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WORKING PAPER

SLUDGE TO ENERGY: AN ENVIRONMENT-ENERGY-ECONOMIC ASSESSMENT OF METHANE CAPTURE FROM SLUDGE IN XIANGYANG CITY, HUBEI PROVINCE

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EXECUTIVE SUMMARY

Rapid urbanization in China has substantially increased the quantity of liquid waste in municipalities, and has led to massive investments in wastewater conveyance and treatment. This increase in the number of wastewater treatment plants (WWTPs) has generated a sharp rise in the volume of sludge, the byproduct of the treatment process. It is estimated that, by 2015, China's municipal WWTPs had produced approximately 40 million metric tons of sludge (80 percent moisture content). While the pollution is a serious local environmental problem, sludge treatment also represents a valuable opportunity to capture and reuse potential energy and reduce greenhouse gases (GHGs) otherwise emitted during the treatment process.

All countries undergoing rapid urbanization, China included, are faced with the need for effective and sustainable solutions for sludge disposal. To ensure that sludge does not pollute the land, water, or atmosphere, cities in developing countries have invested in various technologies aiming at recycling sludge into compost, energy, and biochar. Among these, the idea of "capturing" byproducts of the anaerobic digestion process is a notable option. Xiangyang City, in Hubei Province, China was perhaps one of the first cities in a developing country to explore such a process by investing in a system of high-temperature thermal hydrolysis, anaerobic digestion, and methane capture and utilization. In this system, co-digested sewage sludge and kitchen waste are stabilized, detoxified, and converted (in large part) into reusable products. Additionally, the information presented in this paper indicates that a project design that harmonizes the interests of the city government, the investor, and the financier will produce significant economic benefits for the local community.

CONTENTS

Working Papers contain preliminary research, analysis, findings, and recommendations. They are circulated to stimulate timely discussion and critical feedback and to influence ongoing debate on emerging issues. Most working papers are eventually published in another form and their content may be revised.

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The Xiangyang case study documents how a city with a population of 5.6 million in China has successfully accomplished multidimensional goals: sludge solidification, renewable energy generation, and the recovery of resources through a cost-effective energy recapture treatment process. The World Resources Institute (WRI) was invited to independently review the environmental, energy, and economic benefits of the Xiangyang project. This paper summarizes Xiangyang's experiences and provides insights as to how cities in China and other developing countries facing similar challenges can address their sludge problems in a sustainable manner.

Below are the environmental, energy, and economic benefits of the Xiangyang project:

- **Environmental Benefits**

  - **Nutrient recovery:** The project design intends to use struvite sediments to recover almost all of two key nutrients (nitrogen (N) and phosphorous (P)) from sludge and kitchen waste—96 percent of N and 99 percent of P can be recovered.

  - **Greenhouse gas emissions reduction:** During the 21-year contracted period of operation of the Xiangyang project, an estimated 2.3 million metric tons of sludge and kitchen waste will be disposed of, while emitting only 13,000 metric tons of carbon dioxide equivalent (CO_2e) through the co-digestion approach. The co-digestion process will reduce 98 precent (800,000 metric tons CO_2e) and 95 precent (224,000 metric tons CO_2e) of GHG emissions compared to incineration and landfill, respectively. The biochar produced during the treatment process will be used as a soil enhancement in planting 4.54 million saplings; the mature trees that grow from these saplings will eventually sequester an additional, cumulative 15.75 million metric tons of CO_2e.

- **Energy Benefits**

  Through thermal hydrolysis and anaerobic digestion, the Xiangyang project will produce 45.4 million m^3 of natural gas (NG) during its 21 years of operation. This amount of NG can be compressed to produce compressed natural gas (CNG) and replace about 60,000 m^3 of gasoline, resulting in an additional reduction of 140,000 metric tons of CO_2e emissions.

- **Economic Benefits**

  The project received both political support from the municipal government, and financial support in the form of low-interest loans from an international financial organization, KfW Bankengruppe of Germany, as well as a Chinese policy bank—the Export-Import Bank of China. This "government-bank-enterprise" partnership was key in establishing long-term contractual agreements that ensured a harmonization of interests between all parties: the local government (which wanted to eliminate pollution from sludge), the financing entities (which offered concessional financing as a means of bridging any financial viability gap), and the operator of the Xiangyang project (which was interested in running a sustainable commercial operation through the production of CNG via methane (CH_4) capture and through the sale of biochar for urban forestry programs).

- **Other Key Findings**

  - **The Xiangyang project successfully achieved pollutant reduction, resource recovery, near-zero carbon emissions from sludge treatment, and renewable energy generation in the city.**

    By implementing the technical process of high-temperature thermal hydrolysis, anaerobic digestion, and methane capture and utilization, and producing and using biochar soil, the project successfully recovered and reutilized the nutrients in sludge (carbon (C), N, and P), and avoided pollution of water bodies. More importantly, the Xiangyang project grasped the opportunity to recover bio-energy (biogas) from sludge and kitchen waste, helping cities moving toward clean energy, thus significantly reducing the GHG emissions associated with sludge and kitchen waste treatment and contributing to the low-carbon development target of cities.

  - **A market-oriented perspective for the design of sludge treatment is vital to economic success.**

    The Xiangyang project demonstrated the importance of designing a complete value chain for sludge (and other organic waste) treatment that considers the needs of the market. The specific technology for Xiangyang was therefore selected with careful consideration for the market potential of the treatment's recovered products, CNG and biochar. The presence of potential markets for these products ensures a sustainable flow of capital.

- **Support from the government, financial sector, and private sector through a public-private partnership (PPP) enabled the alignment of incentives necessary to achieve a complex set of development objectives.**

  The successful implementation of a build-operate-own (BOO) contracting arrangement underscored the importance of cooperation between the local government and the private sector. While the government has an obligation to the public good to mitigate the environmental risks posed by sludge pollution, the private sector will only become involved in the development of a circular economy that sustainably recovers resources from sludge when the market signals that it's a financially attractive proposition.

  The pairing of the public and private sectors of the model ensures the availability of concessional financing to bridge the viability gap that is likely to emerge during the initial investment phase. The viability gap can result from diverse factors: investor perceptions of high transaction costs in the supply chain of organic wastes for the anaerobic treatment plant, unfamiliarity with working at the municipal level on a long-term contract, or uncertainty regarding demand and pricing for CNG and biochar.

  Ideally, global climate and other international financial funds will target the mitigation of global externalities, by methods such as capturing methane and other GHGs. The availability of financial incentives will induce the private sector to enter into and promote a circular economy for the stabilization of sludge and the reclamation of sludge byproducts. This, in turn, will help enhance the viability of such projects, and help drive costs down via competition and innovation, making the market even more attractive for private capital investment.

INTRODUCTION

Background

One of the outcomes of rapid urbanization is the massive generation of liquid and solid wastes. In China, as in many developing countries, the disposal of waste products often leads to the pollution of water bodies and farmlands; this pollution is considered a major obstacle to achieving sustainable development. There is an urgent need to develop environmentally sustainable methods of treating and disposing of waste.

Each year, Chinese cities are estimated to collectively generate 40 million metric tons of sewage sludge (with 80 percent moisture content, which is the byproduct of municipal wastewater treatment process).[1] The Chinese government has ignored the treatment and disposal of sludge until very recently. Currently, 80 percent of sludge is not treated at all or is treated using inappropriate methods, such as landfill, which is not effective at removing or neutralizing harmful pollutants and pathogens that are harmful to human health and may cause contamination of soil and water. The investment in sludge treatment and disposal is only 8 percent of the total investment in urban wastewater treatment (Feng et al. 2015). Uncontrolled sludge discharges result in environmental pollution and human health and ecosystem impacts in large- and mid-sized cities all over China.[2] It was only after the adverse effects of dumping untreated sludge on agricultural farmlands were understood (e.g., pollution of rivers, lakes, and aquifers) that policymakers began searching for sustainable solutions for sludge treatment.

At the same time as the consequences of dumping untreated sludge became known, Chinese leaders were promoting the creation of a circular economy, which, by design, is restorative and regenerative. For example, a circular economy recovers and reuses waste products for environmentally beneficial uses (including energy, fertilizers, and building products). The interest in circular economy approaches further reinforced policymakers' determination to find sustainable solutions for sludge treatment that would be both environmentally sound and economically viable.

In 2011, one of the pioneering cities to test out such an idea was Xiangyang City in Hubei Province. The Xiangyang case study documents how the municipal government of a mid-sized city in China has successfully accomplished multidimensional goals: the complete treatment of sludge, the generation of renewable energy, and the recovery of resources through a cost-effective green treatment process. The World Resources Institute (WRI) was invited to independently review the environmental, energy, and economic benefits of the Xiangyang project. This paper summarizes Xiangyang's experiences and provides insights as to how other cities in China and other developing countries facing similar challenges can address their sludge disposal problems in a sustainable manner.

Challenges in Managing Waste

Sustainable waste management, including sludge treatment and disposal, faces some key challenges in developing countries (Figure 1).

- **The first column describes local problems that often arise in cities.**

The first problem is the incomplete separation of solid from liquid wastes and organic from inorganic wastes at the source. The high-nutrient organic waste is corrupted by the inorganic wastes, and the opportunity is reduced to produce biogas (generated by decomposing sewage and organic wastes) or biochar (ash and other organic remnant material from sewage treatment that can be used as a soil amendment for growing saplings etc.). Also, due to inadequate enforcement of environmental regulations, heavy metals and other harmful persistent organic pollutants (POPs) find their way from small- and medium-sized industrial and commercial establishments into the domestic sewerage system.

The second local problem arises because landfills and open dump sites, the traditional sites for waste disposal, do not have the capacity to handle the huge quantity of waste generated in urban areas, many of which have experienced rapid economic growth and converted undeveloped land to urban uses in the past two decades. Without landfills or sludge treatment methods, untreated sludge piles up or is illegally dumped.

