WATER-ENERGY NEXUS IN CHINA AND ITS IMPLICATIONS FOR REGIONAL WATER AND ENERGY SELF-SUFFICIENCY

by

Chu Chu

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LIST OF ABBREVIATIONS

AWT	Advanced Water Technology
DRC	Development and Research Center of China
DRCEP	Department of Resource Conservation and Environmental Protection
EERS	Energy Efficiency Resource Standards
EFW	Energy for Water
ERI	Electric Research Institute
ESCO	Energy Services Companies
ESPC	Energy Savings Performance Contract
FYP	Five-Year Plan
GDP	Gross Domestic Product
GNI	Gross National Income
GNP	Gross National Product
GRP	Gross Regional Product
HVAC	Heating Ventilating and Air Conditioning
IO	Input-Output Analysis
IRP	Integrated Resource Planning
IWHR	Institute of Water Resource and Hydropower Research
LCA	Life-Cycle Assessment
LCI	Life-Cycle Inventory
MEP	Ministry of Environmental Protection
MNRE	Ministry of New and Renewable Energy (India)
MOHURD	Ministry of Housing and Urban-Rural Development
MWR	Ministry of Water Resource
MOF	Ministry of Finance

MOST	Ministry of Science and Technology
NABARD	National Bank for Agriculture and Rural Development (India)
NDRC	National Development Reform Commission
NEA	National Energy Administration
NEC	National Energy Commission
NPC	National People’s Congress of China
PACE	Property Assessment Clean Energy
PAEDP	Pennsylvania Department of Environmental Protection
PPA	Power Purchase Agreement
PV	Photovoltaic
RBC	River Basin Commissions
SERC	State Electricity Regulatory Commissions
SEU	Sustainable Energy Utility
SAWS	San Antonio Water System
SNWTP	South-to-North Water Transfer Project
SOA	State Oceanic Administration
SWRM	Strictest Water Resources Management System
SWRO	Seawater Reverse Osmosis
TDS	Total Dissolved Solids
VW	Virtual Water
WCED	World Commission on Environment and Development
WEN	Water-Energy Nexus
WFE	Water for Energy
WWTP	Wastewater Treatment Plants
YGC	Yunnan-Guizhou-Sichuan Regions

ABSTRACT

China's economic development relies heavily on its water and energy endowment. The country's rapid economic growth in the past decades has caused severe resource shortages and environmental degradations. Additionally, the uneven distribution of water and energy resources at the provincial level further exaggerated the supply-demand conflict. As a response, massive infrastructures were constructed to mitigate the geographical mismatch of water and energy resources. However, the deepened water and energy crises have revealed the incompetence of a 'hard path' in solving these problems. There is an urgent need to search for alternative strategies to achieve long-term water and energy sustainability.

In this study, an emerging tool of the water-energy nexus is adopted to reveal the complex issues underneath China's water and energy systems. If utilized properly, the synergy effect of the water-energy nexus can provide an opportunity to guide China going through this transitional period. Therefore, this dissertation approaches the water and energy challenges in China from the nexus perspective. Using both quantitative and qualitatively analyses, this study explores the nexus-oriented strategy for water and energy management in China.

The results suggest that China's water and energy sectors are highly related and there exist huge regional variances at the provincial level. Moreover, the intensive inter-provincial water and energy transfer is exaggerating the resource

overexploitation and has caused unequal invasion of external resources. Consequently, some provinces are at risk of facing water-related energy problems and energy-induced water shortages simultaneously, while others sacrifice their fragile water systems to bear the burden of the national energy security. Overall, these water-energy trade-offs and inter-provincial interdependence in China call for a shift away from the supply-driven approaches. Alternatively, the government can incorporate the water-energy nexus into policy making to coordinate its water-energy development. For enhanced water-energy compatibilities, efforts should also be made to improve the provincial self-sufficiency through demand-side conservation and supply diversification.

Furthermore, this study encourages policy integration by investigating the institutional capacities. It also identifies the positive or negative synergies existing within the country's future development plans. Based on the policy review, this dissertation gives insight into what strategies the government can adopt to achieve secure and reliable water and energy systems while staying within the local carrying capacity. In addition, this study outlines practical pathways for nexus-oriented management from the perspectives of different stakeholders. Valuable implementation experiences were drawn from five international cases.

Chapter 1

INTRODUCTION

1.1 Research Background

Water and energy resources are both essential for human beings. They are not only indispensable for survival, but also significant for social and economic development. Among all the water on the Earth, only 3.5% is fresh water (Ghassemi & White, 2007), which is unevenly distributed geographically as well as temporally. Both water resources shortage and quality-induced water shortage have intensified the conflicts between water demand and supply. It is widely agreed that the water crisis worldwide will become a major constraint to our future development. Meanwhile, along with the industrialization and the burning of fossil fuel, an energy crisis is emerging as another future challenge for human development. The depletion of fossil fuels, global warming and environmental pollutions all call for an alternative strategy to reshape our energy system. More importantly, these two problems--water and energy crises--are not independent; instead, water and energy security are closely linked together. The fundamental problems in the energy and water sectors cannot be solved in isolation. Therefore, the concept of the 'Water-Energy Nexus' (WEN) has gradually gained significant attention.

In the past two decades, an increasing number of studies have been focusing on exploring the interrelationship between water and energy issues and attempted to search for integrated measures that can solve the two problems together. Both of the water and energy fields, which used to focus on merely their own realms, now begin to pay attention to the interconnectedness of water and energy. For example, the International Energy Agency's report of World Energy Outlook 2012 included a dedicated chapter on water for energy. Meanwhile, the United Nations World Water Assessment Programme specifically chose 'water and energy' as the topic for its World Water Development Report in 2014. It is estimated that global water withdrawals for energy production in 2010 were 583 billion m^3, representing 15% of the world's total water withdrawals (IEA, 2012). The availability of and access to water could become an increasingly serious issue for fuel production and power generation. Conversely, energy consumption for water supply is growing in importance as a criterion for assessing the physical and economic viability of water supply approaches, such as water transfer and seawater desalination. In general, about 8% of power generation is used for water supply and treatment globally (UN Water, 2014). The complex interaction between water and energy sectors requires integrated management.

Now, climate change, coupled with population expansion and economic growth, is forcing us to move towards a more efficient way to utilize our essential natural resources. The huge potential co-benefits of managing water and energy together are waiting to be exploited (ICF International, 2008). Therefore, it is important for countries, particularly those with severe water and/or energy problems, to incorporate the concept of the water-energy nexus into their policies. China is one of these countries that are in desperate need of an alternative development approach that can soften their economic and environmental conflicts. China's industrialization movement has caused severe environmental consequences, social cost, and potential tremendous economic risks in the long run. Understanding its water-energy nexus can offer meaningful implications for addressing its water-energy crises.

1.2 Statement of Problem

Like every nation, China's development is closely linked to its unique water and energy endowment. Thousands of years ago, the once-abundant water resources of the Yellow River had given rise to the nation's invaluable ancient civilization. Today, the affluent and reliable endowment of cheap fossil fuels have transformed China into one of the fastest growing economies in the world. Within a few decades, China has emerged from an agricultural-based civilization into 'The World's Factory'. However, accompanying such aggressive economic development are severe resource depletion and environmental degradation issues. The shortage of water supply and lack of domestic energy production create layers of uncertainties about the country's future development. Equally important, environmental pollution and climate change issues have now become another bottleneck for sustaining the ongoing speed of economic expansion in China. For a country with low per capita resource endowment and a growing thirst for more energy and water inputs, how to handle the dual resource dependency is among the top questions, if it is to achieve long-term sustainability.

Another issue with China's water-energy system that calls for more attention is the strong geographical disparity in distribution and utilization. China's water and energy resources are unevenly distributed, with a water-abundant south and an energy-rich north. On top of that, the country's unequal economic development pattern has exaggerated the spatial conflict between demand and supply. Since the economic reform in 1978, China has adopted a development strategy that favors the coastal region as the 'engine of growth' over the inland (Yang, 1990). While the emphasis on coastal areas has successfully accelerated the industrialization process across the country, such uneven development has also caused an acute spatial mismatch of demand and supply in both water and energy sectors. Large-scale infrastructures, such as the West-to-East Gas Transmission, the West-to-East Power Transmission, and the South-to-North Water Transfer Projects, have been built to channel the resource-scarce and resource-abundant areas in China. But it is unclear what the long-term impacts of these ongoing engineering efforts are and how long they can remain effective.

As the most populous country in the world, how China reacts to its current resource challenges is not only critical to the nation's social and economic development, but will also have strong international impacts. Choices need to be made to balance the trade-offs between resource and development wisely. However, it is unlikely that the current water and energy policy will be sufficient to safeguard a sustainable future. Given all the challenges, there is a need to search for a long-term strategy to achieve water and energy sustainability. The long-ignored water-energy nexus can be used to reveal the complex issues underneath such vulnerable water and energy systems. Understanding the complex and dynamic interlinks between the two systems can help address the existing and upcoming issues using systematic approaches, and manage resources in a sustainable manner. Although previous studies have made great efforts to explore the water-energy nexus in China (Cai, et al., 2014; Hu, et al., 2013; Ding, et al., 2014; Zhang & Anadon, 2013), most of them look at only one side of the problem, water for energy or energy for water. Therefore, there is a need to develop a comprehensive study that emphasizes both sides of the nexus of equal importance.

1.3 Research Objectives & Questions

This dissertation will systematically evaluate China's specific water-energy issues and explore their implications for nexus-oriented resource management. The interconnectedness of water and energy is more of a multi-faceted or 'wicked problem' (Rittel & Webber, 1973), which is difficult to evaluate and lacks a clear optimal solution. Considering the complexity of the water-energy nexus, this study will address these issues in a broad social-economic context of regional development.

The first objective is to build a theoretical foundation for nexus-oriented resource management. Such a foundation can provide an overarching guideline on how to approach issues with water-energy management. By addressing some of the fundamental questions related to the development-environment relationships, this study will explore the role of resource self-sufficiency in achieving strong regional sustainability. It intends to reveal the social impacts and environmental consequences related to domestic resource transfer.

Secondly, this study aims to gain a better understanding on the physical interconnectedness of water and energy in China. Although the nexus approach has attained more popularity recently, there is still limited understanding on their physical interdependency in the context of China, especially at the provincial level. More importantly, there is a lack of coordination between the water and energy sectors. Developing a comprehensive quantitative analysis that highlights equally the bi-direction of water-energy linkages can bridge the two sides of the nexus and, hence, encourage nexus-oriented policy implementation.

The third objective of this study is to provide practical guidance for integrated management and policy implementation. Most current studies on China's water-energy nexus have concentrated on problem identification, while few of them have looked at implementation practices. Therefore, this study intends to fill this knowledge gap and explore the potential of nexus-oriented management in the country.

To meet these objectives, this study will focus on the following research questions:

- What is the role of resource self-sufficiency in achieving long-term sustainability?

- What is the implication of the water-energy nexus for regional resource management?

- What is the current status of the water-energy nexus in China and the future challenges and opportunities?

- What are the social and environmental impacts of domestic water and energy transfer in China?

- How can nexus-oriented management help mitigate the dual pressure of the water-energy crises in China?

1.4 Research Design and Methodology

1.4.1 Conceptual Framework

In order to understand this complex issue of the water-energy nexus in China, both qualitative and quantitative methods will be used. The study consists of three components, the review of supporting theories, the quantification of the water-energy nexus in China, including Water for Energy (WFE) and Energy for Water (EFW), and the analysis of nexus-oriented resource management (see Figure 1.1).

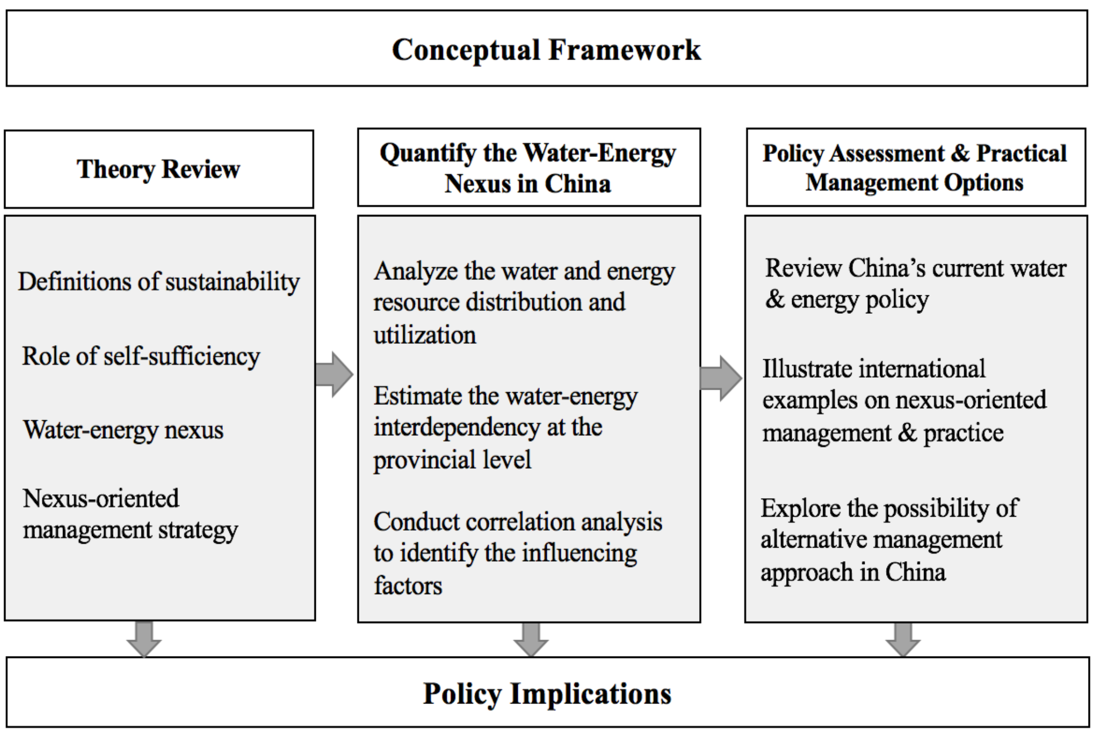

Figure 1.1 Overview of Conceptual Framework

The first task is to review the related concepts involved with this topic, including the critiques on sustainability and contemporary regional development, as well as the concept of the water-energy nexus. This part forms the theoretical foundation of this entire study. First of all, based on the critiques of the classic definition of sustainable development, the study will summarize the key features of strong sustainability and its implications for balancing the relationship between environment and development. Then, under the guidance of strong sustainability, the predominant regional development paradigm will be reviewed to address the role of regional self-sufficiency. Meanwhile, the idea of the water-energy nexus will be introduced, along with its main features and common implications. Based on this theoretical support, this study will discuss the nexus-oriented development strategy for building up local resiliency.

The second component aims to quantify the physical connections between water and energy sectors in China at the national and provincial levels. A three-step quantification analysis will be conducted. It will start with an investigation of China's energy and water supply systems. A combination of several indicators will be used to measure the availability of resource endowment and utilization level in each province, including per capita value, self-sufficiency level, total endowment, etc. During this process, the source of energy and water supply will be divided into two portions, local production and inter-provincial import/export. Second, this study will estimate the water consumption for energy production (virtual water) and energy consumption for water supply (embodied energy). This part will not only demonstrate the water-energy interconnectedness at the provincial level, but also reveal the cross-boundary virtual water and energy flow. Particular focus will be placed on the regional self-sufficiency in terms of both direct water/energy transfer and virtual resource exchange. The third step is to identify the influencing factors of the nexus using correlation analysis. It is believed that social-economic indicators in a particular context can act as key factors that determine the characteristic and magnitude of the water-energy nexus in that area. Therefore, a list of potential drivers will be collected based on literature review and their relationship with nexus-related stress will be examined.

The third part of this study intends to explore the possibility of integrated policy formation in China to improve regional self-sufficiency and capture representative examples of nexus-oriented management approaches worldwide. To achieve this goal, China's past and ongoing water and energy policies and management will be reviewed as essential background information. After China's policy review, attentions will be drawn towards the international examples on nexus-oriented management. Leading countries in the field of the water-energy nexus, like the U.S., are making efforts to apply the nexus-oriented management in practice. This study attempts to create an inventory of innovative integration approaches and successful local initiatives to build a portfolio of various pathways based on previous efforts in different countries. After that, this study will then identify valuable experiences that are applicable to China's case.

Based on the findings of these three components, policy recommendations on integrated water-energy management for China with a focus on regional self-sufficiency will be discussed.

1.4.2 Analysis Unit and Scope

Various water and energy challenges in different provinces require a closer look at their unique situations. Thus, this study will focus on provinces as the primary analysis unit when investigating the quantitative interrelationship between the water and energy sector in China. Also, the national level analysis will also be included in order to address the questions at a higher level.

Figure 1.2 Map of Chinese Provinces

The analysis will cover twenty-two provinces, five autonomous regions, and four direct-controlled municipalities in China[1] as shown in Figure 1.2. Although

[1] Autonomous regions and municipalities directly under the central government have the same rank as provinces and are regarded as the first tier of administrative division of China. The two special administrative regions, Hong Kong and Macau, and the disputed province of Taiwan will not be included in the analysis.

direct-controlled municipalities are small in area, they usually have a comparable population or economic output. For the sake of simplicity, the three types of administration will all be referred to as 'province' as an aggregation in the discussions. Figure 1.2 also grouped all the provinces into the seven major geographical regions, North, Northeast, East, Central, South, Southwest, and Northwest. The seven divisions are commonly used in China. This study will use such subdivision in some narratives in order to help demonstrate the location of the provinces and depict the geographical trend.

1.4.3 Selection of Quantification Methods

There are two types of commonly-used methods to quantify the magnitude of the water-energy nexus, the bottom-up approach and the top-down approach. The bottom-up approach calculates the water for energy (WFE) or energy for water (EFW) from a production perspective (Okadera, et al., 2015). Take the WFE as an example. The bottom-up approach estimates the mass water use for energy by multiplying energy production by water intensity factors (Okadera, et al., 2015). Typically, the water intensity factors are derived from related empirical data during the energy production process. Therefore, the bottom-up approach can measure the magnitude of the nexus during each stage of the energy supply chain and also be location specific.

Conversely, the top-down approach estimates the WEN from the consumption perspective (Okadera, et al., 2015). Studies following the top-down approach usually employ the input-output analysis (I/O) or a hybrid method with a combination of life-cycle assessment (LCA) and input-output analysis at the national level. The water or energy intensity in the top-down approach considers both the direct consumption (e.g., cooling water for electricity generation) as well as indirect or upstream and downstream consumption (e.g., water used to build the power plant, irrigation water for bio-energy) (Li, et al., 2015; Feng, et al., 2014).

Each method has its own merits and both are widely adopted in previous studies. The bottom-up approach can be applied to a broad range of geographical scope, from the national and regional level to provincial and city level, while the top-down analysis mostly focuses on the national level analysis, using a national input/output table. Furthermore, the bottom-up approach considers the direct water consumption for energy production or direct energy input for water production, while the latter takes into account both direct and indirect linkages during the entire life-cycle (e.g., water need for power plant construction).

For the purpose of this study, the bottom up approach serves as a better tool as it is more flexible to measure the nexus at both the provincial and national level. In addition, it is capable of reflecting the linkages in each stage of energy or water supply (e.g., water for fuel mining or power plant cooling, and energy for water pumping, distribution, treatment, etc.).

1.5 Chapter Outline

This dissertation contains seven chapters.

Chapter 1 introduces an overview of the research. It begins with the research background, the statement of the problem, research objectives and questions. This chapter also presents a conceptual framework consisting of three components.

Additionally, this chapter summaries the analytical design, research units, and quantification methods adopted by the study.

Chapter 2 builds the theoretical foundation of this work. It reviews literature on sustainability, examines the weaknesses of contemporary development, and addresses the role of regional self-sufficiency. The chapter also provides an in-depth literature review on the water-energy nexus, introducing its concept and key features, as well as the importance of regional context in studying the water-energy nexus. This chapter concludes with a discussion on the nexus-oriented resource management strategy by addressing the importance of integrated water-energy management in achieving regional sustainability.

Chapter 3 provides a comprehensive review of the water and energy supply systems in China. Utilizing the latest national statistical data, this chapter examines the features of water and energy supply systems at the national and provincial levels. In addition to the conventional infrastructure, this chapter also identifies the magnitude of inter-provincial water and energy transfer. It concludes with a narrative regarding the challenges of China's water-energy system from a cross-sectoral perspective.

Chapter 4 presents the methodology and results of the quantification of water-energy interdependence in China. It outlines the bottom-up estimation method using intensity factors and explains data collection and assumptions. As part of the quantitative analysis, this chapter aggregates the China-specific intensity factors of water-for-energy and energy-for-water from literature. The results suggest that China's water and energy sectors are highly related and there exist huge regional variances at the provincial levels. The correlation analysis in this chapter also reveals the key influencing factors causing such variances.

Chapter 5 examines the current and future water and energy strategy in China from the nexus perspective. It starts with the investigation of the institutional capacity to integrate the water-energy nexus into policy making. It also examines the national development goals for water and energy by 2020 to identify where positive synergies or negative incentives may exist. This chapter further elaborates several controversial policies that could weaken China's water and energy security. This policy analysis gives insight into what strategies the government can employ to achieve secure and reliable water and energy systems while staying within local carrying capacity.

Chapter 6 outlines the practical pathways to integrate the nexus-oriented management. First, it lists the representative options that can be adopted by different stakeholders, including the end-users, water industry and energy industry. Further, it identifies five international cases that can offer valuable experience on China's policy integration and local initiatives.

Chapter 7, the last chapter, summarizes the findings of this research and offers recommendations to enhance sustainable management of energy and water resources in China. This chapter closes by proposing directions for future research.

Chapter 2

THEORY REVIEW

2.1 Sustainability and Regional Self-sufficiency

2.1.1 Definitions of Sustainability

While the idea of sustainability has gained universal acceptable, the answer to what is sustainability remains debatable. Theories of sustainability have been evolving since its formation in the 1970s (Roosa, 2010). It is generally agreed that sustainability is a vague concept (Bartelmus, 1994); the interpretation of it varies among different scholars in various disciplines. One of the most influencing definitions of sustainability is the concept of *Sustainable Development* presented by the World Commission on Environment and Development (WCED) in the Brundtland report of *Our Common Future* as 'development which meets the needs of the present without compromising the ability of future generations to meet their own needs' (WCED, 1987). This definition, for the first time, acknowledges the significant role of environment in social progress. It conceptualized the interlinks between environmental crisis, development crisis, and energy crisis (WCED, 1987). It also noted that today's human interventions on natural systems during the course of development are on a huge scale and 'more threatening to life-support systems both locally and globally' (WCED, 1987).

Although the WCED's concept of sustainable development has gained broad acceptance, the discussions on what is real sustainability continued. Costanza, et al (2015) believe that the sustainable development concept defined by WCED fails to address one of the key necessary conditions for sustainability—that is the transition from economic growth to qualitative development. The WCED report in general supports the rapid economic expansion as a solution to address poverty, which could eventually benefit all (Hopwood, et al., 2005). However, it ignores that our earth ecosystem is finite, and it is impossible to support an unlimited growth with more use of natural resources. The faith of 'a new era of economic growth' envisioned up by the Brundtland report seems untenable.

Acknowledging the limitations of the mainstream definition of sustainability, other scholars have conceived alternative interpretations with stricter constraints. Daly (1990) presents a limited growth theory, in which he posits that 'sustainable development must be development without growth—but with population control and wealth redistribution—if it is to be a serious attack on poverty' (Daly, 1990). It distinguishes development from growth, where 'growth' refers to increase naturally in size by the addition of material through assimilation or accretion, while development means 'to expand or realize the potentialities of; to bring gradually to a fuller, greater, or better state' (Daly, 1990). Some other economists, like Neumanyer (2013), prefer to draw the line between weak and strong sustainability by defining whether natural capital is substitutable. Strong sustainability advocates argue that physical stocks of certain natural capital cannot be substituted by persevering them in monetary value terms.

Other scholars have further developed the concept of strong sustainability. Williams & Millington (2004) state that strong sustainability calls for the establishment of 'a social and economic system that is less destructive towards nature'. To reach a sustainable future, we need to change our current demands made on Earth, and switch towards 'a small-scale decentralized way of life based upon greater self-reliance' (Williams & Millington, 2004). In other words, the scale of growth needs to be consistent with the regenerative and self-repairing capacities of life-support systems.

Overall, sustainability is 'by nature complex, trans-disciplinary, and multidimensional' (Stead & Stead, 2009). Its definition is expected to stay 'fuzzy, elusive, contestable and/or ideologically controversial' (Gladwin, et al. 1995). Acknowledging this important point, it is not the purpose of this study to redefine sustainability. Instead, this section will summarize some of commonly agreed features/criteria of sustainability as related to resource management and regional development.

- Develop within the physical limits

The most straightforward condition of being sustainable is to develop within the physical limits of the ecosystem. These limits are often described as two forms, the *sources* and the *sinks*. On one hand, the natural resources that Earth can offer are finite. On the other hand, the capacities of the world to absorb the emissions during the resource extraction and consumption are also limited. A delay in response to keep the system within its limits would eventually lead to a collapse or an 'overshot' as described by Meadows et al. (2004). However, historical evidence suggests that our exponential growth in population, food production, industrial activities, resources consumption, and pollution are reaching the limits of the sources and sinks (Meadows, et al., 2004). Moreover, they are growing at a speeding rate. Such physical expansion can be controlled by switching from quantitative growth to qualitative improvement. The qualitative improvement here 'does not mean having to be deprived of modern amenities, but it does mean taking firm steps in the right direction' (Slesser & King, 2002). By adopting the appropriate technology and lifestyle, a decent standard of living for all population can be achieved without a high rate of resource consumption (Meadows, et al., 2004).

- Reconnect with nature

Another focal point of the sustainability debate is the human-centered verse the nature-centered paradigms. In the human-centered paradigm, environmental resources are viewed as economic assets to human development. Nature only has value if it directly benefits humans. On the contrary, the nature-centered view values the nature by itself. It acknowledges the fact that human being is merely one element of nature, rather than the ruler of it. Therefore, instead of building engineering project to change the nature, it advises us to adapt to nature. Advocates of strong sustainability request to shift away from current human-centered or anthropocentric paradigm (Litman, 1999). Nature-centered approaches seek to prevent the overconsumption of natural resources or use any technological or economic solutions to replace the stock of natural resources (Haughton, 1999). The nature-centered mindset recommends reconnecting the nature and society, and switch to less aggressive, more flexible and adaptive long-term solutions.

- Environmental Equity

Environmental equity, including intergeneration equity and intra-generation equity, forms a center pillar for all definitions of sustainability. The intergeneration equity is the most widely recognized element of sustainability since the Brundtland summit (Haughton, 1999). It suggests leaving the future generation a better environment, while meeting the needs of the present generation. The intra-generation equity, on the other hand, emphasizes the fair distribution of resources and the equal responsibility of pollution among the contemporary generation. This dimension implies a less frequently mentioned concept of 'geographical equity' (Haughton, 1999), which, for instance, requires the outside polluters to take responsibility of what they caused to the polluted area. Although monetary payment has been used in many cases to compensate victims from the geographical injustice, it is far from enough to recover the loss or damage of natural resources (the loss of biodiversity, etc.) (Ekins, et al., 2003). Therefore, it is necessary to address environmental inequity from its very root to avoid any irreversible social and environmental consequences.

- Robust and resilient system

Sustainability connotes resilient socioeconomic and environmental systems that are capable of self-supporting and self-renewal. To fulfill this goal, we need to embrace a core idea of diversity. The greater the diversity, the better the chance the system could adapt to changing conditions and survive any external impact. The concept of diversity here encompasses not only biodiversity, but also biocultural diversity. There is an ‘inextricable link’ between ecosystem, culture, and other human surroundings (Cocks, 2006). Solutions to environmental problems reside in the dynamic interactions among traditional knowledge, biological diversity, distinct local heritage and economic conditions (Johns & Sthapit, 2004; Cocks, 2006). The focus on diversity gives particular attention to indigenous people, who value the local knowledge, care about local vulnerability, and can contribute to diversity and conservation.

2.1.2 Critiques of Contemporary Regional Development

Using the sustainability criteria above as benchmark, we will now evaluate our contemporary regional development and see how the current system performed. Before addressing that, it is important to readdress one question first—that is what is development. In the simplest form, ‘development means making a better life for everyone’ (Peet & Hartwick, 2009). It refers to ‘improvement in a complex of linked natural, economic, social, cultural, and political conditions’ (Peet & Hartwick, 2009). However, in our contemporary world, regional development is often measured using merely economic indicators (Stimson, et al., 2009). Almost in everywhere, mainstream media or political talks, we can see the level of development being viewed as equivalent to the size of the economy. It is shocking to see how the world is divided into two parts, the developed and developing countries (also known as the global north and the global south), based only on their economic performance, such as gross national income (GNI) and gross national product (GNP).

Such economic dominated development strategy, therefore, embraces a universal recipe built around the discourse of economic competitiveness, trade, the division of labor (Admin, 1999). From this perspective, spatial interactions are defined by the flow of goods, services, and people, reflecting ***comparative advantages and disadvantages*** between regions (Stimson, et al., 2009). Within this paradigm, active trade between areas with different costs and resource endowments is formed to receive optimal efficiency in resource utilization. A region with a comparative advantage in certain aspect is encouraged to utilize and expand this advantage and convert it into economic competitiveness through higher productivity performance or the attraction of new firms and labor (Bristow, 2010).

Such strategy has historically helped some countries, mostly Western countries, to fight poverty, improve life qualify, or speed up their industrial progress. However, this kind of success only took place under certain circumstances. Specifically, the modernization of the West relied heavily on capitalist exploitation, which allowed these countries to accumulate huge economic surpluses in an international trading system that underpriced primary products from colonies. Such a development path has created 'a powerful center and a dependent periphery' (Peet & Hartwick, 2009). Thus, it is quite questionable that whether such a model can be sustained or whether it is possible for the rest of the world to copy such success. In fact, from the environmental perspective, history has already shown the limitations of the contemporary development strategy.

The first undeniable fact is that our current path is environmentally aggressive. Almost thirty years after the publication of the Brundtland report, the current development pattern is still dominated by the overexploitation of resources. Although it is hard to assess precisely how many species have gone extinct, it is evident that human activities are causing an exceptionally rapid loss of biodiversity (Ceballos, et al., 2015). Dramatic extinction of species and the subsequent loss of ecosystem services lead to permanent impacts on human beings. A comparison of 30-year data (from 1970-2000) suggests that ecological footprint of humanity has already surpassed the carrying capacity of the Earth (Meadows, et al., 2004). On top of that, there is still a large number of population struggling desperately with meeting their basic needs, which means the total consumption will keep growing at a faster rate if we continue the business-as-usual.

Furthermore, the contemporary development strategy has led to a vulnerable environmental system that is unable to adjust quickly to external changes. The blind pursuit of economic growth has led to the ignorance of local history, culture, and natural endowment, isolating human beings themselves from their surroundings. The nature of the ecosystem in many places has been disrupted and manipulated to serve for human needs. Expansion of cities with impermeable cover interrupted the natural water cycle, bringing more frequent drought or flooding. Traditional farming with minimal carbon emission was replaced by petroleum-based agriculture to speed up the production. Toxic or non-toxic chemicals are constantly emitted to the air and water at a rate beyond nature’s absorption capacity. Our system is already having trouble dealing with the existing problems, not to mention the arrival of climate change as the most devastating threat to human survival.

However, in many cases, such environmental sacrifice failed to bring economic growth or social improvement. Quite the contrary, this ‘universal recipe’ has proved to be the cause of distributive inequity of wealth and resources within and between countries (Stead & Stead, 2009). Under the current system, it is economically rational for the cash-rich industrial regions to purchase their natural resources from the cash-poor developing regions (Stead & Stead, 2009). It also makes sense for the wealthy countries to move their heavy-polluted industries into the ‘third world’ nations, where all kinds of economic driving force were welcomed. As a result, a new form of a colony was created. In developing regions or any victim of this new colony, resources are depleting at an unsustainable rate. Such colony also pervades within a country, where urban-rural division signals the existence of uneven allocation of resources.

Although the resource-supplying regions often get paid or compensated, the money seldom contributes much to the social welfare of local citizens. Instead, most of those profits are often possessed by a few investors, while the whole local population bears the burden of environmental cost. The past failure of many African economies has obviously denied the applicability of the so-called universal recipe (Rihani, 2003). Even the fast-growing developing countries, like China, India, and Brazil, are experiencing significant inequity in wealth distribution. Resources, such as education, economic wealth, opportunities, health care, concentrate disproportionality in only big cities. Even the economic beneficiaries of such development pattern are also facing challenges. Many cities were often developed through the expansion of one or two strong industries. This industrial specialization could have stuck a region into a lock-in and prevent it from reactively adapting to economic and environmental changes. It poses an ominous threat to communities, as it affects the stability of the local jobs, destructs the continuation of local culture, and undermines the resilience of local capacity (Shuman, 1998).

Recent development effort not only failed to change the status of many regions or the welfare of local people, but also led to huge negative environmental impacts. It is clear that the current development strategy goes against the criteria of sustainability. Although most studies on sustainability tend to present a grave case full of challenges, they generally hold a more optimistic attitude towards the possibility of a sustainable future. Most of them intend to stress the importance of proactive actions and fundamental changes in a timely manner to avoid the final catastrophic consequences. However, the remaining question is what should be happening or what a wise policy is. The challenge is how to apply the sustainability thinking into the real world. The author believes that the regional self-sufficiency could offer some easement in this complex adaptive process.

2.1.3 Role of Regional Self-sufficiency for Long Term Sustainability

Self-sufficiency refers to the idea that a place can survive and thrive relying for the most part on its own resources (Sundkvist, et al., 1999). A self-sufficient nation emphasizes the fewer consumption of external resources and better use of local ones so that it can be less vulnerable to external fluctuations, e.g., variations in climate and changes in national and global economies. Many studies have reiterated the role of the ability to adapt, self-resilience and self-sufficiency in promoting regional sustainability (Admin, 1999; Sundkvist, et al., 1999; Keynes, 1933). From a comprehensive perspective, self-sufficiency can support long-term sustainability, and also benefit the society as a whole (Keynes, 1933). The total economy of a region can be made more stable with increased independence as its supply lines are shorter (Daly & Cobb, 1994). However, it is necessary to note that while self-sufficiency here highlights the reliance on indigenous resources, it does not mean to build tight walls around all units. Instead, it encourages the communication between regions and engagement with the wider world information sharing (Bristow, 2010).

To be more specific, several issues with contemporary development can be mitigated by maintaining a higher level of regional self-sufficiency. First, self-sufficiency can help control the resource depletion and mitigate environmental injustice. It encourages a lifestyle of qualitative improvement that goes within the local physical limits. In addition, greater self-reliance softens the influence of exogenous factors, such as trade and capital mobility on a region's economic performance (Stimson, et al., 2009). It encourages the fair distribution of resources by building a healthy local economy that does not depend on the net import of ecological capacity (Wackernagel & Silverstein, 2000). Local or regional self-sufficient system can also secure economic sustainability by reducing the negative externality of long-distance trade (Curtis, 2003).

Another contribution of self-sufficient to environmental sustainability is to promote local empowerment through the creation of the local and self-reliant system. Self-sufficient system values the social and cultural treasures in different areas. It promotes the local scale of economy, which is compatible with the local ecosystem.

In such system, individual decisions are made based on the local context of distinct communities that understand the vital significance of the local culture, ecosystem, air, water and other elements. A self-sufficient system also highlights the value of decentralization and diversification. To maintain a system that is independent of external resources, it must consist of diversified sources widely distributed across the region.

As a matter of fact, self-sufficiency has often been adopted as a national goal as it is linked to national security. Take the energy self-sufficiency as an example. It has been regarded as a key quality of national security. Especially after the oil crisis in the 1970s, achieving energy independence has been one of the primary goals of energy development (Auer, 1976). However, although energy self-sufficiency at the national level has been discussed in most policy or literature (Hauber & Ruppert-Winkel, 2012; Spero, 1973), regional or local level self-reliance is usually neglected, as it does not threaten national security.

Daly & Cobb (1994) argue that the aim at self-sufficiency should not be ignored at lower levels, especially for countries with various geographical features, like U.S. and China. On the one hand, if a region's economy depends on resources outside it, even the external resources are located within the same nation, it is difficult for it to maintain its internal economic stability, making the region vulnerable to external potential risks (Daly & Cobb, 1994). It also forms some extent of a colony and can often lead to overexploitation of resources (Daly & Cobb, 1994). On the other hand, regional economic interdependence can also give rise to intensive domestic export and import activities that involve long-distance transportation of resources, aggravating the environmental impacts of the entire utilization process. Therefore, it is necessary to address self-sufficiency issues at the local and regional level. Similar to national self-sufficiency, the local and regional self-sufficiency means development within the region's carrying capacity that requires the sustaining of the ecosystem's overall integrity and minimizes 'the adverse impacts on the quality of air, water and other natural elements' (Sundkvist, et al., 1999).

2.2 Water-Energy Nexus

2.2.1 Introduction of the Concept

Water and energy are two of the most important elements of modern society. The interrelationship between water and energy lies on facts that energy generation requires plentiful water input and the water supply also necessitates non-trivial energy input. The water-energy nexus (WEN) has received gradual attention since the 1990s. Gleick (1994) reviewed the myriad connections between our demand for and use of energy and water. As he describes, 'energy and freshwater resources are intricately connected: we use energy to help us clean and transport the fresh water we need, and we use water to help us produce the energy we need' (Gleick, 1994). Following this concept, we can dissect this nexus into two aspects: energy for water (EFW) and water for energy (WFE). On-going discussions on the water-energy nexus have identified interconnectedness in five dimensions, physical, environmental, economic, social, and political (see Figure 2.1).

Water-Energy Nexus	
Physical	• Water input for fossil fuel production and electric generation • Energy input for water supply, treatment, & distribution, etc.
Environmental	• Energy production often affects water quality • Environmental burdens on production areas
Economic	• Dynamic relationship between cost and demand • A strong motivation for change
Social	• Water, energy and food security • Social and environmental justice within and across regions
Political	• Integrated policies with sufficient flexibility • Address trade-offs between various policy goals

Figure 2.1 Five Dimensions of the Water-Energy Nexus

- Physical Dimension

The physical interconnectedness of water and energy is the fundamental element of the nexus. Most of the previous studies focused on exploring the detailed linkages and quantifying the physical connections. In the energy-for-water (EFW) aspect, energy, in the form of electricity, is an essential input for the entire life cycle of water supply. Electricity is needed to abstract water from ground and surface sources, and move or lift water for distribution and allocation, eventually carry it to the end users. Also, energy is required to process the raw water to meet the drinking water standard. It is worth noting that desalination, a process that removes salt from water, is the most energy-intensive and expensive option for treating water (IEA, 2012). In the water-for-energy (WFE) aspect, water is required for practically every step of energy production. Generally, water input for energy takes place in two stages. The first one is water for fuel production. For fossil fuels, water is used in resource extraction, mining, fuel refining and processing, and transport (World Energy Council, 2012). The second process is electricity generation, where water serves for cooling and other process-related needs at power plants. It is estimated that electric power plants account for approximately half of the industrial water withdrawal globally (Davies, et al., 2013). Thus, the energy sector can be highly vulnerable to changes in water resources. In water-scarcity regions, the lack of water for cooling and chemical processes may constrain local energy production.

- Environmental Dimension

The second dimension of this nexus involves with environmental concerns. Energy production process can affect the quality of water used. Water quality may be degraded at every step of the fuel cycle, from mining, extraction, refining, to combustion. Not only fossil fuels themselves are significant water contaminants, the chemicals used to process and refine these fuels also pose huge threats to water quality (Allen, et al. 2011). Wastewater from mining operations, boilers, and cooling systems may be contaminated with heavy metals, acids, organic materials, and suspended solids (Gleick, 1994). Even the discharge of waste hot water from power plants' cooling systems can adversely interrupt aquatic ecosystems by increasing the temperature of rivers and lakes (U.S. Department of Energy, 2006). Some studies have pointed out the intensive use of pesticides and fertilizers to support the expansion of bioenergy will have negative impacts on water quality, as well (Gheewala, et al., 2011). The emergence of shale gas has also added extra concerns on aquifer contamination (Asian Development Bank, 2013). However, while many studies have recognized such water-quality impacts (Allen, et al., 2011; Amercian Geophysical Union, 2012), few of them have expanded their analyses into detailed water contamination measurement or control.

- Economic Dimension

The economic interrelationship between water and energy is now emerging as another critical component of the water-energy nexus. The physical linkages of the two lead to interplay at the economic dimension, i.e., the dynamic relationship between cost and demand. The price of energy has a direct influence on the cost of water production, hence the water price; and vice versa. Such influence is extremely crucial for water production since the cost of energy usually constitutes the largest share of the total cost of water supply. Lofman et al. (2002) describe how price reflects the amount of energy required to move water from the source to the consumer. Studies found that unit pricing of electricity can affect the groundwater use efficiency and productivity positively (Kumar, 2005). More importantly, economic pressure often acts as a stronger motivator for change when facing environmental issues (Bazilian, et al., 2011). Acknowledging this point, an increasing number of studies started to explore the economic linkages of water-energy and draw policy implications.

