論 文 の 内 容 の 要 旨

論文題目 Assessment of GHG emissions of water and wastewater utilities in urbanizing China

（都市化の進む中国における上下水道の温室効果ガス排出量の評価）

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The urbanization level in China has dramatically increased from less than 20% to around 50% during the past 30 years and urbanization is believed to be one of core features to promote both quantity and quality of socio-economic development in China in the following decades. During this lasting urbanization, it is of concern what the impact on GHG emissions is. Public utilities play fundamental roles in local governance of urban areas, in which water utilities, including services of water supply and wastewater treatment, could be one of interesting targets. It is not enough to account for the GHG emissions resulting from operating activities of water utilities but also meaningful to consider GHG emissions for construction activities of water infrastructure, because the provider or governor of public utility usually takes responsibilities to some extent for both ensuring normal operation and making decision of future investment. To promote the incentive to mitigate GHG emissions for the government and other stakeholders, this study also focus on how much improvement can be achieved under different scenarios regarding related policy and technology issues.

Hence, this dissertation manages to answer at what cost of GHG emissions does it come to support current water supply and wastewater treatment services in China, what is the future, and where is the potential to reduce the emissions? The research objectives are formulated: (1) to establish embodied CO_2 emission inventory in order to evaluate Scope 1–3 emissions of water industry sector; (2) to estimate material/energy input and related GHG emissions of water utilities in both construction and operation activities; (3) to summarize the performance of water utilities and relevant GHG emissions in case cities of China; and (4) to project future growth of water utilities and discuss consequent change of GHG emissions in different scenarios.

To analyze the GHG emissions in operation of water utilities, the concept of urban water systems was utilized to set system boundary of assessment, while life cycle thinking was adopted in estimation of indirect emissions for construction of water infrastructure. Detailed assessment of GHG emissions in different sources and categories was based on available Chinese local data in bottom-up estimation mainly according to 2006 IPCC Guidelines. Top-down estimation via input-output analysis (IOA) was conducted to evaluate and supplement the results from bottom-up estimation.

Main outcomes are addressed in Chapter 4–7 in this dissertation.

In Chapter 4, a 135-sector embodied CO_2 inventory of China in 2007 was constructed to reveal embodied information in industrial sectors as much as possible. Original disaggregation process to allocate energy input into each IO sectors is proven reasonable by comparing with previous studies. 42-sector embodied CO_2 inventory is equivalent to 135-sector resolution only in the terms of total embodied emissions, but the allocation of CO_2 emissions in some sectors was found to introduce larger uncertainty. Embodied CO_2 emissions induced by final demands of domestic products of China in 2007 were estimated at 7.1 Gt CO_2, where inducement by gross capital formation, domestic consumption, and export were estimated at 42%, 30%, and 28%, respectively. A framework to evaluate embodied CO_2 emissions of specific industry sector was proposed to correspond with WRI's Scope 3 accounting standard. CO_2 emissions for operation of water utilities were estimated at 22.9 Mt CO_2 (Scope 1+2), while CO_2 emissions for construction of water infrastructure were estimated at 1.1 Mt CO_2 (Scope 1+2). However, if Scope 3 emissions were also taken into account, CO_2 emissions in water services were estimated at 45 Mt CO_2 (Scope 1+2+3), CO_2 emissions in construction of water infrastructure were estimated at 23 Mt CO_2 (Scope 1+2+3). In contrast to predominant contribution from use of electricity and heat to GHG emissions in water sector, GHG emissions embodied in material input for construction activities dominate Scope 3 emissions. Better management to promote energy efficiency in electricity-intensive industries is very helpful to reduce carbon burden.