The third local problem is that city-level institutions are not designed to innovate or test out new solutions for waste management that could fulfill circular economy criteria, attract public-private partnerships (PPPs), or leverage potentially available green funds. Thus, there is little local capacity that can encourage proactive problem solving.

- **The second column summarizes how infrastructure failures can lead to unsustainable outcomes.**

The incomplete separation of solid and liquid wastes, as mentioned above, allows dangerous heavy metals and POPs to travel through the waste stream. When they re-enter water sources and contaminate agricultural land, these pollutants harm the local ecosystem and human and animal health.

Illicit dumping of waste and sludge pollutes water bodies and clogs drains, resulting in standing pools of wastewater and human and animal exposure to contamination. This illicit dumping is caused by two infrastructure failures. First, there is a lack of safe disposal sites for untreated sludge. Second, the government at both national and local levels lacks the knowledge to select and build adequate sludge treatment methods.

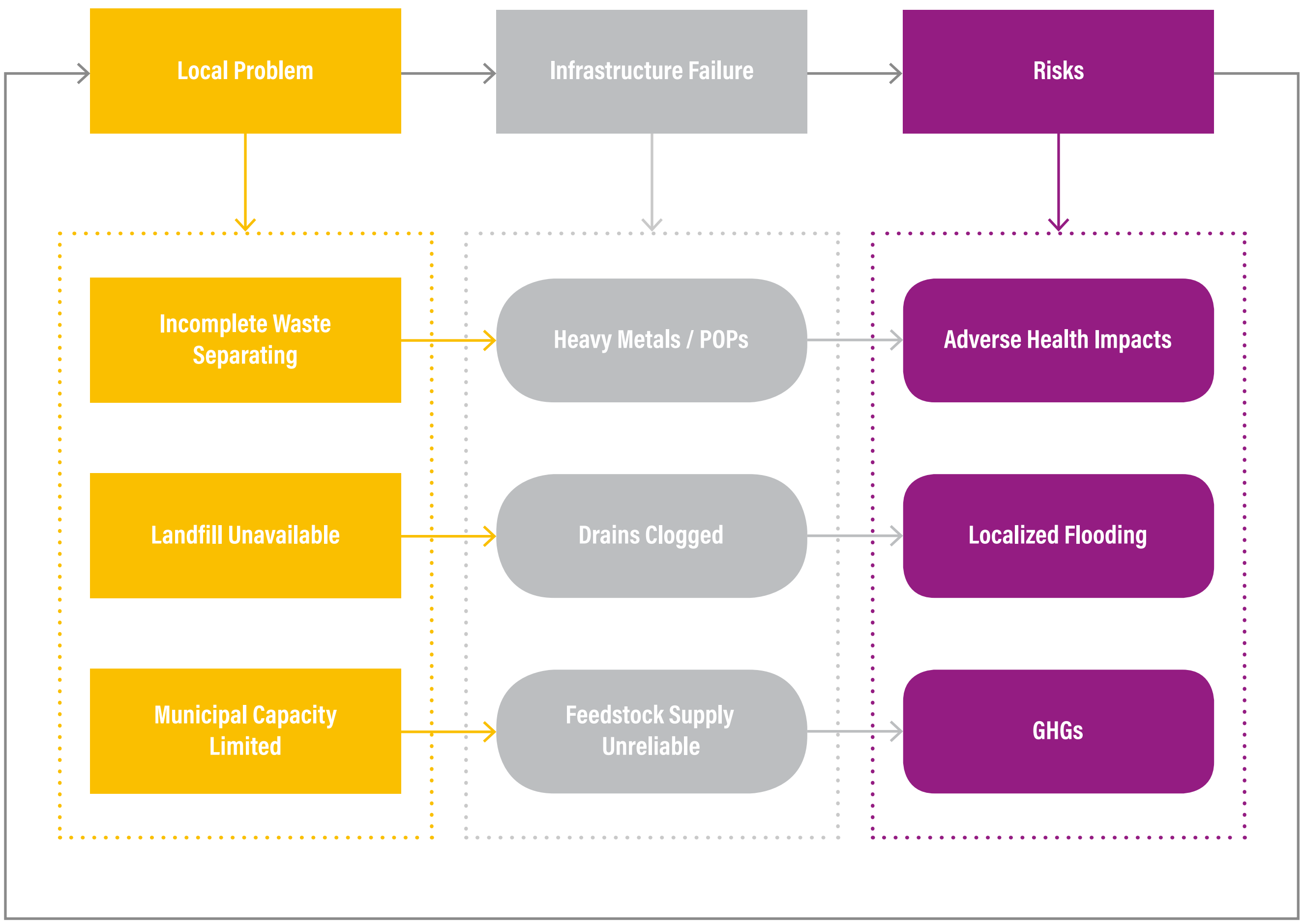
Finally, institutional difficulties in developing dependable waste supply chains from communities to treatment sites reduce the opportunity to generate biogas energy (reducing grid energy demand and greenhouse gases (GHGs)) through renewable energy technologies. Inadequate waste management therefore contributes to global climate change, when it could otherwise provide net positive energy and GHG benefits.

- **The third column outlines how these problems and infrastructure failures are risks not just for the local and regional communities, but for the global community as well.**

Inadequately treated sludge affects both public health and the environment. Heavy metals, POPs, and pathogens in human waste harm human and animal health. Solid wastes that enter drainage channels cause blockages that increase the occurrence of pluvial (storm water) flooding. Emissions of short-lived climate pollutants (SLCPs), such as methane (CH_4) and nitrogen oxides (NO_x), contribute to global warming.[3]

While the first two risks—health problems and localized flooding—are significant, they are primarily local. Municipal water and wastewater systems can also contribute to the global crisis of climate change. They are among the most energy-intensive facilities of public sectors, accounting for about 35 percent of energy used by municipalities.[4] The use of fossil fuel to generate this energy creates carbon

Figure 1 | **Key Challenges and Risks in Sustainable Waste Management**



dioxide (CO_2) emissions. Also, the by-product of wastewater treatment—sludge—can release CH_4 and/or NO_x to the air if dumped directly or treated inappropriately (such as in landfills and incineration). These GHGs ultimately affect both local and global communities. Xiangyang's practice provides a good example in consistently achieving benefits both locally and globally, reducing both pollution caused by sludge and the GHGs emissions associated with the sludge treatment process.

Methodology: Environment-Energy-Economic (3E) Analytical Framework

The WRI team assessed the extent to which the Xiangyang project achieved "3E"— that is, environmental, energy, and economic benefits. These 3E benefits are closely related to sludge treatment goals set by the Chinese government: detoxification, stabilization, reduction, and resource recovery.

Based on material flow analysis (MFA)[5] (Brunner and Rechberger 2004), the 3E analytical framework provides a basis for the quantitative analysis and evaluation of environmental effects, energy recovery, and economic costs and benefits during the entire process of sludge treatment and disposal. The framework can help decision makers select the appropriate sludge treatment technology for a given city by identifying the costs and benefits of each treatment method and by analyzing how the benefits can be distributed across local and global levels (i.e., long-term localized pollutants and short-lived climate pollutants). This involves identifying the following:

- **Environmental benefits:** Assessing the potential for pollutant removal and life cycle reduction in GHG emissions by analyzing the efficiency and completeness of resource recovery (i.e., carbon (C), nitrogen (N), and phosphorus (P)), energy consumption, and transformation into biochar.

- **Energy benefits:** Assessing the potential for biogas recovery and energy management in the sludge treatment process.

- **Economic benefits:** Assessing the economic sustainability of the sludge treatment project by conducting a cost-benefit analysis, and looking at the economic tools that are indispensable to project operation (i.e., subsidies and financing mechanisms).

Structure of the Paper

Section 1 gives a brief introduction to China's sludge challenge and the framework (the 3E analytical framework) used for assessing the Xiangyang project. Section 2 presents an overview of the Xiangyang project. Using the 3E analytical framework, Sections 3 and 4 provide an analysis of the environmental, energy, and economic performance of the Xiangyang project. Section 5 summarizes the key findings and experiences from the Xiangyang case, and discusses questions pertinent to the development of sustainable sludge treatment systems.

AN OVERVIEW OF THE XIANGYANG SLUDGE-TO-ENERGY PROJECT

Xiangyang and the City's Sludge Challenge

Xiangyang is situated in the northwest part of Hubei Province, near the Han River, a tributary of the Yang-Tze River. The Xiangyang sludge-to-energy project is located at Yu Liang Zhou economic development area, which is in the center of Xiangyang. The Xiangyang region has a population of 5.6 million people, with an urbanization rate of 57.3 percent, and a per capita GDP of 60,319 CNY (9,684 USD[6]) (Xiangyang Statistical Bureau 2016). The urban area of Xiangyang is 337.8 km^2, with an urban residential population of around 1.7 million (Hubei Daily 2016).