- Social Dimension

Since water and energy are fundamental resources for a society, the links between the two inevitably interact with various social segments. First, the recognition of the nexus offers a comprehensive approach to reassess water, energy, and food security, and contribute to the well-being of the poorest and vulnerable population (Bazilian, et al., 2011; Bizikova, et al., 2013). Furthermore, the issues of the water-energy nexus become more urgent under the context of climate change. The impacts of global warming on freshwater availability, food production, energy generation and ecosystem pressure us to to reconsider the invisible and long-ignored interconnectedness of water and energy (Chandel, et al., 2011; Scott, 2013). In addition, the social element of the water-energy nexus involves social and environmental justice issues associated with resource allocation. The trade-offs between different users need to be addressed at and across the local, national and transnational scale (Middleton, et al., 2015). Overall, it is significantly important to develop a holist approach to manage these two essential resources in a broader social context. Increasing the social recognition and public acceptances towards conservation, energy efficiency, and alternative water or energy solutions can prepare us for future challenges (Hamiche, Stambouli, & Flazi, 2016).

- Political Dimension

Policies in the water or energy sector can directly or indirectly influence the water-energy nexus issues reflected in other dimensions (Hamiche, et al., 2016). Conventionally, water or energy policy is often developed and implemented in isolation from each other, which could potentially exaggerate the conflicts the two resources at the local and national levels (Scott, et al., 2011). For instance, stricter standards for water quality controls could raise the energy input for wastewater treatment, while subsidies for irrigation water may result in the overexploitation of groundwater and more electricity consumption. Such interactions at the political dimension imply the need for integrated policy to address the complexities and trade-offs between decisions. Defining the key roles and responsibilities of government agencies as well as private sectors is a critical step toward managing water and energy resources in a sustainable manner (Sehlke, 2009). Also, creating boundary-spanning intermediaries could provide the necessary expertise and technical ability to bridge water and energy decision-making and coordinate future resource development strategies (Siddiqi & Anadon, 2011).

2.2.2 Features of the Interdependence of Water and Energy

Quantitative analysis of water-energy plays a fundamental role in developing integrated policy, programs and technology planning (AWE & ACEEE, 2011). Therefore, investigating the physical interdependence of water and energy is now among highest priorities in the domains of water-energy nexus. After reviewing an intensive list of literature, key findings of WFE and EFW are summarized respectively below.

(1) Water for Energy (WFE)

Various approaches have been adopted to explore the water need for energy production. Among them, '***water intensity factor***', defined as the water input for per unit of energy production, is frequently used to describe the magnitude of water required for energy (Byers, et al., 2014; Macknick, et al., 2011; Davies, et al., 2013). Based on the literature, water intensity of energy production depends on a number of factors, including energy sources, generating technology and capacity, location, the surrounding environmental and climatic conditions, etc.

First, the amount of water needed to produce energy varies widely among different types of energy sources. Fossil fuel and nuclear usually are considerably water intensive during the fuel extraction process as well as the electricity generation process (Fthenakis & Kim, 2010). On the other hand, renewable energy systems, such as solar photovoltaic power systems, wind turbines, often require minimal amounts of water (although the upstream production, e.g., device manufacture or power plants construction, still requires water input) (Fthenakis & Kim, 2010). Also, it is notable that some renewable energy technologies are water intensive as well, such as geothermal energy or biofuels. With the aid of recent advanced technologies, shale gas development has been viewed as a promising alternative energy. However, questions have been raised with regard to its environmental consequences, particularly its enormous water demand during extraction (Rahm, et al., 2013). Even hydropower consumes water through evaporation from open surfaces of reservoirs, resulting in a water intensity of 17 m^3/MWh (Asian Development Bank, 2013). Consequently, different energy mix or strategies can yield different water demand.

Second, during the electricity generation process, different generating and cooling technologies[2] play a major role in determining the water intensity (Macknick,

[2] The cooling system condenses steam and carries away the waste heat as part of a steam cycle. Many different cooling technologies are in use, including once-through circulation, wet and dry cooling towers, cooling ponds, and sprayers (Macknick et al., 2011).

et al., 2011; Chandel, et al., 2011). Machnick et al (2011) collected data on operational water withdrawal and water consumption factors for electricity generating technologies in the United States from published primary literature, and found that 'the cooling system employed is often a greater determinant of water usage than the particular technology generating electricity, both in terms of water consumption and water withdrawal'. The water consumption factor for wet cooling towers is roughly twice that of once-through systems (Gleick, 1994). Through a scenario analysis of global water demand for electricity generation, Davies et al (2013) found that the global electric sector can reduce 60% of its total water withdrawals by the end of this century by switching from once-through cooling systems to evaporative cooling systems alone.

Meanwhile, it has been noted that the geographic location is also a non-negligible factor for determining the water intensity of energy. The location of a power plant and the corresponding climatic and environmental conditions can affect its overall efficiency and thus its water use rate. The study of Macknick et al (2011) found that, in the United States, similar fossil plants may have water consumption and withdrawal factors that differ by more than 16%, depending on their locations. Considering the geographical differences, Fthenakis & Kim (2010) proposed the use of different parameters when assessing the water requirement for surface coal mining in the Western and Eastern U.S. In other words, the geographic variation makes it more challenging to accurately estimate the water intensity. Although this issue is widely acknowledged, the number of location-specific studies is still limited.

(2) Energy for Water (EFW)

It has been long recognized that water supply sector requires a significant amount of energy; however, studies on energy for water under the framework of the water-energy nexus are rarely seen. Preference on WFE over EFW in the literature partly stems from the belief that water remains primarily as a local or regional resource, despite globalized approaches to understanding water systems. Some even state that regional water crisis 'does not originate in, and, cannot be solved in, the electricity sector' (Ackerman & Fisher, 2013). On the contrary, there exists strong cross-country interdependence in the energy sector, as well as global efforts on energy transition for climate change. It is believed that energy policy can offer more scope for global change adaptation than water policy (Scott, et al., 2011). However, water crisis and water-related energy crisis are going to be among the severest challenges in the 21st Century. It is necessary to treat energy for water as an equal component of this nexus.

Some recent studies have realized the importance of EFW and began to quantify the energy intensity of water supply and treatment (Lyons, et al., 2009; Plappally & Lienhard, 2012; Mo, et al., 2011; Navigant Counsulting, 2006). Research has been conducted to examine the amount of energy input during each stage of the life cycle water supply, such as water extraction, water treatment and distribution, wastewater collection and treatment, etc. (World Business Council for Sustainable Development, 2009; EPA, 2013). In general, the energy intensity is significantly affected by variations in the geographical location, water availability, the local climate and also economic status (Plappally & Lienhard, 2012). Among them, the water source is unarguably the most influencing factor of energy intensity. Groundwater usually requires more energy input for pumping than surface water during the extraction process (EPRI, 2002; Mo, et al., 2011; Plappally & Lienhard, 2012). Plappally & Lienhard (2012) also noted that it is challenging to accurately estimate energy consumption for end water use due to the diversity of energy sources and the influence of human behavior.

2.2.3 Regional Context

Geographical variance is one of the key features of the water-energy nexus issues. Different countries or regions experience different water-energy challenges in terms of physical connections and policy strategy. Nexus issues in resource-scarce countries are likely to differ substantially from that in resource-abundant areas (Malik, 2002). Correspondingly, the coping strategies should change as well. Scholars have been made great efforts to generate quantification methods applicable to different countries or to design tools or models for specific regions. For instance, intending to account for the variation across geographic locations, Perrone, et al (2011) designed a Water-Energy Nexus (WEN) tool for hotspot analysis, which is capable of generating the location-specified water for energy and energy for water portfolio.

Given the substantial influence of location on the water-energy interdependency, flexible quantification methods and analytical frameworks have been used to identify the nexus issues in different regions worldwide. While most of studies are found in developed countries, led by the United States, the recognition of the water-energy nexus is also meaningful for developing countries to guide their development. Examples of existing studies worldwide (excluding China) are summarized in Table 2.1.

Although research on the water–energy nexus frequently addresses national and global demand for resources, it rarely paid adequate attention to local-scale consequences and impacts (Scott, et al., 2011). The local environmental, economic and social circumstances together determine the unique characteristics of the water-energy nexus issues. That is to say, even within a country, there could be various nexus related issues. In some cases, although the national level analysis indicates a low risk of water dependence on electricity, the subnational-level review suggests a high risk of water shortage in certain places (Fthenakis & Kim, 2010).

Therefore, to gain more accurate understanding of this complex issue, it is necessary to further explore the interlinks at local levels. Only with detailed local analysis, can targeted management approaches be produced accordingly. The study of Sovacool & Sovacool (2009) provides a good example of the local level analysis. It mapped the most likely locations of severe shortages in 22 U.S. counties brought about by thermoelectric capacity additions using county-level data and proposed various policy suggestions based on the local situation, including improving thermoelectric cooling cycles, implementing demand-side management and energy efficiency, and deploying wind farms and solar panels (Sovacool & Sovacool, 2009).

Table 2.1 Examples of Existing Studies in Different Regional Contexts

Country/ Region	Methods and Findings
U.S.	Macknick, et al. (2011) conducted a comprehensive literature view on water consumption and withdrawal factors for electricity generation in the U.S. This study identified three levels of intensity of “minimum”, “median”, and “maximum” for each type of power plants. Lofman, et al. (2002) looked at the local and inter-state water-energy connection in California and western US. Their study demonstrated that the energy usage for pumping and treating water in California exceeds 15000 GWh per year, representing 6.5% of the total electricity used in the State. Among them, the State Water Project, which takes water through the southern San Joaquin Valley to the Tehachapi Mountains, is the largest single user of electricity in California, accounting for 2-3% of all the electricity consumed.
Australia	Marsh (2008) conducted a comprehensive analysis on water-energy nexus, focusing on the context of New South Wales, Australia. Using a combination of historical analysis, input-output analysis, analysis of price elasticity, and scenario analysis, Marsh (2008) provided innovative inputs for improving the integration of water and energy policies in New South Wales, comprising strategies to improve the current institutional arrangements and industrial activities, suggestions to strengthen existing government measures, etc. Using data collected from 15 participating utilities, Cook, et al (2012) reviewed the energy use in urban

	water sector in Australia, including energy for desalination, wastewater service, energy for residential water heating,
United Kingdom	Byers, et al. (2014) constructed a model to quantify the water use for UK's electricity generation. Meanwhile, six scenario analyses were conducted to exam the reduction potentials of carbon and water intensity in UK's electricity sector.
Spain	Hardy, et al. (2012) studied water for energy and energy for water in Spain. The research found that 5.8% of total electricity consumption in 2008 in Spain was attributed to water supply and wastewater treatment. On average, energy intensity of water use cycle in Spain is 0.45 kWh/m^3. In terms of water for energy, it is estimated that energy sector accounts for 25% of total water withdrawal in Spain (Hardy, et al., 2012). Elena & Esther (2010) analyzed the water-energy trade-offs of the use of biofuel in Spain. The study argues that even if increasing the production of domestic biofuel can lower its energy dependence on foreign countries, it will increase Spain's water import and put it in another vulnerable position.
Norway	Based on empirical data and literature review, Venkatesh & Brattebø (2011) summarized the per-capita energy consumption on the operation and maintenance phase of water and wastewater system in Oslo, Norway. The results indicated that, in Oslo, energy consumed for per cubic meter water supply was 0.4 kWh on average, while the wastewater treatment required 0.8 kWh/m^3 (Venkatesh & Brattebø, 2011).
India	Malik (2002) addressed India's water-energy nexus issues in the context of its economy and nature resource endowment, and proposed coping strategies in irrigation and urban water supply sectors.

	Kumar (2005) conducted an empirical study to examine the impact of electricity price on water allocation in India. This study presented that an effective power tariff policy combined with the enforcement of volumetric water allocation could help address the issue of efficiency, sustainability and equity in groundwater use in India.
Brazil	Proença, Ghisi, Tavares, and Coelho (2011) estimated the savings potential of electricity in the water and sewerage utility in southern Brazil and found that the application of water saving measures, like installing dual-flush toilets, reusing greywater and rainwater, could lead to the electricity saving of 4.4 GWh/year in the city of Florianopolis.
Mexico	Scott (2013) studied the impact of electricity supply and pricing on groundwater use in Mexico and the associated emission changes. The study revealed the existence of heavy reliance on thermal power for groundwater pumping in the country, which calls for immediate response.
Middle East and North Africa	Siddiqi, et al. (2013) applied a systematic analytical approach to investigate the water and energy couplings in Jordan. An interesting finding is that in Jordan, a country that faces acute water shortages and limited domestic energy supplies, there is actually little dependence on freshwater for electricity generation as most of its power generation is from gas turbines that are not using water-based cooling systems (p.49). Siddiqi and Anadon (2011) performed a quantitative assessment of water-energy nexus in Middle East

	and North Africa and found strong dependence of water on energy in that area, but relative weak dependence of energy on water.
Central Asia	Rather than studying an individual country, Antipova et al. (2002) focused on the complicated water-energy issues in the Syr Darya basin, where there are international agreements on water and energy resources utilization and upstream-downstream exchanges of electric fuel and energy resources. A model was developed to optimize operation modes for major reservoirs as well as serving as the basis for developing a complex model of the operation of the Naryn Cascade of hydropower plants (Antipova, et al., 2002).
International study	World Energy Council (2012) estimated the water requirements in energy sectors in Africa, Asia, Europe, Latin American and the Caribbean, and North America. The study suggests that future water needs of energy production can be met if new and efficient technologies can enter the industry with proper policy support. Using the intensity factors compiled by Macknick et al. (2011), Davies et al. (2013) estimated the water demands for electricity generation from 2005 to 2095 in 14 geopolitical regions and found that water intensity for electricity varies among regions and it is consistent with the region's evolution over the century.

2.3 Nexus-Oriented Resource Management

2.3.1 Nexus-Oriented Strategy

This section will link the discussion of sustainability with the emerging concept of water-energy nexus, and explore the implication of the water-energy nexus in achieving regional sustainability. As mentioned earlier, strong sustainability calls for a self-sufficient system featured with qualitative improvement, decentralization, and local empowerment, etc. When it comes to water and energy resource management, these features imply an alternative strategy that challenges our current conventional system. Targeting at all the limitations with the current system, this dissertation promotes a shift from a conventional approach towards the water-energy nexus oriented strategy. The latter can be more effective in promoting sustainable resource stewardship and long-term stability and reliability of water and energy system. Figure 2.2 highlights the key features of such a shift.

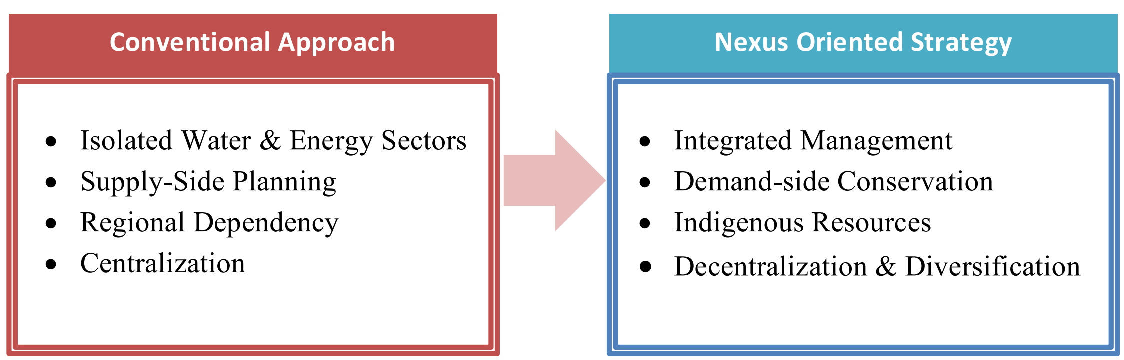

Figure 2.2 Nexus-Oriented Resource Management

First and foremost, the water-energy nexus calls for integrated management of the two. In most countries and regions, water and energy are currently managed totally separately. Each sector has its own administration agencies, with no or little (if any) overlaps. The limitation of such isolation is evident. As water and energy are essentially correlated, overlooking each other can cause various problems. A recent study of Ceres (2016) found that 57% of the wells for hydraulic fracturing in the U.S. were located in water stress regions, including Texas, Colorado, Oklahoma and California. It is important to avoid such shortsighted decision-making by bridging the two sectors from administration level and technical level. Integrated management can provide insightful guidance on future energy and water planning. Making water-smart choices on energy options, such as switching water-efficient technologies, like PV and wind power, could help avoid or minimize energy-water collision in the future and render a stronger power system (Rogers, et al., 2013; Fthenakis & Kim, 2010). Similarly, when putting forward water strategies, it is important to consider any foreseeable energy constraint. For instance, applying seawater desalination at a large scale in countries with limited energy supplies would trigger water-related energy challenges (Siddiqi & Anadon, 2011). Such nexus-oriented thinking is of particular importance when water or energy is partially or seriously limited in quantity or quality, as choices about both energy and water supplies will be far more difficult (Gleick, 1994).

The second implication of the water-energy nexus is the need to go beyond the supply-side planning and to adopt demand side conservation as the priority. Current water and energy sectors are mostly supply-oriented; if there is demand, supply will be made available. It is only legitimate when it comes to serve basic human needs. However, in our modern world, incremental demand often comes from overconsumption. It is impossible to satisfy our endless appetite with the limited water and energy resources. Thus, the new alternative system urges to combine the traditional supply-side planning with demand-side management to develop integrated resource planning (IRP). Demand-side management is no news to water or energy policy makers. Through demand-side programs, the energy utility can improve their grid reliability during peak hours and avoid the need to build additional power plants. Furthermore, the synergic effect of water-energy nexus---saving water to save energy, and saving energy through saving water--introduces more incentives to do so. Studies provide strong evidence that significant opportunities for energy savings exist through water efficiency and conservation, and vice versa (Wang, et al., 2015; Mo, et al., 2011). For example, Wang et al. (2015) estimated that, through the implementation of Energy Efficiency Resource Standards (EERS), three mid-Atlantic states in the U.S. could save 20% of its in-state water consumption by 2025. More importantly, this enormous synergic effect has been underexploited in many countries. It is also widely noted that conservation programs require much less time to plan and deploy than building infrastructure works, making the savings through water-energy conservation the ‘low-hanging fruit’ (Pitzer, 2009).

Another feature of the nexus-oriented system highlights the key role of indigenous resources. Resource transfer has become a popular solution to deal with regional resource shortage. In the energy field, a mature international market has been created to move fossil fuels around the world, along with countless regional and subnational transportation networks. In the water field, the water transfer has emerged to be a new type of water source. Although water resource by its nature often stays within its local system, engineering projects were put into place to overcome the natural boundary of water area. The water-energy nexus addresses such cross-boundary exchange of resources by adopting the concept of virtual water and embodied energy. It offers a different perspective to assess energy trading or water transfer in terms of water-energy security and environmental equity (Wang, et al., 2015; Elena & Esther, 2010). To be specific, the virtual water transfer, associated with inter-regional energy trade, shifts the available freshwater away from energy exporters and place the environmental burdens on energy-producing communities. Such ‘indebtedness’ not only leads to additional environmental cost and environmental degradation in exporting communities, but would also affect the local resiliency in resource importing areas. Thus, nexus-oriented strategy encourages the use of localized sources and the reduction of regional interdependence. As a matter of fact, many populated cities in different countries, such as Berlin, Orange County, Singapore, Seoul, Tokyo, have already started to embrace the idea of water self-sufficiency by adopting water planning, water recycling and rainwater management, and desalination (Rygaardm, et al., 2011). Areas, like California, are leading the transformation towards energy self-sufficiency by promoting conservation and renewable energy.

The fourth key element of nexus-oriented strategy is to promote decentralization and diversification. Current water and energy systems are dominated by centralized supply, following the conventional wisdom of ‘bigger is better’. It is believed that larger projects can lower the unit cost of supply because of economies of scale. Although such theory attributed to the success of large fossil fuel power plants in past decades, the revolutionary progress of renewable energy opened up a new era of ‘thinking small’. Nexus-oriented thinking suggests that a more decentralized and diversified system works better than this centralization model. A decentralized system can be tailored to satisfy the unique local need while utilizing local resources. For instance, instead of relying on outside power production, small-scale renewable power plants can be sited next to the users, cutting off the transmission loss and need for transmission capacity. Furthermore, introducing a diversified supply profile can improve the system reliability. Adding a variety of renewable sources into energy mix, instead of relying solely on a few types of fossil fuels, can increase the energy reliability and reduce the associated water need. This applies to the water sector, as well. Exploring the potentials of alternative water sources, such as direct utilization of seawater, rainwater harvest or water recycle, and water conservation as a new source, can offer some insights to increase system flexibility and decouple it from high energy input. As noted by Lovins (1977), the ‘hard path’ has caused so much environmental disruption and resource waste, it is time to focus more on a ‘soft approach’ that is more harmony with nature. Meanwhile, the decentralization process requires the support of a democratic political system, which empowers the local stakeholders, increases public participation, enables equal decision-making, and hence improves the policy adaptability (Engle & Lemos, 2010). Encouraging the transition towards a participatory governance is of particular importance to countries with a centralized command-and-control system, such as India and China (Lele, et al., 2014).

2.3.2 Implementation Principles

The nexus-oriented strategy does not dictate a uniform solution to all communities. Instead, as many have argued, water-energy nexus calls for a flexible management approach that is tailored to the local vulnerabilities and evolves dynamically to incorporate any changes. In practice, a combination of options can be adopted to address resource scarcity, boost local resilience, and maximize the synergic effect of water and energy savings. Essentially, all the implementation efforts need to consider available options while following the principles described below:

- ***Always look at conservation first*****:** efficiency and conservation is a primary solution to deal with resource shortage. Before considering the construction of any supply infrastructure, it is wise to explore the potential of water- and energy- saving during the entire life cycle in the local areas first. Related solutions include eliminating loss in current supply network to increase system efficiency, increasing prices to change consumer behavior, implementing demand-side programs to promote end-use efficiency, etc.
- ***Assess industrial adjustment if more favorable to the local community:*** Most of our current resources crises are stemmed from aggressive economic development. It is necessary to examine the compatibility of overall socio-economic pattern with the local environmental condition. Any pursuit of economic growth should not go beyond the local carrying capacity. Particularly, large fossil fuel bases need to carefully consider this principle in order to have a farsighted vision for its future

development. It is important to note that the implementation of this principle requires the empowerment of local people and community to overcome the barriers with the conventional top-down policy making system.

- ***Switch to appropriate and viable alternative sources:*** The water-energy nexus provides strong rationale to move towards more renewable energy, such as solar, wind, and small-hydro, that requires minimal water input. It also alerts any large-scale deployment of alternative options, such as water-intensive nuclear power plants or energy-intensive desalination that can possibly worsen the water-energy interdependency. Stakeholder engagement at various administrative levels can provide the information and knowledge needed for customized solutions under the various geographical and cultural circumstances.
- ***Exhaust the local potentials before importing from outside****:* It is imperative for policymakers and resource managers to first exhaust all possibilities for better management before considering external sources. Particularly, the inter-basin water transfer can only be viewed as viable when no other cheaper or less controversial solution is available (Ghassemi & White, 2007). This principle not only contributes to the system reliability, but also intends to mitigate the environmental justice issues associated with resource trade. By encouraging transparency and public participation, the nexus management ensures the fairness in decision-making across the national and subnational boundaries.

Chapter 3

ASSESSMENT OF THE WATER AND ENERGY SYSTEMS IN CHINA

3.1 China's Water System

3.1.1 Overview

China's total water resource ranks as the sixth largest in the world, with a multi-year annual average of 2800 billion m^3 (Liu, et al., 2012). Its ten major river basins together contribute to an average annual precipitation of 6200 billion m^3 (MWR, 2015a). Also, the country is endowed with 2305 lakes with water surfaces larger than 1 km^2, equivalent to a total water storage capacity of over 700 billion m^3 (MWR, 2015a). However, despite the relatively abundant water endowment, China is still among the thirteen most water-deficient countries in the world in terms of per capita possession (Liu, et al., 2012). The annual per capita water resource of 2064 m^3 in China only equals to one third of the world's average, ranking as the 128th worldwide (Tsinghua University & NRDC, 2013).

In addition to the limited per capita volume, China's water system is also constrained by the uneven spatial and temporal distribution of water resources. A majority of the large rivers are located in the eastern part of the country where the monsoonal climate produces abundant rainfall (Cheng, Hu, & Zhao, 2009). As shown in Figure 3.1, there is a clear division between the southeastern and northwestern areas. Southern China is in possession of 84% of the nation's total water resources, while the north has to sustain a similar sized population with only 16% of the water (Wong, 2010).

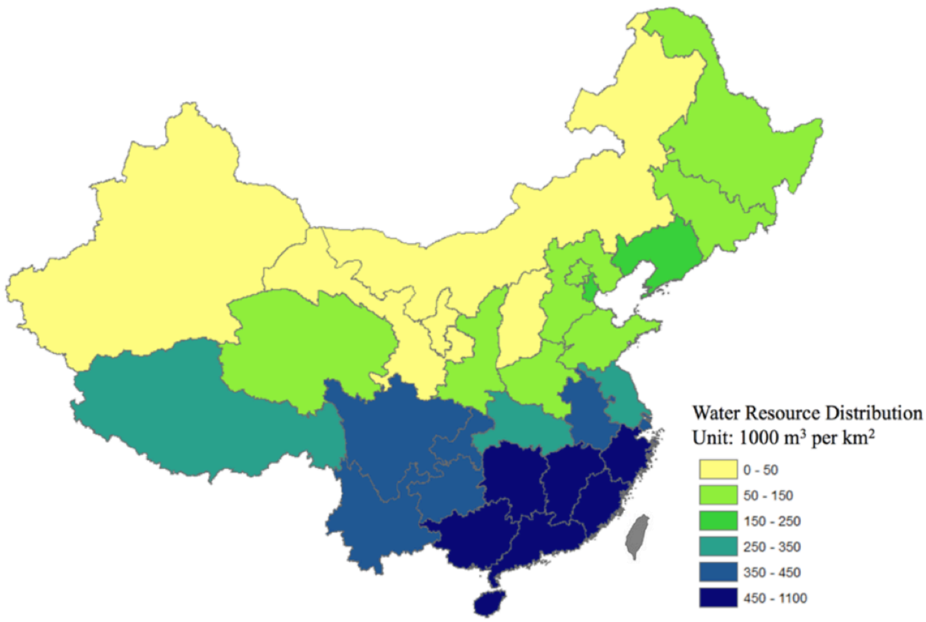

Figure 3.1 Regional Water Resources Distribution in China

(Data source: China Statistic Year Book 2015)

From the per capita perspective, the geographical pattern of water scarcity changes slightly (see Figure 3.2). Provinces with water stress issues concentrate on the northeast, especially the Huang-Huai-Hai Plain (3-H Plain, also known as the North China Plain). Lying in the vast semi-arid and arid zones, the 3-H Plain bears most of China's water deficiency problems. It is home to more than 25% of China's population, and is an important grain production base for the country (Liu & Zheng, 2002). However, the annual runoff of that zone is less than 10% of the nation's total amount, yielding an average per capita water resource much lower than that in the

Yangtze River basin (Liu & Zheng, 2002). Furthermore, the rapid urbanization and population accumulation in the past decades have aggravated the acute water scarcity issues in the 3-H basins (Berkoff, 2003).

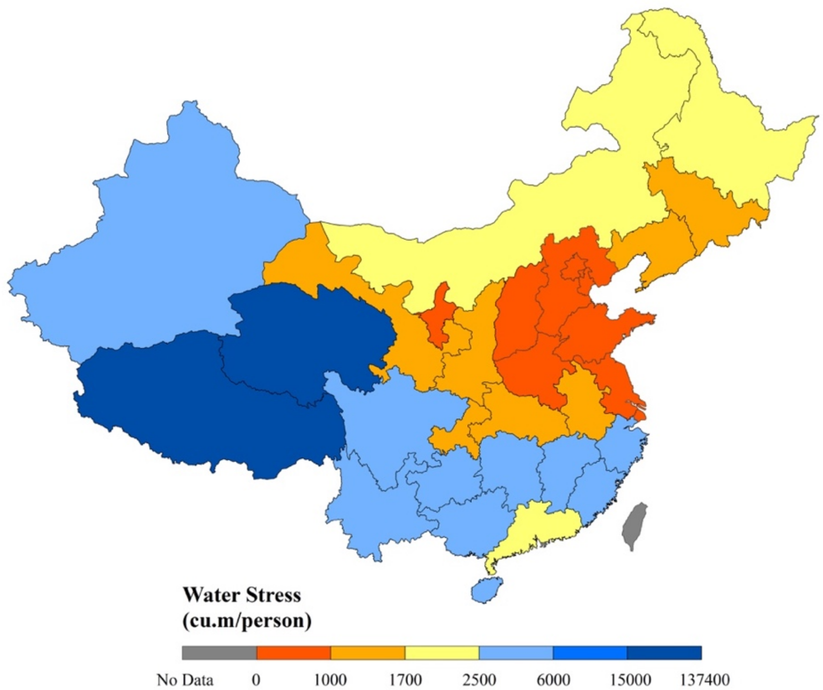

Figure 3.2 Per Capita Water Resources Distribution in China

(Data Source: China Statistic Yearbook 2015)

Against the limited water availability, the total water demand in the country has increased mildly during the past 15 years, with an average annual increase rate of 0.78% (See Figure 3.3). The agricultural sector has been the single largest water consumer in this vast agricultural country, contributing to over 60% of total water use during the period (NBS, 2016a). Meanwhile, the industrial and domestic water uses are increasing steadily. However, the current household water use in China is still much lower than that in many developed countries. Compared to an average per capita water consumption of 350 L/day for Japan and the U.S., the consumption in China is only 212 L/day for urban population and 69 L/day in rural areas (Cheng, et al., 2009). It can be expected that future domestic water demand will continue increasing in accordance with the growing urban population and improved living standard. It is also worth noting that, starting from 2002, there has been water use for ecological protection.

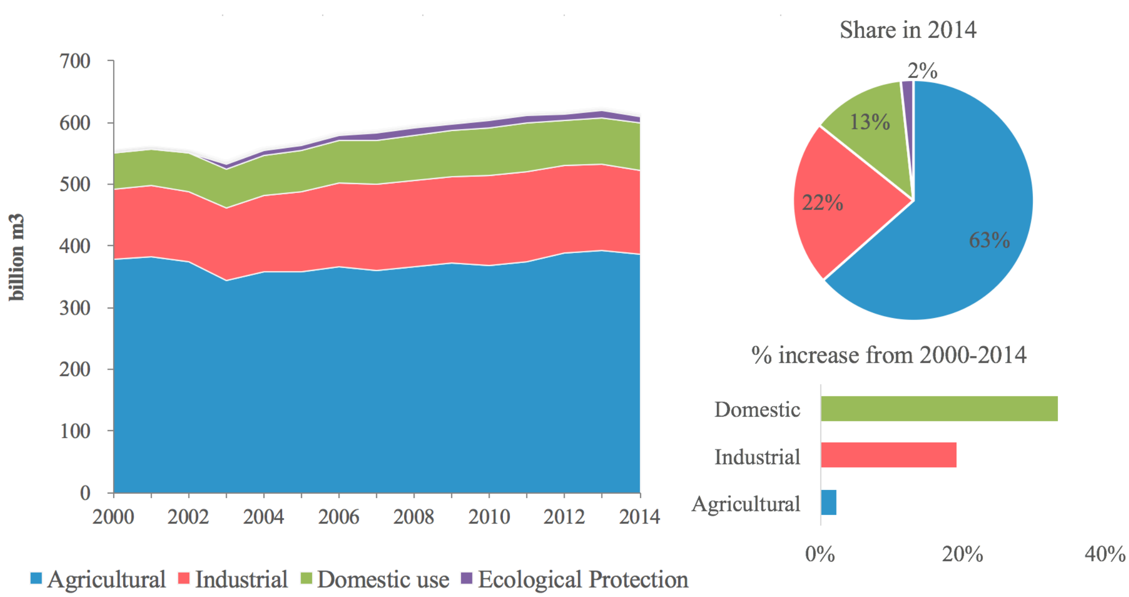

Figure 3.3 China's Water Use by Sectors from 2000-2014

(Data source: China Statistic Year Book 2015)

3.1.2 Water Supply

Supported by massive infrastructure, China's water system so far has been able to maintain a balance between demand and supply at the national level. Surface water sources provided approximately 81% of the country's total water need in 2014 (NBS, 2016a). But a closer look at the provincial data reveals some water shortage issues, especially with groundwater overexploitation.

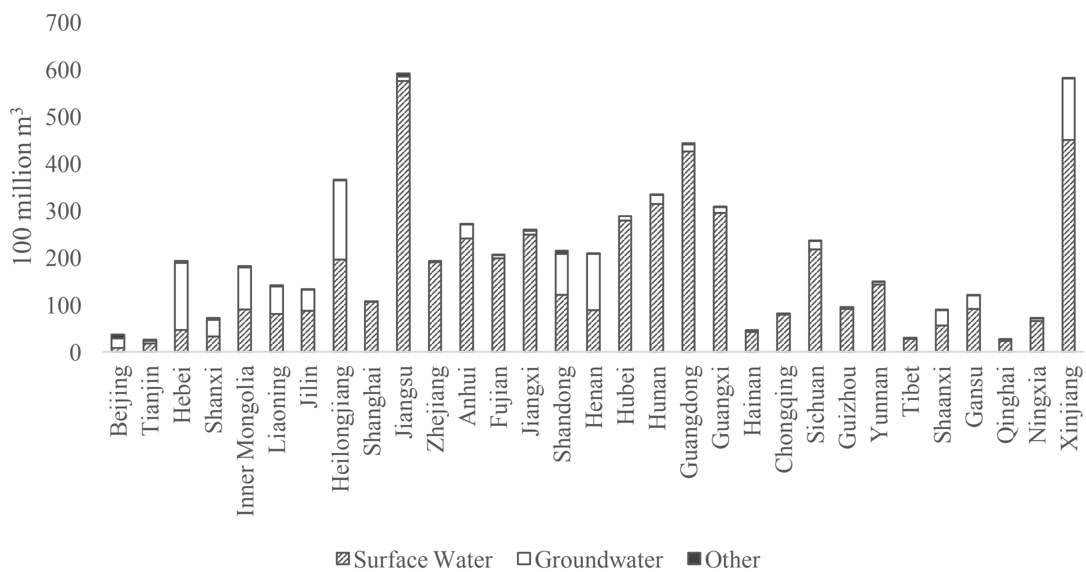

Figure 3.4 Composition of Water Supply Sources by Province
(Data source: China Statistical Yearbook 2015)

In some northern and central provinces, including Beijing, Hebei, Shanxi, Inner Mongolia, and Henan, groundwater accounts for over 50% of water withdrawals. Many of these places fall into the water scarce category with a water availability of less than 1000 m^3 per person. As the population soared, water has been pumped out faster than the natural recharge rate (Gleick, 2008). The over pumping and contamination of groundwater is forcing provinces and cities to pursue alternative solutions to acquire cleaner and adequate water sources. The government responded to the scarcity issues with more infrastructure investment to build dams and reservoirs, to divert water across regions, to improve the water-distribution system, etc.

Meanwhile, in order to enhance supply reliability, China is diversifying its water supply portfolio by increasing the share of rainwater collection, recycled water, and seawater desalination. In 2014, these alternative local water supplies generate 5.7 billion m^3 of water, representing 0.9% of the total water supply (MWR, 2015b). Although the alternative local supply is still in its infancy stage from the national perspective, some cities, where conflict between demand and supply is acute, have made great progress in developing new sources. For example, Beijing and Tianjin met 23% and 10.7% of their total water demand, respectively, through water recycling (Water Conservancy Agency, 2015). Seawater utilization also provides a sustainable option to coastal provinces. As of 2014, all of its 11 coastal provinces have direct seawater utilization projects for thermal power cooling. In addition, 9 coastal provinces have built 112 seawater desalination projects, with a total producing capacity of 926.9 thousand m^3 per day (SOA, 2015). In water scarce provinces, like Tianjin, Hebei, and Shandong, most of the desalinated water was used by water-intensive industry, while in the water abundant southern area, such as Zhejiang, Fujian and Hainan, desalination serves primarily for domestic uses.

3.1.3 Water Transfer

Water transfer has always been an important part of China's massive water conservancy infrastructure to deal with regional water shortage problems. It is designed to transfer water from basins considered to have surplus water to basins where water demand exceeded or was expected to exceed the available supply (Ghassemi & White, 2007). As water shortage becomes a severe issue in many cities and regions, long-distance water transfer is taking on a greater role in the modern water supply system. Since the foundation of the nation in 1949, China has constructed many large water transfer projects in order to mitigate the geographical mismatch in water distribution and optimize the water resource allocation.

A recent survey suggests that there are currently at least 137 water transfer projects in place, most of which were built after 2000 (Gao, et al., 2016). The Ministry of Water Resources also reported that the first-level inter-basin transfer contributed to 3.9% of total surface water supply in 2014 (MWR, 2015b). However, there is no complete public statistic information on total number of projects constructed. Table 3.1 compiles representative examples of large scale water transfer projects in China, using information collected from local water resource agencies. The most famous South-to-North Water Transfer Project (SNWTP), officially approved in 2002, is by far the largest water conservancy project in history. Although less frequently mentioned, there are over a dozen other large-scale projects in China, many of which are inter-basin and inter-provincial projects.

Table 3.1 Large-Scale Water Transfer Projects in China

Project Name	Export Provinces	Intake Provinces	Length (km)	Volume (10^9 m^3)	Operation Date
Dong-Shen Water Project	Guangdong-Dong River	Guangdong-Shenzhen	83		1965
Luan-Jin Project	Hebei	Tianjin	234	1	1983
Luan-Tan Project	Hebei-Luanhe	Hebei-Tangshan	25.8	0.5-0.8	1984
Yellow River to Qing Project	Shandong	Shandong-Qingdao	290		1989
Song-Chang Project	Jilin-Songhuajiang	Jilin-Changchun	52	0.3	1999
Jingdian Project	Gansu	Gansu, Inner Mongolia		0.21	2000
Liu-Jin Project	Qinghai	Gansu		0.04	2002
Shanxi Wanjiazhai Yellow River Diversion Project	Shanxi-Yellow River	Shanxi-Taiyuan, Suzhou, Datong	442.3	1.2	2003;2011
Yangtze River to Taihu Lake	Jiangsu-Yangtze River	Jiangsu, Zhejiang, Shanghai-Taihu	60	2.5	2005
Dahuofang Reservoir water transfer project	Liaoning-Hun River	Liaoning-Shenyang	85+235	1.78	2003-2014
Datonghe to Qinwangchuan Project	Qinghai-Datonghe	Gansu-Lanzhou	87		2014
SNWTP-East	Jiangsu-Yangtze River	Shandong		0.4	2014
SNWTP-Central	Hubei Danjiangkou-Yangtze River	Beijing Tianjin Hebei Henan	1267	3.83	2015
Qinzhong Project	Guizhou-Wu River	Guizhou-various cities			2015

Luan-Jin Project is a well-known example of the early effort. Completed in 1983, it diverts water from the Luan River to Tianjin, located 160 km away (Kataoka, 2010). In 2014, this thirty-year-old project served over 40% of the water demand in this fourth largest city in China by transferring a total volume of 1 billion m^3 of water. In addition to the ones listed in Table 3.1, more projects, such as the Yangtze-Huai River Project and Yellow-Ji Project, are under construction, further exploring the long-distance water transfer potentials of the Yellow and Yangtze Rivers.

These transfer projects express noticeable regional differences. The total number and scale of water transfer projects in eastern, northern, and central regions are relatively larger than the ones developed in the southwest or northwest, corresponding to the population density and economic status of the regions (Gao, et al., 2016). Most of the large transfer projects are located in the Yellow River basin, Shanxi, Shandong and Jing-Jin-Yi region, where booming economic activities were challenged by local water shortages (Sun, et al., 2016). It is also evident that the transfer projects are growing in number as well as in scale. While early projects tend to address the municipal water shortage in a single city, such as the Dong-Shen Project and Luan-Jin Project, recent projects often involve cross-province transfer and serve for multiple water needs. An increasing number of projects have now expanded their focus onto industrial water supply, irrigation, and more recently ecological water need (Gao, et al., 2016). For example, the Yangtze River-Tai Lake Project helps improve the water quality and water environment in the Taihu Basin by connecting it with the Yangtze River and accelerating the regional water exchange (Wu & Hu, 2008).

3.1.4 Wastewater Discharge & Treatment

The annual wastewater discharge is growing fast as a result of a robust economic development. The total volume of wastewater discharge increased 36.6% from 2005 to 2014, while domestic discharge alone almost doubled in the ten-year period. As of 2014, the total wastewater discharge reached 71.6 billion m^3. 71.3% of it was from municipal sewage discharge, while 28.7% came from industrial wastewater (MEP, 2015 a). Guangdong, Jiangsu and Shandong provinces ranked as the top three in terms of the amount of provincial wastewater discharge in 2014 (See Figure 3.5).