Chapter 5 elaborates on decomposition of GHG emissions of water utilities at sub-systems based on evaluation of various material/energy intensities and GHG emission factors in partial or total activities of water utilities reported in literatures. Average annual GHG emissions related to operation of water utilities accounted for 46 Mt $CO_{2\text{-eq}}$, in which 61.5% of emissions came from energy use, 36.8% from treatment processes, and 1.8% from chemical use. Average annual GHG emissions related to construction of water infrastructure accounted for 16 Mt $CO_{2\text{-eq}}$, in which 51.4% of emissions came from material manufacturing, 30.4% from installation activities (earthwork), and 18.2% from annual maintenance. This is not life-cycled allocation but the comparison of annual emissions at subsystems of water utilities based on current activity in China. As China is a developing country, contribution from construction activities is much higher than that in life-cycled inventories, suggesting that improved estimation for GHG emissions of water utilities including water infrastructure is valuable to capture significant emission sources from the perspective of compilation of emission inventory. Wastewater treatment processes in operation and pipeline systems in construction were found to be most significant to the annual GHG emissions.

In Chapter 6, the differences of water utilities in six megacities of China were discussed in terms of various indicators. Cities in the North China suffer severer problems on both quality and quantity of water. Some water infrastructure need to be upgraded or renovated in the next years. Beijing and Zaozhuang were picked up to make case studies to be representative as the megacity/large city and middle city, respectively. Beijing is one of megacities in China, water supply and wastewater treatment systems in the downtown area of Beijing has been well established, but the construction activities was found to be active during 2006–2010 especially for pipeline construction and water reclamation projects. Anaerobic-anoxic-oxic process in WWTP was very popular in Beijing, and landfill dominated the sludge disposal. If there is no methane recovery, the non-CO_2 emissions from treatment processes can be the biggest source of the GHG emissions of water utilities. The case in Zaozhuang shows similar results, but unit electricity use in water supply is much higher than national average, and nitrous oxide emission is of more concern, for sludge incineration is the mainstream treatment pathway in this city.

Chapter 7 provides the projection of future GHG variations related to urban water utilities in China based on comprehensive understanding achieved in previous chapters and consideration of lasting urbanization in China in next two decades. Scenarios regarding three aspects were designed to further discussion, including domestic migration policy and compact city planning, alternative technologies in water utilities, and evolution of carbon intensity in electricity generation. Future GHG emissions of water utilities in cities of China could be 45–55 Mt CO_2-eq annually in operation activities between 2010 and 2030, but this estimation can vary significantly due to different scenarios. Compact urban design without restriction of migration to mega-cities has lower cost of GHG in pipeline systems, but too high density may lead to 3 times energy consumption in lifting water to buildings. Large scale of replacement of water pipe to reduce water leakage will increase GHG emissions, but the avoid emissions due to energy savings in water supply can offset 50% of relevant emissions. Utilization of desalination and tightening wastewater discharge can bring significant impacts on GHG emissions of water utilities in the future. Better management of sludge treatment to recover as much methane as possible can significantly reduce GHG emissions. Reduction of carbon intensity of electricity can only partially mitigate the GHG growth in urban water systems in the future.

In this study, both direct and indirect GHG emissions of water and wastewater utilities in urban areas of China were estimated based on careful design and various sources. Significant emissions sources/subsystems were investigated and recent temporal variations of GHG emissions in urban water systems were also interpreted. Impacts from urban population, urban planning, and technology options in water utilities and carbon intensity of electricity on GHG emissions of urban water utilities were analyzed in different scenarios to suggest better construction and management of climate adapted water utilities.

The highlights of this study include: 1) this study compiles an embodied CO_2 inventory for China with most sector information, which increases the accuracy to interpret indirect impacts at sector level; 2) this study is a leading evaluation for direct and indirect GHG emissions of water utilities for China in a systematic way, and it can be mutual confirmed by top-down and bottom-up approaches; 3) this study proposes a computable model to estimate material/carbon intensity for construction of pipeline systems in spite of data limitation in China; 4) this study reveals complex impacts from urbanization trend on GHG emissions of water utilities for China based on analysis of realistic scenarios.

The valuable suggestions from this study are as follows:

1) Design of urban water systems with the concern of GHG emissions as one of multiple criteria is important to investigate win-win solution between water and climate issues;

2) Compact city development is beneficial to urban water systems to achieve less GHG burdens for construction of pipeline systems;

3) Caution should be exercised to increase desalination for water supply and tighten wastewater discharge permits for significant growth of GHG emissions in operation;

4) Energy saving from better management of water utilities needed to be quantified and impelled by the governors or the third-party to achieve larger reduction of GHG emissions.