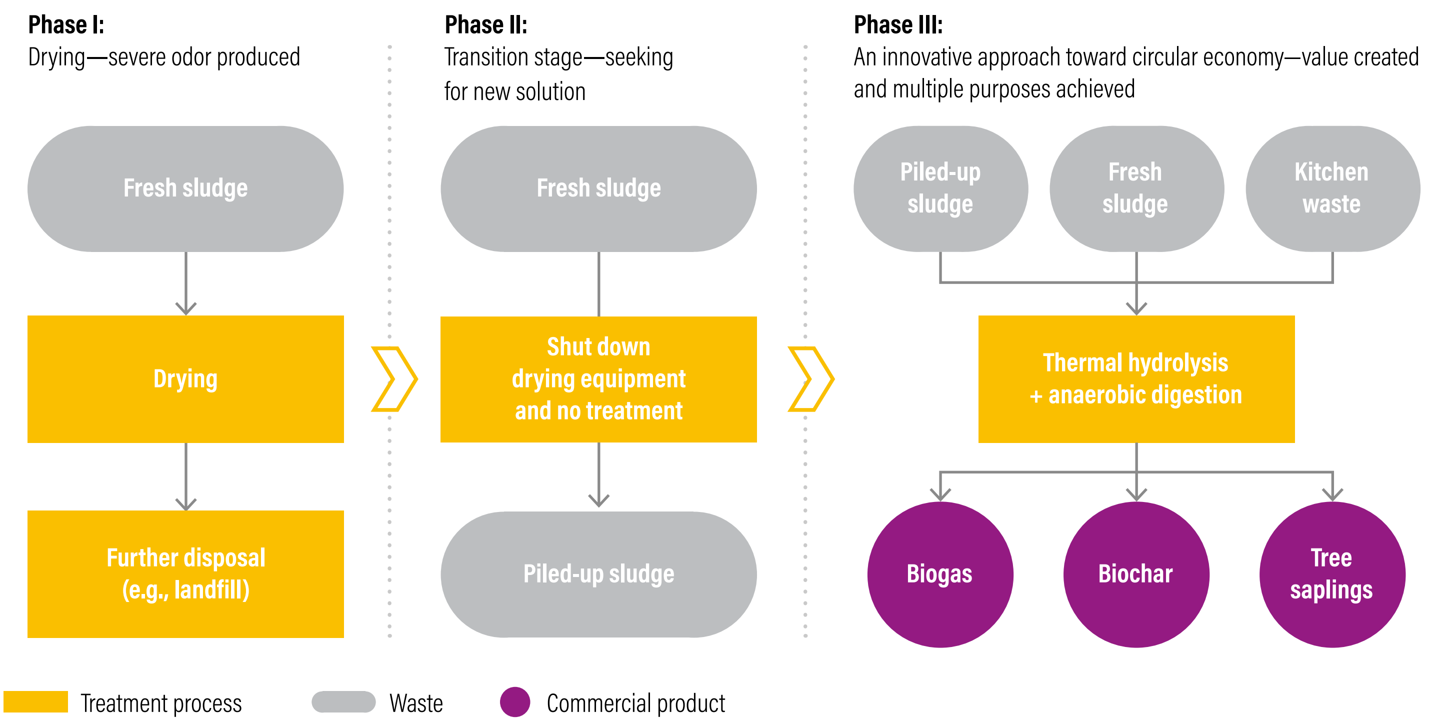
To treat domestic wastewater, Xiangyang has built two wastewater treatment plants (WWTPs): Yu Liang Zhou WWTP with a capacity of 300,000 m^3/day and Guan-Yin-Ge WWTP with a capacity of 100,000 m^3/day. The city's daily sludge production is 180—220 metric tons (80 percent moisture content), making its annual sludge production roughly 65,000—80,000 metric tons. It is estimated that the daily sludge production of Xiangyang's urban area will reach 270 metric tons by 2020, increasing the annual sludge production to 100,000 metric tons.

The municipal government, concerned that untreated sludge would pollute the Han River, built a sludge drying plant beside the Yu Liang Zhou WWTP with a capacity of 30 metric tons/day. However, the public was strongly opposed to this treatment method due to the severe odor and the fear of air pollution caused by the sludge drying process. The local government had to shut down the plant and sludge accumulated beside the Yu Liang Zhou WWTP (see phases I and II in Figure 2). The amount of accumulated sludge exceeded 150,000 metric tons by the end of 2011.

The odor and disposal site problems, plus the realization that sludge contained economically beneficial methane, led the city to explore innovative solutions (see phase III in Figure 2). The municipal government first conducted a sustainability and economic analysis of various options. Instead of pursuing composting, incineration, or landfill, the municipal government chose to invest in a system that involves pre-treating the feedstock (mixture of sludge and kitchen waste) using a high-temperature hydrolysis process, then utilizing anaerobic digestion to generate methane and biochar. The Xiangyang project began construction in April 2011.

The concept behind the Xiangyang project, which aligns with the worldwide movement toward circular economies, is not new. Many cities in developed countries already combine sludge and organic wastes from households and commercial establishments to generate substantial quantities of biogas (see Appendix B). The UK government has been implementing an Anaerobic Digestion Strategy and Action Plan (Defra 2011) since 2012. The goal of the plan is to capture as much methane from human and animal waste as possible. In Washington, DC, the public DC Water utility (the largest single-source consumer of electricity in the city) used a sludge-to-energy project to cut electricity consumption by up to one-third (DC Water 2015).

Figure 2 | **Phases of Sludge Treatment Options in Xiangyang**



The thermal hydrolysis process (THP) and anaerobic digestion (AD) method rests on the following principles:

- The anaerobic digestion of sludge and organic wastes can generate renewable energy, such as biogas, for transportation and electricity generation.
- Co-digestion of sludge and kitchen waste increases total methane production capacity.
- Treated sludge can be further dehydrated for land application or landscaping.

The integrated sludge treatment process enabled the city to achieve multiple local and global goals:

- safe disposal of sludge;
- optimized utilization of the energy potential in sludge;
- reduction of atmospheric GHGs emissions;
- safe disposal of digestate (the material remaining after anaerobic digestion of biodegradable feedstock) as biochar; and
- development of innovative cost recovery and financing mechanisms to generate upfront investment and cover ongoing operating costs.

Technical Details of the Xiangyang Project

Sources of Feedstock and Treatment Capacity

The Xiangyang project is located beside the Yu Liang Zhou WWTP and covers an area of 3 hectares (30,000 m^2). The project has a capacity of 300 metric tons/day (an annual capacity of around 110,000 metric tons). This includes:

- Sludge: 180—220 metric tons/day
  - Sludge produced daily by Yu Liang Zhou and Guan Yin Ge WWTPs with 40—60 percent organic content and 80 percent moisture content. Eighty percent of this sludge comes from Yu Liang Zhou WWTP and 20 percent comes from Guan Yin Ge WWTP.
  - Sludge piled up at Yu Liang Zhou that had been produced in previous years and left untreated. By 2015, all 150,000 tons of stockpiled sludge had been treated.

- Kitchen waste: 80—120 metric tons/day with 80—90 percent organic content
    - Kitchen waste is crushed at the restaurant and transported to the plant. The operator of the Xiangyang project is responsible for installing the kitchen waste crusher and transporting the waste.

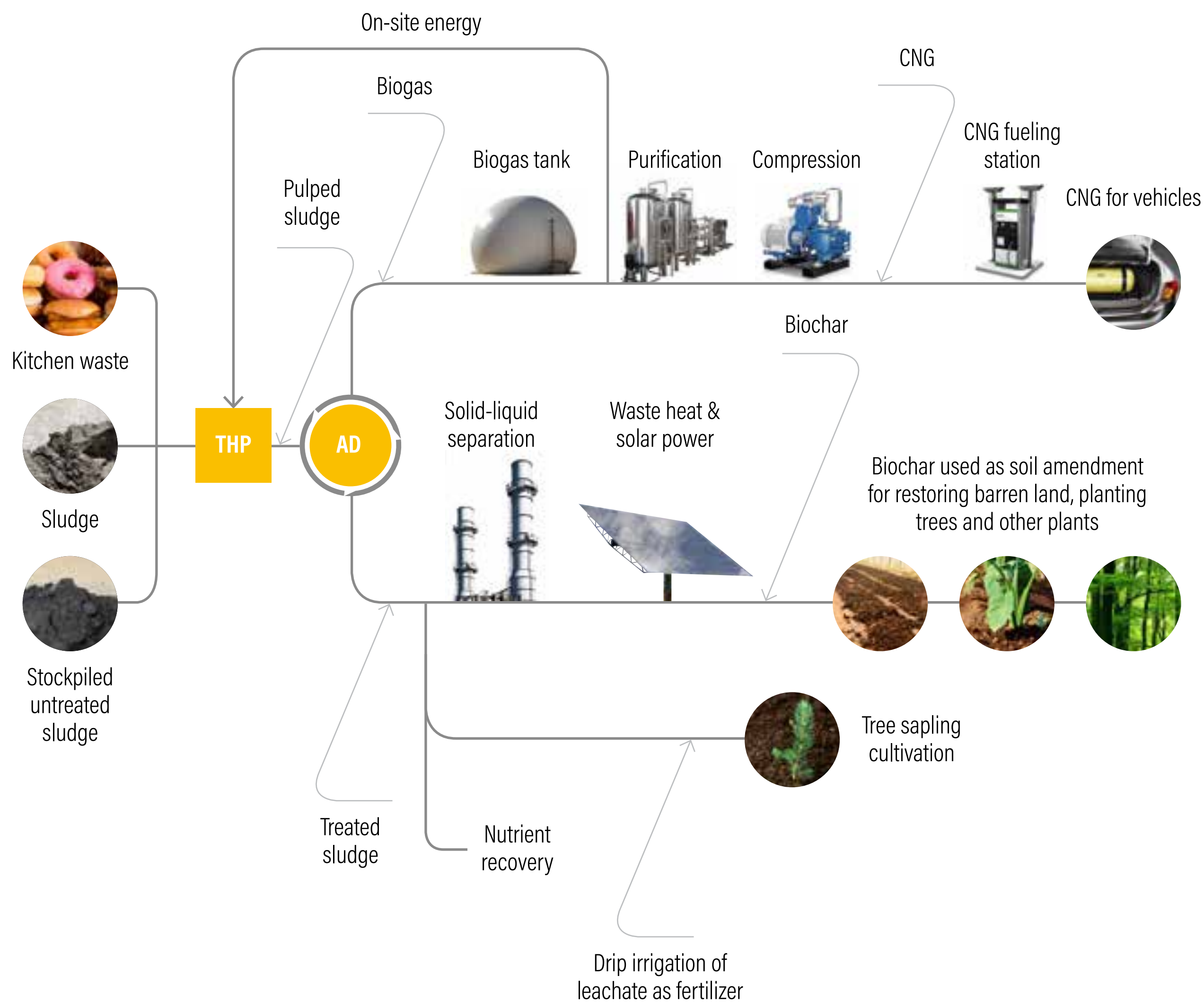
Treatment Technology

The project uses high-temperature THP (170°C)[7] (Wang and Wang 2005) and AD (40°C) treatment[8] to co-digest sludge and kitchen waste produced by the urban residents in Xiangyang. Figure 3 summarizes the treatment process of the project.