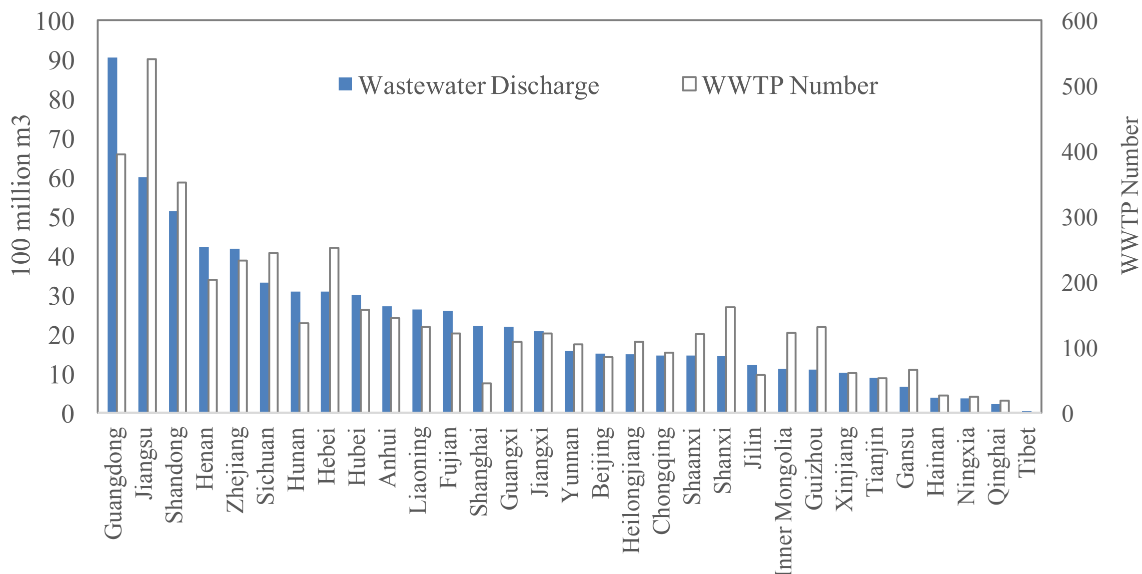

Figure 3.5 Wastewater Discharge and the Number of WWTP by Province in 2014
(Data source: MEP, 2015a)

The drastic industrialization and lack of wastewater treatment have resulted in widespread water pollution across the country. It is estimated that in 2008, about 80% of the industrial wastewater was untreated, mostly from rural industries, and discharged into rivers, lakes and the sea directly (Shao, 2010). A recent case study of Shenzhen also shows a correlation between water deterioration and rapid urbanization, mostly due to the untreated domestic wastewater discharge (Qin, et al., 2014). As a result, water quality problems are constraining China's water system. Many once water-abundant regions are now suffering from quality-induced water shortage. Under such pressure, wastewater treatment was given high priority by the central government and emerged as a new robust industry in China in recent years. By the end of 2014, a total of 4436 wastewater treatment plants (WWTPs) were in operation in China (MEP, 2015b), making it the second largest country in sewage treatment capacity, ranked after the United States (Abbasi, et al., 2016). By the end of 2014, three largest wastewater-producing provinces--Jiangsu, Guangdong and Shandong--include 541, 395, 352 treatment plants, respectively.

The effect of recent regulatory efforts and investment in wastewater treatment is quickly visible in urban areas, resulting in a treatment rate of over 90.2% (MEP, 2015 b). Beijing has one of the highest treatment rates, 96.8% of the total wastewater discharge in its central urban zones were well treated (Water Conservancy Agency, 2015). The Shanghai Water Authority also documented a high treatment rate of 93.3% in its inner city and 82.5% in the suburban area (Water Conservancy Agency, 2015). But, despite the fast growth of WWTPs, wastewater control is experiencing a polarized development in China. The rural area is again lagging far behind with a relatively low treatment rate. At the national level, roughly 69% of the total wastewater discharge in 2014 was treated before entering the waterways (Sun, et al., 2016).

3.2 China's Energy System

3.2.1 Overview

During the first few decades after the country's foundation in 1949, the energy consumption in both industrial and residential sectors were extremely frugal, corresponding to an agricultural-based and self-sufficient system. Drastic change took place after the economic reform (namely the open-up policy) in 1978. In Figure 3.6, we can see the sustained increase of energy production from 1980-2014, especially after 2000, feeding a growing energy appetite of the expanding economy. The per capita consumption also increased fivefold in the past 35 years, as another sign of solid growth in energy intensity.

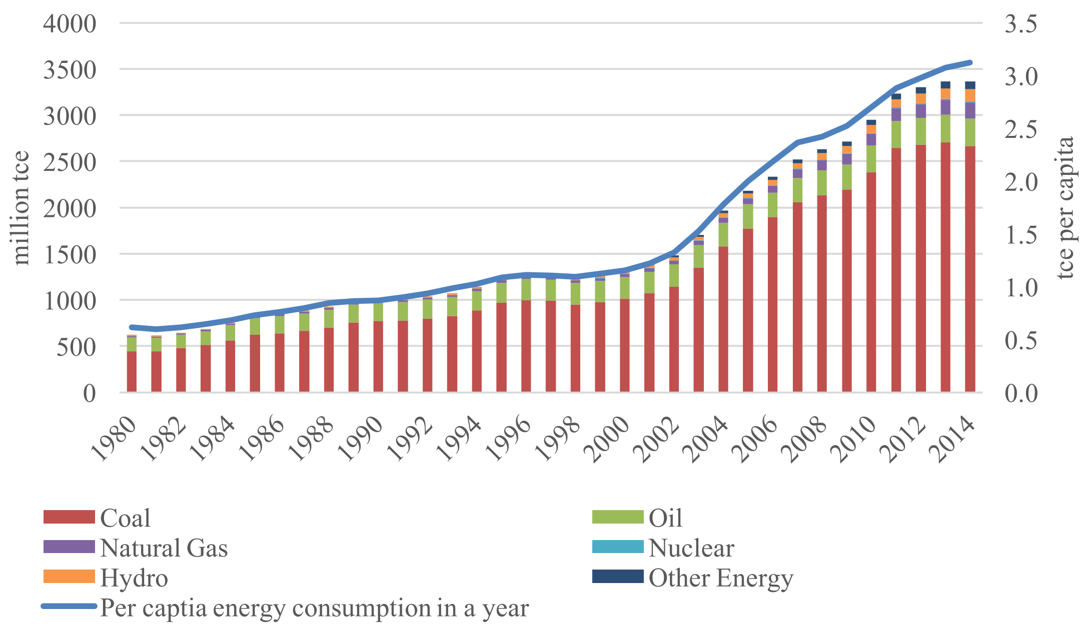

Figure 3.6 Primary Energy Production and Composition in China from 1980-2014

(Data source: China Energy Statistical Yearbook 2015)

What remain unchanged throughout the years is the dominate role of coal, which made China the largest coal producer and consumer in the world (Wu K. , 2014). Despite the government's efforts to limit coal consumption and promote alternative energy sources, coal is still the leading primary energy source (79.2%) in China as the year of 2014, followed by oil (9%) and natural gas (5%). According to BP Statistic Review in 2009, China owns the world's third largest proven coal reserves of 114.5 Gt (Shen, et al., 2012). Attributed to its easy access and affordable price, coal has served as the key energy source for decades in supporting China's economic development.

Meanwhile, total oil production has doubled from 1980-2014, despite a diminishing share, securing its position as the second largest primary energy supplier in China. Lack of domestic supply and crave for more oil in transportation and residential sectors are driving up China's international dependency. It imported over 48% of its crude oil supply in 2014 (NBS, 2016b). Natural gas ranked as the third largest energy source in China. The share of natural gas increased drastically, after it was identified as one of the priority low-carbon energy resources by recent Five-Year Plans. With additional infrastructural support from the West-East Gas Pipeline, China's natural gas consumption has sustained a double digit annual growth rate. China has now surpassed Japan and became the largest natural gas consumer in Asia (Wu, 2014).

The dominance of fossil fuel spread to the power sector, as well. In 2014, the total power generation in China reached 564.05 TWh, 73% of which came from fossil fuel input. Coal is, again, undoubtedly the largest contributor to power supply.

Although the new discovery of shale gas has signaled a promising future for natural gas, current installation of gas fired power plants in China is still quite limited, with a mild grate rate of 3.5% compared to 2013.

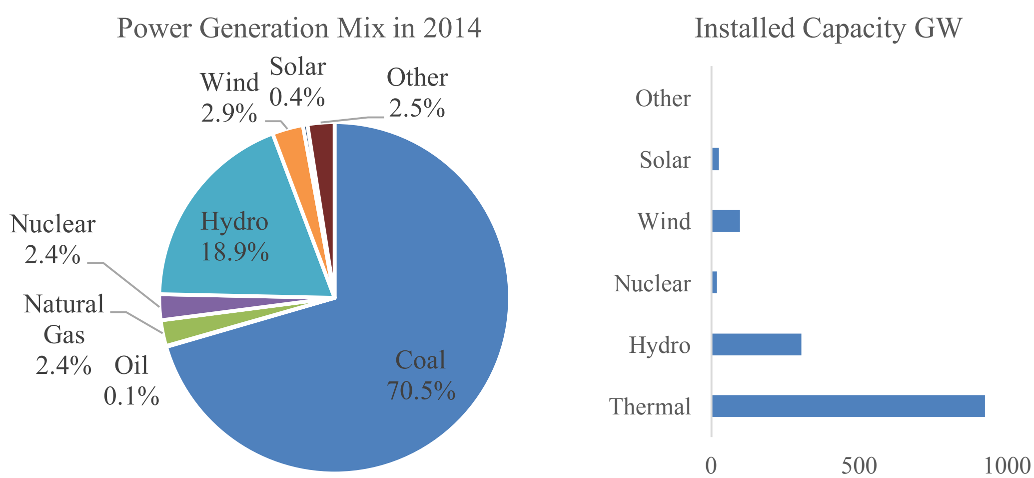

Figure 3.7 Power Generation Mix in China
(Data source: China Electricity Statistical Yearbook 2015)

More diversification is witnessed in the power sector (see Figure 3.7). Blessed with enormous renewable energy potentials, China has made great achievement in building a robust renewable power industry. With the earliest renewable energy efforts dated back to the 1980s (Martinot, 2010), China's power generation mix now contains a large portion from hydro, wind power, and solar PV technologies. Efforts towards more renewables were strengthened under the concern of tightened domestic fossil fuel supply and the intensified environmental pollution. China has now emerged as a world leader in renewable energy development. In 2011, China was responsible for one fifth of the total global investment in renewable energy volume (Liu, 2013), leading to a total installed capacity of 380 GW in 2013 (IRENA, 2014).

Another non-negligible share of power generation mix comes from nuclear power, often referred to as a major source of 'new energy' in Chinese policy. Since the construction of the first nuclear power plant in Qinshan, Zhejiang Province in 1994, nuclear has played an important role in China's energy strategy. Regardless of the impact from the Fukushima accident, China has become a powerful player in the nuclear industry, bringing another round of the nuclear renaissance. China is now ranked fourth among the 30 nuclear power generating countries in the world (Nuclear Energy Institue, 2016). But the share of nuclear in its national power generation is very small (1.1% in 2014), especially when compared to large nuclear countries, like France and the United States.

3.2.2 Primary Fossil Fuel Production and Inter-Province Transfer

3.2.2.1 Top Fossil Fuel Producers

In 2014, raw coal was produced in 25 out of 30 provinces. However, most of the easily accessible coal mines and large government-owned mines are located in the northern provinces (Ladislaw & Nakano, 2011). Over 70% of coal reserves are concentrated in five provinces (see Table 3.2). For example, the most coal abundant province, Shanxi, has a sum of coal-bearing area of 64.8 $*10^3$ km^2, equivalent to 40% of its total area (Shen, et al., 2012). The oil reserves of 3.4 billion tons represents a small share of the world's total reserve. As a result, China imported over 47% of its crude oil supply in 2014. While the output of the country's two largest fields, Daqing (in Heilongjiang Province) and Shengli (in Shandong Province) declined, the drilling efforts in Tianjin and Shaanxi areas pumped new blood into the oil supply system. Despite the slowdown in output of the Daqing field, Heilongjiang Province alone still contributed 18% of the country's total crude oil production in 2014.

Table 3.2 Fossil Fuel Reserves and Production in China

Fuel Type	Coal		Petroleum		Natural Gas	
Ensured National Reserves by 2014						
Total	240 billion tons		3,433 million tons		49,452 billion m3	
Top Five Provinces	Shanxi	38.4%	Xinjiang	17.1%	Sichuan	23.7%
	Inner Mongolia	20.4%	Heilongjiang	13.2%	Xinjiang	19.7%
	Xinjiang	6.6%	Shaanxi	10.6%	Inner Mongolia	16.4%
	Shaanxi	4.0%	Shandong	9.5%	Shaanxi	16.3%
	Guizhou	3.9%	Hebei	7.8%	Chongqing	5.0%
National Annual Production in 2014						
Total	3.9 billion tons		220 million tons		160 billion m3	
Top Five Provinces	Inner Mongolia	25.7%	Heilongjiang	18.2%	Shaanxi	25.7%
	Shanxi	24.0%	Shaanxi	17.1%	Xinjiang	18.6%
	Shaanxi	13.5%	Tianjin	14.0%	Inner Mongolia	17.6%
	Guizhou	4.8%	Xinjiang	13.1%	Sichuan	15.9%
	Shandong	3.8%	Shandong	12.3%	Guangdong	5.2%

(Data source: China Energy Statistical Yearbook 2015)

Most of China's gas fields are located inland, in the north and northwest areas. Historically, natural gas resources were discovered concurrent with the oil field exploration (Higashi, 2009). But the emergence of shale gas changed the landscape of gas distribution. According to the assessment of U.S. Energy Information Administration (2013), China has the largest technically recoverable shale gas resources of 1,115 trillion cubic feet. The recent discovery of the Sichuan gas field has made it the largest non-associated gas field and a big natural gas producer in China. The current three major natural gas basins- the Tarim Basin (in Xinjiang), the Ordos Basin (spreading across Shaanxi, Gansu, Ningxia, Inner Mongolia), and the Sichuan Basin (in Sichuan and Chongqing) hold over half of the country's total natural gas reserves (Higashi, 2009).

3.2.2.2 Fossil Fuel Energy Transfer

The geographical mismatch between supply and demand has determined a regional transportation pattern of fossil fuel products. Intensive energy transfers within the country occurred to link the fossil fuel bases with the consuming regions. Among the 30 provinces, autonomous regions and municipalities, only seven of them maintained self-sufficiency in fossil fuel supply, while others relied heavily on domestic energy flow (see Figure 3.8). A clear spatial pattern can be found from the supply balance sheet. While North and Northwest China experience a supply surplus, East and Southeast China suffer from a deficit, particularly serious for Jiangsu, Zhejiang, and Guangdong, where the majority of the population and industrial activities are located. The outflow regions centered around the main coal bases, namely Shanxi, Inner Mongolia, Shaanxi, Xinjiang. In 2014, the four provinces together produced 63.2% of the total fossil fuel (sum up of raw coal, crude oil, and natural gas) in the country, while 40% of which were transported to other provinces.

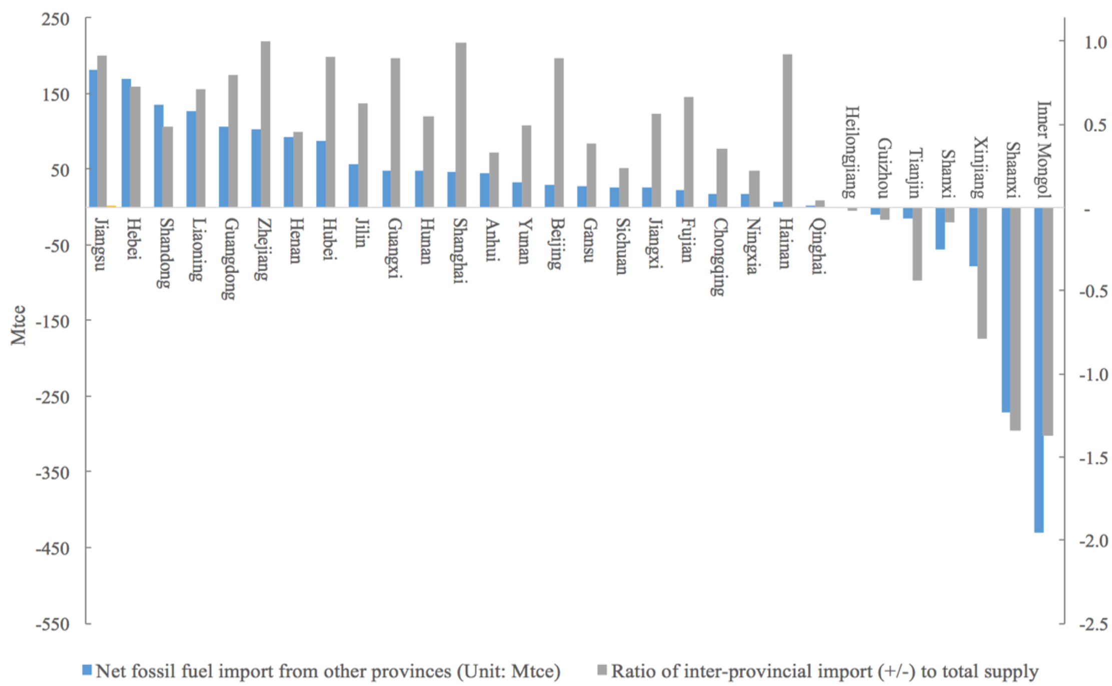

Figure 3.8 Balance of Primary Fossil Fuel Supply of Each Province in 2014

(Data source: China Energy Statistical Yearbook 2015)

Long distance transportation infrastructure was built to fulfill such movement. A complex railway-port network, such as Datong-Qinhuangdao Railway, Shenfu-Huahuang Railway, and Lanzhou-Lianyuang Railway, serves as the main transportation method to move coal from north to south, and from west to east (Wang, et al., 2009). The West-East Gas Pipeline was also put into operation in 2004, connecting the gas generating west with the gas market in the east (Wang, et al., 2013). These infrastructures laid down the foundation for further exploitation of fossil fuel reserves.

3.2.3 Electricity Generation and Transfer

3.2.3.1 Thermal Power Generating Provinces

Thermal power contributed to over 80% of total power generation in 19 provinces (see Figure 3.9).

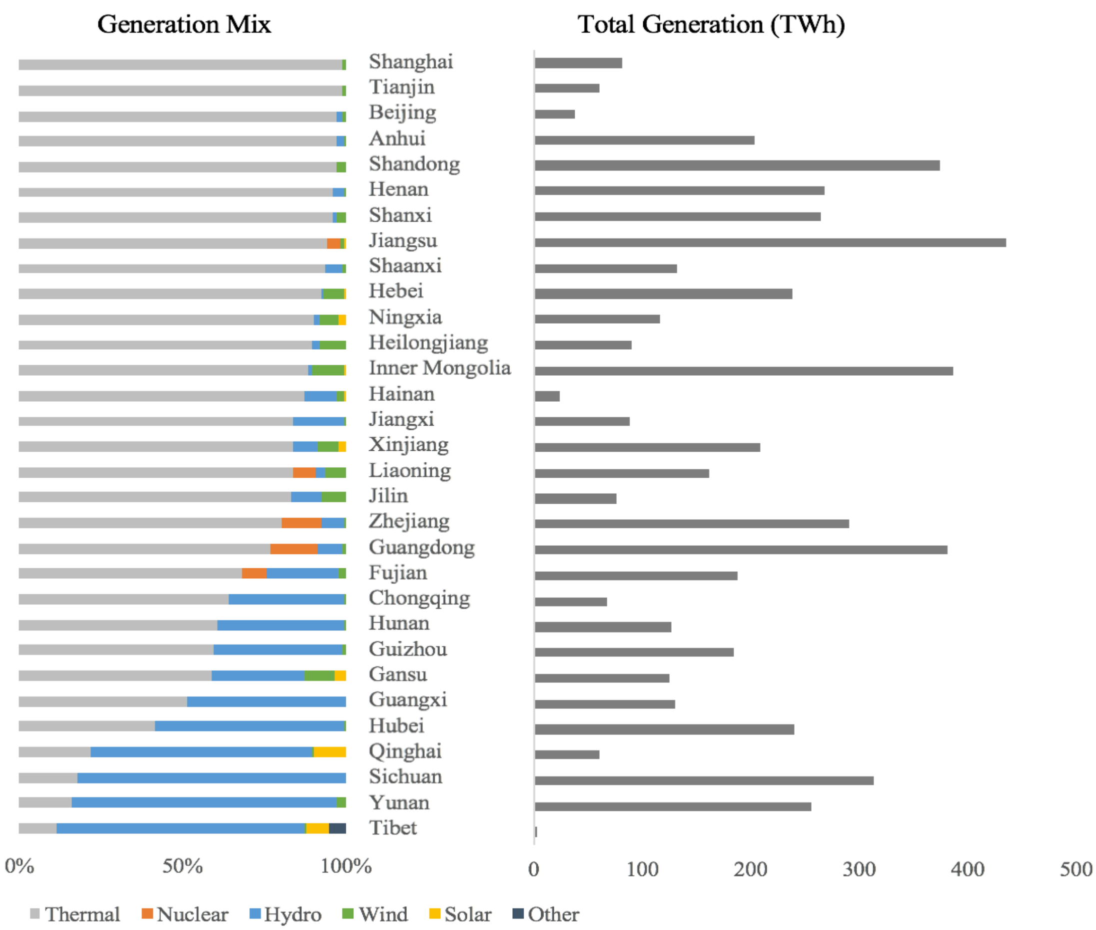

Figure 3.9 Power Generation by Province in 2014

(Data source: China Electricity Statistical Yearbook 2015)

The share of thermal power is particularly high in the three direct-controlled municipalities, i.e., Beijing, Tianjin and Shanghai, where clean power potentials are relatively constrained due to their small size. The top 10 thermal power generating provinces contributed to 65% of total thermal power output in 2014. The comparison between the top 10 provinces shows that the spatial allocation of thermal power plants is largely influenced by coal availability, population density and economy strength.

Table 3.3 Top Thermal Power Generating Provinces in 2014

Group		Top Provinces	Installed Capacity MW	Power Output TWh	Share
1	High demand Low coal	Jiangsu	7,727	409.8	9.7%
		Guangdong	6,863	293.3	6.9%
		Zhejiang	5746	234.0	5.5%
2	High fossil fuel reserve Low demand	Inner Mongolia	6,710	341.5	8.1%
		Shanxi	5564	253.0	6.0%
		Xinjiang	3791	175.6	4.2%
3	High demand Moderate coal	Shandong	7,203	362.7	8.6%
		Henan	5,735	257.1	6.1%
		Hebei	4283	220.0	5.2%
		Anhui	3911	197.2	4.7%

Most of the thermal capacities sited either near the demand center or fossil fuel producing regions. Table 3.3 grouped the 10 provinces into 3 categories. For instance, Jiangsu, Guangdong and Zhejiang have no or minimal coal production, but together they possess 22% of the installed thermal power capacity. The second group include Inner Mongolia, Shanxi and Xinjiang that are relatively poorer in economic aspect and have lower power demand. But the enormous coal reserves there lead to the construction of a large number of coal-fired power plants. The third group of Shandong, Henan, Hebei, and Anhui also forms a strong force in thermal generation, driven by their convenient location to access coal and large local demand.

3.2.3.2 Top Renewable and Nuclear Generating Provinces

Figure 3.10 and Table 3.4 display the distribution of top renewable and nuclear generating provinces in China based on the 2014 statistical data. The allocation of renewable generation capacity, i.e., hydro, wind and solar, is directly linked to the resource availability in each province. On the other hand, the installation of nuclear power plants in the country were all centralized in high demand areas near the east coast, where abundant water resources are available. As of 2014, there are five provinces with operational nuclear plants in China with a total installed capacity of 20.08 GW.

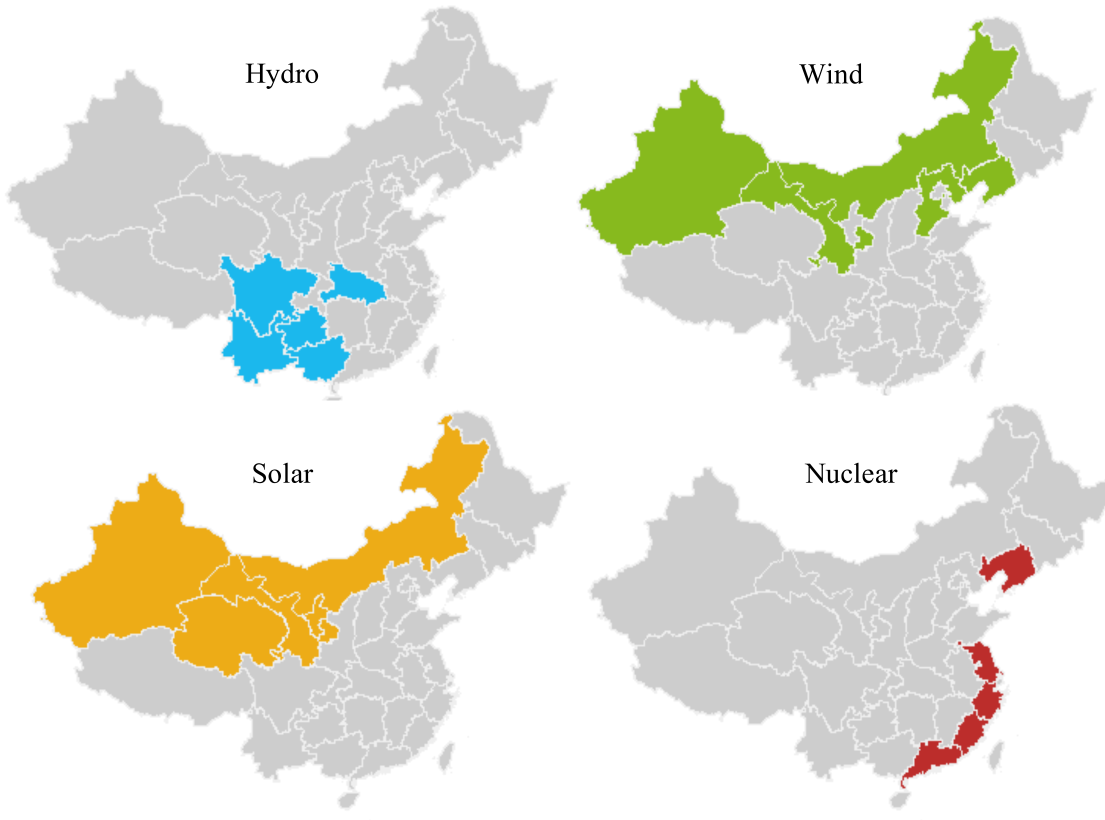

Figure 3.10 Location of Top Five Non-Fossil Fuel Power Generating Provinces

Table 3.4 Top Non-Fossil Fuel Power Generating Provinces (unit:100 GWh)

Hydro		Wind		Solar		Nuclear	
Sichuan	2578	Inner Mongolia	386	Qinghai	58	Guangdong	549
Yunnan	2082	Hebei	164	Xinjiang	55	Zhejiang	354
Hubei	1385	Xinjiang	135	Gansu	50	Fujian	168
Guizhou	733	Gansu	115	Ningxia	26	Liaoning	142
Guangxi	631	Liaoning	104	Inner Mongolia	25	Jiangsu	120

(Data source: China Electricity Statistical Yearbook 2015)

Hydropower is in the leading position among all renewable energies in China. More than 400 large- and medium- scale hydropower stations have been built or are under construction, making China the world's largest producer of hydropower (Hu & Cheng, 2013). It also hosts one of the world's single largest hydropower project—the Three Gorges Project with a total installed capacity of 22.5 GW (CTGPC, n.d.). As the end of 2014, China had 305 GW of hydropower, consisting of 22.3% of total installed capacity. The top hydro provinces are all water abundant regions, located in southwestern and central China, especially the Y-G-C region (Yunnan, Guizhou, Sichuan). The hydro power generation in 2014 increased 16.8 TWh compared to 2013, as a result of the new installed capacity and sufficient water inflow. Two of the provinces, Sichuan and Yunnan, contributed to over 44% of total hydro power supply in the year.

Other emerging renewable technologies have started to gain their market share, as well, under strong governmental support. Despite a late takeoff in 2003, wind has become the second largest source of renewable energy and one of the fastest-growing sources of electricity in China. The annual electricity generation from wind reached 160 billion kWh in 2014, accounting for 3% of the country's total electricity supply. Most of the wind power was distributed in the north and northwest regions, including Inner Mongolia, Hebei, Xinjiang, and Gansu. Although not as aggressive as wind, solar power is also growing steadily and has become the third largest renewable source of power in China. Solar power is largely adopted by the northwestern area, particularly in Qinghai, Xinjiang, and Gansu, which receive abundant solar radiation. An interesting exception is Jiangsu Province. Although its solar potential is not as strong as the top generating provinces, the solar diffusion is fast because of its unique economic status and energy demand.

3.2.3.3 Electricity Transfer

The provincial electricity balance sheet suggests a large scale of domestic power exchange. While most of the electricity demand comes from the eastern coastal provinces, primary fuel sources, mostly coal, are located in the less developed regions in the north and northwest. Furthermore, the majority of renewable potentials are also far away from the direct consumers in the east. As a result, electricity trade between provinces serve as a key mechanism to connect the demand with supply. Four directional interconnections (east, west, south and north) were constructed to transfer electricity generated in western China to energy thirst provinces in the east, and move electricity from north to south when necessary (Lindner, et al., 2013).

The China Electric Power Yearbook (2015) lists the import origins and export destinations of selected provinces with transfer volume greater than 15 TWh (See Figure 3.11). There is an obvious trend that the power is flowing from the north toward the south, and from the west to the east, similar to the pattern of fossil fuel flow. While most of the power exchanges took place between neighboring provinces, like Inner Mongolia to Hebei (83.2 TWh), Inner Mongolia to Liaoning (40.6 TWh), and Anhui to Zhejiang (29.7 TWh), some of largest power exports extended across the first-level regions, such as Yunnan to Guangdong (69.1 TWh), Guizhou to Guangdong (52.6 TWh), Sichuan to Jiangsu (35.3 TWh).

Figure 3.11 Electricity Transfer Routes Larger than 15 TWh in 2014

(Data source: China Electricity Statistical Yearbook 2015)

Figure 3.12 shows that 12 provinces have a net export above 10 TWh. Among them, Inner Mongolia, Sichuan and Yunnan has a net export above 100 TWh. Benefiting from the exceptional high hydro output in the year, electricity export of Hubei, Yunnan and Guizhou has increased over 10% from that in 2013. On the other side, Guangdong, Hebei, Jiangsu, Zhejiang, Beijing and Shanghai are the largest recipients, with a net import larger than 50 TWh. All of them are coastal provinces, except Hebei. Although there is intensive domestic power exchange, the provincial self-sufficiency level is relatively higher when compared to the fossil fuel supply.

Except for Beijing and Shanghai, most of the provinces have a ratio of interprovincial import to supply lower than 0.3, equivalent to a self-sufficiency level of 70%. It is mostly attributed to the fact that many provinces tend to import the fossil fuel and generate electricity locally. Local renewable generation also contributed to mitigating the inter-provincial dependency.

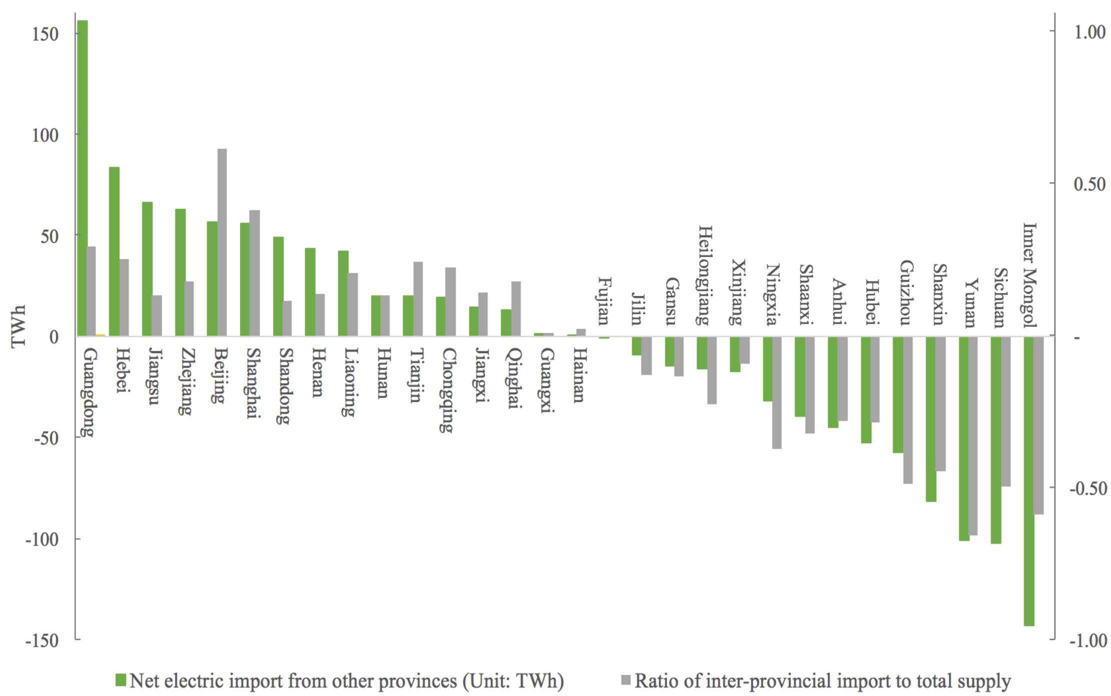

Figure 3.12 Balance of Electricity Supply of Each Province in 2014

(Data source: China Energy Statistical Yearbook 2015 & Electricity Statistical Yearbook 2015)

3.3 China's Water and Energy Challenges

The discussion above provides an overall picture of China's water and energy systems. Problems within each sector alone already contribute to a vulnerable system, not to mention the intertwined issue with the water-energy nexus. This section summarizes the key challenges from a cross-sectoral perspective and presents the main tasks that need to be addressed in later chapters. How China responds to these challenges will have profound long-term implications for its water and energy sustainability.

- Ever-increasing demand for water and energy

In both the water and energy sectors, the fundamental challenge comes from the ever-increasing demand. In the past 15 years (2000-2014), the energy sector has a compound average annual growth rate of 6.6%, while the water sector experiences an average annual increase of 0.65%. Although the increase of water use seems to be mild, the potential extra demand is not to be ignored. A recent assessment concluded that there was an annual water shortage of 50 billion m^3 across the country (Global Water Partnership, 2015). Additionally, more water will be needed to sustain the continued economic activities and to provide safe drinking water to all its population.

In the energy sector, low per capita energy consumption also signals a high probability of future increase. China's per capita energy consumption is barely above the world average (Figure 3.13), although higher than other developing countries, like India and Brazil. The huge gap between China and many developed countries (e.g., U.S. and Canada) implies a potential of future incremental demand. As a populous developing country, China will very likely continue to engage in intensive production and construction activities. It is urgent to handle the acute resource thirst and nexus-effect properly and timely to avoid future resource scarcity.

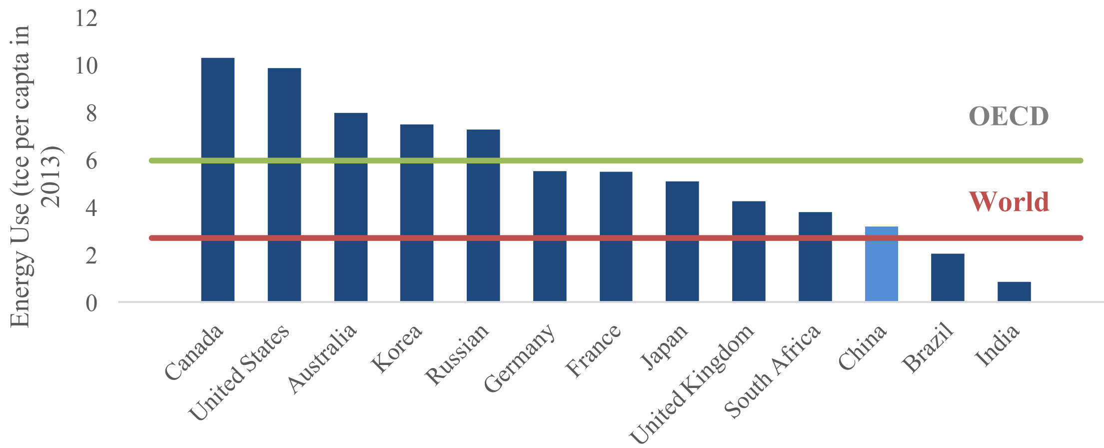

Figure 3.13 Per Capita Energy Use in Different Countries
(Data Source: World Bank, 2016)

- Environmental Pollution

Given China's large consumption of fossil fuels, it is not surprising to see it rise to become the single largest CO_2 emitter in the world, with a total emission of 10 million kt in 2013, almost double the amount of its nearest rival of the United States (World Bank, 2017). As the largest CO_2 emitter, China's emission growth rate is a great concern to the global society. International norms and treaties will undoubtedly exert pressure on China's socio-economic system (Meidan, et al., 2009). Domestically, coal combustion is among the major contributors to air pollution in China (Huo, et al., 2014). 38% of the population in China was exposed to an unhealthy concentration level of pollutants (Rohde & Muller , 2015). The fossil energy dependence has negative environmental impacts on the production side, too.

For instance, the coal mining in the north has resulted in heavy water contamination and now is constrained by the shortage of water. Large-scale hydropower projects are also criticized for their environmental consequences, such as landslides, droughts, earthquakes, and prolonged adverse effects on the ecology (Ladislaw & Nakano, 2011). For instance, the Three Gorges Dam with a reservoir area of 58000 km^2 has fragmented habitats, causing a loss of biodiversity in the Yangtze River delta (Stone, 2008).

Also, it is found that fossil fuel combustion is the main source of soil heavy metal contamination in Tianjin, a typical industrial and mining area in China (Guan, et al., 2014). The mercury (Hg) and arsenic (As) concentrations in soil, especially in metropolitan areas, are often attributed to fossil fuel combustion (Zhang, et al., 2015). Coal mining is also responsible for more than 10% pollution of Hg and cadmium (Cd) in farmland soil throughout China, affecting food security and human health (Zhang, et al., 2015).

Environmental problems in the water sector is equally worrying. The heavy water pollution and overexploitation make it increasingly difficult to acquire water, causing a vicious cycle. For example, the fast drop of groundwater level in the arid North China Plan--1 meter a year between 1974-2000--forced people to dig deeper in order to access freshwater (Qiu, 2010). Compared to the groundwater depletion in the north, southern China is facing quality-induced water shortages. It is estimated that 90% of groundwater in southern and southeastern China is polluted with heavy metals or other pollutants (Qiu, 2010). Growing domestic and industrial wastewater discharges, coupled with limited collection and treatment facility, are the principal drivers of water pollution. In particular, rural industries stand out with the highest untreated discharge (Wang, et al., 2008).

- Concerns on Intense Resource Transfer

The geographic conflicts have given birth to national resource transfer strategies. But those strategies raised a lot of economic, environmental and social concerns, leaving an on-going debate over the long-term sustainability of resource transfer. One of the major concerns with domestic energy transfer is environmental injustice. These energy-producing provinces are scarifying their water environment by bearing the burden of energy production for the entire country (Chen, et al., 2010; Shang, et al., 2016). Moreover, the long-distance transportation of energy products also causes economic and safety concerns. For example, it cost China over $18 billion to build just the first route of the West to East Pipeline (Ziegler, 2006). This cost would be larger more expansive if all social and environmental costs along the routes are taken into consideration.

Similarly, inter-basin water transfer can have multifaceted adverse socio-environmental impacts to both exporting and importing areas. The South-North Water Transfer Project (SNWTP) is probably the most controversial example of water-energy interconnections in China, given its enormous electricity need and high capital investment. The SNWTP requires the resettlement of 330,000 people in the exporting regions, mostly due to the expansion of the Danjiangkou Reservoir (Koga, 2004; Berkoff, 2003). The water importing areas, on the other hand, are vulnerable to water quality degradation by receiving polluted water, invasion of alien species, and ecological impacts of lake impoundment and seawater intrusion (Zhang Q. , 2009). Despite our insufficient knowledge on these impacts, water transfer is gaining more popularity in China. It is growing so fast that the central government, namely the National Development Reform Commission (NDRC) and Ministry of Water Resource (MWR), had to issue a specific regulation in March 2016 to control unorganized water transfer. It is important to assess necessity and applicability of the transfer strategy to ensure it is socially responsible, economically viable, and environmentally sustainable.

- Risks from Yearly Variation of Precipitation and Climate Change

Inter-annual and intra-annual variation of precipitation directly affects the local water supply. Droughts and floods are recurrent natural disasters in China, because of the complicated interactions between its monsoon climate and unique geographical landscapes (Liu, et al., 2015). While the central and middle reaches of the Yangtze River often experience flooding during monsoon season, the break-flow of the Yellow River has constantly troubled the North China Plain near its lower reaches (Piao, et al., 2010). In 1997, Shandong province, whose water supply mainly depends on the flow of the Yellow River, suffered severe loss of agricultural productivity due to the water cutoff (Wong, 2010).

Yearly variation also challenges the success of national strategies on water transfer and hydropower development. In 2011, a extreme drought hit the Hanjiang River and caused the water level of the Danjiangkou Reservoir to drop below its dead water level for 83 days (Liu, et al., 2015). The drought not only placed significant restriction to local water allocation, but also questioned the long-term effectiveness of the SNWT project, as the Danjiangkou Reservoir is the origin of its central route. Moreover, give its emphasis on hydropower, China's energy reliability is also subject to extreme climate. The top hydropower province, Yunnan, was affected by an intense and prolonged drought in 2009 and 2010, with a 60% reduction of rainfall compared to normal condition (Qiu, 2010). The sufficiency of yearly water flow determines the electricity productivity and exporting capability of these southwestern provinces.

