energy nexus can provide important information and point out pathways to achieve this goal. Energy implications of water-use/consumption are significant and should be considered in water strategy [35,36]. Glaciers are shrinking with global warming, which has yielded a simple policy decision. Mass balance considerations provide the answer that the logical solution of the recent accelerated water changing from solid to liquid on mountain tops, requires dams and storage areas (lakes) to prevent all that freshwater from escaping to the lowlands, and ultimately being discharged into the oceans [31]. Stormwater harvesting also has high potential for non-potable uses in new suburbs or developments [37]. Pathogens and trace chemicals need to be managed in stormwater harvested in existing residential areas. Talebpour et al. [38] investigated water and energy nexus of residential rainwater tanks at an end use level in Australia, and found that full flush toilet events had lower energy intensity than half flush events and clothes washer.

Studies on the link between water and energy require interdisciplinary research and comprehensive communication from scientists in environmental science, engineering, ecology, economics and law. It is also need the extensive participation of stakeholders, policymakers and the public. Therefore, fundamental researches on water-energy nexus need to be conducted, especially including water use and energy consumption by agriculture, industry and urban.

Energy consumption in the agricultural sector, which is principally related to irrigation pumping, is generally of lower energy intensity than for the municipal treatment or end use [15]. End use is the most energy intensive stage in the water–energy cycle. In the residential sector, the energy consumption of heating water increases with demand; hot water energy consumption patterns in the residential sector also vary with climate. Human behavior influences energy consumption as well. The greatest potential for energy savings associated with water consumption lie at the end use component of the water life cycle [15]. Therefore, 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. In addition, 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 [2]. A cooperative relationship between water and energy conservation efforts should be an important factor in creating policies that encourage simultaneous savings of both resources [10].

In the same way as energy use and water use amplify each other, also energy and water savings should amplify each other. This idea has been exploited by the methodologies for combined energy and water minimization [39]. The application so far has been mainly within the scope of single processes and only concerning one form of energy — heat in terms of heating or cooling. This observation points to two important new research directions. One is to extend the scope of integration for combined energy and water minimisation from process to site level and maybe supply chains (via virtual water) [40]. A second follow up would be to add power (electricity) into the considerations alongside with water and heat [39]. The recent research by Manenti et al. [41] on fresh water supply via desalination, which demonstrates simultaneous application of renewable resource use (geothermal), process intensification (multi-effect distillation) and heat recovery. Energy recovery from waste and wastewater streams is a good example of combined resource recovery accompanies by waste treatment.

Water saving potential of energy technology development is much larger than that of new energy exploitation [42]. Utilisation of renewables — especially via biofuels, needs a radical reduction of the energy and water footprints —most likely via Process Intensification. This has the chance to make them economically competitive to petroleum products for some locations [39].

The energy–water nexus is a concept reflecting only two of the many dimensions of the performance of industrial processes and regional economies. As indicated in the analysis above, food security is one more such criterion. Another significant aspect of the problem is the environmental performance [39]. Accounting for the energy overhead of virtual water trade and the water footprints of the global energy flows should be investigated.

From the magnitude and complexity of the problems around the energy–water nexus arises also the need for developing an advanced and unified framework for modelling, computation, concept development and decision making. This should be able to quantify and evaluate the effect of various energy and water saving actions as well as assist in assessing proposed solutions for improved supply of other goods and services, especially food [39]. The results interpretation as well as the concept development would depend on the creation of powerful visualizations like the Composite Curves and the tighter integration of modelling code with user-readable documentation [43,44].

At the current pace of growth of food, water, and energy needs, the planet will not be able to provide sufficient resources to meet these demands. There is no one simple solution to resolve these complex issues [45]. When we understand the general connection between water and energy, systematic design and planning in the macro viewpoint will be critical for future optimal allocation and use of limited water and energy resources. For example, tax and subsidy can be employed to encourage the behaviors of institutions, businesses and individuals on water and energy savings as well as research and development for related technologies. Meanwhile, governments, educations, environmental organizations and the mass media should commit to advancing the understanding and attention of society on water and energy savings, by means of law, education, award and guidance.

At present, the lack of good quality data on water and energy nexus also hinders a deeper analysis of the interconnections between the related sectors, which is important for fully addressing the nexus approach. More local data need be further dug and studied. In addition, a lifecycle assessment framework for evaluating water treatment capacity and hydraulic infrastructure projects would aid policymakers as they choose between more and less energy-intensive modes of water provision.

Conclusion

In this study, based on the most recent publications and data mining, we reviewed and summarized the current water and energy nexus in China. The following results are acquired.

Water industry is one of the biggest energy consumption sections in China. There are four ways that can greatly reduce the energy consumption in water industry in China. (1) End-users account for most of the water-related energy use (about 73%), rather than water conveyance and transport (about 20%). End-users in urban areas can play a very important role in water and energy saving through a slightly improving usage habits and upgrading technology. (2) In the coming decades, China's energy consumption for sewage treatment will certainly increase with the increment of treatment level. To seek the sewage treatment measures with high energy efficiency will be crucial for China. (3) Rainwater harvesting and other technologies to use the local water can greatly increase water and energy efficiency and reduce water cost. (4) There will be great potential to use the renewable energy (solar energy and wind energy) to clean water, including brackish water, seawater and sewage.

Pressurized irrigation systems, pumping groundwater, and water distribution consumed most of the energy in agriculture section in China. Due to climate change and over use of groundwater, water shortage will become more severe and more energy will be necessary to overcome this challenge in the future. Efficient irrigation water and energy use technology, such as optimum irrigation scheduling, soil water balance method and reduction of unprofitable evapotranspiration, can increase agricultural production and profits-per-unit of water and energy used.

Due to the industry transformation toward advanced materials and manufacturing, water and energy use per GDP are decreasing rapidly in China. However, the total amount of water and energy consumption is still increase because the rapid increase of industry and population volumes. This is going to be a big challenge for China. More efforts are necessary to identify and understand the water and energy nexus in industries to explore the possible measures for water and energy savings as well as CO_2 emission reduction.

Evapotranspiration of vegetation and water bodies can consume huge amounts of solar energy and result in a significant cooling effect to urban and environment. More researches are necessary to investigate the cooling effect and cooling technology by increasing evapotranspiration.

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