Outputs of the Project

- **Biogas and compressed natural gas (CNG):** Biogas is one of the products of anaerobic digestion. Half of the biogas produced by the Xiangyang project is used to power the project itself. The other half is

Figure 3 | **Treatment Process and Environmentally Beneficial Outputs of the Xiangyang Project**



Note: THP = thermal hydrolysis process, AD = anaerobic digestion, CNG = Compressed natural gas purified, compressed, and used to replace 6,000 m^3 (or 1,668 gasoline gallon equivalent (GGE)) per day of gasoline to fuel 300 municipal taxis. The Xiangyang project also built a CNG fueling station with storage volume of 6,000 m^3.

- **Biochar:** The digested sludge is further dehydrated to produce 55—60 metric tons of biochar (40 percent moisture content) each day. Biochar can serve as a soil amendment to add fertility to the soil.
- **Tree saplings:** Tree saplings are planted in biochar-enriched soil using the container seedling method.

Appendix A explains in detail the morphological changes and migration of C, N, and P in the sludge treatment process and the production of CNG, fertilizer, and biochar. The environmental benefits of the project are described in more detail in Section 3.

Contractual Model

The Toven Co. Ltd., which specializes in the energy sector, signed a build-own-operate (BOO) agreement with the Xiangyang Urban Construction Committee to treat sludge, and with the Xiangyang Urban Management Bureau to treat kitchen waste. Two agreements were needed because sludge and kitchen waste are managed by different agencies in Xiangyang. The concession period of the project is 23 years, which included a construction period of two years. The actual construction period was 17 months. In September 2012, the Xiangyang project started full operations (including the CNG station).

The operator receives a subsidy from the local government and revenues through the sale of CNG to the municipal taxi fleet and the sale of biochar and saplings to the market (see Section 4 for more details).

ENVIRONMENTAL AND ENERGY BENEFITS OF THE XIANGYANG PROJECT

Environmental Benefits

GHG Emissions Reduction Compared with Other Treatment Technologies

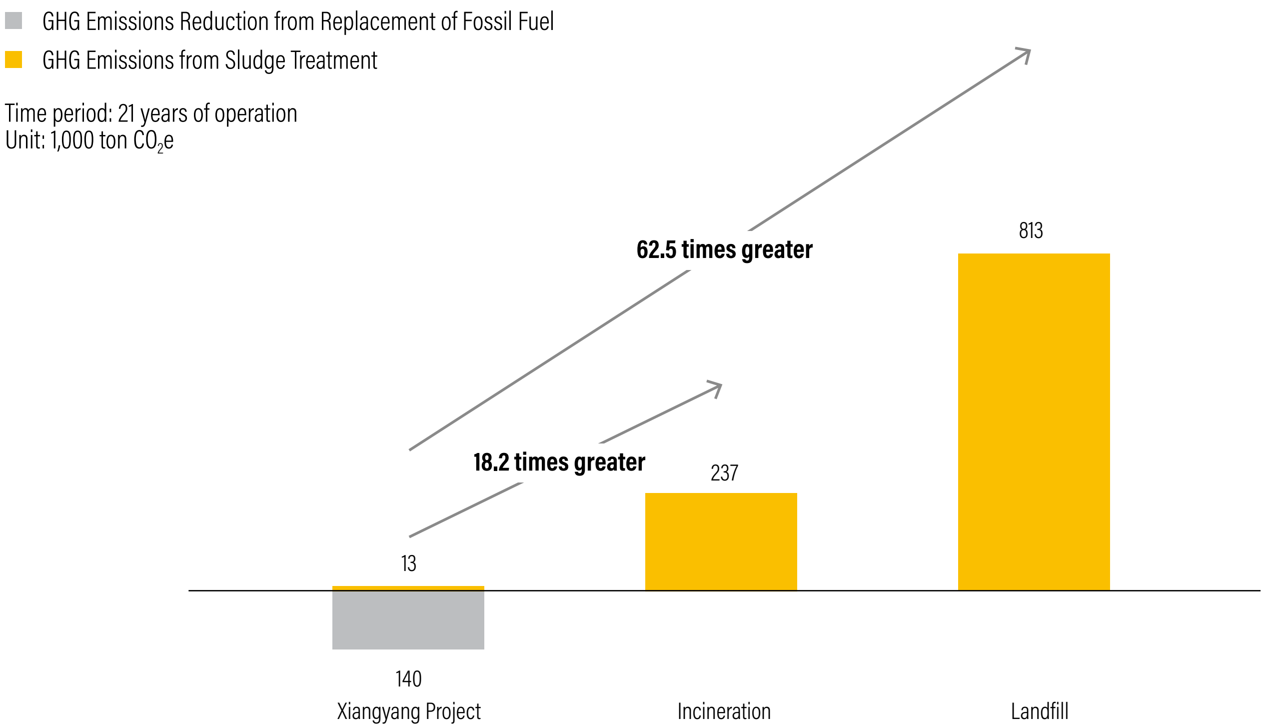
If sludge is dumped directly or not treated properly, GHGs such as CH_4 and CO_2 from decomposing sewage and kitchen wastes will be released into the atmosphere. Although CH_4 stays in the atmosphere for a shorter period of time (12 years) and is emitted in smaller quantities than CO_2 (GMI 2015), it has a much bigger impact than CO_2 in terms of global warming potential (GWP)[9] (IPCC 1995). IPCC increased the GWP of CH_4 from 21 to 25 and then to 28—34 in three assessment reports (IPCC 1995, 2007, 2013).[10] CH_4 emissions have contributed to about one-third of today's anthropogenic GHG warming (GMI 2015). The Xiangyang project, however, achieved near-zero carbon emissions by avoiding the emission of CH_4 in two key ways: first, recovered bio-energy (i.e., biogas, 65 percent of which is composed of CH_4) is used as on-site energy; second, bio-energy is used to replace gasoline in city taxis. Not only does the Xiangyang project avoid emitting CH_4 by capturing and reusing its energy potential, it also replaces the use of other fossil fuels, such as coal and gasoline.

Since the Xiangyang project uses half of the recovered biogas to meet on-site energy needs, the project needed a small amount of coal to start up the sludge treatment process (four metric tons/day for two months). Less fossil fuel used and near-zero CH_4 emissions significantly reduced GHGs emissions compared with other technologies. According to WRI's estimate, the Xiangyang project will treat 2.3 million metric tons of the mixture of sewage sludge and kitchen waste during its 21 years of operation. The co-digestion process used on this sludge will generate 13,000 metric tons CO_2e (equivalent to 606 metric tons CO_2e/year). If the same amount of sludge were disposed of by landfill, 813,000 metric tons of CO_2e would be generated (including CH_4 and CO_2 releases to the atmosphere), which is 62.5 times the emissions of the Xiangyang project. If the sludge were treated by incineration, 237,000 metric tons of CO_2e would be produced, which is 18.2 times the emissions of the Xiangyang project. (See Appendix C for the methodology used in this paper to calculate GHG emissions.)

GHG Emissions Reduction from Substituted Energy

Besides using half the biogas produced (approximately 69.8 million m^3) to meet the energy requirement of the project, the Xiangyang project will produce 45.4 million m^3 (7.3 million GGE) of natural gas during the 21 years of operation. The natural gas will be compressed to replace about 60,000 m^3 of gasoline, reducing emissions of CO_2e by an extra 140,000 metric tons. Compared to gasoline, CNG is a cleaner energy source, has lower GHG emissions,[11] and emits lower amounts of other air pollutants such as NO_x, CO (carbon monoxide), and HC (hydrocarbon) (Hao

Figure 4 | **Contribution of the Xiangyang Project to GHG Emissions Reduction**



et al. 2009). Figure 4 summarizes the GHG emissions reduction benefits of the project.

Biochar and Carbon Sequestration from Sapling Production

The Xiangyang project employs an innovative and sustainable method to use the nutrients recovered: treated sludge is dehydrated into biochar which can be used as a soil amendment for tree saplings.

- **Using biochar to plant trees provides a reliable solution for the stabilization of sludge during resource recovery.**

With an annual biochar production of 21,600 metric tons (60 metric tons/day), it is estimated that 216,000 saplings can be planted in biochar-enriched soil each year (assuming 100 kg biochar to plant one sapling). This provides a way to deal with the problem of using treated sludge that faces many developing cities. The treated sludge does not end up in landfill but is turned into a resource. Since the project's inception, over 12,000 saplings (such as camphor, crepe myrtle, flowering cherry, and osmanthus) have been fertilized and planted at the Hongtoushan landfill (180,000 m^2, equivalent to 18 hectares) to restore the environment and ecosystem of the landfill.

Currently, sludge is not allowed to be directly used on farmland in China. The Xiangyang project therefore plants tree saplings using the container seedling method.[12] This approach helps to reduce the risk that any heavy metals remaining in the biochar contaminate local soil or migrate into water bodies or aquifers.