Additionally, climate change is increasing the frequency of extreme events, placing more pressure on the stressed water and energy supply system. From the long-term perspective, the impact of climate change will cause larger uncertainties of future river runoff and water resources (Chen, et al., 2014). Over the past few decades, the south and northwest of the country have received more precipitation, while, on the contrary, the northeast regions witnessed a decline in water runoff (Piao, et al., 2010), which is likely to worsen the existing water shortage in water stressed regions. Moreover, as the warming temperature increases the glacial meltflow in the near future, it could leave western China in a vulnerable position facing the possible exhaustion of glacial runoff. The uncertainty of seasonal and inter-annual change in precipitation implies the need for adaption efforts and strategic planning.

Chapter 4

QUANTIFICATION OF THE WATER-ENERGY NEXUS IN CHINA

4.1 Scope and Method

4.1.1 Scope

The main task of this chapter is to quantify the physical interconnectedness of water and energy in China at both national and provincial levels, using the latest annual data. Figure 4.1 illustrates the scope and key elements of the analysis. After the estimation of WEN, a correlation analysis will be conducted to examine the influencing factors for WEN.

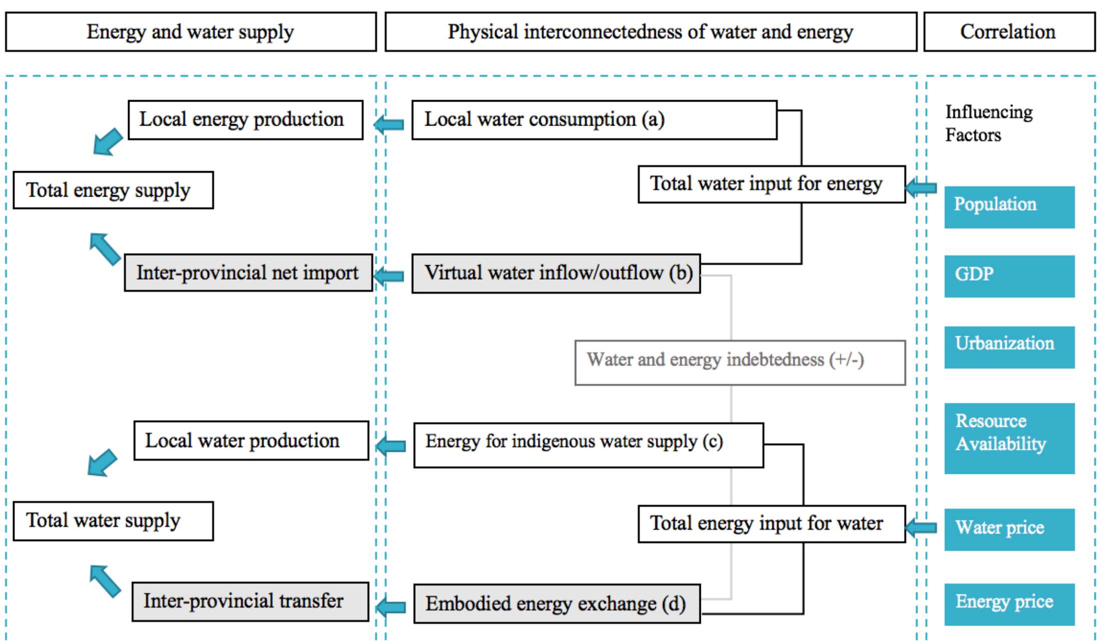

Figure 4.1 Analytical Framework for the Quantification of the Water-Energy Nexus

As shown in Figure 4.1, there are two types of interconnectedness, indigenous consumption (a & c) and regional transfer of virtual embodiment (b & d). Water consumption for indigenous energy production (a) refers to water consumption for energy production that takes place within the area, while virtual water inflow/outflow (b) means the total volume of water embodied in domestic energy transfer, moving in (+) or moving out (-) of a province. Similarly, energy consumption for indigenous water supply (c) describes the energy input for water production that takes place within the province, while embodied energy transfer (d) represents the energy consumed outside the province to divert external water into the area. The inter-provincial energy imports and the associated virtual water inflow, and the inter-provincial water transfer and the associated embodied energy inflow together reflect the magnitude of a province's dependence on other regions' water and energy resources, i.e., water and energy indebtedness. Also, it is important to note that (b) and (d) are the portion of water-energy indebtedness that has been long overlooked.

Key influencing factors of WEN will be identified and their impact will be addressed quantitatively. The literature review shows that several social-economic indicators may have significant impacts on the WEN, including population, urbanization, level of economic development, industrial structure, as well as local resource availability. Understanding the role of these indicators and their relationships with a region's water-energy nexus can provide insightful guidance on policy making. Thus, this part will investigate the potential influence of a list of social-economic indicators using correlation analysis.

It should be noted that the scope of water for energy (WFE) here is defined as 'water consumption'. While 'water withdrawal' describes the total amount of water abstracted from a source, such as rivers, lakes, or aquifers, 'water consumption' refers to only the portion that is withdrawn but not returned to the source, including water consumed through evaporation, transpiration and product incorporation (Amercian Geophysical Union, 2012; Macknick, et al., 2011). By definition, the amount of water withdrawals for an activity is larger than or equal to its water consumption. But the consumptive water use reduces the amount of water available to satisfy water demand downstream (International Energy Agency, 2012). In addition, more data on water consumption for energy can be found than its counterpart. Given the relative importance and data availability, only water consumption is considered in this quantitative analysis.

4.1.2 Estimation Method of the Water-Energy Nexus

A principle goal of this analysis is to identify the geographical distribution of water-energy interdependence and to track the exchange of virtual water and embodied energy at the provincial level. Considering the research unit, bottom-up intensity factors will be used to calculate the physical interconnectedness of water and energy.

- Approach to Estimate the Water for Energy Production (WFE)

WFE analysis focuses on three primary fossil fuels (i.e., raw coal, crude oil, and natural gas) and electricity generation. Since most of the uranium used in China's nuclear power industry was imported from overseas (Cai, et al., 2014), the water for uranium mining is excluded. Water for indigenous energy production (WFE_{in}) and virtual water associated with energy transfer (*VW)* will be calculated separately for each province. The estimation method for WFE_{in} is illustrated by Equation (1).

$$WFE_{in} = WFE_{ff} + WFE_{elec} \tag{1}$$

$$= \sum_{i=1}^{n} WIp_i \times FF_i + \sum_{i=1}^{n} WIe_i \times EG_i$$

where

WFE_{in}: Water consumption for indigenous energy production, including water for fossil fuel production (WFE_{ff}) and water for electricity generation (WFE_{elec}), m^3;

i: Type of fossil fuel, i.e., coal, natural gas, and oil;

FF_i: Annual production of each primary fossil fuel within a province, GJ;

WIp_i: Water consumption intensity for each type of fossil fuel production, m^3/GJ;

j: Type of power generating technology, including thermal power generation, nuclear, solar, wind, and hydropower, etc.;

EG_j: Annual in-province electricity generation from different technologies, kWh;

WIe_j: Water consumption intensity for each electricity generation technology, m^3/kWh.

Virtual water flow (*VW*) will be estimated using the same method as Equation (1). Only this time, indigenous energy production will be replaced by the import/export of fossil fuel and electricity. A positive sign (+) represents virtual water inflow, while a negative sign (-) means virtual water outflow.

- Approach to Estimate the Energy for Water Production (EFW)

The estimation of energy consumption also uses bottom-up intensity factors, following Equation (2). Energy needed for each stage of the water supply cycle will be calculated separately, including energy for water sourcing ($EFW_{Sourcing}$), energy for water treatment & distribution ($EFW_{T\&D}$), and energy for wastewater collection & treatment (EFW_{Waste}). To distinguish the local energy consumption from the embodied energy, energy for local water supply and treatment was marked as EFW_{in}.

$$EFW_{in} = EFW_{Sourcing} + EFW_{T\&D} + EFW_{Waste}$$
$$= \sum EI_{s,\varphi} \times W_{s,\varphi} + EI_{T\&D} \times W_{T\&D} + EI_{Waste} \times W_{Waste} \qquad (2)$$

where

EFW_{in}: Energy consumption for local water supply and treatment, kWh;

φ: Sources of water supply, including surface, groundwater and seawater, water recycle, water transfer, etc.;

$EI_{S,\varphi}$: Energy intensity of extracting water from source φ, kWh/m^3;

$W_{S,\varphi}$: Total volume of water supply extracted from source φ, m^3;

$EI_{T\&D}$, EI_{Waste}: Energy intensity of water treatment & distribution and wastewater treatment & collection, respectively, kWh/m^3;

$W_{T\&D,}$ W_{Waste}: Total volume of water at the stage of treatment & distribution and wastewater treatment, respectively, m^3;

In addition, energy associated with inter-provincial water transfer ($EFW_{Transfer}$) will be estimated, separately, by multiplying the total volume of annual inter-provincial water transfer with the corresponding energy intensity.

- Approach to Estimate the Water-Energy Nexus (WEN)

After the WFE and EFW are calculated for each province, their monetary values in per capita terms will be estimated following Equation (3). The purpose of this estimation is to apply a uniform unit to both WFE and EFW in order to synthesize the results and enable a direct comparison of the two. The per capita economic value of WEN in a region serves as an indicator to measure the nexus intensity of a region.

$$WEN = WFE_{econ} + EFW_{econ} = \frac{WFE_{in} \times P_w}{Population} + \frac{EFW_{in} \times P_e}{Population}; \tag{3}$$

where

WFE_{econ}: the monetary value of per capita water-for-energy in a region, *yuan*;

P_w: average water price in each province, yuan/ m^3;

EFW_{econ}: the monetary value of per capita energy-for-water in a region, *yuan*;

P_e: average electricity price in each province, yuan$/kWh$.

4.1.3 Data Sources and Assumptions

4.1.3.1 Energy Data

China publishes detailed provincial energy balance data in the *China Energy Statistical Yearbook,* which includes data on indigenous energy production and domestic energy transfer. The 2015 yearbook, containing data for the calendar year of 2014, is the lasted version available. It has a primary energy balance sheet for 30 provinces in physical quantity (e.g., ton or m^3), with the exception of Tibet. This dataset includes comprehensive data on indigenous production and inter-provincial import/export of primary fossil fuel in each province. All the physical units of fossil fuel are converted into coal equivalent.

China Energy Statistical Yearbook also includes the total electricity generation and inter-provincial transfer. More detailed data on electricity generation mix in the year of 2014 can be retrieved from *China Electricity Statistical Yearbook* 2015. As it is difficult to identify the origin of electricity exchange, national average generation mix is used to estimate the water input for imported electricity. Although these two datasets do not specify the exact movement between provinces, the data are sufficient enough to generate WFE and VW associated with energy transfer.

It is necessary to point out some data uncertainties within these statistic yearbooks in China. Historically, Chinese provincial authorities tend to overestimate the production as a reflection of their economic achievement (Liu & Yang, 2009). Researchers also reported 18% discrepancy between national and provincial energy statistics in 2012, due to inconsistent revision of coal production (Guan, et al., 2012). Similar discrepancy was found in the 2015 yearbook. The aggregated provincial coal supply of 4848.57 million tons exceeds the reported national total of 4118.34 million by 17.7%. As a result of such discrepancy, coupled with the statistical error, the aggregated national provincial import does not equal to the total provincial export. While acknowledging these statistical issues, the results presented below still follow the original provincial Energy Balance Sheets, at it is the most updated and comprehensive dataset available to the public.

The conversion factors for energy units used in this analysis are listed in Appendix A.

4.1.3.2 Water Data

Table 4.1 lists the data source for the water supply cycle and the key assumptions. Like the energy data, the water data are annual statistical data for the calendar year of 2014.

Table 4.1 Sources of Water Data

Stage, Source		**Data Source**	**Assumption**
Water Sourcing	Surface Water	China Statistical Yearbook 2015	
	Groundwater	China Statistical Yearbook 2015	
	Water recycle	Water Resource Bulletin 2015	
	Desalination	National Seawater Utilization Report 2015	Annual operation rate of 35%
	Water Transfer	Water Resource Bulletin 2015 Websites of Province Water Agency	Based on design capacity of transfer projects
Water Treatment & Distribution		Water Resource Bulletin 2015	Only for domestic & industrial water use
Wastewater Treatment		China Statistical Yearbook 2015 Environmental Statistic Bulletin 2015	Average treatment rate of 69%

The *China Statistical Yearbook* and the *Water Resource Bulletin* of each province includes the breakdown data on water sourcing from surface water, groundwater, and water recycle. The seawater desalination capacity (m^3 /day) in each province can be found in the *National Seawater Utilization Report 2015*, issued by the State Oceanic Administration (SOA). In order to estimate the total volume of desalinated seawater, an annual operation rate of 35% is used for all desalination projects. The operation rate here is defined as the percentage of time a desalination plant is operating in a year. This value is selected based on the reported national operation rate of 38.9% in 2012 (Wang J. , 2014) and the actual 2014 operation rate in Tianjin (31.5%) and Liaoning (34.4%) (MWR, 2015b; SOA, 2015).

The retrieval of water transfer data is relatively challenging, due to lack of national statistical data. First of all, small-scale water diversion, although often used in many places, is excluded in the analysis, since most of them use gravity water supply work that requires minimal power input. The estimation on the energy for water transfer concentrates on large-scale inter-basin transfer that requires extra power to lift the water. While the *Water Resource Bulletins* in a few provinces specify the inter-basin water transfer within and/or across provinces, most of them do not. As supplement, the list of water transfer projects in Table 3.1, Chapter 3, are used to estimate the annual volume of intra-province and inter-province water transfer, based on the design capacity and scope of each transfer project.

The volume of water treatment and distribution depends on the end user types. The water users in China are typically divided into four types, agricultural water use, industrial water use, domestic water use, and ecological water use. Only domestic and industrial water uses are accounted for the energy for water treatment and distribution. Lastly, the total wastewater discharge in each province is listed in the *China Statistic Yearbook*. According to the *Environmental Statistic Bulletin*, the national average treatment rate is 69% in 2014 (MOEP, 2015).

4.1.3.3 Water and Energy Prices

The *National Energy Administration* issued a biannual report on electricity prices of all national power companies in 2015. The national average electricity price in 2014 was 0.65 yuan/kWh (NEA, 2015a). Meanwhile, the water price database, maintained by the H2O China, contains an intensive list of water prices in reported cities, yielding a national average water price of 2.46 yuan/m^3 (H2O China, n.d.). The prices used in this analysis are the retail prices of water and electricity in each province, and do not reflect the life-cycle cost.

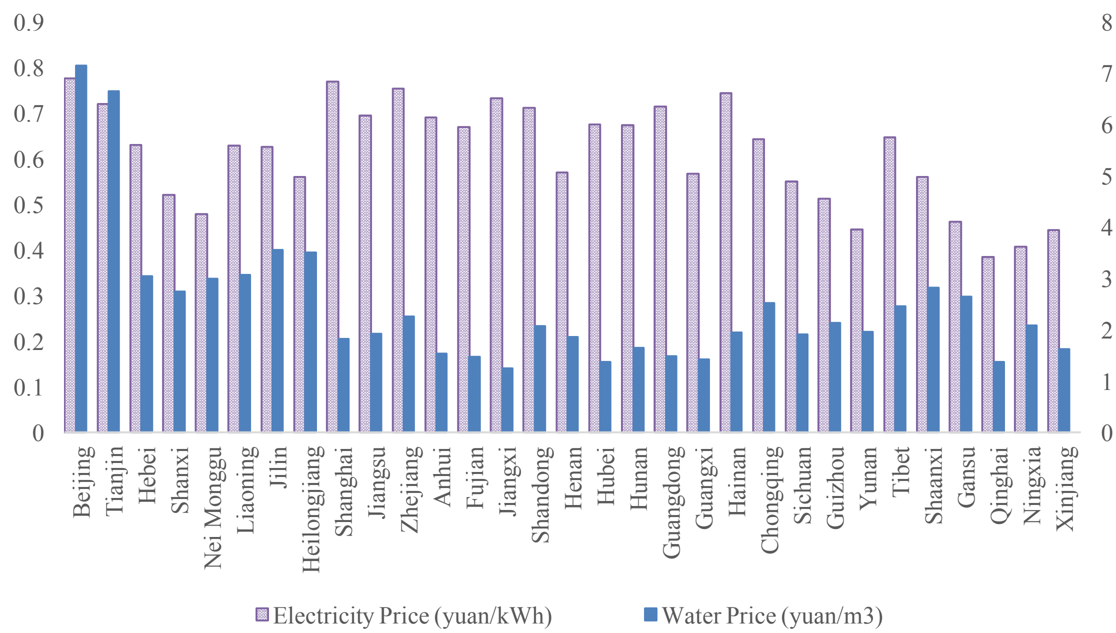

Figure 4.2 Water and Electricity Prices by Province in 2014

Figure 4.2 displays the electricity price and water price in each province collected from the two sources. There is great variation among different areas, especially the water price. The water price reaches 7 yuan/m^3 in Beijing and Tianjin, two of the most water-stressed regions, but is merely 1.3 yuan/m^3 in water abundant provinces, like Jiangxi, Hubei, and Guangxi.

4.1.4 Correlation Analysis

4.1.4.1 Analysis Method

This correlation analysis aims to identify connections between the water-energy nexus variables (e.g., WFE_{in}, VW, EFW_{in}) and a selection of potential influencing factors. Potential influencing factors are selected based on findings from previous studies and the features of water and energy nexus.

The Pearson correlation test was used to measure the correlations among pairs of variables. The bivariate correlations function of SPSS software was used to generate the Pearson correlation coefficient (r) and the two-tailed significance (*p* value). The correlation coefficient (r) measures the strength and direction of the linear relationship between any pair of the variables, (+) as positive, while (-) as negative. Following the general guidelines, the strength or magnitude of the correlation are defined as follows:

$0.1 < | r | < 0.3$, weak correlation

$0.3 < | r | < 0.5$, moderate correlation

$0.5 < | r | < 1.0$, strong correlation

The p value represents the statistical significance of such relationship. A *p* value of less than 0.05 indicates that the relationship between two variables is statistically significant.

4.1.4.2 Potential Influencing Factors

- Population

Population (Pop) is presumably a dominant driver for growth in water and energy interdependency across the country (Smith, et al., 2015). Typically, the larger the population, the more energy input for water supply, and the more water input for energy production. China's *National Bureau of Statistics* provides 2014 data on total population and urban population in each province.

The proportion of urban population (Pop_{urban}) is an indicator of urbanization. It will be used to examine a hypothesis that areas with a higher share of urban population would have stronger water-energy interdependency and lower resource self-sufficiency.

$$Pop_{urban} = \frac{Pop_{urban}}{Pop_{total}} \times 100\%$$

- Economic and industrial variables

Economic development could have mixed impacts on WEN. On one hand, intensive economic activities could lead to more energy and water demand; on the other hand, improved economic condition could mean more advanced and efficient technology, and hence lower nexus intensity. In order to exam the relationship between economic level and WEN variables, gross regional product (GRP) is selected as an economic variable. Similar to gross domestic product (GDP), GRP is a concept that measures the newly created value through production in a region, usually a state, a province, or a city.

The industrial structure is also a variable worth studying that might have complicated impacts on WEN. China reported its gross production originating from three categories, the primary (agricultural), secondary (industry), and tertiary (service). As a vast agricultural country, China's irrigation and other agricultural water need could raise the electricity consumption in the water sector in its grain production bases. But China's industry centers are also often associated with higher water and energy consumption. Therefore, the share of agriculture in gross regional production ($GRP_{\%\,agri}$) will be used to determine the correlation between WEN and industrial structures.

$$GRP_{\%\,agri} = \frac{GRP_{agriculture}}{GRP_{total}} \times 100\%$$

- Resource Variables

Thinking intuitively, the local resource availability can be a big factor on determining the degree of resource utilization. The higher local availability often leads to a higher level of resource consumption. It would be interesting to see how that works out for WFE and EFW. It is possible that provinces with higher water endowment would be willing to spend more water on energy production, while regions with less energy concentration may pursue energy-efficient water strategies. Total local water resources and total fossil fuel reserves will be used to test this hypothesis.

In addition, the analysis will check whether the resource prices, i.e., water price ($Price_{water}$) and electricity price ($Price_{elec}$), play any role in determining WFE and EFW.

4.2 Intensity Factors of WEN

The analysis intends to use China's contextualized water and energy intensity factors in the estimation. But previous researches on WFE and EFW in China are scattered among different areas, often narrowed down to specific linkages, looking exclusively at water for coal or water for one type of renewable energy resource. Meanwhile, the comparison of China's contextualized EFW and WFE intensity factors in various studies suggest that research location, methodology, and study scope are all detrimental elements that affect the value of intensity factors. Even among studies using similar approaches, the results can vary remarkably, sometimes yielding a difference of over ten times, due to different period of record, sample area or technology under consideration. Therefore, this section reviewed a range of various intensity factors reported by previous studies and synthesized the findings to provide easy data access. To address the data variation question, this study used the median value of these factors as the national average when calculating the WFE and EFW. In addition, China's contextualized data were compared to international values to check for any anomalies.

4.2.1 Water Intensity Factors for Energy Production

4.2.1.1 Water Intensity Factors for Fossil Fuel Extraction

Table 4.2 lists the water intensity factors for primary fossil fuel production collected from the literature. Fossil fuel production typically consist of several steps, from mining, preparation to transportation or secondary conversion. While each step is associated with water consumption, this study only surveyed the water for mining and on-site processing, as this is the step that is directly related to the production location. Also, water for mining and extraction has the most data availability. Therefore, all the intensity factors below account for only mining and on-site processing. In addition to China-specific data, the international factors from the World Energy Council (2010) and Gleick (1994) were also included as a comparison.

- Raw Coal

A considerable volume of water is required during the coal mining process for mining equipment cooling, de-dusting, tunnel washing, etc. (Pan, et al., 2012). Local standard, mine location and coal availability together determines how much water is needed (Williams & Simmons, 2013). On average, underground mining consumes much more water than surface mining. In China, 95% of the coal is extracted from underground (Pan, et al., 2012). In one of the major coal production province, Shanxi Province, the Industrial Water Use Standard requires that large-scale underground coal mines to consume 0.35 to 0.42 m^3 of water to mine one tce of coal (Pan, et al., 2012). But smaller coal mines can be less water efficient in general. In individual provinces, water for coal mining can range from 0.08 to 2.24 m^3/tce, depending on local coal resources and water standards (Pan, et al., 2012). The lower end of Shanxi's case is very close to the reported international value. Considering the overall national situation, the intensity of 0.35 m^3/tce was used in the analysis.

- Crude Oil

The extraction of oil involves the injection of a large amount of water into a well to extract oil. Over 80% of China's oil producing capacity is located onshore

(U.S. EIA, 2015), corresponding to a freshwater consumption intensity of 0.762 m3/tce for the Eurasia region (Williams & Simmons, 2013). As large oil fields in China are approaching their production peak, many oil fields adopted enhanced oil recovery (EOR) techniques to maintain steady production, which typically consumes more water than conventional oil production (Gleick, 1994). The median value of 0.726 m3/tce was used in the analysis, which is higher than the international onshore extraction intensity, but lower than the EOR intensity.

- Natural Gas

Conventional natural gas production does not require water injection, and most of the water consumption comes from drilling and onsite processing. Also, since natural gas is often produced together with oil, intensity factors of the two are often reported together. The quantity of water consumed for conventional natural gas extraction is approximately 0.42 m3/tce (Gu, et al., 2014). In some cases, the reported water intensity of gases is smaller, because a large portion of the gases are recovered as byproducts in industrial production processes (Zhang & Anadon, 2013). But the newly emerged hydraulic fracturing for shale gas highly depends on water input. Currently, the utilization of shale gas in China is still quite scarce, corresponding to an immature shale gas industry. But future transition from coal to gas could have significant influence on the water demand.

Table 4.2 Water Consumption Intensity for Primary Energy Production

Energy Type	China Specific Value				International Values [b]	Values Used
	m3/tce	m3/GJ	Source	Scope, Method [a]	m3/tce	m3/tce
Coal	0.35-0.42	0.012-0.014	Pan et al 2012	Mining, empirical data (Shanxi)	0.35	
	0.08-2.24	0.003-0.076	Pan et al. 2012	Mining, empirical data (national)	deep mining	
	0.14	0.005	Gu et al 2014	Mining & preparation, IO model		0.35
	0.188	0.006	Chang et al 2015	Onsite mining & washing, IO-based hybrid LCI		
	0.261	0.009	Zhang & Anadon 2013	Mining, IO model		
Oil	0.762	0.026	Williams & Simmons 2013	Onshore oil production, empirical data (Eurasia)	0.188 m3/tce onshore extraction	0.762
	0.42	0.014	Gu et al 2014	Petroleum drilling, IO model	3.5 m3/tce	
	0.771	0.026	Zhang & Anadon 2013	Oil extraction, Mining, IO model	EOR	
Natural Gas	0.42	0.014	Gu et al 2014	Natural gas drilling, IO model	0.188 m3/tce gas processing; negligible for gas extraction;	0.42
	0.278	0.01	Zhang & Anadon 2013	Natural gas extraction, IO model	0.232 m3/tce	
	0.762	0.026	Chang et al 2015	Shale gas, IO-based hybrid LCI		

a: Water intensity factors usually come from two ways: 1) empirical data (such as industrial survey or government report or standard), and 2) input/output (IO) analysis.
b: Source: World Energy Council 2012, Gleick 1994, Meilke et al 2010.

Table 4.3 Water Consumption Intensity for Electricity Generation (unit m3/MWh)

Technology		China Specific Value				International Values		Value Used
		Direct Intensity	Life-cycle Intensity	Source	Scope, Method	Gleick 1994	Macknick et al. 2011	
		2.85		Pan et al 2012	11th FYP target			
		1.35		Tan et al 2015	estimated based on CEC data			
		1.83		Yuan et al 2014	CEC data			
		2.0-2.2		Zhang C et al 2014	empirical			
	Closed Loop	1.95-2.31		Qin Y et al 2015	existing study			
		1.5-3.75		Jiang & Rmas 2015	sample survey-Shandong			
		1.47-2.36		Zhang & Anadon 2013	LCA/IO			
Coal		1.21-2.46	2.42-3.32	Feng et al 2014	LCA	1.9	1.526-2.124	1.83
			3.3	Li X et al 2015	LCA-Inner Mongolia			
		2.63		Chang Y et al 2015	LCA-China 2011			
	Air-Cooled	0.23-0.4		Qin Y et al 2015	existing study			
		0.29		Yuan et al 2014	CEC data			
		0.31		Yuan et al 2014	CEC data			
	Once-Through	0.23-0.29		Qin Y et al 2015	existing study			
		0.15-0.45		Jiang & Rmas 2015	sample survey			
		0.29		Yuan et al 2014	CEC data			
Oil		1.21-2.46	2.42-3.32	Feng et al 2014	LCA	1.85		1.83

Technology	China Specific Value				International Values		Value Used
	Direct Intensity	**Life-cycle Intensity**	**Source**	**Scope, Method**	**Gleick 1994**	**Macknick et al. 2011**	
Natural Gas	2.42 1.13		Feng et al 2015 Chang Y et al 2015	LCA Shale Gas	1.85	0.76-1.46	1.83
Nuclear	2.294 3.17	3.1	Feng et al 2016 Tan et al 2015	LCA existing study	2.7	0.379-3.201	2.29
Hydro	17.8 13		Feng et al 2017 Liu J et al 2015	LCA National survey data	17	5.398-17.01	13
Biomass	1.226 0.13-3.65	24.52	Feng et al 2018 Tan et al 2015	LCA existing study		0.133-2.095	1.226
Wind	0.1176 0 0.64	0.56 0.7 	Feng et al 2019 Tan et al 2015 Li X et al 2015 Li X et al 2012	LCA existing study LCA-Inner Mongolia 	0	0-0.004	0
Solar	0.5239 0.02 	1.69 0.9	Feng et al 2020 Tan et al 2015 Li X et al 2015	LCA existing study LCA-Inner Mongolia	0.1	0-0.125	0.02
Geothermal	0.02-2.73		Tan et al 2015	existing study		3.652-6.985	-

4.2.1.2 Water Intensity Factors for Electricity Generation

Table 4.3 shows the water intensity factors for electricity generation collected from literature. Water intensity varies significantly among different technologies.

- Thermal Power

In China, coal contributed to over 93% of thermal power generation in 2014. Depending on the cooling technology, the water intensity for coal power plants can range from 0.23 to 3.75 m^3/MWh. Coal power units with closed-loop cooling technology usually consume more than six times that of open-loop or air-cooled technologies (Yuan, et al., 2014). Meanwhile, studies also identified coal combustion technology (i.e., subcritical, supercritical, ultra supercritical, IGCC) as another element in determining its water efficiency (Qin, et al., 2015; Chang, et al., 2015; Yu, et al., 2011), although less influential compared to cooling technology.

Despite the wide range of water co-efficiency, the average water requirement keeps dropping throughout the years as a response to the water efficiency efforts made by the power sector. The 11th Five Year Plan (2006-2010) set up a water consumption target of 2.85 m3/MWh (Pan, et al., 2012). Although the goal seemed to be a challenge to many power plants at its inception, the efficiency efforts started to show promise a couple of years later. The *Water Efficiency Guide for Key Industrial Sectors*, issued by Ministry of Industry and Information Technology in 2013, reported that the total water use for thermal power generation was 2.45 m^3/MWh (excluding once-through cooling) in 2010. Later on, the *China Electricity Industry Annual Report 2016* indicates that, as of

2015, the water consumption for thermal power generation dropped to a surprisingly low level of 1.4 m^3/MWh. In order to reflect the declining trend as well as the still widely spread closed loop systems, a median value of 1.83 m^3/MWh was used in the analysis.

Compared to coal fired power systems, oil and natural gas-fired power plants consume relatively less water to generate one unit of electricity. A hybrid life cycle inventory model analysis suggests gas-fired technology is 34% to 60% lower than currently dominant coal-fired system in China (Chang, et al., 2015). But, currently, less than 7% of electricity in China comes from the burning of natural gas. Existing studies on the water associated with natural gas power generation in China are also less frequent. Given the limited data and market share of natural gas, this study used the intensity factor for coal (1.83 m^3/MWh) for all thermal power generation.

- Nuclear

Nuclear power plants usually have higher water intensity, compared to thermal power plants. AP-1000, the most favorable model in China's inland nuclear expansion, requires up to 3.17 m^3 of water to generate one MWh of electricity (Ding, et al., 2014; Tan, et al., 2015). The study of Feng et al (2014) reflects a water consumption intensity of 2.29 m^3/MWh during electricity generation, contributing to 74% of the life cycle water consumption of nuclear power plants. This value is slightly below the median value reported by Macknick et al. (2011) and was used in the WEF analysis.

Although water withdrawal is not covered by the scope of this study, it is worth mentioning that water withdrawal of nuclear power plants, especially the ones with once-through cooling technology, is gigantic, ranging from 95 m^3/MWh to 227 m^3/MWh

(Macknick, et al., 2011). This could cause severe fresh water conflicts among different water users.

- Renewable Energy

Enormous water is consumed for hydropower generation through evaporation. Liu et al. (2015) investigated the hydroelectric water footprint in China by surveying the water consumption of 209 hydropower plants (representing 53% of total hydro capacity in China) and found an average intensity of 13 m^3/MWh (Liu, et al., 2015). This number is slightly lower than the U.S. intensity of 17 m^3/MWh (Gleick, 1994), but falls into the range reported by Mackinick et al. (2011).

Other renewable energy technologies, such as solar and wind, are often regarded as needing zero or negligible amount of water for power generation (Cai, et al., 2014). As a comparison, Table 4.3 includes a couple of intensity factors considering both direct and indirect water use for solar and wind power. Even after adding the indirect use, the water intensity for solar or wind power are still much lower than those of thermal power.

If considering the upstream water use (i.e., crop irrigation), biomass would rank first in terms of water consumption for power generation (Feng, et al., 2014). The water footprint of bio-energy can be 70 to 400 times larger than that of traditional energy mix (Gerbens-Leenes, et al., 2009). It is estimated that the current use of biomass in China come mostly from crop residue and kitchen waste without additional water consumption (Cai, et al., 2014).

4.2.2 Energy Intensity Factors for Water Supply and Treatment

The entire life cycle of water supply and treatment require significant amounts of energy. This study divides the water life cycle into four major energy-consuming components, including water extraction (including surface, ground water, and alternative sources), water treatment and distribution, end-uses, and wastewater treatment. The energy input for each stage is mainly electricity, with the exception of the end use part.

It is notable that this study does not take into account the energy for end water use. Admittedly, a large amount of energy is needed for end uses, such as household water heating. But data availability in this field is quite limited. Moreover, energy for end uses is not directly related to resource management and there is still a debate on whether energy for end water use should be considered as part of energy for the water supply cycle (Hu, et al., 2013). Thus, it is not included here.

Table 4.4 Energy Intensity Factors for Water Supply Cycle

Unit: kWh/m3		Intensity	Source	Scope	International Comparison			Value Used
					EPRI 2002	WBCDS 2009	Plappally & Lienhard, 2012	
Water Sourcing	Surface Water	0.19	Wang 2008	Anqing, Anhui	0.08	0.37	0.02-0.05 (pumping)	0.19
		0.009-0.023	Gao 2012	agriculture				
		0.069-0.23	Gao 2012	urban water				
		0.43	Tan et al 2015	Qingdao, Shandong				
	Groundwater	0.78	Tan et al 2015		0.18-0.20	0.48	0.14-0.69	0.40
		0.19-0.42	Gao 2012					
		0.40	Wang et al 2012	survey, depend on the local ground water level				
	Desalination	3.5	Xie 2009		-	2.58-8.5	-	3.5
		1.4	Tan et al 2015	Brackish water				
		4	Tan et al 2015	Seawater				
	Recycled Water	0.82	Tan et al 2015	Qingdao, Shandong	-	1-2.5	-	0.82
		0.2-1.5	Gao 2012					
	Water Transfer	0.0045/km	Gao 2012		-	-	0.004-0.005 (per km)	0.5 in-province 1.8 inter-province
		0.7-1.14	Tan et al 2015	Qingdao, Shandong				
Water Treatment & Distribution		0.29	Smith 2015	Urban Water Plants	0.37-0.48	-	0.184-0.47	0.40
		0.189	Wang 2008	Anqing, Anhui				
		0.20, 0.40, 0.47	Gao 2012	Urban Water Plants				
Wastewater Treatment (& collection)		0.29	Yang et al 2008	559 WWTPs	0.25-0.50	0.62-0.87	-	0.30
		0.1-0.4	Gao 2012	Representative examples				
		0.30	Yu et al 2014	National average				
		0.2	Li et al 2015	Shenzhen, Guangdong				

- Surface Water Extraction

Energy is needed to extract water from different water sources (river, lake, reservoir) for direct use or further treatment. For some water uses, like agricultural irrigation, water is often pumped from the surface water body and moved directly to the irrigation area, with an average distance of 2-5 km, which implies a minimal energy intensity of 0.009-0.023 kWh/m^3 (Gao J. , 2012). But municipal water supply systems often locate at a distance from the water sources and require extra power to maintain the water pressure in order to reach the water treatment plants. Depending on the distance and water head need, water intensity for surface water extraction varies. It is reported that Qingdao (a water scarce city in Shandong) consumes 0.43 kWh/m^3 (Tan, et al., 2015) for surface water production, whereas Anqing (a city in Anhui) uses 0.19 kWh/m^3 (Wang X. , 2008).

- Groundwater Pumping

Groundwater supply often requires about 30% more electricity than surface water supply on a unit basis (EPRI, 2002). In water-stressed areas, especially the northern China, the lift height acts as a determinant factor to energy intensity of groundwater pumping. Wang et al. (2012) surveyed 366 villages in 11 provinces in China and reported a median value of 0.40 kWh/m^3 for groundwater pumping for irrigation. This value is comparable to international cases listed in Table 4.4, but approaching the higher end. It makes sense because most of the Chinese data were based on northern China, which experienced big groundwater level drops after years of overexploitation.

- Desalination & Wastewater Recycle

Seawater desalination and wastewater recycling have gradually become viable alternative water sources in China, but the process of which can be energy exhaustive. Desalination is the most energy-intensive water sourcing approach that consumes up to 3.5 kWh/m^3 to produce freshwater from seawater (Xie, 2009). The minimum energy input is typically proportional to the salinity of the water and highly depends on the desalting technology used (Plappally & Lienhard V, 2012). Typically, it takes more energy to desalinate brackish water (1.4 kWh/m^3) than seawater (4 kWh/m^3) (Tan, et al., 2015). But current utilization of desalination is still quite limited to a few coastal provinces in China. Wastewater recycling, on the other hand, is gaining more popularity in many provinces, with a relatively moderate energy intensity of 0.2-1.5 kWh/m^3 (Gao J. , 2012).

- Water Transfer

Considering the magnitude of inter-basin water transfer in China, it is necessary to account for the electricity consumption for long-distance conveyance, which requires additional power input than traditional surface water extraction. The conveyance distance plays a key role in determining the energy intensity of water transfer. For instance, it requires 0.7 kWh/m^3 of energy to transfer water from the Yellow River to Qingdao, a megacity in Shandong Province, compared to the energy need of 1.14 kWh/m^3 to divert from the Yangtze River, located further away (Tan, et al., 2015). Using empirical hydraulic formula for long-distance transfer, Gao (2012) found that both the South-to-North Water Transfer Project and the Luan-Jin Project consume approximately 0.0045 kWh of electricity to deliver 1 m^3 of water for 1 km. This value is similar to the transfer intensity in U.S. and Spain of 0.004-0.005 kWh/m^3/km (Plappally & Lienhard, 2012). Based on the weighted distance of existing inter- and intra-province transfer projects, the average electricity intensity for water transfer is assumed to be 1.8 kWh/m^3 for inter-province transfer, and 0.5 kWh/m^3 for inter-basin transfer within the province.

- Water Treatment & Distribution

Prior to the distribution, water for industrial or domestic use needs to be treated to meet the water quality standards. Technically, domestic water supply has higher energy factors than those of industrial water due to the higher drinking water standard (Sanders & Webber, 2012), but most studies grouped the two users together into one category under municipal or public water supply. After the treatment, a non-trivial amount of electricity consumption occurs during the distribution process to maintain stable water pressure. The stage of water distribution can comprise 80%-90% of the total energy need of urban water supply systems (Gao J. , 2012). This is particularly true for public water supply systems with a long-distance distribution network. A breakdown analysis of Wang X. (2008) shows that only 0.004 kWh/m^3 is required for water treatment, whereas 0.185 kWh/m^3 is consumed by the distribution pumping. Another empirical study reveals that the electricity use for urban water supply in China in 2011 was 0.29 kWh/m^3, including the electricity for abstraction and conveyance of source water and treatment and water distribution system (Smith, et al., 2015).

Energy intensity of water treatment & distribution is also connected with the size of water system, and more specifically, the efficiency of the pumps. Large systems are typically equipped with more advanced pumps that yields a lower energy intensity. As shown in Table 4.4, the reported Chinese values lie within the range of U.S. and international values. However, there is a lack of data on rural public water supply systems with smaller scale, lower pump efficiency, higher water leakage ratio, and possibly longer distribution distance. To incorporate the rural element, a national average of 0.40 kWh/m^3 is assumed for the following calculation.

- Wastewater Collection & Treatment

As the last step of the water supply cycle, wastewater collection and treatment is also energy intensive, in many cases, requiring more energy than the upstream. Currently, the activated sludge process is the major technology adopted by most Chinese sewage treatment plants, which results in an average energy consumption of sewage treatment of 0.30 kWh/m^3 (Yu, et al., 2014). The result is comparable to the findings of other studies of 0.29 kWh/m^3 (Yang, et al., 2008; Gao J. , 2012). Li et al. (2013) reported an even lower energy requirement of 0.20 kWh/m^3 for wastewater treatment in Shenzhen, one of the most advanced cities in China. The values of Chinese cases are lower than the reported California value of 0.29-1.2 (U.S. Department of Energy, 2016) or the international average of 0.62-0.87 (WBCSD, 2009). Such deviation is reasonable considering that most of Chinese wastewater treatment facilities were recently built and use more up-to-date technology with higher efficiency.

4.3 Results

4.3.1 Water for Energy

4.3.1.1 Water Consumption for Indigenous Energy Production

Water consumption for indigenous energy production (WFE_{in}) is estimated by combining water for indigenous fossil fuel production (WFE_{ff}) with water for indigenous electricity generation (WFE_{elec}). In 2014, the total water input for energy production in China was 23,109 million m^3, representing 3.8% of the country's total annual water use. Among that, 1,282 million m^3 of water was due to fossil fuel mining and extraction, while 21,827 million m^3 of water was associated with power generation (see Table 4.5). The result shows that China's power sector consumes more than ten times the water for its primary fossil fuel production, reflecting a strong water dependency for power generation.

Among the WFE_{ff}, coal mining represents the highest water consumption (76%), followed by oil (19%) and natural gas (6%) (See Table 4.5). Such composition of WFE_{ff} corresponds mostly to China's fossil fuel mix, since water intensities for coal, oil and natural gas are close to each other. On the other hand, the composition of WFE_{elec} does not follow the generation mix because of the significant variation among water intensities of different technologies. While hydropower produced only 19% of total electricity in 2014, it contributed to a majority of WFE_{elec} of 63%, given its exceptionally high water intensity. But the magnitude of water consumption for thermal power should not be overlooked, as water for thermal power requires even larger amount of direct water withdrawal.