- **Saplings can be planted on barren land to reduce the use of limited fertile land.**

One of the challenges facing tree planting is a shortage of land. Assuming that two years are needed for the plants to reach maturity (at which point they can be sold or transplanted), 800,000 m^2 (80 hectares) of land is needed to plant 432,000 trees every two years. The container seedling method allows trees to be planted in containers and transplanted later, reducing the demand on limited fertile land. It also brings environmental benefits by restoring barren land and creates economic benefits generated from that land.

- **Tree cultivation creates a potential carbon sink in cities, while producing economic benefits.**

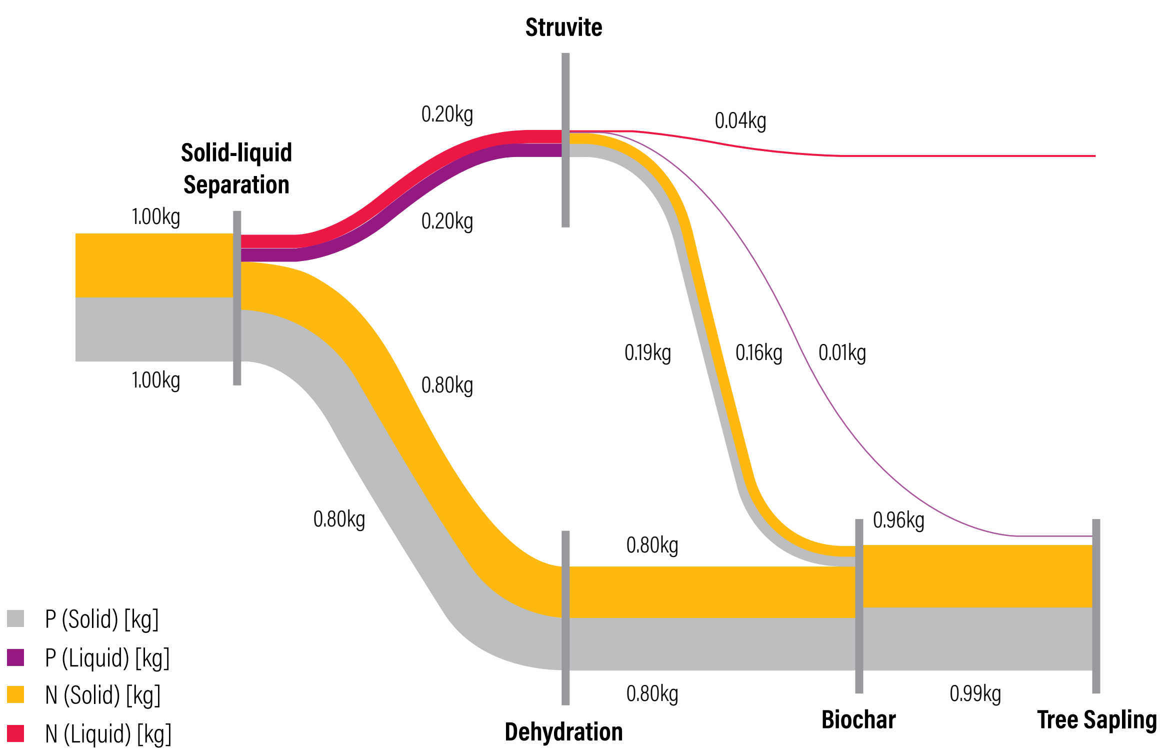
Assuming that carbon sequestration by trees begins two years after being planted, at a rate of 18.3 kg of carbon dioxide (CO_2) stored per year,[13] the total amount of carbon sequestered during the 21-year operation period will reach 750,000 metric tons CO_2e. The development of cities usually leads to increasing demand for trees. Assuming the area of green space in Chinese cities increases to 40 percent of total area (The State Council 2016), 1 billion trees will be planted, bringing significant potential demand and economic benefit for the tree market.

Nutrient Recovery of the Xiangyang Project
Figure 5 illustrates the N and P flows of the Xiangyang project.

- During the wastewater treatment process, large quantities of N and P accumulate in sludge. The concentration of total nitrogen (TN) and total phosphorus (TP) can reach 300—2,000 mg/L and 70—200 mg/L, respectively (Zhao et al 2004; Geng et al. 2013), which is significantly higher than the nutrient level of livestock manure.[14] However, if sludge is recklessly piled or dumped, N and P can run off into water bodies, causing excess algal growth and reduced oxygen levels, a condition known as eutrophication.

- To prevent this problem, the design of Xiangyang project is to use struvite precipitation to recover N and P from sludge. There is a small amount of P and N left in the leachate, which is used in the drip irrigation system that feeds the tree saplings planted in biochar-enriched soil. Under the design conditions, 96 percent of N and 99 percent of P will end up in biochar residue. It is proposed to use the anaerobic ammonia oxidation method (ANNAMOX) to remove most of the remaining N by transforming ammonium (NH_4^+) into N_2 and H_2. This method is currently being tested.

Figure 5 | **Nitrogen and Phosphorous Flows of the Xiangyang Project**



Energy Benefits

The Xiangyang project has brought significant energy benefits by not only capturing energy byproducts (mainly CH_4) of the AD process, but also recycling heat to support the system as much as possible.

Captured Byproducts to Substitute Primary Energy

During its 21 years of operation, the Xiangyang project will produce at least 140 million m^3 biogas by treating 2.3 million metric ton of sludge and kitchen waste mixture. Half of the biogas produced (approximately 69.8 million m^3) will be used to meet the energy requirement of the project, and the other half will be purified to produce 45.4 million m^3 (7.3 million GGE) of natural gas.

Heat Recycling and Energy Management

Energy consumption is the major source of GHG emissions from sludge treatment. For the Xiangyang project, energy is consumed to maintain the temperature of the reaction, and to power the sludge pump, mixing equipment, and biogas compressor. The current electricity consumption of the Xiangyang project is 6,000 kWh/day (approximately 20 kWh/metric tons sludge with 80 percent moisture content). The project is designed to be nearly energy self-sufficient in the following ways:

- As discussed above, recovered biogas is used to power the entire project. Biogas is captured and combusted on site to provide energy and heat for the system's operation. Fossil fuel was used only during the two-month system startup, when 240 metric tons of coal (4 metric tons/day for two months) was needed to power the initial stages.

- Heat is recovered and reused as energy to dry the digested sludge. This heat is captured when the sludge, first heated to 170°C during the THP, is cooled down to 40°C to enter the AD process. The recovered heat provides 80 percent of the required energy; the rest is solar energy from sunlight.

ECONOMIC BENEFITS OF THE XIANGYANG PROJECT

Financial Analysis of the Xiangyang Project

Benchmarks of Costs for Sludge Treatment

The construction, investment, and operating costs are determined by various factors, such as the characteristics of the sludge, origin of the equipment, scale of the project and levels of automation. Table 1 shows that the construction investment and operating costs of THP+AD are higher than landfilling, but lower than incineration and composting.

Table 1 | **Cost Comparison of Different Sludge Disposal Methods**

Treatment Method	Fixed Cost (1,000 CNY/ton sludge[e])	Operating Cost[f] (CNY/ton sludge[e])
Anaerobic digestion [a]	200-400 [g]	60-120 [g]
Incineration [b]	300-700 [g]	>400 [h]
Composting [c]	250-450 [g]	120-160 [g]
Landfilling [d]	180 [g]	70-80 [g]
Thermal hydrolysis + anaerobic digestion	300 [i]	110 [i]

Note: a) the anaerobic digestion here refers to the traditional anaerobic digestion. The cost of concentration and dewatering of sludge is not counted; b) the fixed asset depreciation is not included in the operating cost of incineration; c) the cost of land acquisition is not included in the construction investment of composting; d) the construction investment cost is calculated in terms of a 20-year period of landfilling capacity; e) the moisture content of sludge is 80%; f) operating cost refers to the expenses which are related to the operation of the project. The fixed asset depreciation, and other financing costs are not included; g) the data comes from Technology Guideline for Sludge Treatment and Disposal from Municipal Wastewater Treatment Plant; h) the estimated operating cost of incineration comes from selected projects, such as Chengdu no.1 sludge incineration project,[15] Shenzhen sludge incineration project (Qiu 2014); i) both construction investment and operating cost are estimated based on Xiangyang project's data.

Cost of the Xiangyang Project

The costs of the Xiangyang project include:

- Cost of sludge treatment: 254 CNY/metric ton of sludge treated (37 USD/metric ton[16], 80 percent moisture content). This cost of treatment can be disaggregated as:
  - Fixed costs: 110 CNY/metric ton sludge treated (16 USD/metric ton, 80 percent moisture content);
  - Operating costs: 110 CNY/metric ton sludge treated (16 USD/metric ton, 80 percent moisture content). In the operating cost, labor, electricity, chemical agents, and equipment updates account for 81.8 percent of the operating costs (See Figure 6).
- Operating cost of kitchen waste treatment (include labor, electricity, and chemical agents): 75 CNY/metric ton (11 USD/metric ton, 80 percent moisture content). Fixed costs, financial expenses, depreciation, and other expenses that arise in the treatment plant are absorbed entirely into the cost of sludge treatment.
- Amortization of loan (principal and interest): 11 million CNY/year (1.6 million USD/year);
- Tax payments to the government: 900,000 CNY/year (130,510 USD/year);
- CNG price adjustment fund: 1 CNY/m^3 of CNG sold. This fee has been cancelled since 2014.[17]

Considering that the heat supply for the THP was obtained from the waste heat collected before pulped sludge entered the digestion process, the cost of THP accounts for 15–20 percent of the total cost of treatment; drying accounts for 30–35 percent, and digestion accounts for 5 percent. If the heat used for THP were provided by an external heating source, the cost of the THP would increase to 30–40 percent of the total cost.

Revenue from CNG, Biochar, and Saplings

Currently, the Xiangyang project's main revenue sources are the sale of CNG and biochar; however, revenue will rise with the sale of tree saplings.

Figure 6 | **Breakdown of the Operating Costs of the Xiangyang Project**

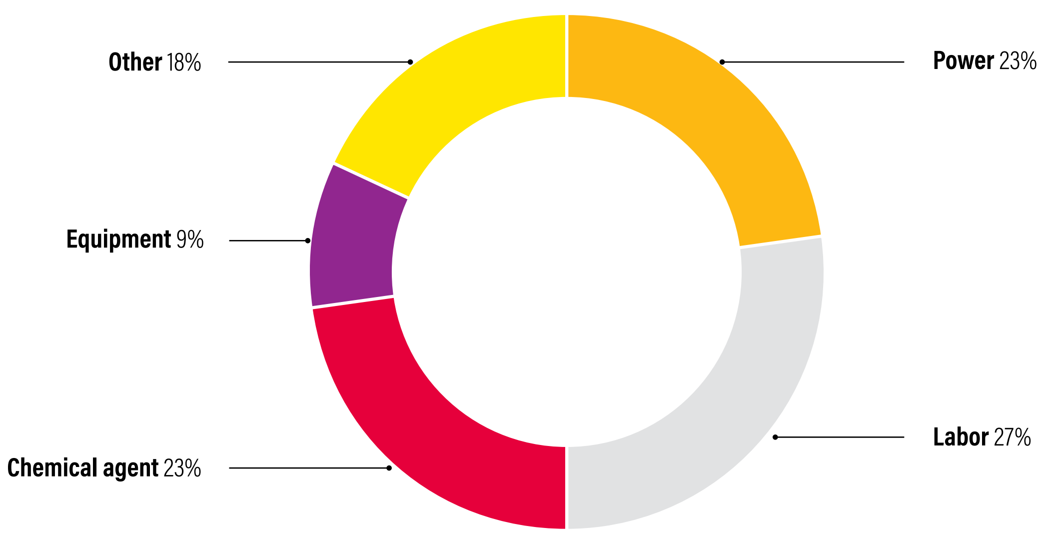


Table 2 | **Annual Cost and Benefit Breakdown of the Xiangyang Project**

Revenue [a] (million CNY)		Cost [a] (million CNY)	
Sludge Treatment Subsidy	**18.3**	Sludge Treatment Cost [b]	**15.8**
Kitchen Waste Treatment Subsidy	**2.6**	Kitchen Waste Treatment Cost [b]	**2.7**
CNG Sales Revenue	**9.7**	Clean Energy Fund	**0.2**
Biochar Sales Revenue	**0.8**	Taxes	**0.9**
		Financial Expense [c]	**2.4**
		Indirect Expense	**8.5**
Total	**31.4**	**Total**	**30.5**

Note: a) the estimation of revenue and cost is on an annual basis (360 days); sludge and kitchen waste are calculated as 200 tons/day and 100 tons/day, respectively; b) treatment cost of sludge and kitchen waste includes the fixed cost and the operating cost; c) financial expenses include the annual interest of the loan. See Appendix C for a detailed cost-benefit analysis.

- Revenue from the sale of CNG: The daily CNG production (6,000 m^3) can meet the energy requirements of 300 cars. At a price of 4.5 CNY/m^3 (0.74 USD/m^3), the sale of CNG will generate an annual revenue of 9.72 million CNY (1.41 million USD).

- Revenue from the sale of biochar: In the first two years of operation, the operator used biochar (moisture content 40 percent) to plant trees. However, biochar is also a product with market value. Currently, the Xiangyang project operator is dehydrating biochar to various moisture content levels based on consumer needs. The price of biochar with 60 percent moisture content is 20—30 CNY/metric ton (2.9—4.4 USD/metric ton) while the price of biochar with 10 percent moisture content is 140—150 CNY/metric ton (20—22 USD/metric ton). The revenue from the sale of biochar could reach 0.8—2.1 million CNY/year (0.12—0.30 million USD/year).

- Potential revenue from the sale of tree saplings: Tree saplings are the products with the greatest potential revenue. Based on the calculation of 60 tons biochar, and a two-year growth period of trees before selling to the market, 800,000 m^2 (80 hectares) of land is needed to plant the trees. In addition, it is estimated that the net profit for each tree is 200 CNY (29 USD).[18] Thus, a net profit of 43.2 million CNY (6.3 million USD) for the 216,000 trees planted each year will be received. This translates to approximately 400 CNY net profit for each ton of sludge treated.

Financial Viability

From 2012 to 2014, the Xiangyang project sold only CNG to the market and broke even, with revenues matching expenses. Operating costs were offset by subsidies and the production and sale of CNG. Since 2015, the project has been selling biochar, significantly increasing the profitability of the project (see Table 2). When tree saplings are sold, the project will have even greater profit-making potential.

Operation and Financing Mechanism

The operator of the Xiangyang project signed a BOO agreement with the Xiangyang Urban Construction Committee to treat sludge and with the Xiangyang Urban Management Bureau to treat kitchen waste. The concession period is 23 years with a construction period of two years and an operational period of 21 years.

The Xiangyang project has a total investment of 134 million CNY (20.7 million USD[19]).

- 89.3 million CNY (13.8 million USD) was invested in sludge treatment equipment.

- 44.7 million CNY (6.9 million USD) was invested in pre-treatment equipment for kitchen waste (such as sorting, pulping, and drying), the CNG station, and kitchen waste collection trucks.

The project has three major sources of funding:

- 30 percent of the total investment came from corporate equity of 40 million CNY (6.2 million USD).

- 60 percent of the total investment was from low-interest loans of 80 million CNY (12.4 million USD). The interest rates were five percentage points lower than the central bank's benchmark lending rate:

  - Export-Import Bank of China (China Exim Bank) loan of 72.5 million CNY (11.2 million USD), with a 12-year maturity

  - KfW Bankengruppe concessional loan of 7.5 million CNY (1.2 million USD), with a 12-year maturity

- 10 percent of the total investment was provided in the form of subsidies by the local government, amounting to around 14 million CNY (2.2 million USD).

Government Contributions to the Xiangyang Project

The Xiangyang local government pays the operator a subsidy for each metric ton of feedstock treated. Currently, that rate is 254 CNY/metric ton (37 USD/metric ton, 80 percent moisture content) for sludge,[20] and 72 CNY/metric ton (11 USD/metric ton, 85 percent moisture content) for kitchen waste. The level of subsidy is based on an estimate of the operational cost of treatment and the potential revenue received from selling CNG. These payments are adjusted every two years based on the Consumer Price Index (CPI) and vary by about 3—5 CNY/metric ton (0.4–0.7 USD/metric ton).

This report has found the following:

- To determine the subsidy level, the local government considered the methane production potential of kitchen waste and sludge. Kitchen waste has a higher CNG recovery potential than sludge, endowing it with greater earning potential and allowing for lower subsidies.

- Since there is ultimately little difference between the actual revenue generated by kitchen waste and sludge, there is no significant difference in the willingness of the operator to treat one feedstock rather than the other.

Currently, the subsidy is the Xiangyang project's major revenue source. Table 3 shows that Xiangyang's subsidy is relatively high compared to sludge projects in other cities. This is a deliberate effort by the local government to establish a solid financial foundation for the stable and sustainable operation of the project.

Table 3 | **Subsidy of Selected Sludge Sludge Treatment Projects in China**

Province/City	Project Name	Sludge Treatment and Disposal Methods	Subsidy (CNY/ton)
Xiangyang	Yu Liang Zhou sludge reclamation project [a]	Anaerobic digestion	254
Dalian	Dalian Dong Tai Xia Jia river sludge treatment plant [b]	Anaerobic digestion	135
Ninghai	Cheng Bei sludge treatment plant [c]	Anaerobic digestion	200
Beijing	Sludge treatment project of Beijing Cement Co., Ltd. [b]	Sludge dehydration (treatment of sludge and cement feedstock)	315
Xiamen	Xiamen municipal sludge dehydration and reclamation project [b]	Sludge dehydration to make bricks or for landscaping	130
Guangzhou	Guangzhou Jinsheng sludge treatment plant [d]	Sludge dehydration to make bricks	195
Qinghuangdao	Hebei Province, Qinghuangdao municipal sludge treatment project [b]	Composting	130
Shandong	Weihai municipal sewage sludge harmless treatment and reclamation [b]	Composting	180
Jiangsu	Kunshan sludge deep dehydration and full combustion [b]	Incineration	258
Jiangsu	Wujiang Ping Wang waste incineration power plant [e]	Incineration	95
Hongkong	Hongkong municipal sludge drying process and incineration [e]	Incineration	HKD 1000
Suzhou	Suzhou waste incineration power plant [f]	Incineration	180-200
Shanghai	Shanghai Shi Dong Kou sludge drying and incineration project [b]	Incineration	280
Zhejiang	Xiaoshan sludge srying and incineration project [b]	Incineration	100

Source: a) authors; b) China Water Net; c) Provided by CSD (Beijing) Green Enegy; d) Yang (2007); e) people.com.cn; f) China's Renewable Energy Power Web.

Social Cost of Carbon in the Xiangyang Project

The social cost of carbon ($SC\text{-}CO_2$)[21] is a tool that can be used to estimate the climate benefits of GHG emissions reductions. According to WRI's estimate, the Xiangyang project has already produced significant benefits.[22]

- The carbon emissions reduction from the sludge treatment stage alone accounts for a climate benefit between 6.9 and 43 million USD (2011 USD). The variance of the social benefits results from using different social discount rates (Song 2016).
- Running Xiangyang taxis with CNG instead of gasoline results in an additional reduction in carbon emissions, and raises the climate benefit to between 34 and 216 million USD (2011 USD).
- Finally, the carbon sequestered by tree saplings grown in biochar soil raises the climate benefit to between 42 and 260 million USD (2011 USD).