Table 4.5 Water Consumption for Energy Production by Province in 2014 (unit: million m^3)

Province	WFE	WFE_{ff}				WFE_{elec}				
		Sub	Coal	Oil	Natural Gas	Sub	Thermal	Nuclear	Hydro	Other
Beijing	76	1	100%	0%	0%	75	88%	0%	12%	0%
Tianjin	145	34	0%	97%	3%	111	100%	0%	0%	0%
Hebei	445	26	72%	25%	3%	420	96%	0%	4%	0%
Shanxi	741	233	99%	0%	1%	507	91%	0%	9%	0%
Inner Mongolia	934	264	94%	1%	5%	670	93%	0%	7%	0%
Liaoning	353	24	52%	46%	2%	329	75%	8%	17%	0%
Jilin	222	16	48%	45%	6%	206	56%	0%	44%	0%
Heilongjiang	237	63	28%	69%	3%	174	84%	0%	16%	0%
Shanghai	147	0	0%	39%	61%	146	100%	0%	0%	0%
Jiangsu	811	7	69%	31%	0%	804	93%	5%	2%	0%
Zhejiang	773	-	-	-	-	773	55%	10%	34%	0%
Anhui	446	32	100%	0%	0%	414	87%	0%	13%	0%
Fujian	807	4	100%	0%	0%	803	29%	4%	67%	0%
Jiangxi	315	7	100%	0%	0%	308	44%	0%	56%	0%
Shandong	738	66	55%	44%	0%	671	99%	0%	1%	0%
Henan	637	41	87%	12%	1%	595	79%	0%	21%	0%
Hubei	1,987	4	74%	24%	2%	1,983	9%	0%	91%	0%
Hunan	788	14	100%	0%	0%	774	18%	0%	82%	0%
Guangdong	1,056	17	0%	78%	22%	1,038	52%	12%	36%	0%
Guangxi	944	2	70%	29%	0%	942	13%	0%	87%	0%
Hainan	72	0	0%	81%	19%	72	55%	0%	45%	0%
Chongqing	404	12	81%	0%	19%	392	20%	0%	80%	0%
Sichuan	3,483	31	62%	1%	38%	3,452	3%	0%	97%	0%
Guizhou	1,199	46	100%	0%	0%	1,153	17%	0%	83%	0%
Yunnan	2,792	12	100%	0%	0%	2,780	3%	0%	97%	0%
Shaanxi	510	191	69%	22%	10%	319	71%	0%	29%	0%
Gansu	616	20	58%	41%	0%	595	22%	0%	78%	0%
Qinghai	558	10	45%	24%	31%	548	4%	0%	96%	0%
Ningxia	238	21	100%	0%	0%	216	89%	0%	11%	0%
Xinjiang	609	81	45%	38%	17%	528	61%	0%	39%	0%
Total	23,109	1,282	76%	19%	6%	21,827	35%	1%	63%	0%

At the provincial level, WFE_{in} reveals directly how much water was consumed within a province for energy production. Figure 4.3 shows the water for energy production and the share of WFE_{ff} and WFE_{elec} in each province. Overall, the provincial review indicates a strong regional variation of WFE_{in}, ranging from the highest of 3,483 million m^3 in Sichuan to the lowest of 72 million m^3 in Hainan. Looking at the WFE_{ff} and WFE_{elec} separately, we can see that WFE_{elec} plays a dominate role in determining the magnitude of WFE_{in}. In most provinces, the share of WFE_{elec} is above 90%, whereas the portion of WFE_{ff} is visible only in the largest fossil fuel producing provinces, like Shanxi, Inner Mongolia, Shaanxi, Xinjiang and Heilongjiang.

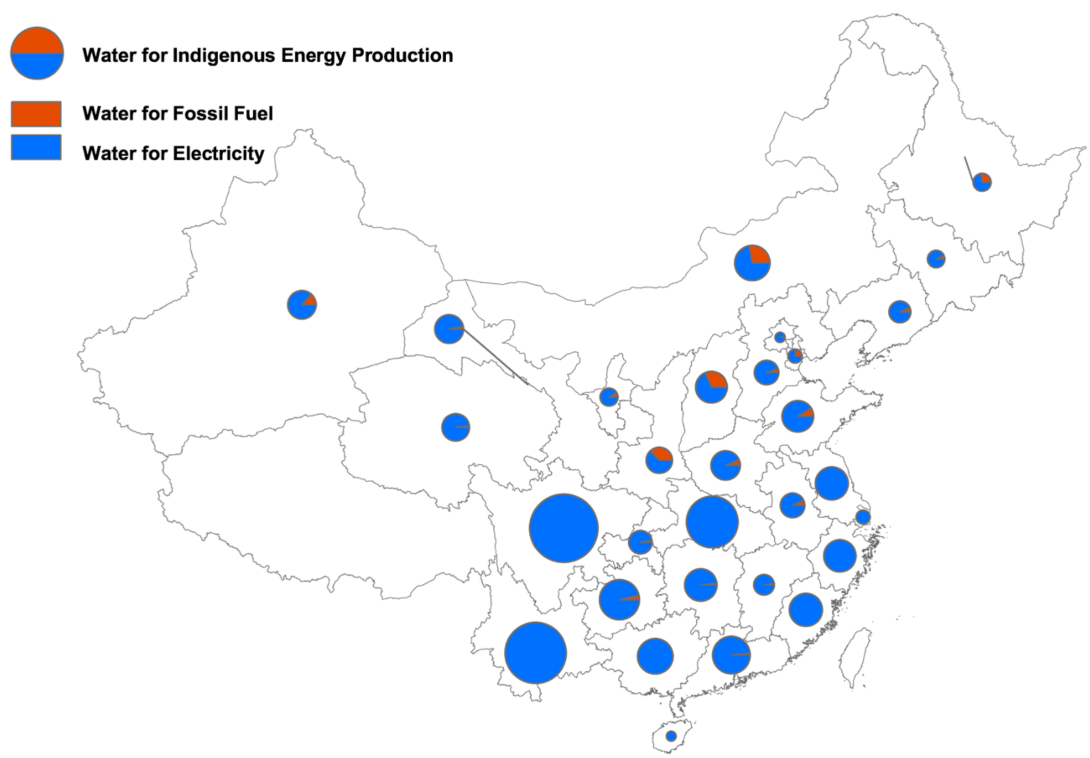

Figure 4.3 Distribution of Water for Indigenous Energy Production

Provinces with higher WFE_{in} are either the resource center or demand center. The top three provinces, i.e., Sichuan (3,483 million m^3), Yunnan (2,792 million m^3) and Hubei (1,987 million m^3), are all known for their tremendous hydropower capacities. Several provinces in North and Northwestern China have a large volume of water consumption because of their abundant fossil fuel production, such as Shanxi (741 million m^3), Inner Mongolia (934 million m^3), and Xinjiang (609 million m^3). Other provinces ranked high on WFE_{in} are mostly due to the cooling water needed for the huge local thermal power generation. Representative examples include Jiangsu (811 million m^3), Zhejiang (773 million m^3) and Guangdong (1056 million m^3). In several of these big energy-producing provinces, water consumption for energy is equivalent to over 40% of total annual industrial water use, led by the fossil fuel bases of Shanxi (52.2%), Inner Mongolia (47.4%) and Xinjiang (45.8%), and hydropower bases of Sichuan (77.9%), Guizhou (43.3%) and Yunnan (113.5%).

4.3.1.2 Virtual Water Inflow/Outflow

In addition to the water for indigenous energy production (WFE_{in}), this study also traces the virtual water flow (VW) associated with energy transfer within the country. Table 4.6 divided all the provinces into two categories by their virtual water balance, the net virtual water importer and exporter. Among all the thirty provinces, 13 of them are net virtual water exporters, while the other 17 provinces are net virtual water importers. Most of the virtual water exporters are located in North, Northwest and Southwest China. The largest virtual water importers, as expected, are the most energy intensive and populated areas, located in East, Central and South China.

Table 4.6 Virtual Water Balance

Region	Provinces with Virtual Water Import	Provinces with Virtual Water Export
North China	Beijing (3.09), Tianjin (0.39) Hebei (0.87)	Shanxi (-0.46) Inner Mongolia (-0.76)
Northeast	Liaoning (0.65)	Jilin (-0.06), Heilongjiang (-0.36)
East China	Shanghai (1.66), Jiangsu (0.41) Zhejiang (0.37), Fujian (0.00) Jiangxi (0.21), Shandong (0.31)	Anhui (-0.36)
Central China	Henan (0.31), Hunan (0.13)	Hubei (-0.08)
South China	Guangdong (0.62), Guangxi (0.03) Hainan (0.07)	
Southwest	Chongqing (0.20)	Sichuan (-0.11), Guizhou (-0.19) Yunnan (-0.14)
Northwest	Qinghai (0.09)	Shaanxi (-0.51), Gansu (-0.07) Ningxia (-0.48), Xinjiang (-0.18)

Table 4.6 also specifies the ratio of virtual water flow (+/-) to water for indigenous energy production (WFE_{in}) in order to reflect the magnitude of provincial water interdependency. For energy importing regions, the higher the ratio is, the stronger external water dependency it has; for energy exporting regions, a lower negative ratio represents heavier water burden placed by other provinces. For example, Beijing has the highest virtual water import ratio of 3.09, meaning that virtual water inflow via energy import is more than three times the local water consumption for energy. In other words, 75% of Beijing's energy supply relied on outside water. Inner Mongolia, on the contrary, has the lowest ratio of -0.76, which suggests that 76% of WFE_{in} ended up flowing into other regions in the form of virtual water.

Similar to WFE_{in}, virtual water flow is also closely linked with energy resource availability. A general trend is that North and Northwest China are the major virtual water exporter via primary fossil fuel exports, and Southwest China exports virtual water through their export of enormous hydropower. On the importing side, the huge gap between energy supply and demand in many populous areas have resulted in heavy external water dependency. The top three single virtual water importers are Guangdong (657 million m^3), Hebei (389 million m^3), and Jiangsu (330 million m^3).

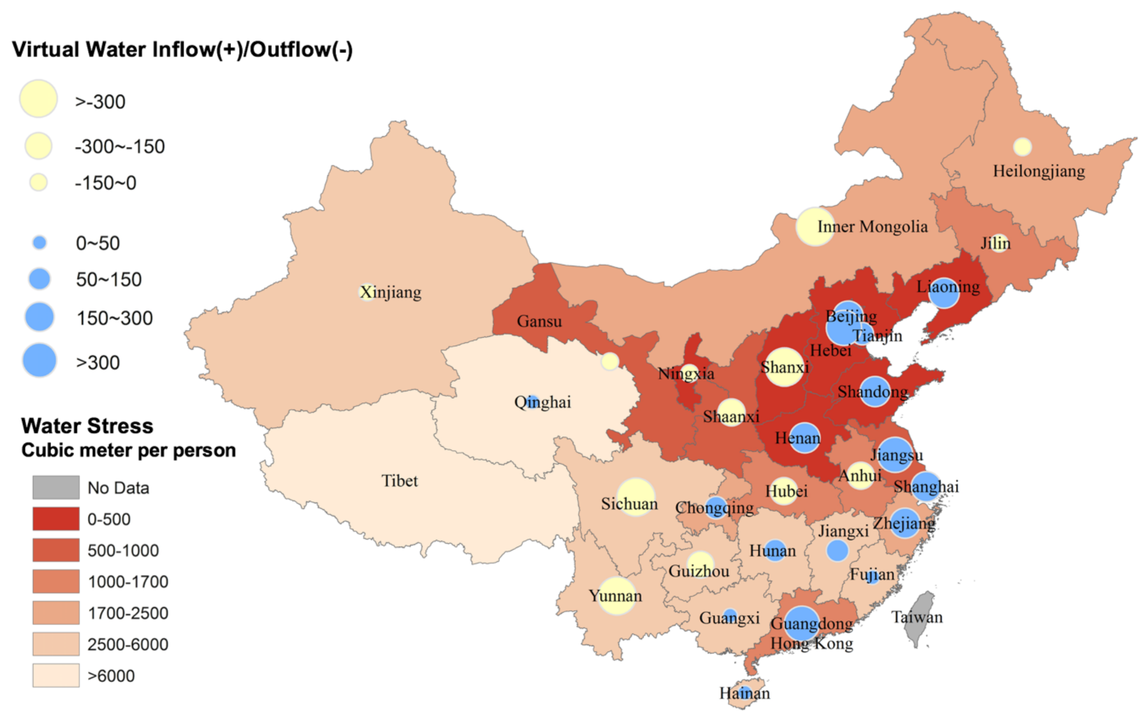

Figure 4.4 Virtual Water Flow Associated with Inter-Provincial Energy Transfer

Figure 4.4 maps virtual water flow against the local water resource availability. It shows that the water-scarce North China Plain is importing virtual water, and water abundant Yunnan-Guizhou-Sichuan (Y-G-C) regions are exporting virtual water. This mechanism can help reallocate the water resource and mitigate the water shortage in water scarce regions. However, this is only half of the story. Figure 4.4 also reveals an alarming situation that most of the provinces that export virtual water via thermal power or fossil fuel export, like Shanxi, Shaanxi, Ningxia and Inner Mongolia, are experiencing water stress or, even worse, water scarcity. Virtual water importing provinces, including Zhejiang, Jiangxi, Guangxi, and Hunan, etc., on the other hand, possess higher than average per capita water resources. This implies that areas with water shortage are pumping their precious water to support other regions' energy need. Producing fossil fuel or thermal power for others have obviously caused an extra burden on the local water system of these provinces. Such a situation raises concern on the justification of the current energy utilization pattern in China.

4.3.2 Energy for Water

4.3.2.1 Energy for Water Supply & Treatment

The result of EFW_{in} analysis is presented in Table 4.7. In 2014, a total of 249 TWh of electricity was used for water supply and treatment in China. The EFW_{in} contributed to 4.5% of the country's total annual electricity consumption. During the entire water cycle, water sourcing has the largest share of electricity consumption (59.9%), followed by the water treatment & distribution (34.1%) and wastewater collection & treatment (6.0%). This share is slightly bigger than the U.S. case of 4% projected by the Electric Power Research Institute (EPRI, 2002), but is below the UN's international estimation of 8% (UN Water, 2014).

Table 4.7 Electricity Consumption for Water Production by Province in 2014

Province	EFW_{in}	$EFW_{Sourcing}$					$EFW_{T\&D}$		EFW_{Waste}	
	10^8 kWh	10^8 kWh	%	Surface Water	Ground-water	Other	10^8 kWh	%	10^8 kWh	%
Beijing	**28**	**17**	58%	*10%*	*47%*	*43%*	**9**	31%	**3**	11%
Tianjin	**15**	**9**	59%	*40%*	*25%*	*35%*	**4**	29%	**2**	13%
Hebei	**95**	**70**	73%	*13%*	*82%*	*6%*	**19**	20%	**6**	7%
Shanxi	**43**	**29**	68%	*21%*	*48%*	*30%*	**11**	25%	**3**	7%
Inner Mongolia	**69**	**55**	79%	*31%*	*66%*	*3%*	**12**	17%	**2**	3%
Liaoning	**75**	**50**	67%	*30%*	*46%*	*24%*	**19**	25%	**5**	7%
Jilin	**54**	**35**	66%	*47%*	*51%*	*2%*	**16**	30%	**3**	5%
Heilongjiang	**126**	**105**	83%	*36%*	*64%*	*0%*	**19**	15%	**3**	2%
Shanghai	**61**	**20**	33%	*100%*	*0%*	*0%*	**36**	59%	**5**	8%
Jiangsu	**248**	**119**	48%	*92%*	*3%*	*5%*	**116**	47%	**12**	5%
Zhejiang	**87**	**38**	44%	*94%*	*2%*	*3%*	**40**	46%	**9**	10%
Anhui	**118**	**63**	53%	*73%*	*19%*	*8%*	**50**	42%	**6**	5%
Fujian	**89**	**41**	46%	*92%*	*6%*	*1%*	**43**	48%	**5**	6%
Jiangxi	**92**	**52**	57%	*90%*	*7%*	*3%*	**35**	38%	**4**	5%
Shandong	**131**	**95**	73%	*24%*	*36%*	*40%*	**25**	19%	**11**	8%
Henan	**118**	**75**	64%	*22%*	*63%*	*14%*	**34**	29%	**9**	7%
Hubei	**115**	**57**	49%	*93%*	*6%*	*0%*	**52**	45%	**6**	5%
Hunan	**125**	**67**	53%	*89%*	*11%*	*0%*	**52**	41%	**6**	5%
Guangdong	**192**	**88**	46%	*91%*	*7%*	*2%*	**85**	44%	**19**	10%
Guangxi	**104**	**61**	59%	*91%*	*8%*	*1%*	**38**	37%	**5**	4%
Hainan	**15**	**9**	63%	*86%*	*13%*	*1%*	**5**	31%	**1**	6%
Chongqing	**41**	**16**	38%	*96%*	*4%*	*1%*	**22**	54%	**3**	7%
Sichuan	**91**	**50**	54%	*83%*	*14%*	*3%*	**35**	38%	**7**	8%
Guizhou	**40**	**20**	50%	*87%*	*6%*	*8%*	**18**	44%	**2**	6%
Yunnan	**52**	**31**	60%	*88%*	*7%*	*5%*	**18**	34%	**3**	6%
Tibet	**8**	**7**	84%	*77%*	*23%*	*0%*	**1**	14%	**0**	1%
Shaanxi	**40**	**25**	63%	*42%*	*54%*	*4%*	**12**	30%	**3**	8%
Gansu	**41**	**31**	76%	*56%*	*36%*	*8%*	**8**	21%	**1**	3%
Qinghai	**8**	**6**	71%	*74%*	*24%*	*2%*	**2**	24%	**0**	6%
Ningxia	**18**	**15**	81%	*84%*	*15%*	*1%*	**3**	15%	**1**	4%
Xinjiang	**151**	**139**	92%	*61%*	*38%*	*1%*	**10**	7%	**2**	1%
Total	**2,490**	**1,493**	60%	*63%*	*30%*	*7%*	849	34%	**148**	6%

Although the water sector is not among the largest electricity consumers at the national level, the EFW_{in} consists of over 8% of total power consumption in a few provinces, such as Heilongjiang (17.9%), Jiangxi (9.1%) and Hunan (8.3%), owing to their specific water environment and industrial structure.

Within the water sourcing phase, over 62.6% of electricity use was associated with surface water extraction, while 29.9% went to groundwater pumping. Although the alternative water resources, including seawater desalinization, water recycling and water transfer, provided only less than 3% of total water supply in 2014, the energy used is more than 7% of $EFW_{Sourcing}$ due to the energy intensive feature of alternative water sourcing. Unique characteristics of the water system in each province have led to their different EFW_{in}. But, in general, the sources of water supply have powerful influences over EFW_{in}, in some cases, even reversing the rank of $EFW_{Sourcing}$. For instance, although Heilongjiang is not one of largest water suppliers, its exceptionally high groundwater usage (16800 million m^3) has resulted in an extremely high power consumption.

The electricity for water treatment & distribution falls into a reasonable range of around 34%. The composition of different end users has a great play in determining the magnitude of energy intensity of $EFW_{T\&D}$. Agricultural water, especially irrigation, has a relatively lower water intensity, as it does not require water treatment and often are pumped onsite or near the irrigation area. On the contrary, domestic water use, although typically contributes to a small share of total water use, is much more energy intensive, especially in urban areas with higher water quality standards and longer distribution systems. As a result, the share of $EFW_{T\&D}$ in EFW is comparatively lower in major agricultural provinces, such as Xinjiang (7%), Heilongjiang (15%), Hebei (20%), but higher in more industrialized and urbanized areas, like Jiangsu (47%), Shanghai (59%), Zhejiang (46%).

Lastly, the wastewater collection & treatment used 14.8 TWh of electricity, making up only 6% of total EFW_{in}. This portion is extremely low, compared to the U.S. case of 52% (EPRI, 2002). Even in Beijing and Shanghai, areas with the highest wastewater treatment rates, EFW_{Waste} is only 11% and 8%, respectively, corresponding to an annual per capita intensity of 14 kWh and 19 kWh.

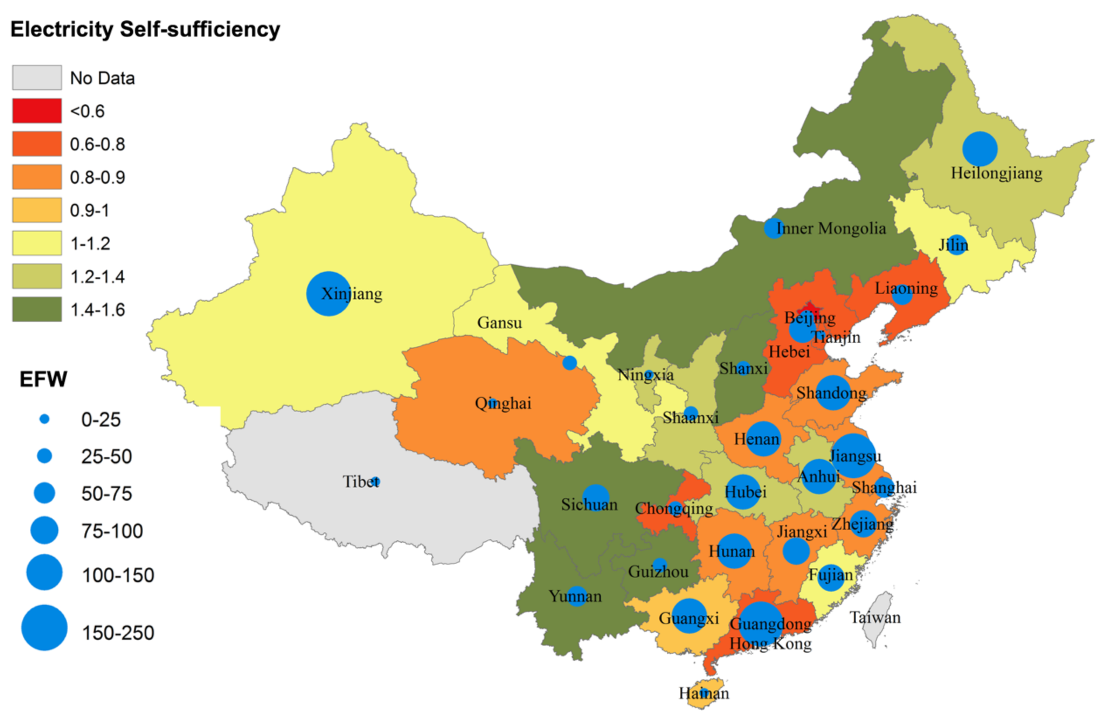

Figure 4.5 Distribution of EFW and Electricity Self-sufficiency

Figure 4.5 visualizes the links between the provincial EFW and the electricity self-sufficiency. It is evident that the power sector is bearing big responsibility as the driving force for water supply. In the energy-poor provinces, water supply has undoubtedly added more pressure to their already constrained electricity systems. We can easily spot a handful of provinces with large EFW_{in} that relied heavily on electricity import.

4.3.2.2 Embodied Energy for Water Transfer

As a vehicle of resource exchange, embodied energy via larger scale inter-basin water transfer ($EFW_{Transfer}$) is another focal point of this WEN analysis. It is valuable to discuss it in greater detail, given its high popularity in China. Before expanding the discussion, it should be noted that the result of $EFW_{Transfer}$ is subject to the limited data availability. It is to the author's knowledge that major transfer projects are taken into consideration. Exceptions may exist due to lack of publicly-accessible data.

Table 4.8 Energy for Large-Scale Inter-Basin Water Transfer

Region	**Province**	**Energy for In-Province Transfer**	**Energy for Inter-Provincial Transfer**
North	Beijing		1.4
	Tianjin		19.6
	Shanxi	6.0	
Northeast	Liaoning	8.9	
	Jilin	0.15	
East	Anhui	3.4	
	Shandong	31.3	0.36
Central	Henan	9.6	
	Hubei	0.14	
Southwest	Guizhou	0.22	
	Yunnan	0.57	
Northwest	Gansu	1.1	0.4

Table 4.8 lists two types of embodied energy. For inter-basin transfer took place within a province, the embodied electricity remained within the province. The portion of electricity consumption is already included in $EFW_{sourcing}$ as part of alternative water resources in Table 4.7. But for inter-provincial transfer projects, embodied electricity moved into the water recipient areas. While admitting the cross-national impact of large water transfer projects, it is difficult to depict the flow of embodied energy between provinces, as it is hard to actually separate the electricity used along the water transfer route. Therefore, only provinces that imported embodied energy are listed. Overall, there is hardly a clear pattern for the spatial distribution of transfer, although the volume of transfer is relatively small in southwest and south China.

A more important implication of $EFW_{Transfer}$ is its relationship with local electricity availability. Among the four provinces receiving embodied energy from outside, three of them also have low energy self-sufficiency. It appears that the water transfer helps the water scarce provinces with their water shortage and eases local energy stress by importing embodied energy. But such improvement comes at the cost of another province's energy and water systems. If one digs deeper, one can find an astonishing fact that most of the embodied energy is imported from energy importing provinces. Tianjin serves as a good example to explain this situation. It imported embodied energy from Hebei, also an electricity-deficient province. This means a third energy-producing province has to work harder and produce more extra power in order to support the water transfer between Hebei and Tianjin. In another case of Jiangsu province, as one of the origins of the SNWT project, it contributed a large share of the embodied electricity flowing into Beijing, but Jiangsu itself has to survive on electricity imports from several provinces. Such kind of resource transfer seems to mitigate the supply-demand conflict in resource-scarce areas, but what is behind is a vicious cycle and a waste of resources. Despite the limited quantitative analysis, the current results have pointed out the significance of embodied energy transfer and its potential to worsen the current water-energy condition in a region.

4.3.3 Comparisons of Water-for-Energy and Energy-for-Water

In order to directly compare WFE_{in} and EFW_{in} using a uniform unit, this study estimated the corresponding economic value of the water and energy inputs in per capita terms. On average, the electricity spent in the water sector in 2014 was equivalent to 120.3 yuan per capita, while the cost of water input for energy production equaled to 48.7 yuan per capita.

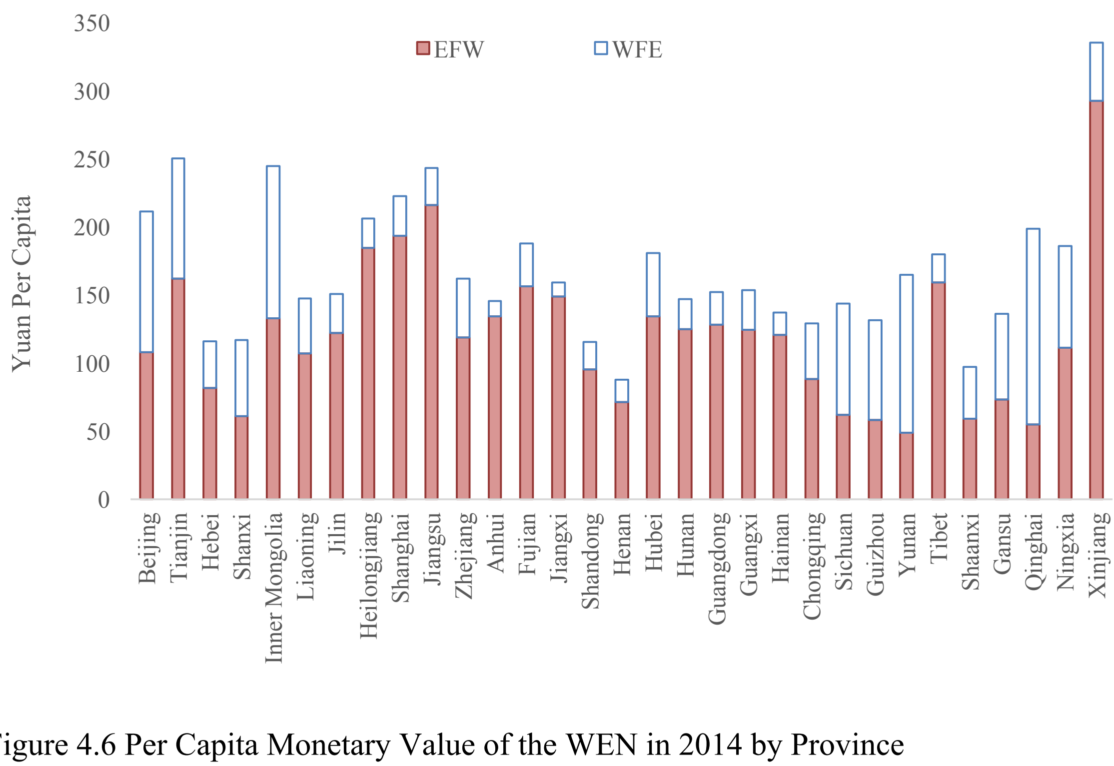

Figure 4.6 Per Capita Monetary Value of the WEN in 2014 by Province

It is evident that in most provinces energy spending for water has a larger economic magnitude, compared to water input for energy. This fits an institutive thinking that electricity is the single largest component in water cost, while water is a less important ingredient for energy production. Meanwhile, Figure 4.6 also shows the cost of WFE can be just as significant as that of EFW in some provinces, including the major fossil fuel and electricity exporters (Shanxi and Inner Mongolia), large hydro power producers (Yunnan, Sichuan and Guizhou (Y-G-C region), as well as Qinghai), and the extremely water scarce areas (like Beijing, Gansu and Ningxia). This comparison of WFE and EFW highlights the importance of the bi-direction of the nexus issue from the economic perspective. It also suggests that the often-ignored linkage of energy-for-water could potentially have significant environmental and economic implications, especially in major food bases that require large amount of water for irrigation.

4.3.4 Correlation between Variables

This section presents the results of correlation analysis between WFE and EFW and its influencing factors. All 22 provinces, 5 autonomous regions, 4 direct-controlled municipalities are included in the analysis for EFW. Tibet is excluded from the analysis for WFE due to insufficient data on water for fossil fuel production. Table 4.9 provides a summary of the correlation results.

Table 4.9 Correlation Results

		POP	Pop_{ur}	GRP	$GRP_{\%ag}$	Water Resource	Fossil Fuel Reserve	Electric Price	Water Price
WFE_{in}	Pearson Correlation	.394*	-.388*	0.152	0.221	.672**	0.049	-0.275	-0.324
	Sig. (2-tailed)	0.031	0.034	0.424	0.24	0	0.799	0.142	0.081
WFE_{ff}	Pearson Correlation	-0.098	-0.114	-0.12	-0.034	-0.226	.848**	-.367*	0.107
	Sig. (2-tailed)	0.607	0.55	0.526	0.859	0.229	0	0.046	0.575
WFE_{elec}	Pearson Correlation	.400*	-.376*	0.161	0.223	.689**	-0.026	-0.241	-0.332
	Sig. (2-tailed)	0.028	0.04	0.394	0.236	0	0.89	0.199	0.073
VW	Pearson Correlation	.390*	.415*	.587**	-.363*	-0.148	-.520**	.578**	0.044
	Sig. (2-tailed)	0.033	0.022	0.001	0.048	0.434	0.003	0.001	0.818
EFW_{in}	Pearson Correlation	.759**	0.09	.787**	-0.001	0.026	-0.093	0.242	-0.332
	Sig. (2-tailed)	0	0.629	0	0.996	0.892	0.621	0.189	0.068
$EFW_{sourcing}$	Pearson Correlation	.610**	-0.026	.582**	0.18	-0.051	0.025	0.035	-0.224
	Sig. (2-tailed)	0	0.891	0.001	0.332	0.786	0.892	0.853	0.227
$EFW_{T\&D}$	Pearson Correlation	.697**	0.194	.786**	-0.199	0.118	-0.212	.414*	-.384*
	Sig. (2-tailed)	0	0.295	0	0.284	0.527	0.251	0.021	0.033
EFW_{waste}	Pearson Correlation	.893**	0.235	.958**	-0.283	0.035	-0.149	.428*	-0.263
	Sig. (2-tailed)	0	0.204	0	0.123	0.851	0.425	0.016	0.153

*. Correlation is significant at the 0.05 level (2-tailed);

**. Correlation is significant at the 0.01 level (2-tailed).

- Analysis of Influencing Factors for WFE_{in}

There is a moderate positive relationship (r(30)=0.394, p=0.031) between population and WFE_{in}. However, coefficients for the relationship between WFE_{in} and the Pop_{urban} are r (30) = -388, p=0.034. It suggests that the higher urban population leads to lower WFE_{in}. This is linked to the fact that highly urbanized areas tend to import fossil fuel or electricity from outside and thus requires less local water for energy production. There is a positive relationship between water resource availability and WFE_{in}, while no relationship between fossil fuel and WFE_{in}. This is probably because the magnitude of water for cooling is overshadowing the water for fossil fuel production. Economic factors are less influential. There is no obvious relationship between GRP and WFE_{in} (r (30) =0.152, p=0.424) or between $GRP_{\%ag}$ and WFE_{in} (r (30) =0.2221, p=0.24), suggesting no influence from industrial structure.

The breakdown analyses on WFE_{elec} and WFE_{ff} provide a deeper understanding on how factors influence WFE_{in}. For both variables, the results demonstrate a strong resource dependency. WFE_{ff} is determined mostly by the fossil fuel reserves in the region (r (30) =0.847, p=0.00). There is no correlation between population or GRP and WFE_{ff}. On the other hand, WFE_{elec} is highly correlated with local water resource (r (30)=0.689, p=0.00). The significant relationship between WFE_{elec} and local water resource can be explained by the large proportion of water-intensive hydropower in the power mix. It is also the result of building power plants closer to water sources. For instance, nuclear power was only produced near water abundant coastal regions. The positive relationship (r (30) =0.394, p=0.031) between population and WFE_{elec} also prove that power plants are built near consumption.

It is interesting to note that a higher WFE is often associated with a lower water price, although less significant (r (30) = -0.324, p=0.081). It implies that water price can, to some extent, influence the water use in the energy sector. But, on the other hand, if one only looks at WFE_{ff}, one can find a moderate positive relationship (r (27) = 0.417, p=0.03) (exclude two outliners of Beijing & Tianjin) between WFE_{ff} and water price.

Such a relationship suggests that current water prices do not send an economic signal to control the water for fossil energy production.

- Analysis of Influencing Factors for EFW

Different from the strong resource dependency of WFE, EFW is significantly correlated with social-economic factors, namely population (r (31) = 0.759, p=0.00) and GRP (r(31)= 0.787, p=0.00). The local resource endowments, i.e., water resources and fossil fuel reserve, do not seem to have any statistically significant impact on the magnitude of EFW_{in}. It appears that the local water and energy availability do not form any restriction on the EFW_{in}. EFW_{in} in water-scarce provinces is not necessarily smaller than that in water abundant areas.

Similarly, the breakdown analyses of $EFW_{sourcing}$, $EFW_{T\&D}$, EFW_{waste} all suggest that population and GRP are the two principal factors. Again, there is no significant relationship between water availability and these EFW variables. $EFW_{sourcing}$ is complicated by the mix of water sources. In water-abundant provinces where surface water serves as a major source, the water sourcing is, sometimes, less energy demanding despite the large volume of water withdrawal. On the contrary, although the water withdrawal in water scarce provinces is smaller, the energy needs for that can be as large as that of the largest water consuming provinces, due to their reliance on groundwater. It is surprising to find a moderate negative relationship (r(31)= -0.384, p=0.033) between water price and $EFW_{T\&D}$. It means the provinces with higher water prices tend to have lower energy input for water treatment and distribution. One explanation could be that higher water prices typically lead to less domestic and industrial water usage, thus, lower energy input. The positive relationship between electricity price and EFW is also intriguing. Provinces with higher electricity prices tend to spend more power to treat water and wastewater. This may be explained by the significant positive correlation existed between electricity price and local economic level.

- Analysis of Influencing factors for Virtual Transfer

Virtual water flow (VW) are influenced by a series of socio-economic factors. First, there is a significant strong positive relationship (r (30) =0.587, p=0.001) between GRP and virtual water import and a moderate positive relationship (r (30) =0.390, p=0.033) between population and virtual water import. This shows a trend that virtual water is flowing into more populous and richer provinces, reflecting the resource dependency of China's economy. It is also interesting to see a moderate negative relationship (r (30) =-0.363, p=0.048) between $GRP_{\%ag}$ and virtual water import. Provinces with a higher share of agricultural production have less virtual water import through energy. This once again proves that more virtual water is flowing from less developed areas to more industrialized areas. In addition, fossil fuel endowment also has a significant negative impact on virtual water import (r (30) =-0.520, p=0.003). Despite the recent utilization of local renewable energy, lack of fossil fuel availability forces many provinces to import energy, and hence the associated virtual water. The role of electricity and water prices is also worth discussing. There is little relationship (r (30)=-0.044, p=0.818) between local water price and virtual water import. The hypothesis that higher water price might lead to more virtual water does not stand. But there is a significant positive relationship (r (30) = 0.578, p=0.001) between electricity price and virtual water import. It further shows that the energy resource scarcity is a main reason for virtual water import.

Due to lack of data, no correlation analysis was conducted to examine the influencing factors for $EFW_{Transfer}$. But it is almost obvious that local water resource acts as a dominant player.

4.4 Discussion

The dataset used in this study may contain some discrepancies due to statistical issues, as mentioned earlier. However, it is believed that these discrepancies are not large enough to compromise the results of this assessment. Furthermore, the examined water transfer projects did not fully represent the whole scope of water transfer in China and are not sufficient enough to support a correlation analysis. Also, due to lack of data, assumptions were used in several places, including the estimation of the annual production of desalinated seawater, the total volume of treated wastewater, as well as the generation mix of cross-provincial power flow. In order to minimize the potential error, all the assumptions are made based on existing empirical data or the national average value. Despite the data constraints, the analyses in this chapter still provide advisable insights on the current water-energy nexus in China.

The results above have demonstrated a strong water-energy interconnectedness at both the national and provincial levels. The provincial analysis shows huge regional variances of WEN, influenced by social-economic factors and resource availability. Population is a major indicator for provincial water consumption, energy consumption, and the magnitude of water-energy nexus. Strong resource interdependency can be witnessed in all highly-populated provinces. Meanwhile, the resource allocation closely follows the spatial pattern of the unevenly distributed economic accumulation. It suggests that the economic development across the country heavily relies on intensive water and energy consumption. Not a single province achieved major economic outcome without excessive water and energy input.

Such a resource-intensive development pattern has resulted in massive water and energy transfer among provinces, reflecting a modern version of a resource colony within the country. Provinces with higher urbanization and economic levels are built on intensive local resource consumption and outside resource transfer. A direct consequence is the overexploitation of indigenous resource and the regional invasion of resource. Raw materials are flowing across the country, moving from poorer regions to richer areas. Inside the richer regions, competition over resources is also fierce because of high population density. From the cross-sectoral perspective, we can see the energy sector is pumping up scarce water in water short regions, whereas water supply consumes more power in energy-deficient areas.

Current development strategy has trapped provinces in a plight with various resource dilemma. Some places are now at risk of facing water-related energy problems and energy-induced water shortages simultaneously, such as Shandong, Henan and Jiangsu Provinces, and megacities like Shanghai and Beijing. The combination of high population density, overexploitation of natural resources and climate risks create a threatening scenario for these areas. Other regions, like Shanxi, Shaanxi, and Ningxia, are experiencing tremendous water shortages while bearing the burden of energy production for other places. The concentration of fossil fuel energy production in the north puts extra weight on its already stressed water system, and has caused energy-triggered water pollution. Southern provinces, like Zhejiang and Guangdong, although endowed with sufficient water resources, are having difficulties in meeting their rising energy demands. All of these regional variances need to be addressed separately with an understanding of the local context.

In the meantime, the comparison between provinces also exhibit significant water-energy trade-offs between different water and energy options in China. The reliance on fossil fuel and thermal power generation determined the water intensive nature of its energy system. This issue is of particular importance, given the fact that eighty percent of China's fossil fuel reserves are located in the water-starved north and northwest (Cai, Zhang, Bi, & Zhang, 2014). Even some alternative energy technologies have complex water implications. In this leading hydropower nation, a large amount of natural water flow is temporally disrupted by the widespread hydropower infrastructures. The nuclear power generation, another alternative technology favored by the Chinese government, also requires significant water withdrawal. On the water side, the current strategy to diversify water supply portfolios is challenging the reliability of energy supply. New alternative water retrieving approaches, such as seawater desalination and wastewater recycling, are extremely energy-intensive. While these approaches can mitigate local water shortage, they also result in extra power requirements. It is hard to justify the wide deployment of such technology in energy-deficiency regions, for the sake of regional energy security. In addition, the boom of water transfer projects is placing extra tension on the tightened energy supply system in the water outflow regions.

There is no simple answer to the question of whether it is reasonable to prioritize water needs over energy needs or vice versa. But significant trade-offs need to be addressed in a regional context. The synergy effect of the water-energy nexus, if utilized properly, can work as a great opportunity to guide China going through this difficult period; or, it may become a barrier that traps the country in a vicious cycle of resource collision, if mistreated. Continuing to ignore the synergies between water and energy would only exaggerate the situation. For instance, an increasing number of large inter-basin transfer projects are under construction and more are in the planning stage. The water delivery of the SNWT project to Beijing alone increased from 80 million m^3 in 2014 to 760 million m^3 in 2015. Opportunity to improve current conditions exists by carefully applying the synergy effect of the water-energy nexus, and deploying more localized and flexible strategies in a timely manner. The urgent matter right now is to take the proper policy actions immediately.