The Xiangyang project exemplifies the inherent value of a circular economy: local waste is converted into reusable resources and the externalities of improper sludge treatment and disposal are mitigated at the local, regional, and global levels. The local externality for residents of Xiangyang is the environmental and social cost of the waste generated in the city; the regional externality is the POPs pollution of water and land resources around Chinese cities; and the global externality is the emission of methane and CO_2 into the atmosphere. If the Xiangyang project's mitigation of these three externalities were monetized, the project would demonstrate a substantial economic rate of return. Appendix D details the methodology for calculating the social cost of carbon and estimating the $SC\text{-}CO_2$ of the Xiangyang project.

CONCLUSIONS

The inappropriate treatment and disposal of sludge in China has become a severe environmental challenge. Currently, more than 80 percent of sludge in China is not treated at all or is treated in ways that pollute the environment and waste the resources in sludge. If the 40 million metric tons of sludge produced in 2015 (80 percent moisture content) were placed in a landfill, they would emit 14.4 million metric tons of CH_4 (WRI estimate). Meanwhile, the economic potential of capturing and reusing nutrients such as nitrogen and phosphorus would be lost.

However, the development of sustainable sludge treatment processes is hampered by high treatment costs and unreliable financing mechanisms. Some sludge treatment methods yield products that have little market potential—such as soil amendments made from compost. Without revenue potential from these products, corporations have little incentive to run sludge treatment projects. Circular economies never form.

The Xiangyang project provides valuable experiential knowledge of practices that worked. These lessons can be used to scale up similar programs using combined treatment of sludge and kitchen waste through thermal hydrolysis and anaerobic digestion in China and other developing countries. Much can be learned and replicated about selecting a technical method that produces marketable byproducts, establishing financing mechanisms that benefit all parties, and developing efficient operating procedures. Several projects that use methods and technologies similar to Xiangyang in Beijing, Hefei, Changsha, Dalian, and Ninghai are already in the planning or operational stages.

The following are key conclusions from our analysis of the Xiangyang project:

- **The Xiangyang project successfully achieved pollutant reduction, resource recovery, near-zero carbon emissions from sludge treatment, and renewable energy generation.**

The technical process of high-temperature thermal hydrolysis, anaerobic digestion, and methane capture and utilization, and the use of biochar allowed the project to successfully recover and reutilize the nutrients in sludge (C, N, and P), while avoiding the secondary pollution of water bodies. During its 21 years of operation, the project will reduce 95–98 percent of GHG emissions compared to traditional sludge treatment methods. It will also produce 45.4 million m^3 of CNG to replace 60,000 m^3 of gasoline, resulting in an extra reduction of 140,000 metric tons of CO_2e.

- **A market-oriented approach to the design of sludge treatment is vital to its economic success.**

The Xiangyang project demonstrates the importance of designing a complete value chain for sludge treatment, one that considers the needs of the market. The specific treatment technology for Xiangyang was selected with careful consideration for the market potential of the two recoverable products: CNG and biochar. The presence of potential markets for these products makes it more attractive to private investors and more likely to draw a sustainable flow of capital.

- **Support from government, the financial sector, and the private sector through a PPP arrangement enabled the alignment of incentives necessary to achieve a complex set of development objectives.**

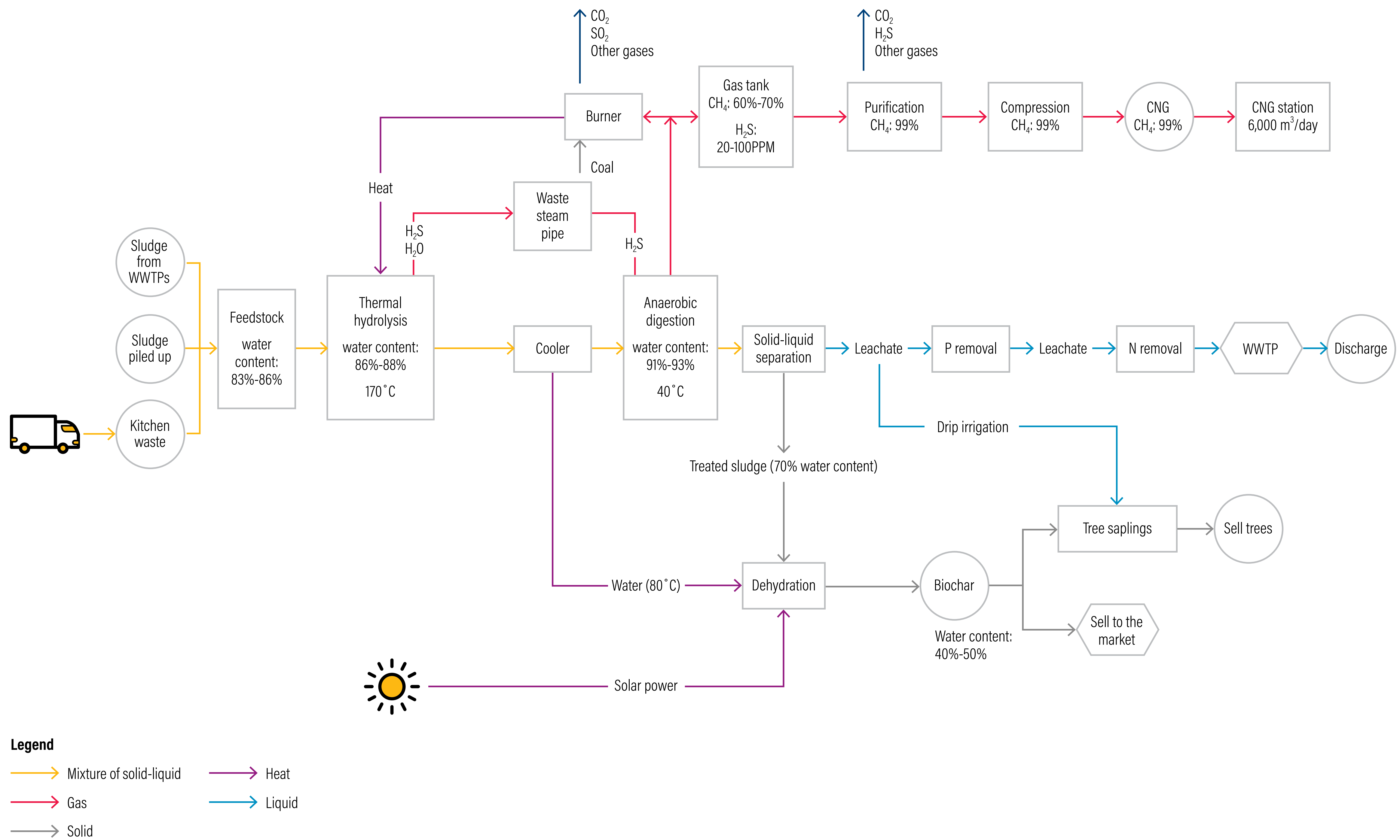
The successful implementation of a BOO contract underscored the importance of cooperation between local government and the private sector. While the government has an obligation to the public good to mitigate the environmental risks caused by sludge pollution, the private sector will only become involved in developing a circular economy model for sustainable sludge resource recovery when the business model responds to market signals and is clearly financially viable.

The pairing of the public and private sectors ensures the availability of concessional financing to bridge the viability gap that is likely to emerge during the initial investment phase. The viability gap can result from diverse factors: investor perceptions of high transaction costs in the supply chain of organic wastes for the anaerobic treatment plant, unfamiliarity with working at the municipal level on a long-term contract, or uncertainty regarding demand and pricing for CNG and biochar.

Ideally, global climate and other international financial funds will target the mitigation of global externalities, by methods such as capturing methane and other GHGs. The availability of financial incentives will induce the private sector to enter into and promote a circular economy for the stabilization of sludge and the reclamation of sludge byproducts. This, in turn, will help enhance the viability of such projects, and help drive costs down via competition and innovation, making the market even more attractive for private capital investment.

APPENDIX A. CARBON, NITROGEN, AND PHOSPHORUS MATERIAL FLOW CHART OF THE XIANGYANG PROJECT

Figure A-1 | Material Flow of the Xiangyang Project



Source: Provided by the Toven Co. Ltd.

APPENDIX B. METHANE CAPTURE FROM SLUDGE: A SUMMARY OF INTERNATIONAL EXPERIENCE

The organic matter in the sludge produced by WWTPs is an excellent source of nutrients. There are several possible ways to reuse the sludge resources, including for agricultural and forestry,[i] construction materials (Zhao et al. 2004), and energy recovery. Methane recovery from the anaerobic digestion process is widely used in the United States and Europe.

Sludge treatment and disposal in the United States and Europe evolved from dumping in landfills, to incineration, to land application. Incineration, though it was once the favored method of waste disposal, cost more than other treatment methods to meet strict toxic gas emissions standards (Cao and Pawlowski 2013). That cost rose even more in the United States after the U.S. Environment Protection Agency (EPA) proposed new emissions control rules for sewage sludge incinerators (SSIs) in 2015 (EPA 2015).

Over the years, developed countries continued to explore treatment technologies that both reduced pollution and had low costs. After much experimentation, anaerobic digestion and aerobic fermentation became the favored methods for stabilizing and detoxifying sludge in the United States and Europe. Of the two, anaerobic digestion is more effective at reducing pollutants, stabilizing and detoxifying the sludge, and recovering resources. Table B-1 enumerates the current operational status of facilities using anaerobic digestion (MoHURD 2011).

There are two primary methods for anaerobic digestion treatment of sludge in the United States and the European Union.