Chapter 5

ASSESSMENT OF CHINA'S WATER AND ENERGY STRATEGY

5.1 Water and Energy Institutional Framework

Effective coordination between water and energy policy is critical in addressing the trade-offs between the two sectors. However, the integrated decision-making across water and energy sectors faces institutional challenges in China. The current management of water and energy in China is fragmented. Also, the lack of adequate understanding on the complex nexus issues can often lead to misaligned policies. Therefore, this section first reviews the relevant institutional and regulatory frameworks in the water and energy sectors and then identifies the direction for enhanced institutional arrangements for integrated management.

5.1.1 Water Policy & Institutional Actor

5.1.1.1 Water Institutional Actors

Figure 5.1 displays the current institutional structure of water-related agencies. Also highlighted in the graph are the departments under each ministry directly linked to water management. The State Council is "the highest executive organ of state power" in charge of carrying out the policies and laws of China (Burke, et al., 2009), overseeing over 80 ministries, bureaus, and other institutions. Despite the recent reorganization of various ministries to reduce overlapping responsibilities among government agencies, the responsibilities of water resource management still scattered into multiple agencies at the central government level (Cheng & Hu, 2012).

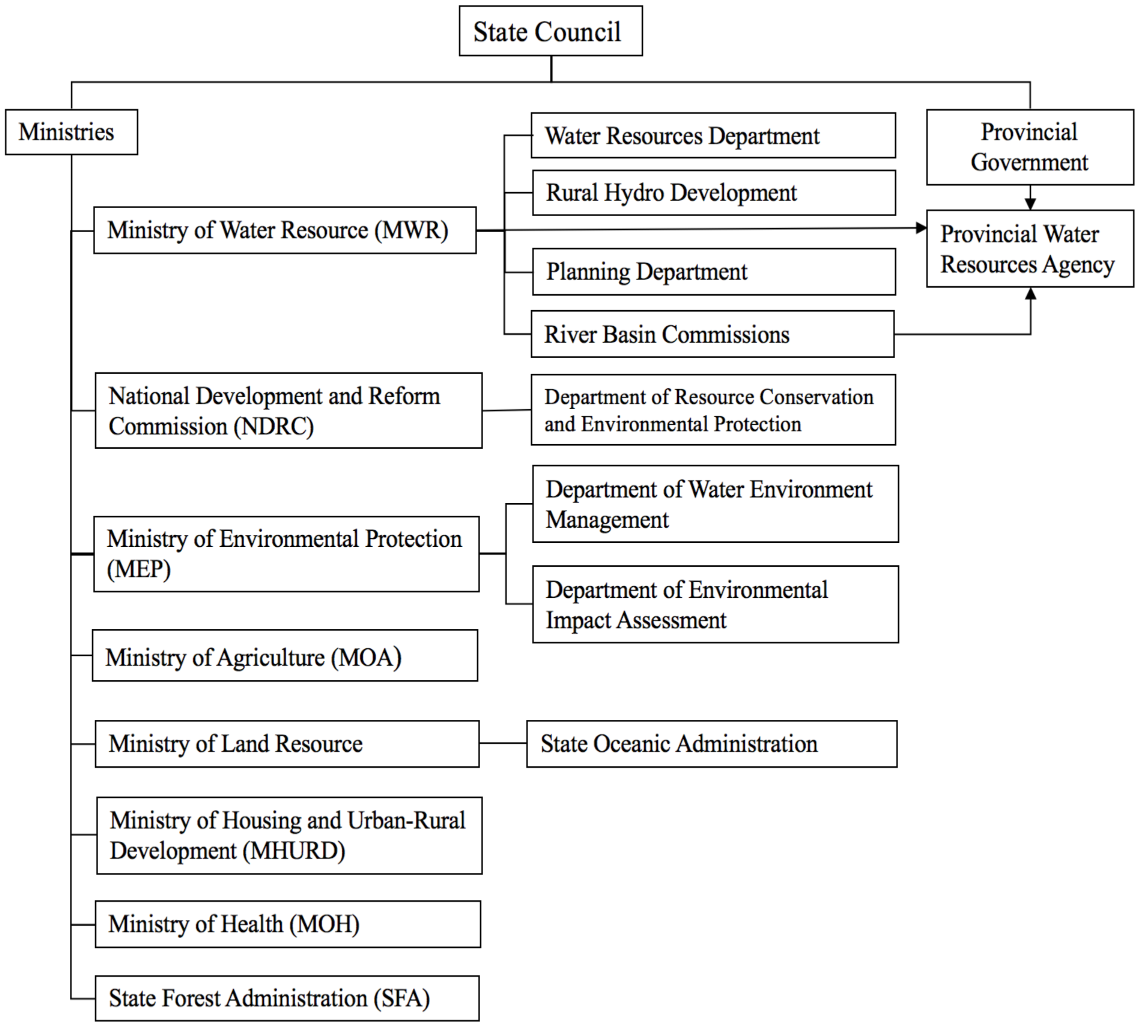

Figure 5.1 Major Institutional Actors in the Water Sector

This complex water administrative system in China is often described as "nine dragons that administer water" (Song, et al., 2010), referring to the different ministries involved in water management. A key feature of this system is that it separates the water quality management from water quantity management. While the MWR was given the managerial power in water management by the 2002 Water Law (Li, et al., 2011), the Ministry of the Environmental Protection (MEP) is in charge of the prevention and control of water pollution by regulating activities on land (Shen, 2009).

Meanwhile, the NDRC plays a supervisory role in the planning of water resources development and ecosystem building. Additionally, the Ministry of Housing and Urban-Rural Development (MOHURD) has the authority to manage urban water supply and discharge, whereas the Ministry of Health is involved with rural drinking water safety. Other key actors include the State Oceanic Administration (SOA), as the leading agency in seawater utilization, and the Ministry of Agriculture for the agricultural water use. Collaboration often took place in the areas with shared responsibilities. For instance, the MOHURD works with the NDRC every year to nominate the water conservation cities to promote local conservation efforts (MOHURD, 2017).

Coupled with the shared responsibilities among ministries, the top-down approach in China's political system further complicates the administration process. The provincial water resources agencies, although functioning as the local arm of the MWR, depend on the political and financial support of the local governments (Cheng & Hu, 2012). Such intertwined relationship between local water agencies and local governments often compromise the policy implementation. In the meantime, the MWR created seven river basin commissions (RBC) as the sub-agencies responsible for regional planning, flood control and water allocation etc. (Song, et al., 2010). These RBCs have a higher authority in water allocation over provincial agencies, adding one more layer to the decision making and implementation process.

5.1.1.2 Legal Framework of Water Management

To date, the central government has enacted several national laws directly relevant to water management. The ministries and local authorities have also issued supervisions, regulations, rules and administrative decrees to support the implementation of the laws. Table 5.1 lists the key water policies in China. The layout of the involved agencies also confirms the allocation of responsibilities and inter-sector cooperation.

Table 5.1 Major Water Policy in China

Category	Selected Policy	Time	Agency
Law	Water Law	Aug. 2002	NPC
	Water Pollution Prevention and Control Law	Feb. 2008	NPC
	Soil and Water Conservation Law	Dec. 2010	NPC
	Flood control Law	Aug. 1997	NPC
(Ministerial) Regulation	Opinions on Implementing the Most Stringent Water Management System	Feb. 2012	State Council
	Regulation on Urban Drainage & Sewage Treatment	Oct. 2013	State Council
	Guideline on Project Construction & Investment for Rural Sewage Treatment	Nov. 2013	MEP
	Opinions on Water Resources Assessment in Large-scale Coal & Power Base Development	Dec. 2013	MWR
	Guidelines on Promoting Water Pricing Reform in Urban Areas	Dec. 2013	NRDC, MOHURD
	Action Plan for Water Pollution Prevention & Control	Dec. 2016	MEP, NRDC, MOHURD, MWR
Development Planning	2011 Central Document No.1	Jan. 2011	Central Committee
	National Plan on Groundwater Pollution Control	Oct. 2011	MEP
	13th FYP for Reform and Development of Water Conservancy	Dec. 2016	NDRC, MWR, MOHURD
	13th FYP for National Seawater Utilization	Dec. 2016	NRDC, SOA
	13th FYP for Constructing National Municipal Wastewater Treatment and Recycle Facilities	Dec. 2016	NRDC, MOHURD

The 2002 *Water Law* is the foremost important legislation that marked the transition from the infrastructure-centered strategy to the management-and protection-focused strategy (Cheng & Hu, 2012). It sets forth a series of measures to rationalize water management, especially in water-scarce regions, and stresses the need for restrictions on water consumption as well as the implementation of water-saving techniques in the agricultural sector (Lasserre, 2003). Also, it explicitly states a water management system with a combination of river basin management and jurisdictional management. Other water-related laws, including the *Water and Soil Conservation Law*, *Water Pollution Prevention and Control Law*, and *Flood Control Law*, further strengthen the regulatory control for the prevention and control of water pollution and use of fresh water resources (Liu, et al., 2013).

Under this legal framework, different institutional actors have authorities and enforcement duties on various aspects of water management. In accordance with the principles set in the laws, ministries issue specific regulation to manage the water issues within their jurisdiction. For instance, the MEP issued a national plan on groundwater pollution control in October 2011 to elaborate implementation strategies outlined by the *Water Pollution Prevention and Control Law*, with a total investment of RMB 34.66 billion yuan (MEP, 2011). Together, these laws and regulations have formed the legal framework for water resource management.

Another key component of China's water policy is the short-term and long-term development plans, issued periodically. Every five years, China publishes a Five-Year Plan (FYP) that manifests the major goals and strategies in the forthcoming years. Meanwhile, the *Central Committee Document No.1 of the Communist Party,* released at the beginning of each year, is also an important guiding policy for that year and beyond. Particularly, the 2011 Central Committee No.1 Document, entitled "*The Decision on Accelerating the Reform and Development of Water Conservancy*", positioned the emergence of the strictest water resources management system (SWRM) as the strategic move to transform its water system (CPC Central Committee and Council, 2010). The iconic symbol of the SWRM is the "three-red-lines" requirement, which consists of 1) control of development and utilization of water resources, 2) control of water use efficiency and 3) restriction of pollutants in water function areas (Zuo, et al., 2014). Since then, China has vigorously pursued the strictest water resources management system with detailed measurement and funding supports.

5.1.2 Energy Policy & Actors

5.1.2.1 Energy Institutional Actors

Figure 5.2 presents a graphical framework of the energy policy making structure in China with key institutional actors. Similar to the institutional system of the water sector, the State Council serves as the overarching agency of the energy sector by overseeing all the energy-related policies. The NDRC is the foremost government institution influencing China's energy policy. Its functions include approving major power projects, formulating plans for the development of the energy sector, and promoting a sustainable development strategy (Liang, et al., 2008). Departments and bureaus under the NDRC contribute to various aspects of energy policy. For example, the Department of Climate Change is responsible for analyzing the impact of climate change, organizing and coordinating the formulation of key strategies, plans and policies, and collaboration and coordination related to international negotiations and cooperation (NDRC, n.d.a).

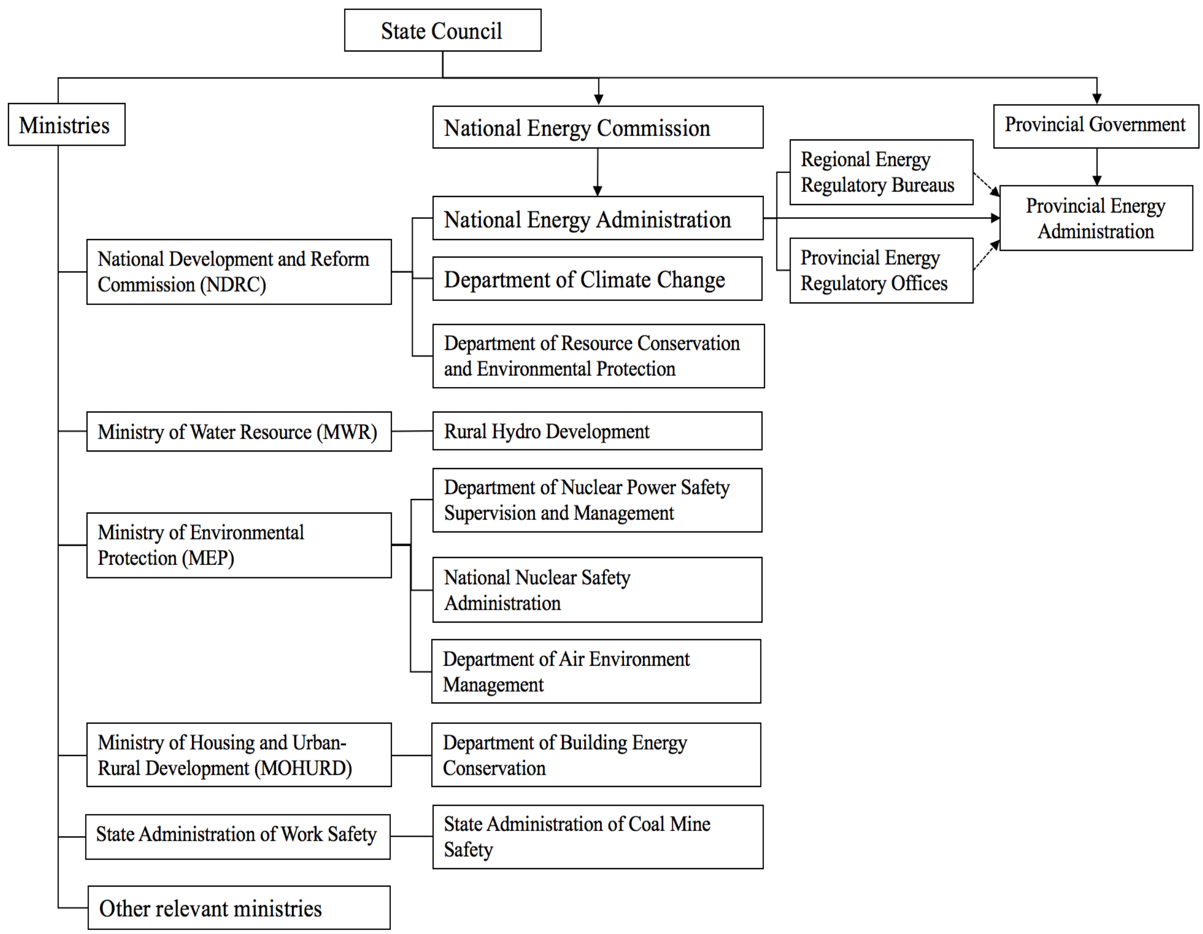

Figure 5.2 Major Institutional Actors in the Energy Sector

Established in 2008 under the jurisdiction of the NDRC, the National Energy Administration (NEA) is a dominant actor in shaping energy policy and regulating the energy market in China (NEA, 2013). After the incorporation of the functions of the former State Electricity Regulatory Commissions (SERC), the NEA represents a major achievement of China's energy reform. Intended to take the lead in the governance of the energy sector, the NEA is responsible for broad duties, including drafting energy plans and policies, managing the energy industries, organizing R&D, and promoting international energy cooperation, etc. (Deiaco, 2014). The National Energy Commission (NEC), announced together with the NEA, is a senior strategic body focusing on the formulation of national energy strategy and the deliberation of key issues in energy security and energy development. Working together, the NEA carries out the day-to-day activities and exercises the policy implementation functions of the NEC.

Additionally, some other agencies also play important roles in energy policy making. While the nuclear power safety is in the hand of the MEP, coal mine safety issues are regulated by the State Administration of Work Safety. More recently, many R&D efforts and policies on advanced energy technologies, such as smart grid, fuel cell, and secondary battery, are made by the Ministry of Science and Technology (MOST). Meanwhile, the Ministry of Finance (MOF) carries out a diversity of financial incentives to support the development of renewable energy technologies. Likewise, the Ministry of Agriculture have conducted a lot of policy and planning on rural electrification and rural renewable energy development.

Due to multiple rounds of restructuring of energy and power regulation systems, overlaps and gaps exist between energy regulatory institutions at the central and local levels. Provincial energy administration bureaus are placed directly under the provincial governments, relying heavily on the economic and political force of the provincial government. As a result, provincial governments usually have more influences on local energy administration than the NEA does (Chen J. , 2011). Besides, the local arm of the

NEA, known as the regional and provincial energy regulatory offices, also have prevailing influence on power market monitoring, power policy enforcement and operation safety, etc. (NEA, n.d.).

5.1.2.2 Legal Framework of Energy Management

China's energy legislation can be classified into six sub-systems: coal industry, oil-natural gas, electric power, nuclear energy, renewable energy, and energy conservation, each sub-system consisting of different components ranging from general energy laws to specific regulations and standards (Yu X. , 2010). While China is still in the process of enacting the *China's Energy Law* that aims to take a leading role in energy legislation, it has enacted four single laws that directly targets at different aspects of the energy domain, i.e., the *Electric Power Law,* the *Energy Conservation Law*, the *Renewable Energy Law*, and the *Law on Coal Industry*.

The existing legal framework in China serves as an umbrella for its energy policy and establishes the foundation for a low-carbon energy transition (See Table 5.2). The *Energy Conservation Law*, first issued in 1997, with a recent revision in October 2007, provides an overarching guideline to the nation's energy conservation programs and encourages the utilization of energy efficient technology. Meanwhile, the National People's Congress (NPC) adopted the *Renewable Energy Law* in 2005, which set out the roles and responsibilities of major actors (including the government, enterprise and consumers) related to renewable energy development (NPC, 2005). It highlights the importance of formulating national long-and medium-term targets for the deployment and utilization of renewable energy sources.

Table 5.2 Major Energy Policy in China

Category	Selected Policy	Time	Agency
Law	Electric Power Law	Dec. 1995	NPC
	Law on Coal Industry	Aug. 1996	NPC
	Renewable Energy Law	Feb. 2005	NPC
	Energy Conservation Law	Oct. 2007	NPC
Ministerial Regulation	Regulation on protection of oil and natural gas pipelines	Aug. 2001	State Council
	Emission standard of air pollutants from thermal power plants	Jan. 2004	MEP
	Guidance on enhancing demand side management of power sector	May. 2004	NDRC
	Regulation of electric power supervision and management	May. 2005	State Council
	Regulation on power grid dispatching management	Jan. 2011	State Council
	Renewable energy fund management	Apr. 2015	MOF
Development Planning	13^{th} FYP for Power Development (2016-2020)	Nov. 2016	NDRC, NEA
	13^{th} FYP for Energy Development (2016-2020)	Dec. 2016	NDRC, NEA
	13^{th} FYP for Coal Industry Development	Dec. 2016	NDRC, NEA
	Action Plan on 13^{th} FYP for Energy Conservation and Emission Reduction	Dec. 2016	State Council
	13^{th} FYP for Renewable Energy Development	Dec. 2016	NDRC, NEA

Under the legal framework, detailed targets, incentives, policies, and implementation measures were put in place to support the defined tasks of the energy sector, such as power sector reform, emission control, energy efficiency improvement and renewable development. The five-year plan for energy is among the most anticipated official documents that have far-reaching impacts on China's energy policy. For instance, the *11th Five-Year Plan*, for the first time, specified a quantitative target of reducing energy intensity by 20%, with the energy efficiency strategy focusing on both the supply and demand sides. Recent FYPs, combined with the detailed operational instructions, offer guidance on building a sustainable and reliable low-carbon energy path in China.

5.1.3 Institutional Capacities for Nexus Integration

Institutional capacity building is key to facilitate the implementation of the water-energy nexus approaches (Czunyi & Thiam, 2015). Despite the recent efforts made by the leading and relevant ministries on water and/or energy sustainability issues, there is still a lack of streamlining of the nexus approach that considers the bi-relationships between the two. Consequently, it is necessary to further strengthen the institutional ability to address the interlinks of water and energy through capacity building.

- Cross-sectoral Coordination and Collaboration

First of all, the inter-agency coordination and collaboration are essential to foster the effective integration of the WEN approach. In the absence of an overarching agency that holds the responsibility of the water-energy nexus, the NDRC, as the central and national planning commission, can serve as the primary guiding actor to coordinate and oversee efforts among different sectors. It also has the capability to introduce the nexus perspective into water and energy planning.

Moreover, even though the segmentation of water and energy administration has caused cross-sectoral conflicts in the past (Cheng & Hu, 2012; Downs, 2008), such ‘segmentation’ also represents great opportunities to stimulate cross-sectoral collaboration. Capacitive building activities can benefit from previous experiences on inter-agency cooperation. The two leading agencies in the domain of water and energy--

the MWR and the NEA--have shared duties on several matters. For instance, the hydropower development is managed by the MWR as the water conservancy infrastructure, while also overseen by the NEA as a major power contributor. The MWR is also stepping in to regulate the coal industry by limiting its water usage. Therefore, there are many existing communication vehicles and cooperation experiences that can be utilized to form a dialogue for systematic water-energy management.

Further capacity improvement also can be achieved through enhanced coordination between subsectors within a ministry. For instance, The MOHURD has been promoting the energy and water conservation in the building sector, but the duties are split into two subdivisions; while the Department of Building Energy Conservation & Science leads the energy conservation efforts, water conservation efforts are mostly carried out by the Department of Urban Construction as part of its urban eco-planning initiative (MOHURD, n.d.). Such separated responsibility, coupled with ineffective coordination, can result in insufficient conservation efforts. Alternatively, the government can maximize the efforts by promoting an integrated green building initiative that emphasizes both the water and energy conservation simultaneously.

- Provincial Initiative

In China, most of the policy decision-making is driven by the conventional top-down administrative system, rather than stakeholder engagement (Song, et al., 2010). As a result, the top-down policy approaches, although with the mandate from the central government and ministries, may encounter implementation barriers at the local level due to the complicated process and conflict of interests. Considering these obstacles, initiatives at the provincial level are likely to be more productive. Turning over the central role to the local government can not only bypass the institutional barriers at the ministerial level, but also target at the particular needs within the province.

As mentioned in Chapter 4, there are huge spatial variances of the WEN among provinces. The uniform or general national policy can only provide a broad direction of the water-energy management. When it comes to implementation, customized practices will be needed to tackle the specific situation of each province. Local initiatives, or, bottom-up initiatives, would be more effective with the commitment of the local government at the provincial or city level, given its larger influence on local water and energy administration over the central government. In fact, the local government is already replacing the ministries to become a primary implementer of energy saving practices (Zhao, et al., 2014). Through the empowerment of the provincial governments, it is possible to enable a policy system that encourages stakeholder participation and implementation flexibility with diverse funding sources.

- Interdisciplinary Knowledge Base

The creation of an interdisciplinary knowledge base is also an important part of the capacity building process in order to disseminate the knowledge on integrated solutions and to well inform the decision makers. The policy formulation process in China can benefit from the input of think tanks. Government affiliated think tanks, including the Development and Research Center (DRC) of the State Council, Institute of Water Resource and Hydropower Research (IWHR) of MWR, and the Energy Research Institute (ERI) of NDRC, and academic institutions, such as the Chinese Academy of Sciences and the Chinese Academy of Social Sciences, can provide strong scientific support and offer valuable insights on water- or energy-related decision making (Meidan, et al., 2009; Zuo, et al., 2014). In addition to the national-level evaluation, it is also necessary to direct the technological transfer and innovation, policy analyses, and scientific assessment on specific local realities.

5.2 Evaluation of Policy Strategies under Nexus-Oriented Framework

As a response to the numerous challenges faced by the water and energy sectors, the Chinese government has sent out a strong signal to transform its water and energy management strategies. However, despite recent policy efforts, many challenges persist beyond 2015. Concerns were raised, questioning China's determination and its ability to move towards a more sustainable path. Is current transition leading towards the right direction? Whether the ambitious targets can be implemented effectively? What role does the water-energy nexus play in future policy making?

This section intends to provide some insights on these questions, by following the nexus-oriented management criteria developed in Chapter 2. The discussion below looks at the latest Five-Year Plans and major policy announcements by the Chinese government to evaluate the nation's present policy strategy and future direction beyond 2015. It examines how these national strategies affect the water-energy linkages and also aims to identify the policy gaps. Appendix B includes a complete list of policy documents reviewed below.

5.2.1 Integration of Water and Energy

Water resources in China have gained growing attention as a constraint to its energy development, more specifically, the coal industry. Started from the *11th FYP for Coal Industry Development*, the water scarcity and water pollution was listed as a factor that affects the national geographical layout of coal production plans. The worsened water vulnerability in recent years has prompted more stringent water regulation in coal bases. For instance, the *13th FYP for Coal Industry Development* addresses the water shortage issues in East Inner Mongolia by limiting the production scale.

The *Opinions on Water Resources Assessment for the Development of Large Coal Power Bases,* issued by the MWR in December 2013 (MWR, 2013), also represents a major progress on policy integration of water-energy nexus. It sends out a clear message that the coal development should not be based on the sacrifice of local water security. This regulation states several principles on water use to promote water conservation in coal mining and power generation bases:

1) Coal-fired power plants, particularly those located in the North, are encouraged to prioritize the reuse of mine drainage and water recycling;
2) The use of groundwater, other than mine drainage, is prohibited;
3) Newly planned power plants should focus on conservation before consumption;
4) Coal-fired power plants in water-deficient areas should use air cooling technology to reduce the water intensity;
5) Thermal power plants under planning should have a designed water consumption intensity of 0.1 m^3/second/million kW or less (equivalent to 0.36m^3/MWh).

To implement these mandates, all large coal power bases need to complete a water resource feasibility report and submit it to the local water agency, the river basin commission, and the MWR for approval. Once agreed on by the MWR, the plan will be reviewed by the NEA for final approval. The provincial energy agency will be in charge of the feasibility study, with support from the local water agency.

It is evident that both water and energy agencies are working together to place a tangible constraint on energy planning. Water agencies are given the power to affect or even overturn the energy planning decision made by local energy agencies if it failed to meet the water requirements. However, in contrast to the rising attention on water for coal, the water protection during oil and gas extraction (although briefly mentioned) was not listed among the top tasks in current energy planning (NDRC, 2016a; NDRC, 2016b). It is also worth mentioning that most of the actions at the ministerial level were taken by the MWR, while the NEA does not express equal interests on water for energy, according to the latest FYPs.

Another concerning limitation of current policy is that the concept of energy-for-water barely appears in any policy regulation. The lack of energy consideration for water development can be problematic when it comes to implementation. For example, the 13th FYP highlights the role of seawater desalination and water recycling in the Jing-Jin-Yi (Beijing-Tianjin-Hebei) region. But the power sector in this area highly depends on interprovincial import. Increasing the share of the energy-intensive alternative water source can put more pressure on its power system.

5.2.2 Conservation

Water and energy shortages are among the acutest challenges resulted from the economic growth, population expansion, and rapid urbanization. To cope with the growing supply-demand conflict, conservation has been adopted as one of the principle measures by both water and energy sectors. Recent FYPs listed water and energy conservation as the top priority with quantitative targets. Combined with conservation goals are the targets for water and energy efficiency on both supply and demand sides. Table 5.3 displays the national goals for water and energy consumption in these FYPs.

Table 5.3 Conservation Targets for Water and Energy

Planning Periods		11th FYP (2006-2010)	12th FYP (2011-2015)	13th FYP (2016-2020)
Targets for Water Conservation and Efficiency				
Total water consumption		-	635 billion m3	670 billion m3
Ratio of measurement	urban & industrial water use	-	-	85%
	irrigation water use	-	-	70%
Utilization coefficiency of Irrigation		0.5	0.53	0.55
Urban water pipeline leakage		<15%	<18%	<10%
Water Consumption Per Unit of GDP		Reduce 20%	Reduce 30%	Reduce 23%
Water Consumption Per Unit of Industrial Added Value		Reduce 30%	Reduce 30%	Reduce 20%
Targets for Energy Conservation and Efficiency				
Primary Energy Production		2.97 billion tce	3.62 billion tce	4 billion tce
Primary Energy Consumption		3.25 billion tce	4.3 billion tce	<5 billion tce
Raw Coal Consumption		-	3.96 billion ton	4.1 billion tce
Electricity Consumption		4 trillion kWh	5.69 trillion kWh	6.8-7.2 trillion kWh
Energy Consumption Per unit of GDP		-	[Reduce by 16%]	[Reduce by 15%]
Power grid loss		6.5%	6.64% (6.3%)	<6.5%

Since 2005, the government has issued a comprehensive policy outline to guide the development and application of water conservation technologies and to improve the legislative and administrative management of water conservation. During the 2005-2015, Chinese government managed to cut the water use per 10,000-Yuan GDP from 304 m^3 in 2005 to below 105 m^3 in 2015 (NDRC, MWR, & MOC, 2006; NDRC, MWR, MOHURD, 2017). The 13th FYP set up a goal to limit the total annual water consumption to 670 billion m^3. In the meantime, national caps are also set for energy consumption and production in order to control the total use as well as maintaining a national self-sufficiency level above 80%. The specific caps on coal consumption and electricity consumption provide strong incentives to lower energy intensity while switching to cleaner sources.

Overall, the general goals are to control the water and energy consumption, to slow down the speed of growth, to lower the energy-water intensity, and to decouple the economic growth from resource inputs. Although some of the national caps do not require an absolute reduction, they still have positively effect on conservation activities. Because there is still a large portion of rural population waiting to gain access to sufficient modern energy and clean tap water. Without proper control, additional water and energy needs beyond 2015 would be much higher. The implementation results of the recent FYPs suggests that the FYP has become an effective tool to carry out water and energy saving in China (Hu A. , 2016). But we still need to wait before making any conclusion on the finial effectiveness of these policies, since most conservation goals are anticipated values, instead of binding targets, which could potentially compromise the initial commitment.

5.2.3 Indigenous Resources

As the shortcomings of resource transfer become more evident, the idea of regional resource independence has attracted some attention. The recent FYPs adequately expressed a primary principle that water and energy exploitation should stay within the local ecological carrying capacity. At the provincial level, the central government has started to tighten up the policy towards inter-provincial transfer and impose more regulation to manage domestic resource flow. However, the current change is not enough to reverse the overall trend. In general, the supply-oriented mindset still dominates the policy-making in China, causing the lack of emphasis on the provincial water and energy self-sufficiency.

- **Control of the unregulated water transfer**

The recent rampant proliferations of water transfer projects across the country raise concerns among policy makers. As a response, the NDRC and the MWR jointly issued the *Guidance on Preliminary Work of Water Transfer Projects* in 2015 to control the unregulated water transfer (NDRC, 2015). It stressed on the principle of 'three-first rules' that translates to 'conservation before transfer, pollution treatment before diversion, environmental protection before water use'. The *13th FYP for Water Conservancy and Reform* also repeatedly highlighted the importance of scientific assessment of water transfer.

Although doubts have been cast on the long-term feasibility of water transfer in some places, no fundamental changes were made to shake the status of water transfer in China's water strategy. In consistence with previous policy, the period of 13th FYP continues the emphasis on the role of water transfer in fighting China's regional water shortage and improving regional water resource allocation, and, ultimately, ensuring the water supply reliability in major economic bases and cities. Engineering efforts to build water transfer projects will be carried forward during 2016-2020. The *13th FYP for Water Conservancy and Reform* not only calls for timely completion of a list of key projects under construction, including Han-to-Wei Project (引汉济渭) in Shaanxi, Yao River Water Transfer project (引洮供水) in Gansu, but also urges to speed up the preliminary evaluation of projects under planning, including Yangtze-Huai Project (引江济淮), Chen-Zhong Water Transfer Project (滇中引水), Chuo-Liao Project (引绰济辽). However, how to deal with the negative socio-economic and environmental impacts of transfer were not thoroughly discussed, leaving a big question mark on the future sustainability.

- **Conflict between energy interdependence and self-sufficiency**

The overemphasis on energy transfer and large energy bases during the 11th and 12th FYP has caused several problems that were unforeseen by the central government, and eventually triggered a conflicted attitude towards energy self-sufficiency at the provincial level in the 13th FYP. During 2011-2015, capacity building for regional resource reallocation was among the primary tasks to ensure energy reliability. As of 2015, the total primary gas transmission pipeline totaled to 112 thousand km, and the West-to-East Power transmission capacity reached 140 million kW (NDRC & NEA, 2016). However, such aggressive approach has ironically resulted in a surplus of capacity in energy exporting provinces. While the traditional energy-producing provinces continued building large-scale plants and relying on export, the growth of energy demand in major energy consuming provinces has started to slow down in a slowing economy. The less attraction to external energy sources has caused a large waste of the installed capacity in energy producing provinces.

To address this issue, the 13th FYP presents the first task in the coming five years as to optimize the regional landscape of energy development. The *13th Five Year Plan for Energy Development* explicitly states:

> "The energy affluent regions need to wisely plan the exploitation scale of large energy bases and schedule the developments accordingly, innovate the development and utilization pattern, increase the ratio of local use, establish exporting infrastructure based on the demand of the targeted market. The energy consuming regions need to develop distributed energy according to the local conditions, and reduce dependency on the external energy source." (NDRC & NEA, 2016)

It seems like the central government is trying to reverse the trend and to maintain a dynamic balance of energy supply and demand in different regions. But the policy makers were caught in another dilemma, blocking the way of fundamental changes. Most of the abandoned power capacities are the recently-installed large-scale wind, solar and hydro power. Furthermore, focusing on the indigenous energy source means the newly-constructed energy transmission route will keep operating at a low-efficiency rate. It is not an economical choice to simplify give up those infrastructures that have cost vast investment. To cope with the current situation, the central government encourages the energy affluent provinces to enlarge its local demand to internally consume the extra power generated. Meanwhile, it plans to build a strong trans-provincial power trade system to facilitate the utilization of installed capacity. A big move was the creation of two national level trading platforms in 2014, Beijing and Guangzhou Power Trade Center, that connect the power supply region with the potential consumer directly, based on the real-time production and market price (Yang Z. , 2016).

While this mechanism can indeed improve energy reliability and infrastructure efficiency, there could be severe side-effects that worsen the regional dependency and long-term security. By enlarging the local demand as a solution to justify large-scale deployment of renewable, it misplaced the essential role of renewable energy and regional transfer infrastructure, which is to address energy shortage. Ironically, they have now become a cause of incremental demand. Such short-sighted solution on a single-dimension would also exaggerate the fossil fuel exploitation in traditional energy producing provinces, since fossil fuels are still the most competitive energy sources in the market. The central government needs to look into the underneath problems to search for solutions, rather than enlarging the local demand for the sake of supply. Overall, the short-term strategy failed to address the fundamental issues with the regional disparity in energy development, and the indigenous source has yet become the central point of local energy security and reliability.

5.2.4 Decentralization & Diversification

China has been making efforts to diversify its water and energy supply by exploring alternative sources. Starting from the 11th FYP, quantitative goals for diversification have entered the scope of the national resource planning and the trend continues in the 13th FYP. Table 5.4 shows the numerical goals set by the recent Five-Year Plans regarding water and energy diversification.

Table 5.4 Diversification Goals in Recent Five-Year Plans

Planning Periods	11th FYP (2006-2010)	12th FYP (2011-2015)	13th FYP (2016-2020)
Targets for Alternative Water Sources			
Seawater Desalination	800-1000 thousand m3/d	2200 thousand m3/d [1000 thousand m3/d]	2200 thousand m3/d
Direct seawater utilization	55 billion m3	110 billion m3	140 billion m3
Urban wastewater treatment rate	70%	85%	95%
Utilization rate of recycled water	<10%	15%	>20%
Water recycling capacity	12.1 million m3/d	38.85 million m3/d [26.53 million m3/d]	41.58 million m3/d
Targets for Alternative Energy Sources			
Share of non-fossil fuel in consumption	8.1%	11.4%	15%
Hydro	240 GW	290 GW	340 GW
Solar	0.3 GW	21 GW	110 GW
Wind	10 GW	100 GW	210 GW
Biomass	5.5 GW	13 GW	15 GW
Nuclear	10 GW	40 GW	58 GW

* [ ]: implemented portion by the end of the period.

The 13th FYP contributes to the water diversification by further encouraging the inclusion of alternative water sources, such as rainwater, seawater, recycled water, mine water and brackish water, into regional water resource planning and allocation. The seawater utilization, in particular, received more emphasis as one important measure to improve the capability of urban water supply system in this new plan (NDRC & SOA, 2016). Meanwhile, areas experiencing water shortage and severe water pollution are required to prioritize the use of recycled water for industrial, urban greenbelt and ecological water needs. Despite the fact that several goals of the alternative water sources fell short by the end of 2015, it does not overshadow their rising importance in the policy.

At the same time, the diversification has been a central theme of China's energy policy. As energy conservation is treated as the priority, the new and renewable energy is also bearing a huge responsibility to resolve the shortage of energy supply and mitigate environmental problems. Guided by the government's inspiring targets, many concrete efforts can be witnessed in recent years. The White Paper of *China's Energy Policy 2012* sent a strong signal to the world that China has set up a priority of its energy policy aiming at a low-carbon development. The overall energy transition mandated by this plan has huge potential to decouple the water-energy interdependency.

But there are several areas that need further improvement. First, the central role of diversification and decentralization is still absent in the core policy strategy. Although there have been lots of encouragements toward new water sources or renewable energy sources, the central government still favors the traditional and centralized approaches over diversified and decentralized ones. As a result, the present centralized system gave rise to massive transmission systems, causing the low efficiency and the collateral environmental damage along the transmission line. Second, the lack of water-energy integration causes many problems in the diversification strategy. For instance, the energy implication of expanding desalination is not carefully addressed. Such ignorance also has also led to the large-scale expansion of water-intensive nuclear power. The share of non-fossil fuel is largely filled by installed and planned nuclear power capacities, some of which located in the inland areas. This most notorious centralized energy solution poses a risk to the regional radiation safety, and would also affect the local water availability if the need for large water withdrawals is not properly addressed.

5.3 Trade-offs of Controversial Options: Illustrative Cases

The section above summarizes the key achievements and challenges of China's future energy and water strategy. Generally speaking, the 13th FYPs address the sustainability issues with sincere commitments, but many trade-offs of water-energy are not yet fully incorporated into the policy making process. When it comes to implementation, such unclearness could worsen the existing problems with the water-energy nexus. Given the unique water-energy linkages in different provinces, this section selects a couple of 'hot spots' for further evaluation.

5.3.1 Desalination in Coastal Provinces

The movement towards desalination led by the central government has created a fast growth of the seawater desalination industry in the past ten years. The *Opinion on Speed up the Seawater Desalination Industry*, issued by the State Council in 2012 to offer political supports, have paved the way for future market penetration (State Council, 2012). The Department of Resource Conservation and Environmental Protection (DRCEP) of the NDRC published the 12th FYP for Seawater Desalination, which aims to increase the total producing capacity to 2 million m^3 per day. A cross-sectoral coordination mechanism was formed under the leadership of NDRC, involving a dozen of relevant ministries and agencies (State Council, 2012). Although the latest report shows China falls short of the goal, it does not change the government's ambition towards enhanced utilization of seawater. In 2017, the NDCR and the State Oceanic Administration (SOA) issued the *13th FYP on National Seawater Utilization*. It presents a new goal to increase the total producing capacity to 2.2 million m^3 per day by the end of 2020, doubling the current capacity of 1.0 million m^3 per day. Most of the new anticipated capacities will be installed in coastal provinces and cities under water stress and coastal islands. It also intends to expand the deployment of desalination technique into brackish water treatment in western China by adding a new capacity of 1.05 million m^3 per day in the inland.

Currently, there are nine provinces with seawater desalination with a total of 121 desalination plants. In different provinces, the desalinated water is used to supplement the water need of various end users. In Tianjin, Hebei, and Shandong, seawater desalination projects serve mostly for water intensive industries, whereas the desalinated water is used solely by residential consumers in isolated coastal islands in southern provinces, such as Zhejiang, Fujian, and Hainan. Nationally, 31% of the desalinated water was consumed by thermal power cooling, 3.8% by nuclear power cooling, and 32.8% by residential use, while the rest went to other water-intensive industries, like the chemical, petrochemical and steel industry (SOA, 2015)

The water-energy tradeoff with desalination is more apparent than any other options, given its energy intensity. Table 5.5 compiled some indicators to illustrate the resource features in provinces with desalination capacity. The majority of the existing capacity is located in the most water-and energy-stressed provinces along the eastern coast. Desalination might be pursuable in some remote southern islands, where freshwater availability has posed a constraint on basic human needs. But it is still debatable whether large-scale desalination is a good choice for the water deficient north. From the nexus perspective, investing in more desalination projects in water-energy stressed areas could potentially worsen their power shortage by adding more demand.

Table 5.5 Resource Features in Provinces with Desalination Plants in 2014

Province	Desalination		Energy and Water Availability		
	Capacity (1000 m^3 /day)	Power for Desalination (GWH)	Power Import (TWH)	Water Resource (m^3/person)	Features
Hainan	1.6	0.4	0.6	4,266	High water and energy self-sufficiency
Fujian	10.9	4.9	-1.1	3,218	
Guangdong	45.8	13.8	156.2	1,608	Moderate water stress Severe energy stress
Zhejiang	207.8	63.3	62.8	2,057	
Jiangsu	5.1	2.3	66.5	502	Severe water and energy stress
Shandong	165.2	73.9	48.6	152	
Tianjin	317.2	127.9	19.8	76	
Hebei	167.5	74.9	83.5	144	
Liaoning	87.7	38.5	42.1	332	

There is no clear vision of an energy solution to match the upcoming boom of desalination in any of the recent policy announcements. It appears that provinces are encouraged to build combined desalination plants with existing thermal power plants. This approach is intended to provide easy power access to desalination, and also to feed the desalinated water back to the thermal power cooling process. While there is no specific study available to support or against its feasibility, this concept itself raises alarms. Apparently, such action tightens the linkages of water and energy supply by using desalinated water for power cooling. It is doubtful that this is an 'efficient' use of resources, but rather a form of environmental indulgence. Another key issue with desalination left unsolved is the ecological impacts, such as how the discharge of the concentrated seawater with high salinity would impact the marine species.

Therefore, it is strongly recommended to consider other water solutions before seawater desalination, especially not to use it to nurse water-intensive industries. In the northern areas, the direct seawater utilization may serve as a better option. It is also suggested to explore the possibility of renewable powered desalination as a future solution, particularly in the remote islands.

Even if desalination is viewed as a necessity, technology innovation and cautious planning will be needed before massive deployment. China has already placed lots of emphasis on technology innovation as the center force to promote desalination. A representative example is the creation of a national laboratory, Tianjin Seawater Desalination and Utilization Research Institute, that is dedicated to improving the desalination techniques and explore the less-energy intensive solutions. While the Chinese government committed to develop its own desalination technology, international cooperation on technical breakthrough could also offer valuable insights.

5.3.2 Hydropower in Southwestern China

The hydropower system has been widely adopted in China as a major tool to control energy and water resources. The domestic environmental concerns, particularly the air pollution in the north and east, and international pressure to reduce carbon emission, together, prompt a new round of hydropower construction in China, mostly in the remote but water abundant southwest.

Even though China already has the world's largest hydro capacity of 305 GW (as of 2014), the central government made bigger plans for it towards 2020 and beyond. The hydropower development is listed as another primary task during the *13th FYP for Energy Development*, with the intention to utilize China's tremendous unexploited hydropower potentials to replace the country's long-time addiction to coal. During 2016-2020, the central government plan to add another 40 GW of conventional hydropower capacity, and reach a total installed hydropower capacity of 340 GW (NDRC & NEA, 2016). The Energy Research Institute (ERI) under the NDRC projected that the installed capacity of hydropower can reach 554 GW in 2050 under a high renewable scenario (ERI, 2015). China's hydropower expansion is not only because it is almost the cheapest alternative sources, but also thanks to China's decades of engineering experiences in hydropower planning and its strong state command over land resources and investment capital (Vermeer, 2012).

Figure 5.3 shows the hydropower status in the top nine provinces. As the traditional hydropower provinces get close to exhausting their hydro potentials, the southwestern provinces are prepared to take over the lead. A new rising star is Sichuan Province. It is now the top one province in hydropower, after its installed hydro capacities increased more than fivefold in the past ten years from below 10 million kW to 53.61 million kW. Further hydro plans will also concentrate on the southwestern provinces, especially Yunnan and Sichuan, which will be the major recipients of a 500-billion-yuan hydro investment during 2016-2020.

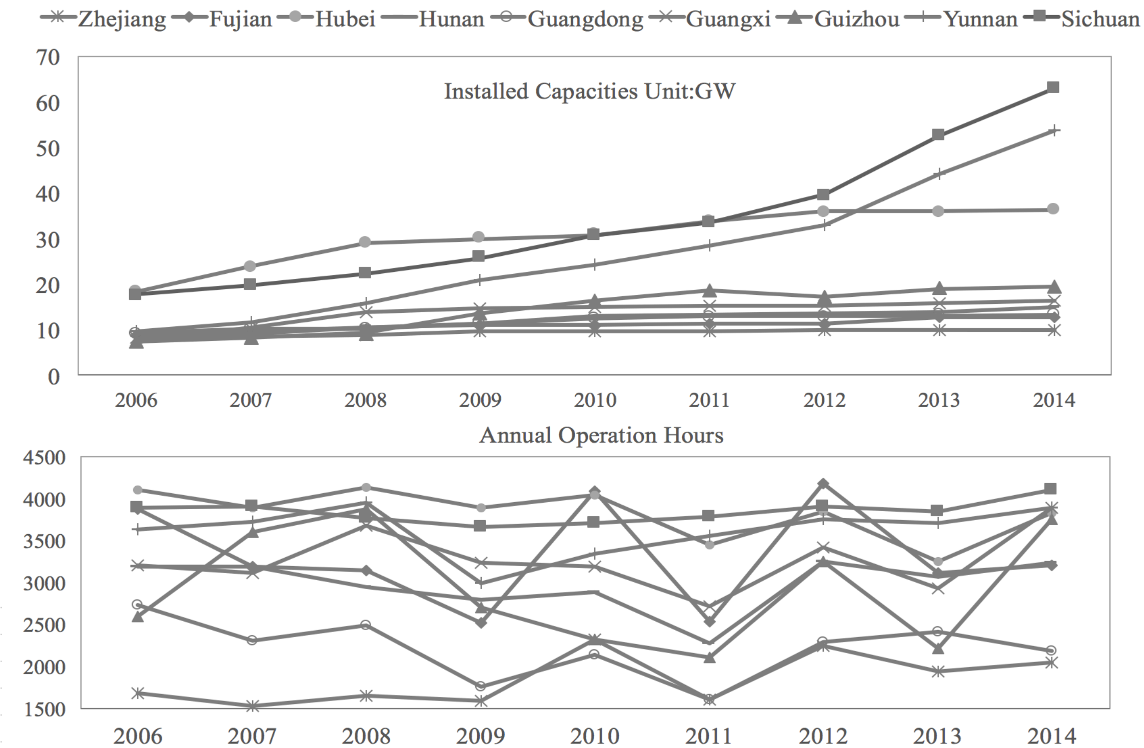

Figure 5.3 Hydropower Status in Top Nine Provinces

(Data Source: Multiple-years Power Statistic Yearbook of China)

Although the hydro expansion is intended to lower the carbon emission while increasing the reliability of power system, the technology comes with flaws. Hydropower system, by its nature, involves multilayer of trade-offs between social, economic, and environmental impacts. It is one of the most debatable options to balance the trade-offs between water and energy. The analysis in Chapter 4 demonstrated the strong influence of hydropower on water for energy production in China, due to its high water-intensity and its large share in China's power generation mix. Additionally, a recent study found that the hydropower development in South China, where increased reservoir evaporative losses under a warmer climate, has caused increased tradeoffs between water availability for irrigation and hydropower generation (Zeng, et al., 2017). Moreover, hydro is vulnerable to climate change and yearly variation. The historical data in the past decade suggest that the average annual operation hours of hydropower in each province can vary over (+/-) 30% each year (See Figure 5.3). The uncertainty of runoff is always going to be a major factor affecting the productivity of hydropower plants (Cheng, et al., 2012). Some even criticized the ability of hydro to replace thermal power, citing that for every new hydropower dam built in the southwest, an additional coal-fired power plant is constructed to solve the problem of peak energy load and ensure a stable supply of power during the dry season (Walker & Liu, 2015).

In addition to the controversial issues around the technology itself, the recent setback encountered by China's hydro industry raises more uncertainty over its future prosperity. In the past five years, the southwestern provinces have abandoned many of their hydropower productions. For instance, in Sichuan province, at least 9700 million kWh of hydropower went wasted in 2014, equivalent to 3.8% of the total hydroelectric generation in the area (EBCEPY, 2016). If this trend continued, the wasted hydropower in Sichuan will reach 35000 million kWh by 2020 (NEA, 2015b). The abandoned hydropower production is triggered by a combination of reasons. A major cause is that the growth rate of hydropower has outpaced the increase in power demand, creating an overall surplus of supply (NEA, 2015b). Basically, there is no sufficient power demand in the hydro bases to absorb all the power generation, and the extra power generated cannot be delivered to other provinces due to infrastructural constraints. Furthermore, the peak shaving need during flooding season forced many large hydropower plants to abandon a portion of water that could be utilized for power generation (NEA, 2015b).

Unsatisfied with the current situation, the central government is looking at ways to deal with the 'discarded water' (hydropower). As a response, the13th FYP requests the large hydro provinces in the southwest to intentionally increase their local energy demand so that they can 'absorb the extra hydroelectricity generated' internally. It implies that more energy-intensive industries will be moved to the mountainous remote areas with hydropower. Furthermore, the long-distance transmission of hydropower from the southwest to the manufacturing hubs in the coastal areas is further encouraged with more financial support, despite the large power loss. However, it seems problematic to justify the expansion of hydropower by encouraging energy consumption, which could probably be avoided through demand side management. It is unclear how this action would interact with the national energy efficiency improvement and energy conservation efforts. Does the surplus of the hydropower mean less impetus to improve the efficiency? If the question is not well addressed, the strategy on hydro could be counterproductive at multiple levels.

The aggressive expansion of hydropower has caused many problems in China as well as conflicts surrounding international rivers. Even though small-scale hydropower is more eco-friendly, the uncontrolled and disordered expansion of small hydro in China has also caused degradation of downstream ecosystem services due to the periodic drying-up of the river (Pang, et al., 2015). The government agencies should stay cautious to prevent the overdevelopment of hydropower. Comprehensive planning and integrated management will be necessary if hydro is to play a key role in enlarging the renewable energy penetration. Meanwhile, small-scale hydropower with stricter regulation should receive more support than the large-scale projects. Lastly, the central government needs to pay more attention to the operation of existing hydropower plants and provide more financial and decision-making tools to achieve the effective management.

5.3.3 South-to-North Water Transfer

Regardless of the controversies surrounding it, the inter-basin water transfer is inarguably an influential strategy to relieve the severe water shortage in northern cities and provinces in China. The South-to-North Water Transfer Project (SNWTP) is the largest, and also the most challenging water transfer project ever built in China. While the strategic conception was conceived back to the 1950s, it was the increased urgency to halt the environmental degradation in the new century that finally led to the construction of this massive national project (MWR, 2003). With a total 500-billion-yuan investment, the SNWTP aims to transfer 44.8 billion m^3 of water annually from Yangtze River to alleviate the water shortage in the north.

An overall layout of SNWTP consists of three routes, the eastern, central and western routes, corresponding to divert water from trunk and branch streams of downstream, midstream, and upstream of Yangtze River (See Figure 5.4). The construction of SNWTP officially started in December 2012. As of 2015, the first phase of the Eastern Route Project and the Central Route Project were finished. And the western route project is listed among the priority tasks in the 13^{th} FYP.

Figure 5.4 Routes of the South-to-North Water Transfer Project
(Source: New York Times)

The Eastern Route diverts water from the main stream of the Yangtze River near Yangzhou, Jiangsu Province. It targets to resolve the urban and industrial water use in the Eastern 3-H Plain and to improve the agricultural irrigation in the Huaibei Region. The **Central Route** serves for Beijing, Tianjin and North China Plain. It aims to transfer 9.7 billion m^3 of water from the Danjiangkou reservoir, to Hubei, Henan, and Hebei provinces, and ultimately reach Beijing and Tianjin, serving the country's political, economic and cultural center as well as its major food production areas (Liu & Zheng, 2002). The **Western Route** is the most controversial part of the SNWTP, as it involves with the source region of the Yangtze River as well as the ecological fragile region by connecting the upstream of the Yangtze River with the upstream of the Yellow River.

While some scholars highlight the ecological and environmental benefits of SNWTP (Chen & Xie, 2009; Yang, et al., 2012), others' attentions center on its adverse effects on both intake and exporting areas (Gao, et al., 2006; Yang & Zehnder, 2005). Proponents believe the project is economic attractive given its enormous social and environmental benefits. It could alleviate water scarcity in northern China, increasingly improve the degraded eco-environment in the importing areas, even achieve the quality of life with the improved domestic water supply (Liu & Zheng, 2002; Lin, et al., 2012). This huge project is also regarded as an effective adaptation to climate change, natural disasters, and food security (Li S. , 2012; Chen & Xie, 2009). However, it is hard to overlook the social and environmental concerns, such as the large scale of involuntary resettlement, inundation of cities and villages, seawater intrusion, as well as the water quality degradation along the canal by introducing severely polluted south water to the north (Berkoff, 2003; Zhang Q. , 2009; Liu & Zheng, 2002).

The trade-offs between energy and water with SNWTP is also building a case against its legitimacy. The East Route alone has 13 cascade pumping stations along the line with a total head of delivery of 65 meters (HRWRC & HRC, 2003). To achieve the goal of diverting 8.9 billion m^3 of water from the Yangtze River, it has to extract energy input from the cities and provinces along the line. However, the water exporting area of the Eastern Route is one of the most populous and energy-deficient areas in China. The starting point in Jiangsu Province is even among the top energy importers in the country. Pumping water to the north added another energy consuming item on its already crowded energy dispatching lists. No to mention the not-so-good water condition in Jiangsu. Despite the large volume of river run-off entering Jiangsu Province, the dense population there dilutes the available per capita water. The project could challenge the environmental equity if it jeopardized the water and energy reliability of the exporting regions.

While the debate on the complex social and environmental impacts continues, some argue that the project could be avoided by adopting better water management in the receiving areas. A major argument is that, in China, the scope for water savings from increased efficiency in the retention and distribution system is considerable, probably even greater than the prospective gains from water transfer projects. If a city, such as Beijing, pursues a sustainable development strategy, the gap between water demand and supply could be eventually closed without additional water supply (Feng, et al., 2005). Others question the justification of SNWTP by introducing the virtual water perspective. After examining all the water embodied in domestic commodity trade, Ma et al. (2006) found that south China actually imported 52 billion m^3 virtual water from north China in 1999. This was more than the maximum water transfer volume of the three routes of the SNWT Project. This fact illustrates that the current direction of virtual water trade in China runs opposite to the proposed physical transfer of SNWTP. While physical water transfers are proposed from 'surplus' to 'deficit' basins, inter-provincial virtual water flow moves from water-scarce regions to water-rich ones. This would cause a vicious cycle of water overexploitation in the north.

As the SNWTP is already implemented, further discussion can hardly change the status. But lessons should be learned on how to guide its future operation, how to improve the water management in the intake regions, and more importantly, on the preliminary assessment of all the upcoming transfer projects across the country. Essentially, inter-basin water transfer could only be viewed as viable when no other viable or less controversial solution is available. Before considering the construction of any large-scale transfer project, it is wise to explore the potential of water saving in the local areas first. Moreover, the inter-basin water transfer is only a partial solution to the chronic water shortage problem. Water-deficient areas should actively implement and enforce water demand management programs to improve water efficiency and promote water conservation. At the same time, the regional planning should take into consideration of local water conditions. For the sake of the long-term sustainability, industrial and agricultural structures need to stay in accordance with the balance of the water cycle.

5.4 Summary and Policy Implications

This Chapter evaluated the current and future key policies in China with regard to water and energy management. The analysis reveals that, overall, the central government has a strong intention to address water-energy challenges simultaneously. Some initial efforts have already been made to integrate water-energy nexus. Major achievements can be found in the area of infrastructure improvement. First, strong inter-connected power transmission grids were constructed and are being expanded to produce a stronger national power security. Notably, the national drinking water initiative and rural electrification projects are put into place to cover the rural population with poor access to safe water and modern energy. Also, the municipal wastewater treatment plants and treatment rates have grown significantly, yielding a cleaner water cycle. Meanwhile, a number of sustainable strategies were undertaken to improve the long-term security. A diversified water portfolio has been the focal points of water management in many water deficient cities, whereas renewable energy is deployed at a fast pace to replace inefficient coal power plants. In addition, a number of nationwide initiatives were put into place to provide a society-wide impetus for resource recycling and conservation, such as the *Circulating Economy* and *Water Saving Society* initiatives.

However, given the existing challenges of water-energy interlinks in China, there are many areas that call for further actions. First and foremost, the level of integration of water-energy nexus is still limited. Although the water constraints have been included in the planning of national energy strategy, especially the coal industry, it still hasn't gained the influencing power in all the spectrum of energy supply. Nuclear power is penetrating the inland market, despite the uncertain water availability. Large-scale hydropower is given highest priority while its impacts on local water resources is not fully examined. Furthermore, the energy for water still has not captured enough attention at the policy level. Such ignorance has resulted in the expansion of energy-intensive water technology into energy-deficient areas, without having a solid energy plan in place.

Equally important, the existing water and energy systems are still dominated by the centralized and supply-driven approaches, despite the recent conversation and diversification efforts. China's water and energy strategies in the past decades have relied heavily on the construction of massive projects in the form of dams and reservoirs, hydro-power plants, water transfer projects, and transmission infrastructure, nuclear reactors, etc. But, the deepened water and energy crises have revealed the incompetence of a 'hard path' in solving many of the problems. New challenges keep emerging, while short-sighted solutions incubate more problems.

Looking beyond 2015, more efforts are necessary to sustain a paradigm shift to ensure the sustainable development of water and energy resources. China needs to commit to building resilient water and energy systems with stricter conservation goals, more diversified supply, and more comprehensive environmental standards in this new century. The water-energy nexus has emerged as a comprehensive tool for resource management globally. China should also take urgent action to incorporate nexus-oriented management into its policy making at all government levels. Further policy intervention should target at the most critical issues with water-energy interdependences, including:

- Encourage cross-sectoral collaboration, feasibility analysis, and data-sharing;
- Identify strategies that are water and energy compatible and go within the local carrying capacity;
- Explore the synergic saving potentials by focusing on the water-energy nexus;
- Adjust regional economic development path and adopt efficient technology to decouple economy from resource dependency;
- Balance regional development pattern to mitigate the ecosystem overwhelmed by the dense population concentration and overexploitation of nature resources;
- Prioritize demand-oriented approach, downplaying the role of engineering in managing the water and energy while promoting the concept of 'conservation as a resource';
- Improve regional dynamic self-sufficiency by focusing more on indigenous resources and reduce virtual and embodied resource dependency;
- Continue to develop decentralized and diversified systems with strong reliability and affordability, while considers the water-energy compatibility.

The existing institutional framework can provide a solid foundation for such policy integration. The most stringent water management system of China already implies a future potential of water-energy nexus-oriented management. All the existing institutional actors also have the capacity to adopt the nexus-oriented policy making. Especially at the provincial level, local initiatives and efforts can bypass the barriers of the cumbersome political system. Effective actions can be taken immediately without waiting for any big institutional reform.

Chapter 6

NEXUS-ORIENTED MANAGMENT OPTIONS AND INTERNATIONAL PRACTICES

6.1 Practical Options for Nexus-Oriented Management

Stakeholders, especially the end-users and water and energy utilities, play key roles in facilitating nexus-oriented management. First, stakeholder participation is critical for effective policy implementation, particularly when cross-sectoral collaboration is challenging. By engaging these stakeholders, it is possible to promote joint efforts, pool together resources, bridge the knowledge gap, and thereby achieve cost-effective implementation. Meanwhile, in the absence of enhanced policy integration, proactive industrial and residential players can also take voluntary efforts to tackle the weak spots of water-energy interdependencies, and hence, supplement existing policy.

Viable nexus-oriented solutions are widely available. Different stakeholders can adopt a combination of practical options to address the local water-energy challenges. The end users, as the final consumers of water and energy products, can largely determine the water and energy demand and specific local preferences. They are the most important players that can contribute to disconnecting growing urban population from increased water and energy demand. End-users can also benefit from conservation and efficiency improvement through reduced water and energy bills.

Meanwhile, the energy and water industries, as the supply chains that provide the critical resource services, represent the largest opportunities for decoupling water and energy generation from the upstream. Water utilities can boost their overall performance by improving pump efficiency, reducing pipeline leakage, adopting advanced treatment technology, or introducing new sources. Energy utilities can also lower its water demand by increasing its conversion efficiency or diversifying supply. Many of these efforts can also contribute to its economic competitiveness. The scope of industry here is not limited to traditional water or energy utilities, but also includes the emerging water and energy services companies and innovative technology providers.

Table 6.1 list some practical solutions that can be undertaken by end-users and industrial players. These options emphasize the high level of water and energy efficiency on both the supply and demand sides, intend to exhaust all conservation potential and local alternative sources, and thereby reduce the need for water and energy transfer. The following discussion elaborates these options.

Table 6.1 Nexus-oriented Management Options

	Water Sector	**Energy Sector**	**End-Users**
Conservation & Efficiency	Improve efficiency; Reduce leakage;	Reduce transmission loss; Improve conversion efficiency	Reduce demand Behavioral Change; Install efficient equipment
Industrial Improvement	Switch to less energy intensive approach (e.g., rainwater harvest);	Switch to less water-intensive cooling technology;	Move water-intensive industrial near water source
Local Alternative Sources	Use renewable energy to power desalination or wastewater recycling	Replace fossil fuel with renewable energy that requires less water	
External Sources	Water Transfer (least favorable)	Energy Transfer (least favorable)	

6.1.1 End Users

End-use efficiency and conservation forms the foundation of mitigating the water-energy tradeoffs (U.S. EPA, 2012). It is among the most effective ways to capture the co-benefit with water-energy interdependences (Bartos & Chester, 2014). Water conservation can achieve direct water savings as well as indirect energy saving, whereas energy conservation can lead to energy savings and indirect water savings. A broad array of strategies can be taken to facilitate end-use conservation and harness the co-benefit, including industrial efficiency improvement, irrigation retrofit, building energy upgrade.

Energy and water savings in the residential and commercial buildings are widely viewed as the 'low-hanging fruit', which can be achieved through behavior change or cost-effective efficiency upgrade.

Behavior Change for Conservation

Consumer behavior change can lead to instant savings effect. The education program, installation of the smart meter, and usage information disclosure are all effective ways to trigger consumer behavior change. Thanks to technology improvement, smart meters are now being installed in many countries to provide customers with real-time information on their water and energy consumption. It enables customers to identify conservation opportunities in their homes. Research conducted by the German universities found that the real-time feedback reduces the length of the shower, hence the water and energy consumptions (Tiefenbeck, 2016). A joint initiative by SP Services, Energy Market Authority, the Public Utilities Board and City Gas in Singapore, aims to raise public awareness on water and energy conservation by redesigning their utility bill. The redesigned bill gives consumers a snapshot of their utility usage, in comparison with the average consumption of neighbors, and personalized tips on how to be more energy-and-water- efficient.

Energy-Water Efficiency Retrofit

Energy and water efficiency improvement in residential and commercial buildings, although sometimes requiring substantial investment, is a cost-effective solution to achieve energy conservation and reduce carbon emission. In addition to the reduced water and energy costs, conservation upgrade can also improve the comfort level as well as increase the property value (Cajias & Piazolo, 2013). Such feature of building retrofit provides a strong motivation for property owners or managers to invest in efficiency improvement. Common water and energy saving technologies adopted by green buildings include rainwater harvesting design, low flow toilets, water saving fixtures and appliances, building envelope insulation, thermostats reprograming, occupation sensor, heating ventilating and air conditioning (HVAC) upgrade, and efficient lighting fixtures.

6.1.2 Energy Companies and Utilities

Cooling Technologies of Coal Power Plants

The majority of water use in the energy sector, mostly for the use of coal, takes place during the cooling process of power generation. Correspondingly, water cooling systems account for the largest potential for water savings (Pan, et al., 2012). Several practical options can be adopted, including the reduction of water losses during evaporation, switching to less water-intensive cooling technology, and the utilization of seawater for power cooling in coastal areas.

Table 6.2 compared the three major types of cooling technologies used for thermal power cooling. Among them, air cooling is viewed as a key technology option that can significantly lower the water demand of power generation. As water scarcity becomes the most challenging environmental constraints for coal power generation, air cooling technology has been widely deployed in North China (Zhang, et al., 2014). However, it should be noted that there are complex trade-offs by switching to air cooling, as shown in the table. It is more appropriate to consider air cooling units in most arid areas. In the coastal provinces, the direct utilization of seawater for cooling can serve as a preferred alternative.

Table 6.2 Cooling Technologies- Advantages and Disadvantages

Cooling Technology	Advantages	Disadvantages
Once-through (OT)	Lower consumptive use of water High cooling efficiency Mature technology Lower capital cost	High water withdrawal
Closes-loop (wet cooling)	Significantly lower water withdrawal Mature technology	Higher consumptive use of water than OT Lower plant efficiency Higher capital cost than OT
Dry (air-cooling)	No or very low water consumption	Higher capital cost Higher power consumption Lower plant efficiency Large are requirements Higher carbon emission

Source: (O'Hagan & Maulbetsch, 2009) (modified by the author)

Innovative Renewable Energy

Substituting fossil-fuel power plants with low-water renewable technologies can reduce water inputs during the fuel mining process as well as the power plant cooling process. The solar PV and wind power are among the most praised solutions for decoupling the water requirement of the power sector. If the 13th FYP goal of increasing wind power capacity to 200 GW is achieved, it would be able to save 800 million m^3 of water (Li, et al., 2012), while also reaping double benefits of carbon reduction and supply diversification. Replacing thermal generation with solar or wind power can contribute significantly to the water conservation in the northern part of China.

But not all renewable energy technologies are water-free. Some innovative energy solutions have negative impacts on water conservation. The *13th FYP for Renewable Energy Development* plans to install 5000 MW solar thermal power as part of its 110-GW solar goal. However, it raises concerns about its future water need. A recent scenario analysis indicates that the deployment of solar thermal infrastructure under the 13th FYP could lead to an additional increase of annual industrial water use of 0.08 billion m^3 by 2020 (Xu & Chen, 2017). Overall, integrated analyses will be needed to evaluate the whole ecological influence of each option.

Wastewater Recycling in the Fossil Fuel Industry

Given the large amount of water withdraws by the fossil fuel industry and the wastewater discharged into water bodies, a large potential of water saving exists in the fuel extraction process through water recycling. The current rate of treated wastewater recycling is only 22 percent (Pan, et al., 2012). China can explore this portion of water savings by increasing the water recycling rate during fossil fuel mining.

6.1.3 Water and Wastewater Utilities

Reduce Leakage Rate

The elimination of water losses due to leakages is an evident intervention to increase the utilization efficiency of energy at the supply stage of the water cycle. There are a number of strategies that can be used to reduce the leakage in a cost-effective manner. For example, the use of pressure control can effectively reduce existing leaks, prevent the emergence of the leaks, as well as lower the incidence of pipeline rupture (Nogueira Vilanova & Perrella Balestieri, 2014). Acoustic instrumentation is also often used to detect and locate nonvisible leakages.

Optimize Pipelines

Optimal design of water distribution systems can reduce the power required to head losses of a pumping system and account for energy savings. Pipeline optimization through the selection of appropriate valves, optimizing pipeline diameter and length can gain 5% to 20% energy savings (EPRI, 2009).

Install Energy Efficient Equipment

Municipal water and wastewater utilities can also identify their energy savings potentials through energy audits. Pumps are used extensively in public water supply systems to send water to a treatment facility or deliver treated water to the end-users. Pumping typically accounts for the largest energy use during water supply operation. Therefore, energy efficiency improvement, such as switching to efficient motor or pump sets, can provide significant energy savings (EPRI, 2009). Additionally, the installation of variable frequency drives to control pump can also optimize the energy performance of the system.

Increase Utilization of Renewable Energy in Water Supply Systems

The use of renewable energy sources for water pumping and treatment represents a possible solution to decouple water systems from the energy input. Renewable energy sources, especially solar and wind, are considered as feasible alternatives to the conventional energy source for water pumping (Nogueira Vilanova & Perrella Balestieri, 2014). Studies have examined the technological feasibility and economic attractive of the integration in various areas. For example, photovoltaic water pumping systems are suitable for irrigation, household water pumping, and water supply for rural areas lacking electricity access (Gopal, et al., 2013). Also, solar, wind or geothermal based desalination systems can be used to offset the energy intensity of seawater desalination (Ghaffour, et al., 2014). With a holistic planning, the integration of renewable energy with water supply systems can play a vital role in reducing the need of conventional energy sources and lowering the environmental impacts.

6.2 International Practices

International practices can offer valuable experience on policy implementation and industrial initiatives. This section focuses on initiatives led by local community and industries, as well as implementation example of government programs to illustrate *what to do* and *how to do,* using pioneering cases worldwide. To provide future reference for integrated management, this Chapter selected five cases based on the current needs and the future policy strategy of China. These cases target at various aspects of water-energy nexus management. Some of them address the financial challenges or overcome the institutional barriers, while others experiment the scale-up of advanced technology. Each case analysis includes the introduction of the key innovation and contribution, the implementation experience, stakeholder involvements, and valuable lessons to China.

6.2.1 Case 1-Building Water-Energy Efficiency

6.2.1.1 Background and Overview

The building sector demonstrates the largest savings potential at the demand side. However, the scale-up of energy efficiency faces several financial challenges, including the initial capital cost, long payback periods, and performance risks. A number of financing mechanisms have been adopted to address these barriers. Efforts in the U.S. and other leading countries offer great examples to ensure vigorous enforcement. The Energy Savings Performance Contracting (ESPC) (also referred to as ESCO/ESPC model) serves as a dominant model in current energy efficiency market (Kim, 2012)). ESPC is now a popular model used by public and private entities to implement efficiency improvement projects without the upfront cost. In addition, there have emerged some other promising innovative models over the past few years, including Energy Service Agreement (ESA), Property Assessment Clean Energy (PACE) and on-bill finance, which offer alternative options to enlarge the energy efficiency investment in both commercial and residential buildings.

This case study introduces a best practice using the example of the Delaware Sustainable Energy Utility (SEU). The Delaware Sustainable Energy Utility (SEU) is a unique non-profit organization offering a one-stop resource through its Energize Delaware Initiative to promote energy efficiency and renewable energy installations across the state. It utilized an innovative financing model to tap into the water and energy efficiency potentials in public buildings.

6.2.1.2 Innovation & Leadership--Energy Efficiency Bonds of Delaware SEU

In July 2011, the Delaware SEU issued $72.5 million in tax-exempt revenue bonds, the first of its kind in the U.S., to fund energy efficiency retrofit projects across Delaware. The bond program involves three state agencies (Office of Management and Budget, The Department of Corrections, Department of Services for Children Youth and their Families) and two institutions of higher learning (Delaware State University and Delaware Technical and Community College). It affects approximately 4% of Delaware's total state-owned or managed building stock (FREE, 2013). Six different energy service companies (e.g. NORESCO and Honeywell) were selected to implement the energy efficiency retrofits.

The energy savings potential of the projects funded by the SEU revenue bond is substantial. The bond issuance is purposely designed with extended payback period of 14 years on average and the longest maturity of 20 years so that participating agencies can install deep energy efficiency retrofits that need high up-front cost. Therefore, it offers an opportunity to realize long-term comprehensive energy consumption reduction. This bond is expected to generate $148 million in energy savings against total costs (including debt service) of $110 million, achieving an energy use reduction of 25% over 20 years (Byrne, et al., 2014). A recent study shows that the participating projects are outperforming the guaranteed savings. Energy service companies (ESCO) verified savings of the seven completed projects exceeds the guaranteed savings by 3% (Chu, et al., 2015).

The Delaware SEU successfully overcomes several well-known barriers to energy efficiency investment by using the innovative financial structure. A salient feature of this case is the use of the energy savings contract and green bonds. By aggregating all the participants under a single financing package, the bonds issuance lowers transaction costs and borrowing costs. Meanwhile, in order to lower the project performance risk, this financing strategy is backed by ESCO's energy savings guarantees. For each project, a Guaranteed Energy Savings Agreement was signed between the energy service companies and the participating agency, in which the ESCOs guarantee a fixed amount of energy & water savings to the agencies during each guaranty period.

More importantly, a key feature of this revenue bond is its risk mitigation mechanism (FREE, 2013). The tax-exempt bonds are backed by the government's taxing authority to guarantee repayment, which strengthens the creditworthiness of this investment and attracts private investment. Although this arrangement did not equate to a general obligation bond in which the State's taxing authority is pledged to repay debt from investments, it significantly reduced investor's reliance upon the project revenue streams and strengthened the investment's credit worthiness (FREE, 2013). The bond investment received an AA+ rating from Standard & Poor's Rating Service. Such a structure is proved to be attractive to investors. In fact, when the Delaware SEU offered the revenue bond issue, it was oversold in two hours, generating a premium in excess of $5 million (Byrne, et al., 2014).

Table 6.3 Stakeholders of the DE SEU Energy Efficiency Bonds

Stakeholders		Roles & Responsibilities
End-user	Municipal government, universities	*benefit from the reduced energy cost and improved building environment; pay back bond using energy savings*
Energy Industry	Energy Services Company	*Implement energy efficiency upgrades; monitor and report savings*
	Utility	*Assistance with utility data*
	SEU	*Bond issuance; coordinate the financing activates*
Others	Private investor	*Provide initial funding through energy efficiency bonds; collect bond payment*

Such a voluntary conservation effort is of particular importance to the energy security of the state of Delaware. Delaware relies heavily on imported electricity from PJM and imported coal from Pennsylvania and Kentucky, making it a net virtual water debtor (Wang, et al., 2015). Reducing energy consumption can not only reduce in-state water need for electricity generation, but also reduce virtual water imports, contributing to regional sustainability and equity. From the regulatory perspective, such efforts can also contribute to the implementation of electricity savings target required by the Delaware Energy Efficiency Resource Standards (EERS). By utilizing the new financial model, the Delaware SEU empowers community members to pursue energy efficiency in a cost-effective manner. Even though Delaware has not announced its electricity savings goal beyond 2015 (DSIRE, 2015), this financial model can still create a continued customer demand for energy efficiency improvement.

6.2.1.3 Lessons for China

China's building sector accounted for 28% of the nation's total energy consumption (WRI, 2016). Building efficiency in China calls for greater attention, given its upward pressures on building energy use due to economic growth, urbanization and rising living standards (WRI, 2016). In the backdrop, the 13^{th} FYP mandates stronger action on building energy efficiency. China has also adopted a national building code that requires all public buildings to meet the energy label. Although the policy regulation is driving up the market for building energy efficiency, the high up-front cost is still a principle barrier for buildings managers to install energy efficiency projects.

The innovative financial mechanism adopted by the Delaware SEU demonstrates the viable financial strategy to overcome the economic barriers. It provides monetary incentive to motivate end-users to engage in energy efficiency efforts. Through the application of the ESCO model, it further mitigates the project risk, providing customer confidence. Presently, China has fostered more than 5000 energy service companies (ESCOs) that can provide support on various technical and financial energy solutions (IEA, 2016). There are significant potentials to further utilize such innovative model to implement cost-effective energy and water conservation measures.

6.2.2 Case 2-Renewable Powered Desalination

6.2.2.1 Background and Overview

Desalination has gained increasing attentions worldwide during the past decades as the stress of water scarcity grows. Despite the environmental controversy with this technology, desalination is considered one of the most critical solutions for future water security. Currently, over 300 million of people in the world rely on desalinated water for daily use (IDA, 2015). The Gulf region, where desalination has taken a key role in drinking water supply, hosts about 40% of the world's desalination capacity. But one of the biggest concerns with desalination is its high energy intensity, making it economically impractical in the short term and also challenging energy security in the long run.

Against this background, countries are experimenting with the application of renewable energy, particularly the solar power, in desalination. The idea is to expand desalination without placing extra loads on the existing energy supply system. But the intermittency nature of solar power has made it difficult to convert this idea into practice. Benefited from the ample sunshine, the Gulf countries are among the pioneers that are experimenting with the solar-powered desalination projects. After years of pilot programs, some nations have successfully put this innovation into practices. For instance, Masdar in Abu Dhabi launched the Renewable Energy Desalination Program in 2013 to demonstrate the advanced and innovative desalination technologies that work with renewable energy sources (Ramahi, 2017). Currently, around 0.8% of the global desalination capacity is supplemented by solar power (B'kayrat, 2014). While many previous pilot projects have a capacity of 100~1000 m^3/day, Saudi Arabia is building the world's first utility-scale solar powered desalination plant in the city of Al Khafji. This case study will look at this example and reveal how Saudi Arabia makes the large-scale solar desalination feasible.

6.2.2.2 Innovation & Leadership—Solar Desalination in Saudi Arabia

The Kingdom of Saudi Arabia (KSA) has the largest desalination market in the world, making up 22.2% of the world's desalinated water (Al-Alshaikh, 2017). Even sitting on a huge amount of oil reserves, the Kingdom are keenly aware that pouring oil to boost the desalination plants is unsustainable and economically unacceptable (AWT, 2015). Fighting against the old habit of cheap oil, Saudi Arabia is considering solar, another strong natural endowment, as the alternative choice.

In 2010, the King Abdullah's solar desalination initiative set up a deployment plan for solar water desalination. A major goal of this initiative is to lower the cost of solar-powered desalination to less than US$0.40/$m^3$ (Riyal 1.5/m^3), representing a substantial reduction compared to the current cost of RO desalination of US$0.67-1.47 m^3 (Riyal 2.2-5.5/m^3) (Al-Alshaikh, 2017). The initiative consists of four phases:

- Phase I: construction of a solar-powered desalination plant in Al-Khafji with a producing capacity of 30,000 m^3/d (increased to 60,000 m^3/d);
- Phase II: construction of a solar-powered desalination plant with a producing capacity of 300,000 m^3/d;
- Phase III: Implement the initiative throughout the Kingdom;
- Phase IV: Apply the experience to provide low-cost water to the agricultural industry.

The Phase I plans to build the world's first large-scale desalination plant powered by solar energy. The state-owned Saudi company Advanced Water Technology (AWT) takes the lead in building this project. The AWT is the commercial arm of the King Abdulaziz City for Science and Technology, a scientific government institution. In 2015, the AWT entered a partnership with the Spanish technology company Abengoa to build this utility-scale seawater reverse osmosis (SWRO) desalination and PV Plant, which is scheduled to go online in 2017 (Abengoa, 2015). A solar farm with a total capacity of 15 MW, using polycrystalline solar cells, will be located near the seawater intake area. With a total value of US$130 million, this pilot plant will be able to produce 60,000 m^3 of water per day and supply the desalinated water to the local residents of Al-Khafij in North Eastern Saudi Arabia.

This SWRO project aims to get 100% of its energy from the solar farm and achieve net zero emissions. The AWT is working with the Saudi Electrical Company (SEC) to connect the solar system with the electric grid. The grid serves as an ‘energy storage system’. During daytime, the SWRO plant will function with the input of solar power. Any excessive solar output during peak hours can be fed back into the SEC grid. During the nighttime when this is no solar power, the SEC will supplement the power supply to the SWRO plant. By working with the energy utility, this project will be able to maximize the efficacy of using solar power and overcome the intermittent issues.

The technological breakthrough of desalination methods is another reason that makes this project the economically feasibility. The reverse-osmosis (RO) technology is often criticized by its energy intensity and high cost. RO with solar PV in a closed system is considered uncompetitive in Saudi Arabia, compared to existing technologies (Napoli & Rioux, 2016). By incorporating a number of engineering improvement, this project will be more efficient than conventional desalination technologies. It customized a reverse osmosis nanomaterial membrane to cope with the high salinity in the region while reducing the energy input. Together, these technologies bring down the cost and make desalination less expensive.

Led by a state-owned company, the project actively engages different stakeholders and is built on the support from the government and research center. The key stakeholders involved are listed in Table 6.4.

Table 6.4 Stakeholders of the Solar Desalination Project in Saudi Arabia

Stakeholders		Roles & Responsibilities
Government	Ministry of Water and Electricity Ministry of Finance	*Set policy requirement*
Energy Industry	Technology Service Companies (Abengoa)	*Provide technical and funding support*
Water Industry	Advanced Water Technology	*Develop the solar desalination plant*
Energy Utility	Saudi Electrical Company	*Purchase excess solar power during peak hours*
Scientists	KACST	*Provide technical support*
End-user	Local residents	*benefit from the diversified water supply*

6.2.2.3 Lessons for China

Following the footsteps of the most water-stressed countries in the Gulf region, China is pioneering desalination in its coastal provinces as an engineering solution to deal with the ongoing water scarcity. China's continued emphasis on desalination is likely to place more pressure on the energy deficient areas like this. In Zhoushan, an island city in Zhejiang Province, 58% of the desalination cost is due to the energy spending (Shifflett, et al., 2015). As China is determined to diversify its water supply with desalination, it has to make a long-term energy plan for it.

This solar-powered desalination plant in Saudi Arabia offers a new direction for China to consider. This case study suggests that it can be technological and economically viable to incorporate renewable energy with desalination at a large-scale. It not only highlights the importance of customized technology innovation, but also demonstrates how the strong public-private partnership plays in carrying out such project. It is recommended that the national laboratory of Tianjin Seawater Desalination and Utilization Research Institute can play a leading role in facilitating solar desalination technologies in China. Coupled with other efforts, such innovation will create a cumulative transformative effect on the desalination industry in near future.

6.2.3 Case 3-Energy Neutral Wastewater Treatment

6.2.3.1 Background and Overview

Energy neutral wastewater treatment has gained a lot of attention in water utilities. An emerging principle of advanced water-energy management is to treat wastewater treatment facilities as 'renewable resource recovery facilities that produce clean water, recover energy and generate nutrients' (U.S. EPA, 2012). Wastewater treatment utilities worldwide are practicing such a principle by generating renewable energy from wastewater. Examples has proved that today's technology and knowledge is capable of making wastewater facility energy self-sufficient. After years of efforts, the Marselisborg Wastewater Treatment Plant in Aarhus, Denmark has transformed from an energy consumer to an energy producer through the implementation of energy-saving technologies and the utilization of onsite biogas, achieving a net energy production of 153 percent in 2015 (Aarhus Vand, 2016). The Southern Ontario Water Consortium in Canada is also exploring the 'energy neutral' solution for wastewater treatment by cooperating with the local universities and technology companies (SOWC, 2017).

This case study will use the example of the San Antonio Water System (SAWS) to illustrate sustainable strategies for wastewater facilities. SAWS is a public water and wastewater utility owned by the City of San Antonio, TX. It provides water and wastewater services to more than 1.6 million people in Bexar County, as well as parts of Medina and Atascosa counties, TX. As part of its mission, Sustainable, Affordable Water Service, SAWS has great efforts in energy management and conservation. SAWS is also the first large-scale public utility in the U.S. to capture and sell biogas generated during sewage treatment.

6.2.3.2 Innovation & Leadership—Water-Energy Strategy of SAWS

The Dos Rios Wastewater treatement plant (WWTP) is the largest sewage treamtment facility of the San Anotonio Water System (SAWS). It has actively engaged in a variety of energy conservation projects, including implementing lighting retrofit, switching to high-efficiency pumps and motors, etc. In recent years, SAWS promotes a set of various water-energy management approaches at this WWTP to minimize its environmental footprint, Figure 6.1 demonstrates all the efforts taken by the Dos Rios WWTP.

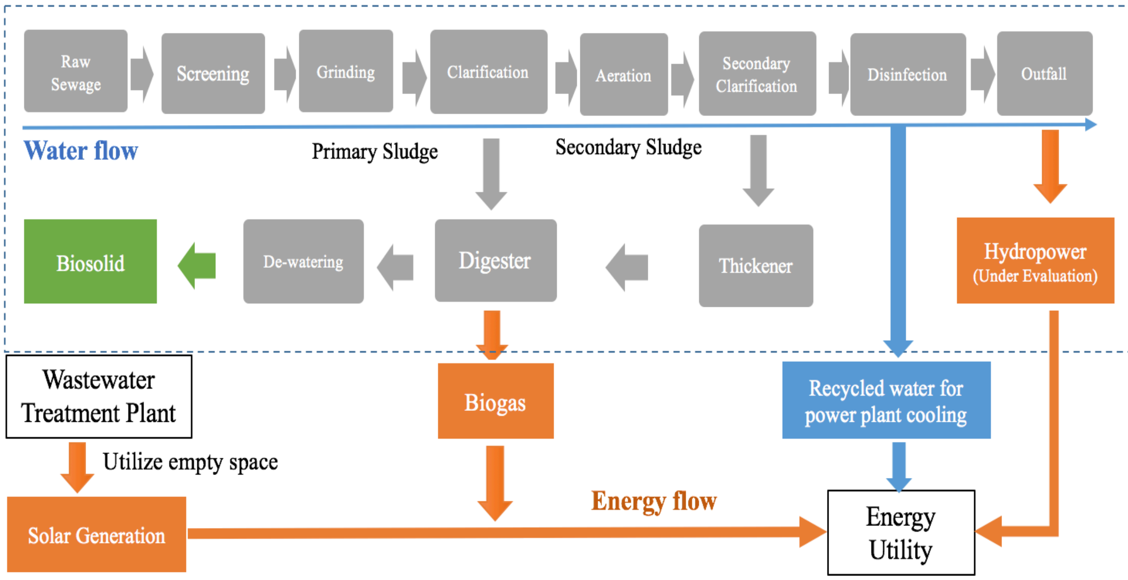

Figure 6.1 Water-Energy Strategies at Dos Rios WWTP

- Recycled Water

SAWS has the largest direct recycled water delivery system in the nation. More than 130 miles of pipelines, also known at SAWS as the 'purple pipe', deliver recycled water to commercial and industrial users. Notably, CPS Energy, the local energy utility has contracted with SAWS to use up to 50,000 acre-feet (61.7 million m^3) of the treated effluent water per year to cool its power plants at the Calaveras and Braunig Power Stations (SAWS, n.d.; Galvan, 2014).

- Biogas and Biosolid

While most utilities simply burn up the biogas generated onsite during the digestion process, SAWS has partnered with Ameresco, a national energy service company (ESCO), to treat and transfer at least 900,000 cubic feet of biogas to a nearby commercial pipeline and sell on the open market. Ameresco utilizes a minimum of 90%

of the generated gas for beneficial use with the remainder utilized by SAWS for heating the sludge. The extracted digester gas is filtered to remove liquids and particulate matter prior to being delivered to high-pressure compressor for delivery to the pipeline. Annually, Ameresco pays SAWS 12% of the net income of the gas sale as a royalty. The digestion process creates another byproduct, the biosolids, which is converted into useable compost with commercial value and send to local retailers and nurseries.

- Solar PV Generation and Hydropower Energy Recovery

SAWS has also contributed to the city's energy sustainability by hosting a 20 MW solar farm at its Dos Rios WWTP. The solar PV system was developed by SunEdison under a 25-year solar power purchase agreement (PPA) with CPS Energy. As opposed to build its own system, SAWS coordinated with energy service companies to build the project. In such way, SAWS engages in renewable energy industry without the need of putting together the funding or assigning additional staff to manage the projects. Meanwhile, a hydropower recovery project is under consideration, aiming to capture the hydropower at the outfall of the Dos Rios WWTP. If implemented, this hydro system can produce 3,241,200 kWh/yr.

- Demand Side Management

SAWS is participating in the Demand Side Response Program of CPS Energy. This is a program designed to shave the peak load by incentivizing customers to reduce their energy load during peak hours in summer. As SAWS is one of the largest energy consumer in the City of San Antonio, this program is beneficial to both parties. Since

2009, SAWS has received a total of $1,566,746 from CPS as an incentive to lower its peak demand.

Table 6.5 Stakeholders of the Water-Energy Management of SAWS

Stakeholders		Roles & Responsibilities
Energy and Water Industry	Water Utility	*Monitor daily energy usage, identify conservation & renewable energy opportunities*
	Energy Utility	*Assistance with utility data; provide demand-side program*
	Energy Service Companies	*Implement efficiency upgrades; offer financial and technical package for renewable energy*

The achievement at SAWS on water-energy integration can be largely attributed to the creation of the energy office. The primary task of this energy office is to keep track of daily energy usage, and monitor the energy consumption trend to spot conservation opportunities. It developed an online web-based database to track all the detailed information on energy bills, including energy consumption (kWh), energy demand (kW), and the corresponding charges. With the available data, the energy team is able to conduct a variety of the energy analysis to model the cost/benefit of alternative energy options. Meanwhile, the energy office takes the leading role to develop an annual energy cost budget for each major facility. Through the budgeting process, the facility managers will gain a better understanding of the energy cost and become more aware of how the daily operation activities can affect their energy bill. Also, the energy office maintains a good relationship with its energy provider, and often holds dialogues with CPS Energy on energy-related issues.

6.2.3.3 Lessons for China

In China, the sewage treatment has placed increasing pressure on total energy consumption as domestic water consumption grew slowly. The impact will be further enlarged as the wastewater treatment scale expands and treatment standards increase. The intensifying conflict between economic development and resources and environmental restriction in China suggest that China's wastewater industry needs a paradigm shift (Zhang, et al., 2015). However, traditionally, there exist split incentives between water and energy management at large water utilities. The top task of the water facility managers is to provide sufficient water or sewage service, and energy cost is often regarded as the necessary expense for operation. But such tradition is not sustainable. This emerging industry in China has to learn to fully utilize wastewater as a resource, and serve as an entry of energy recycling.

SAWS offers a good example on how a water utility can explore its onsite renewable energy opportunities as well as the energy conservation potentials. It provides valuable experience on how to overcome the economic and technical difficulties and bypass administrative barrier. First, through the creation of an energy office, it bridges the gap between water and energy management in the water utility. Second, it addresses financial barriers by engaging the local energy utility and energy service companies. Limited funding availability is always a concern for public WWTPs to pursue energy improvement. SAWS successfully avoided the initial investment and performance risk by working with energy companies to utilize innovative financing models.

6.2.4 Case 4-Wastewater Reuse from Shale Gas

6.2.4.1 Background and Overview

Wastewater discharge is one of the environmental concerns of oil and gas industries. The water-intensive feature of hydraulic fracturing brought the water issues to the forefront of the public debate on the emergence of shale gas (Mielke, et al., 2010). The produced water and the flowback fluids during the fracturing process typically has a high concentration of total dissolved solids (TDS) that may adversely impact the soil and water quality if released without properly treatment (Schmid & Yoxtheimer, 2015). The future growth of this unconventional energy sector depends on careful management and legislation as well as the industry's ability to adopt integrated water management practices. Recycling the wastewater generated during the oil and gas production process provides a solution to reduce the water costs while controlling the environmental impacts.

Researchers have conducted analyses to examine the possibility of wastewater recycling for shale gas. The findings suggest that the use of recycled wastewater does not affect the production of shale gas wells, and it can be cost competitive compared to other treatment or disposal options since it reduces the cost to obtain and transport fresh water (Schmid & Yoxtheimer, 2015). The following case looks at the wastewater recycling efforts in the Marcellus region, which has the highest-producing shale gas formation in the U.S.

6.2.4.2 Innovation & Leadership—Wastewater Recycle in Marcellus Shale

Since the shale boom in 2004, the number of shale gas wells has grown significantly in the Marcellus region, so does the amounts of water used for fracturing

(Schmid & Yoxtheimer, 2015). During the early stage, most of the wastewater was collected and moved to wastewater treatment facilitates, when less than 5% of water was recycled (Schmid & Yoxtheimer, 2015). In 2010, the Pennsylvania Department of Environmental Protection (PA DEP) issued a regulatory change to limit the amount of wastewater a public sewage treatment plant could take. Meanwhile, the shale gas companies were asked to voluntarily stop sending their wastewater from unconventional wells to facilities that did not have the capacity to adequately treat the high concentration of TDS. This change led to a surge of wastewater recycling and reuse in fracturing and drove up the recycled ratio from 2% in 2009 to 23% in 2013.

Against this background, a business model named *Sourcewater Marketplace* was launched to strengthen the market force in wastewater management of the shale industry. Although still in its start-up stage, this model presents a future possibility of a cost-effective solution to address the wastewater issues in shale gas industry. The *Sourcewater* is an online exchange tool that provides users with a list and interactive map of all available freshwater and wastewater, wastewater treatment facilities, shippers, and other water-based services (Matheson, 2017). It started as an Energy Ventures Program at the Massachusetts Institute of Technology, with the goals to reduce water management cost of the energy industry, ensure water supply availability, and minimize the environmental impact of energy activities (Thicket, 2014).

A fracking firm may list its wastewater with information on the key characteristics via *Sourcewater* and name a price they are willing to pay for hauling it away. Shippers and treatment facilities can bid on transporting and treating the water. Alternatively, a nearby gas-drilling firm may offer to take away the wastewater and use it for its own operations. From all these offers, the selling firm can choose the deal that best fits its budget and schedule. A great feature of this model is to promote wastewater as a commodity. By selling the wastewater to another nearby fracking firm, it can reduce the amount of wastewater discharge for the selling firms and eliminate the need of freshwater withdrawals for the buying firms, thereby lowering the cost for both parties.

Currently, the *Sourcewater* website has about 1.4 billion barrels of water listed online, primarily in the Marcellus Shale region of the United States, including Pennsylvania, Ohio, and West Virginia (Matheson, 2017). The future plan of *Sourcewater* is to create a search platform for water-based resources that offer real-time tracking, measuring, and verification (Thicket, 2014).

Table 6.6 Stakeholders of Wastewater Recycling Efforts in Pennsylvania

Stakeholders		Roles & Responsibilities
Government	PA DEP	*Set up regulation on wastewater management for shale gas industry*
Energy Industry	Shale gas firms	*Trade wastewater*
Water Industry	Water treatment and services companies	*Collect and treat wastewater*
Local community	Sourcewater	*Offer a marketplace where transaction can be made at a lower cost*

6.2.4.3 Lessons for China

As China is slashing a future plan for shale gas in Sichuan Province, the government needs to make arrangements for the associated wastewater. The 13th FYP has an ambitious goal to produce 30 billion m^3 of shale gas in 2020 (NDRC & NEA, 2016). Predictably, the share-gas extraction in China will compete against the agricultural, industrial and domestic sectors for limited water resources. It is projected that the water use of hydraulic fracturing in Sichuan Basin, one of the most promising shale gas basins in China, would reach 20-30 million m^3/year during the next decade (Yu, et al., 2016). In addition to the water shortages, potential water pollution from China's shale gas production poses more serious problems to its local water resources (Guo, et al., 2016).

This case study shows that the governmental regulation to limit the wastewater can create strong market incentives for wastewater recycling in the unconventional energy industry. Functioning as a third-party information agency, the *Sourcewater* demonstrates a business model on how to implement strict water regulations in a cost-effective way. Since approximately 10% of total capital expenditure of a typical shale gas well is attributed to water management (Cain, 2014), this model presents an economic opportunity by lowering the wastewater management cost. It suggests that the shale gas industry can reduce its operational expense while complying with local or national regulations. The conceptual breakthrough in this case is to build a 'bridge' for information exchange. The effective data dissemination provides fundamental support to the success of this model. By connecting the wastewater sellers with the potential buyers directly with transparent prices, this mechanism reduces the transaction costs and cut down the negotiation process, which are often the major barriers to wastewater reuse.

6.2.5 Case 5-Solar Pumping for Rural Water Supply

6.2.5.1 Background and Overview

Energy use for irrigation, including electricity and diesel gas, contributed to 50%-70% of total energy-related carbon emission in the agriculture sector (Xou, et al., 2015). Solar pumping, among all the innovative technologies, has emerged as one of the preferred solutions in addressing the water and energy need, especially in remote areas without the power grid. Given its reliability, flexibility, and scalability in meeting diverse energy demands, the solar pumping system can play a positive role in decoupling the irrigation need from fossil fuel, while improving livelihoods of the rural community (IRENA, 2016).

Attracted by the potential benefits, a growing number of countries have launched programs to accelerate the deployment of solar pumping systems. For example, Bangladesh plans to deploy 50,000 solar pumps by 2025, whereas Morocco has a goal to install 100,000 solar pumps by 2022 (IRENA, 2016). This case study will be drawn for the example of a national solar pumping program in India.

6.2.5.2 Innovation & Leadership—National Solar Pumping Program in India

The Indian Ministry of New and Renewable Energy (MNRE) launched the *Solar Pumping Program for Irrigation and Drinking Water under Off Grid and Decentralized Solar Applications Schemes* in 2014. It targets to implement 100,000 solar pumps every year and deploy at least 1 million solar pumps by 2020-2021 (SHAKTI, 2015). Of the 100,000 target in the period of 2014-2015, the State Nodal Agencies will be responsible for installing 50 thousand solar pumps for irrigation and 20 thousand for drinking water, while the rest 30 thousand to be implemented through National Bank for Agriculture and Rural Development (NABARD) throughout the country (MNRE, 2014). The first round of allocation covers 21 states in India.

Indian government invested an initial financial support of US$60 million (Rs.400 crores) to support the implementation of 2014-2015. The MNRE provides 30% capital subsidy to the farmer for installation of solar pumps for irrigation through the State Nodal Agencies. It also provides 40% subsidy with a mandatory loan to farmers for irrigation purposes through NABARD. The state government can further subsidize the cost by leveraging funds from various sources. Also, the state government has the liberty to identify various implementation models. Financing options outlined by the scheme include a conventional model, a loan model that allows financing through lending agencies, and innovative business models like 'water as a service' (MNRE, 2014).

Another salient feature of this program is the combination of water and energy efficiency. It promotes efficiency of water usage, utilizes solar tracking, low friction piping system and other solutions to reduce the system cost and improve the overall efficiency. Meanwhile, it intends to control over-exploitation of water by integrating drip irrigation system. The encouragement on the integration of overall efficiency in agricultural activities can also help farmer leverages subsidy and funds from other schemes.

To ensure the scale-up of the solar program, the scheme highlights the role of effective communication strategies with a focus on awareness raising and technical training. The State Nodal Agency is encouraged to adopt various communications tools, such as awareness program, electronic media, supplier demonstrations, site visits, to enhance awareness and to build the knowledge base for necessary acceleration. Moreover, training programs regarding different aspects of the program, such as operation and maintenance of solar pumps, reporting, and monitoring, will be conducted at various levels to build the stakeholder capacity.

Table 6.7 Stakeholders of the Solar Pumping Scheme in India

Stakeholders		Roles & Responsibilities
Central Government	Ministry of New & Renewable Energy	*Program administration; oversee the implementation*
	Ministry of Agriculture and Ministry of Drinking Water & Sanitation	*ensure effective coordination for integration of various schemes*
	NABARD	*financing agency to provide loan and/or extends subsidy*
Local government	State Nodal Agency Power/Energy Department Agriculture & Horticulture Department Renewable Energy Department	*overall program implementation; identify target; selection of suppliers; leverage subsidy from other sources; awareness generation; monitory and evaluation;*
Lending agencies	Regional rural banks, scheduled commercial banks, multilateral/bilateral lending agencies	*provide funding in the form of loan or grants*
End user	Farmers	*Application for installation; provide upfront contribution; selection of manufactures; provide space; routine maintenance;*
Industry	Supplier/Manufacture	*Installation, maintenance, awareness generation*

If implemented effectively, the distributed systems can provide better energy reliability to the water-stressed regions in India. It is too early to conclude the overall performance of this scheme. However, the recent implementation suggests a difficult take-off. As of April 30, 2016, only 25,059 pumps were installed, falling far short of the 100,000 target (MNRE, 2016). In Maharashtra, one of the states that have taken a leading role in this scheme, the state government has contracted to install 10,000 solar pumps, while only 6,500 farmers have applied (Bridge to India, 2016). Even the 95% capital subsidy failed to attract farmers to enroll in this solar pumping scheme. Many blame the procurement design and stringent eligibility criteria for the limited interest among farmers (Bridge to India, 2016). The Maharashtra government requires the applicant to have a landholding smaller than five acres (20,234 m^2). This design was intended to prioritize farmers with worst agrarian crises and ensure the society benefit of the poorest, but some eligible farmers, who are also the poorest, are reluctant to even contribute 5% of the upfront cost.

6.2.5.3 Lessons for China

Several provinces in China are experimenting the solar-based water solutions through demonstration and small-scale pilot programs. For example, a pilot project in Qinghai, supported by the Asian Development Bank, demonstrated that a 2 kW-peak solar-powered water pumping system are capable of providing both drinking water and small-scale irrigating water (Yeager & Radstake, 2012). The results indicate the technical, economic and environmental feasibility of the solar PV pumping system in the rural area of the north and northwestern China. However, despite that the Chinese government has designed favorable policy and subsidies towards distributed solar PV system, there is still a lack of policy support for the scale-up of solar PV in irrigation and drinking water systems. Some of the water-deficient provinces, such as Xinjiang, Qinghai, Gansu, are also among the underdeveloped zone in China. Therefore, the governmental assistance for solar pumping systems can generate vast social benefits in these areas (Liu, et al., 2010).

The Indian case shares some similarities with China's situation. Both countries have a large rural population with poor water access and a water-demanding agriculture system. The overall design of the Indian solar pumping program provides valuable experiences in several aspects. First of all, it is necessary to create dedicated initiative and financial incentives to scale up the deployment of solar PV in the rural water system. The government can shift the subsidies on rural electricity and diesel to solar water pumps by establishing a special fund for the solar PV irrigation system. Moreover, it encourages irrigation water efficiency to avoid possible overdraft of water led by the lower cost of solar pumping. At same time, this case also rings an alarm. The emphasis on subsidy or over-subsidy does not necessarily guarantee effective implementation. Proper program design, enhanced stakeholder engagement, effective communication with participants, and continuous feedback and improvement will be needed to ensure the success of such program.

Chapter 7

CONCLUSIONS AND RECOMMONDATIONS

7.1 Conclusions

This dissertation built a theoretical framework to analyze the water-energy nexus and its implications for resource management. In particular, the regional self-sufficiency was highlighted as a crucial pathway to achieve long-term water-energy sustainability. Following the theory review, this dissertation developed a quantitative analysis to assess the water-energy nexus in China and identified the areas for further policy integration. The key findings of this study are summarized below.

7.1.1 Sustainability and Resource Self-Sufficiency

This study looked into the concept of sustainability to define the role of self-sufficiency in resource management. A strong sustainability concept indicates that development should not go beyond the local environmental capacity. Unlimited economic accumulation based on aggressive resource exploitation cannot be sustained by finite resources. Therefore, the resource self-sufficiency, although often ignored at the subnational level, has impacts on the resource sustainability for a country, a region or a local community. First, by focusing on the regional resource self-sufficiency, we can proactively prevent any unrecoverable resource depletion. Furthermore, the regional self-sufficiency promotes the role of local knowledge and indigenous culture and value to bring back a harmonious relationship between humans and the environment. More importantly, resource self-sufficiency directly addresses the environmental injustice issues across the national or subnational borders. Lastly, being self-reliant can contribute to the system reliability by lowering the impact of external risks. Overall, a self-sufficient system minimizes its ecological footprint, cherishes the local available resources, and often has strong adaptability supported with smart designs. Therefore, this study adopted the principle of regional self-sufficiency as an overarching guideline for resource sustainability.

7.1.2 Water-Energy Nexus and Resource Management

This study utilized the emerging tool of the water-energy nexus to synthesize the management of water and energy resources. The concept of the water-energy nexus offers a cross-sectoral perspective to reassess the two essential resources for human survival and modern development. Energy, in the form of electricity, is the indispensable power source for the entire water supply cycle, while water input is needed to produce fossil fuel and generate electricity. Owing to these interlinks, the water crisis often comes with energy conflicts, and holistic approaches are needed to address them together.

The energy intensity of water supply and the water intensity of energy production depend on a number of factors, including the local resources availability, technology capacity, surrounding environment and climate, socioeconomic circumstances, as well as indigenous culture and customs. Therefore, there exist great geographical variances of the water-energy nexus in different regions. In order to address a country's water-energy issues, it is necessary to first understand the unique interlinks at both the national and local levels.

Connecting the idea of resource sustainability with the concept of the water-energy nexus, this study developed a nexus-oriented resource management strategy with four features:

- Integrated Management

  The interdependency of these two resources calls for holist management. Different energy solutions require various amounts of water input, while various water supply methods can lead to different energy uses. Thus, gaining insight on the water-energy nexus in a region can encourage information exchange, provide guidance on its future energy and water planning, and help avoid or minimize potential water-energy collision.

- Demand-Side Conservation

  The nexus perspective implies the need to change the supply-dominated mindset by focusing more on the demand-side management. Prioritizing the demand-side conservation and efficiency is a cost-effective way to control the future incremental demand and restrict the unnecessary expansion of infrastructure. Moreover, the demand-side management exploits the enormous synergic savings through water and energy conservation, e.g. 'save energy to save water' and 'save water to save energy'.

- Indigenous Resources

  The nexus-oriented system also emphasizes the value of indigenous resources. A region should understand the strengths and weaknesses of its local endowments and utilize them rationally and accordingly. By doing so, its development can be compatible with its local water and energy environment. It also makes sure that a region's development does not come at the price of another region's resource depletion or environmental degradation.

- Decentralization and Diversification

  A region's water and energy systems can also benefit from decentralization and diversification. Small-scale and diversified systems can contribute to system reliability and resilience and adapt to the changing local needs. Additionally, they offer the flexibility to incorporate alternative water or energy solutions to decouple the energy sector from water input, as well as lower the energy need of water production.

7.1.3 Water-Energy Interconnections and Challenges in China

The study dissected the water-energy situations in China from the perspective of the water-energy nexus. Most of the challenges are derived from the water-energy trade-offs between various technologies in use and/or the spatial variations at the provincial level.

- Water Supply Cycle and Energy-for-Water

In 2014, China used a total of 6,097 billion m^3 of water for agricultural, industrial, domestic, and ecological purposes. Correspondingly, a sum of 249 TWh of electricity was used to power these water supply and treatment activities. Water sourcing has the largest share of electricity consumption (59.9%), followed by water treatment & distribution (34.1%) and wastewater collection & treatment (6.0%). Within the water sourcing phase, over 62.6% of electricity use was associated with surface water extraction, while 29.9% went to groundwater pumping. Together, the energy for water contributed to approximately 4.5% of the total national electricity consumption in 2014.

The introduction of energy-intensive sourcing techniques is a factor that might increase the future EFW. It is important to note that unconventional water sourcing techniques, like seawater desalinization, water recycling and water transfer, provided only less than 3% of total water supply in 2014, but used more than 11.1 TWH of electricity (equivalent to 7.4% of $EFW_{Sourcing}$) due to their energy-intensive nature. The energy need in the downstream is also noticeable. Due to the relatively low wastewater treatment rate of 69% in China, the energy need for wastewater collection & treatment was 14.8 TWh in 2014, making up only 6% of the total energy for water. However, the annual wastewater discharge and treatment capacity are growing rapidly, and so will the future associated energy input.

Although the central government placed a national cap of 670 billion m^3 by 2020 to limit the total water consumption, it is predicted that the associated energy inputs could increase drastically, given the introduction of energy-intensive sourcing techniques, improved water quality standards as well as the extended wastewater treatment coverage.

- Energy System and Water-for-Energy

The total energy production in China in 2014 equals 3618.6 million tce, 79.2% of which came from coal, making China the largest coal producer and consumer in the world. The power sector is also dominated by coal-fired power plants with closed loop systems. The water intensity of coal mining is estimated to be 0.35 m^3/tce, while the average water requirement of thermal power generation in China is approximately 1.83 m^3/MWh. Hydropower, the second largest electricity source in China, consumes as high as 13 m^3 of water for per MWh electricity generated. The dominance of water-intensive energy sources in China yields an energy system that is highly dependent on water resource availability.

Given the energy mix in 2014, the total water consumption for energy production in China was 23,109 million m^3, equivalent to 3.8% of the country's total annual water use. Among them, a total of 1,282 million m^3 of water was consumed to produce fossil fuels, while 7,640 million m^3 was attributed to the cooling needs of massive thermal power plants across the nation. Furthermore, this study found that the widespread deployment of hydropower projects, as a low-carbon replacement for coal, exaggerated the water-energy interdependency by introducing an additional 13,751 million m^3 of water consumption due to the evaporation. It is evident that the water availability is becoming a growing concern for China's energy security.

- Regional Variations

China's water-energy nexus issues have significant regional variations, corresponding to its natural geographical characteristics as well as its economic and social development patterns. These regional variations have caused two layers of conflicts, the spatial mismatch of supply and demand as well as the regional disparities of water and energy.

In the energy sector, traditional fossil fuel production is concentrated in a few northern and northwestern provinces, like Shanxi, Shaanxi, Xinjiang, Inner Mongolia, etc. Most of the hydropower is generated by southwestern Sichuan and Guizhou Provinces. In addition, the bases of new large-scale renewable power plants, namely solar and wind power, are also located in relatively remote areas. However, a large portion of the national energy demand comes from the rich eastern coast and the populated areas of Central China. This distribution pattern has given rise to massive interprovincial energy transportation and power transmission infrastructure across the country. Moreover, this layout of energy distribution is further confronted with incompatible water resources. Since 80% of coal production is located in water-stress provinces, including Shanxi, Shaanxi and Inner Mongolia, the water-for-coal has overtime become a key factor that determines the feasibility of coal mines and coal-fired power plants.

Similar concerns exist within China's water sector. The feature of the total water resources appears on a diminishing scale from south to the north. In the meantime, the per capita water availability in the east is much lower than that in the west. The 3-H plain, which is the major food production base and the most populous area in China, is struggling with severe water stress. As a result, water transfer projects with various scales emerged as a measure of water reallocation. Currently, there are more than 127 water transfer projects nationwide to mitigate the geographical mismatch of water distribution. More importantly, provinces with the largest energy-for-water, such as Jiangsu and Guangdong, fall into the category of electricity-deficit, implying that the water supply is adding heavy pressure to their already constrained power system.

7.1.4 Impacts of Domestic Water and Energy Transfer

China has constructed massive engineering transfer projects to connect the resource-scarce areas with resource-abundant regions. This study found that, although these projects aim to optimize resource allocation, they can lead to overexploitation of resources, cause environmental injustice, and magnify the environmental impact of human activities. Especially, from the perspective of the water-energy nexus, intensive domestic transfer projects could harm the local water systems in the energy bases, and affect the energy security in water-exporting provinces.

As the focal point of this study, Chapter 4 assessed the virtual water associated with domestic energy transfer in China. Among the thirty provinces, autonomous regions, and direct-controlled municipalities, thirteen of them are net virtual water exporters, and most of them are located in North, Northwest and Southwest China. The correlation analysis suggests that the virtual water, along with the energy products, is flowing from less developed provinces to richer and more industrialized areas. More alarmingly, several provinces that export virtual water via thermal power or fossil fuel export are under severe water-stress, including Shanxi, Shaanxi, Ningxia and Inner Mongolia. The fossil fuel and power transfer places extra water pressure on the water-scarce regions, causing environmental injustice.

Similarly, the energy embodied in water transfer is also often overlooked. Owning to the lack of data, this study was not able to present a comprehensive scope of the energy flow associated with interprovincial water transfer. But the data in this analysis are sufficient enough to demonstrate the significant magnitude of energy consumption for water transfer. What's more concerning is that most of the embodied energy originated from energy-deficient provinces, such as Jiangsu and Hebei, further aggravating their energy dependency. It is worrisome that these transfers projects are creating a vicious cycle of water-energy depletion by locking in the incremental demand.

Furthermore, although built upon intensive environmental sacrifice, these engineering projects do not always guarantee the water and energy security in the intake areas. Instead, it often gives birth to new problems. This study examined some representative cases to reveal the tradeoffs between economic, social, and environmental elements of resource transfer. The results show that the transfer is often subject to annual variation of precipitation of the origin areas, the success of which depends heavily on the accuracy of prediction of precipitation and water demand. In the case of SNWTP, the risk of water quality degradation along the canal is also a top concern as it introduces the severely polluted south water to the north. Moreover, many of the energy projects are not well managed and planned, causing a low utilization rate and potential future risks. More specifically, the hydropower and wind power were deployed in a large scale as the major emerging sources for power transfer in China. However, their curtailment rates were very high in the past few years, leading to a waste of resource and investment.

7.1.5 Nexus-Oriented Approaches for China

Through the analyses of China's water-energy nexus in physical and regulatory dimensions, this study demonstrates that the nexus-oriented management offers a holistic approach to regulate the two intertwined resources together, and hence mitigate the country's water and energy challenges while facilitate transitions towards higher provincial self-sufficiency.

First of all, the integration of water and energy can address the mismatch of water and energy availability by tackling the current energy-related water vulnerability and lowering the water-associated energy consumption. China's domestic energy production, especially the coal mining and coal-fired power plants, has endangered local water security in large energy bases. Although the central government has already taken action to promote water conservation in coal power bases, extra efforts will be needed to further extend the scope. Through the cross-sectoral collaboration, the policy makers will be able to include the water-for-energy and energy-for-water into a region's long-term planning process. Regulations, such as thorough water feasibly study, in combination with effective water pricing mechanisms, can help further limit the water-for-coal in water-scarce regions. At the same time, it is important to consider the energy-for-water and assess its long-term implications for energy security when designing a province's water strategy. This approach provides guidance on where to or how to accommodate energy-intensive water solutions, such as desalination or wastewater recycling. Areas without sufficient energy support should not apply energy-intensive water solutions before a solid energy plan is set forth.

Meanwhile, the water-energy nexus thinking also encourages the exploitation of the synergic effects of water and energy savings. Predictably, the demand of water and energy in China will continue increasing in the foreseeable future. Therefore, demand-side conservation and efficiency practices could serve as effective, low-cost and low-impact measures to ease the conflict between supply and demand. The implementation of demand-side program can achieve direct water or energy savings, as well as indirect savings by capturing the co-benefit of savings. China's water and energy agencies have already launched national and local conservation initiatives separately. The next step is to include the synergic effect into policy evaluation in order to provide extra incentives to strengthen the existing efforts and target at a higher efficiency performance.

Thirdly, the nexus-oriented approach that highlights the indigenous resources directly addresses the issues with current provincial resource interdependency in China.

Regional disparity in China not only is an environmental concern, but also affects the social equity in the country. The huge potentials of indigenous resources point out a way out of this dilemma. Many of the energy-importing provinces, such as Jiangsu and Guangdong, are sitting on enormous renewable energy potentials, with access to abundant solar and wind power. Not only these two renewable generating technologies are now economically competitive in the market, they also require minimal water input during the operation process. The provinces that serve as the GDP engines of the country should also take the lead to facilitate an energy transition towards higher energy self-sufficiency. On the other hand, the water-deficit northern provinces need to reevaluate its water supply strategy as well as its industrial structure to make sure its long-term development path can be sustained by local resources.

Last, the nexus-oriented management promotes resilient water-energy infrastructure through diversification and decentralization. China's water-energy systems are facing a wide spectrum of challenges, ranging from the need to provide access to rural and remote population and handle domestic environmental pollutions, to the fight against the external risks, such as climate change. Contrast to the rigid traditional systems, a diversified and decentralized system is capable of serving these multifaceted purposes together. For instance, decentralized water system powered by renewable energy sources could extend the access coverage without putting together the expansive transmission grid or water pipelines. In the environmental aspect, adding more renewable energy technologies, especially wind and solar, into its energy supply systems can lower the reliance on highly-polluting coal and also reduce the associated water consumption.

When implemented together, these measures can reinforce the effectiveness of each other. Introducing water-efficient energy solutions or energy-smart water technologies provides an opportunity to decouple development from resource depletion. Meanwhile, the need of transfer projects can be eliminated by diversifying its supply portfolio with local indigenous sources. To sum up, the water-energy nexus approach can effectively reduce the total water and energy consumptions in China, and cut the need of inter-provincial transfer projects, yielding a more self-sufficient system with improved water-energy security. A concluding note is, when applying these principles to achieve the regional sustainability, all the measures should be tailored to meet the specific local needs. International examples provide valuable lessons on numerous integrated practices. A combination of practices that target at the unique local needs will achieve the optimal outcome.

7.2 Recommendations

This study identified future policy recommendations to address China's water-energy challenges at the national and provincial levels. A set of recommendations are presented below.

- Incorporate the nexus-oriented management approach into policy making

The policy assessment in Chapter 5 indicated that the water and energy management and planning are largely separated in China, except the recent moderate integration efforts by the water sector to regulate the water need for coal production. As the water consumption comes in naturally as a concerning constraint for coal mines or coal-fired power plants, the water for other types of energy sources requires proper regulation as well. Furthermore, the energy-for-water failed to attract equal attention. The energy intensity of alternative water sourcing was not mentioned in current policy documents. Therefore, enhanced policy intervention is needed to target these critical issues with water-energy interdependences. The governmental agencies at both the central and local levels are recommended to take active actions to synchronize the water and energy targets, launch cross-sectoral collaboration, encourage data sharing, and provide financial support to integrated management.

- Facilitate economic transition and green growth to reduce regional disparity

The imbalance of the water-energy nexus challenges in China stems from the provincial geographical and economic heterogeneity. The significant correlations between the water-energy nexus variables and socio-economic indicators suggest that the uneven socioeconomic growth was the root of the regional environmental injustice issues. More importantly, the uneven spatial development strategy is widening the economic disparity between provinces while encouraging invasion and overexploitation of external water and energy resources. Without adjusting the uneven spatial strategy and industrial structures, the economic growth will continue to act as the primary source for future water-energy crises.

The central government in China has been promoting the concept of a circular economy that aims to decouple its development from intensive resource input. Thus, this study recommends utilizing this existing policy vehicle to tackle the country's regional disparities and alleviate the provincial environmental injustice. Instead of focusing merely on the economic competitiveness, the provincial governments need to consider the long-term welfare of its local communities. Meanwhile, the central authorities should empower the provincial government with the flexibility to adopt customized solutions and optimize the economic structure to conserve local resources.

- Rural development as an opportunity

There is still a large number of rural residents in China that lack proper access to safe water and reliable electricity, living at a resource level below the global average. As China's urbanization movement continues, a majority of future incremental demand of water and energy will likely come from the rural development. More water and energy consumption will occur concurrently with the increased living standard, improved sanitation level, and continued rural industrial expansion. Although filling the gap in rural areas poses challenges to existing systems, it also represents a great opportunity to implement the water-energy nexus-oriented practices through early intervention.

Since additional water-energy infrastructure is still to be built, it is possible to include the concept of the water-energy nexus as well as the innovative designs into the planning process. Also, in places without centralized water or wastewater utilities, decentralized water harvesting and collecting systems can find its way to penetrate the market. Opportunities also lie within the rural electrification. The huge potential of rural renewable energy resources, if exploited appropriately, can lighten up a bright prospect.

- Enhance institutional capacities to support policy integration

It is undeniable that the Chinese government has made firm resolution to reduce the ecological footprint of its development. However, there is a lack of institutional capacity to strengthen policy integration of the water-energy nexus. Although the policy integration is taking place gradually, existing barriers discourage an effective transition.

To achieve a fundamental reform, China will have to overcome these barriers. Continued efforts should be made to build up the institutional capability of implementation.

Existing institutional framework and policy can be utilized to pave the way for a smooth policy transition. The NDRC, as the central and national planning commission, can serve as the primary guiding actor to coordinate and oversee the efforts among different sectors. Other major institutional actors can also strengthen their abilities to adopt the nexus-oriented policy making by extending their existing cross-sectoral cooperation efforts. Moreover, considering the complicated implementation process and conflict of interests, initiatives at the provincial level are likely to be more productive as they can bypass the cumbersome institutional barriers.

To achieve this goal, it is necessary to build an interdisciplinary knowledge base to support the decision making. Deep understanding on local circumstances is a prerequisite to ensure the adequate improvement to its water and energy systems. The right long-term decisions can be made through proper technology transfer and innovation, knowledge dissemination, policy innovation as well as scientific assessment on local realities.

- Engage stakeholders for effective implementation

Although government-led programs serve as the driving force for integrated management of water and energy systems, it is necessary to encourage the participation of end-users and also highlight the role of major energy and water industrial players. Case studies from different countries suggest that the successful implementation of government regulations won't be achieved without stakeholder involvement. Strengthened stakeholder engagement can offer an accurate understanding of the problem and thus promote targeted solutions and joint efforts. This is particularly important to China's policy makers, since most policies are designed following the top-down approach, which could be vague, general, or even arbitrary or biased. Involving key players in the decision-making process provides an opportunity to investigate what the actual needs are and which measures are preferred. Additionally, stakeholders represent a strong force in facilitating the integration management through the use of cost-effective measures.

7.3 Future Research

This study has some limitations. To further promote the policy integration of the water-energy nexus in China, future research needs to focus on several areas.

The quantification of the water-energy nexus in this study is constrained by the data availability. The intensity factors used in the analysis are national average numbers or empirical data in certain areas in China. Given the different geographical feature and the wide range of technologies used in different provinces, it is necessary to develop intensity factors in each province for a more accurate estimation. Also, the study was not able to provide a comprehensive geographical picture of the virtual flow of water and energy transfer as it is difficult to identify the specific places of origin and destination. Future research can consider expanding this part, which would be beneficial to draw more detailed policy recommendations.

In addition, the quantification assessment of this study is limited to the physical quantity of water and energy resources. While acknowledging the environmental pollution related to the water-energy nexus, this study did not establish a quantitative analysis to measure the water, soil and air pollution. Therefore, this study advocates a detailed study on the environmental pollution in China under the framework of the water-energy nexus.

Another limitation of this study is that it only looked at the domestic issues. However, China's energy strategies are often influenced by international markets as well as global climate change policy. The country also experiences issues with the exploitation of international rivers near its border. Although it is outside the scope of this study, it is worthwhile to explore these international issues and its implications for self-sufficiency.

Last, although this study tries to cover most of the critical aspects of the water-energy nexus in China, it was only able to develop in-depth discussion on a few complex issues. The water-energy nexus approach contains a wide spectrum of topics that require detailed analyses, such as the controversial water issues with biomass and its conflicts with food security, or the carbon-water trade-offs with various cooling technologies. Further detailed analyses on each of these aspects in the context of individual province or area can offer more insights on the policy design.

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Appendix A

CONVERSION FACTORS

Fossil Fuel Conversion Factor

Fuel Type	Conversion Factor to Coal Equivalent
Raw Coal	0.7143 kgce/kg
Crude Oil	1.4286 kgce/kg
Natural Gas	1.1kgce/m^3
Thermal Conversion	1 tce =29.30 GJ

Appendix B

LIST OF POLICY DOCUMENTS

11th Five-Year Plan for Water Conservancy (2006-2010)

11th Five-Year Plan for Energy Development (2006-2010)

12th Five-Year Plan for Water Conservancy (2011-2015)

12th Five-Year Plan for Energy Development (2011-2015)

12th Five-Year Plan for Renewable Energy Development (2016-2020)

12th Five-Year Plan for Establishing National Water-saving Society (2011-2015)

12th FYP for Seawater Desalination (2011-2015)

13th Five-Year Plan for Energy Development (2016-2020)

13th Five-Year Plan for Power Development (2016-2020)

13th Five-Year Plan for Renewable Energy Development (2016-2020)

13th Five-Year Plan for Water Conservancy and Reform (2016-2020)

13th Five-Year Plan for Establishing National Water-saving Society (2016-2020)

13th Five-Year Plan for National Seawater Utilization (2016-2020)

13th Five-Year Plan for Coal Industry Development (2016-2020)

13th Five-Year Plan for Natural Gas Development (2016-2020)

13th Five-Year Plan for Oil Development (2016-2020)

China's Energy Policy (2012)

Opinions on Speed up the Seawater Desalination Industry (2012)

Opinions on Water Resources Assessment for the Development of Large Coal Power Bases (2013)

Guidance on Preliminary Work of Water Transfer Projects (2015)