Table B-1 | **Development of Anaerobic Digestion of Sludge in Developed Countries**

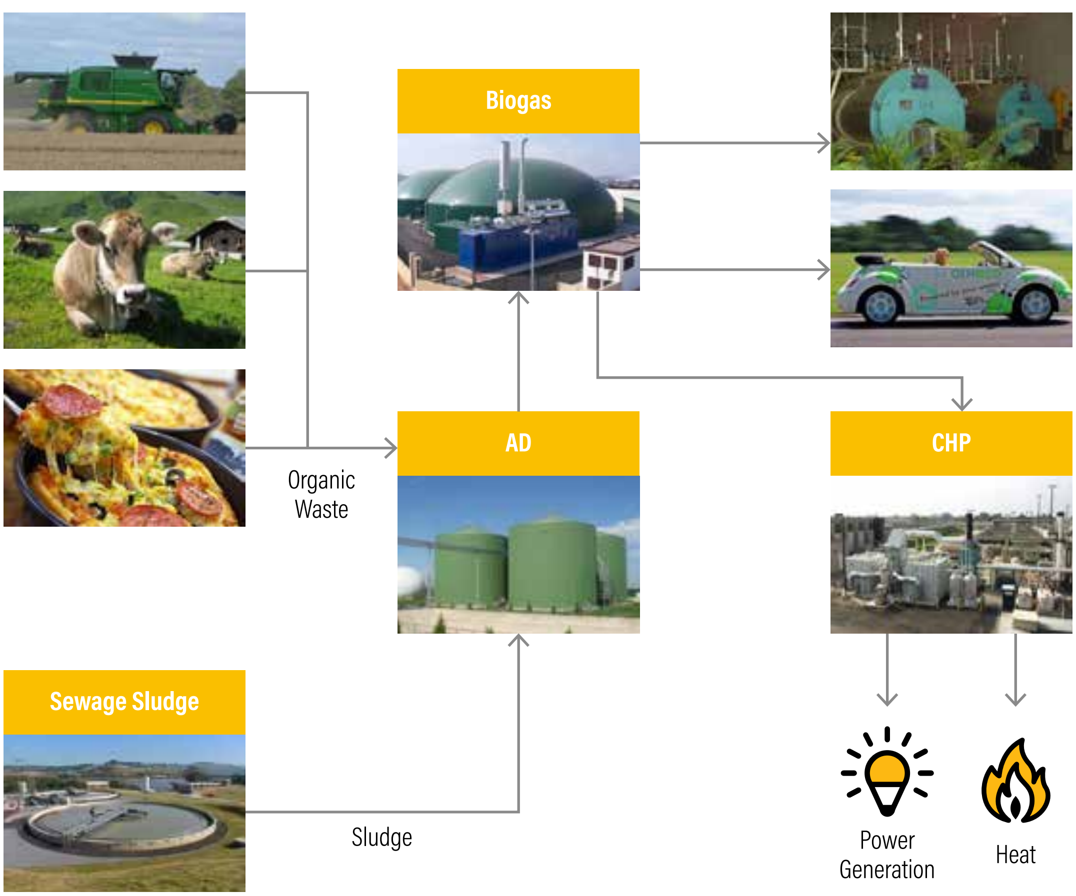
Country	Year	Anaerobic Digestion Facilities		Energy Produced
		Feedstock: sludge	Feedstock: kitchen waste/ agricultural waste	
		Number of plants	Number of plants	GW/year
United Kingdom [a]	2013	146	143	1,509
Sweden [a]	2013	465	147	1,118
Norway [a]	2013	1,400	8,220	27,730
Germany [a]	2013	38	44	2,578
Brazil [a]	2013	5	13	7,637
Denmark [a]	2013	57	97	912
United States [b]	2013	NA	239	NA

Note: NA indicates missing data
Source: a) IEA (2015); b) EPA (2011)

The first method is to use thermal hydrolysis before anaerobic digestion, as it markedly improves the efficiency of both dehydration and digestion, increasing the production of biogas. More and more cases of this technique are appearing in the United States and Europe. For example, *Kaponusciska* WWTP in Bydgoszcz, Poland has used this method to increase the solidity content of sludge from 20 percent to 31 percent, which reduces the volume by half.[ii] As another example, Dublin's Ringsend WWTP increased its unit capacity gas production to 3.5 m^3/day, which is 350 percent of the efficiency of production if only digestion is used.[iii]

The second method for anaerobic digestion treatment is the co-digestion of sludge, food and kitchen waste, livestock manure, and other organic matter (see Figure B-1). Because food waste and livestock manure naturally contain high quantities of organic matter, combining these materials with sludge helps facilitate digestion, stabilization, and detoxification. Meanwhile, sludge can also help provide the bacteria needed for the digestion of food waste and manure. Co-digestion improves gas production, contributing to the overall economic efficiency of this method.

Figure B-1 | **Co-digestion of Sewage Sludge and Kitchen Waste for Methane Capture**



Note: AD = anaerobic digestion; CHP = combined heat and power
Source: Veolia Water

APPENDIX C. METHODOLOGY FOR CALCULATING GHG EMISSIONS FROM DIFFERENT SLUDGE TREATMENT METHODS

GHG Accounting Boundaries and Sources of GHG Emissions

To compare the GHG emissions of different sludge treatment methods, this study defined accounting boundaries based on the "Environment Management-Life Cycle Assessment and Framework" (ISO14040) (ISO 2010) and the GHG Protocol for Cities (WRI and WBCSD 2015) (Figure C-1).

The system expansion method (ISO 2010)[lv] is used to account for both the GHGs emitted during the sludge treatment process and the simultaneous reduction in emissions due to the use of biogas and biochar. The following elements are included in the accounting:

- Emissions from the use of fossil fuel within the boundary.
- Emissions from the transportation of sludge and kitchen waste to the treatment plant.
- Emissions avoided due to the use of bio-energy to replace fossil fuels (such as coal and gasoline).

Table C-1 lists the sources of GHG emissions for different methods of sludge treatment.

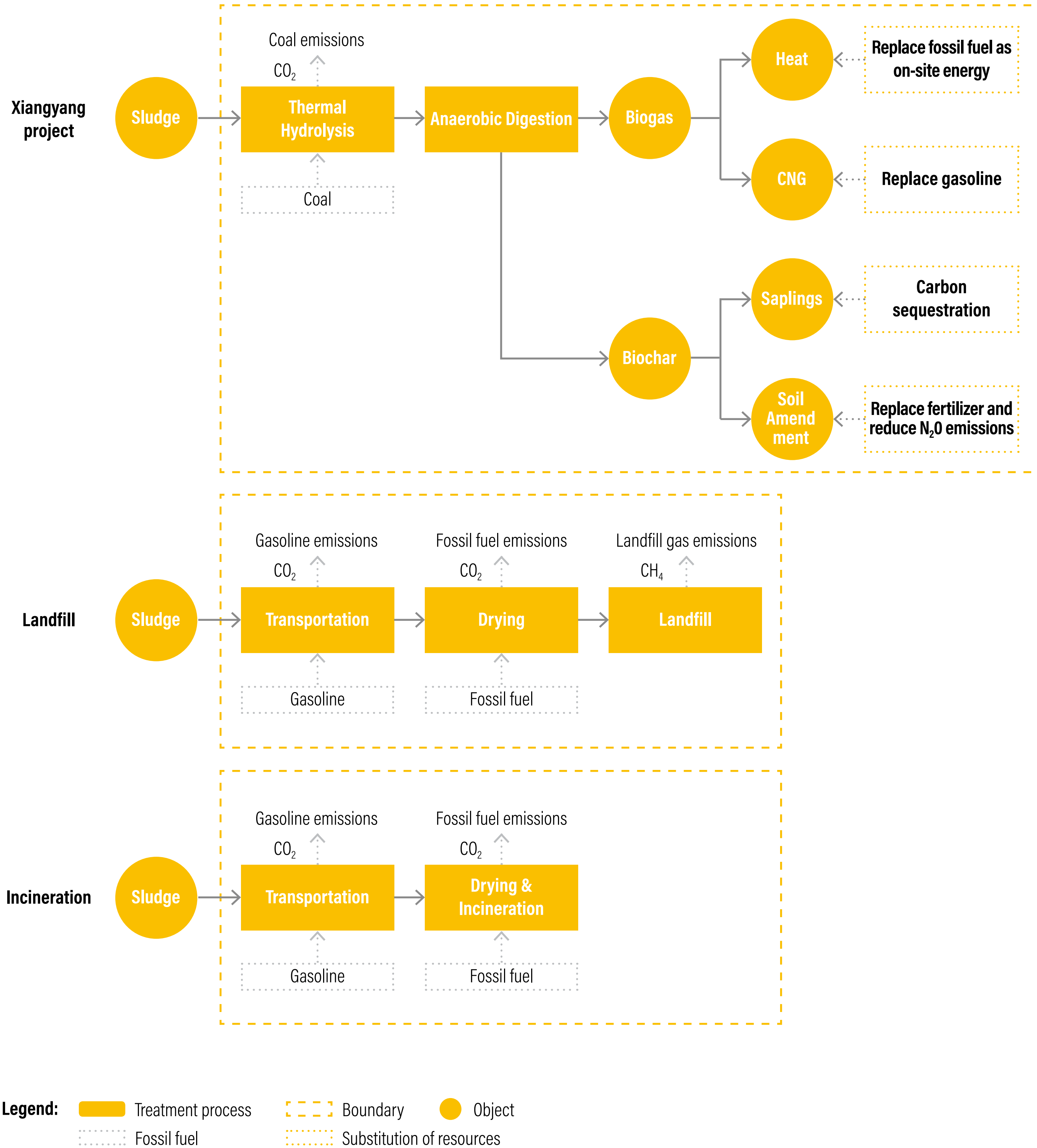
It should be noted that biogas does emit CO_2 when it undergoes combustion; however, as the carbon contained in sludge is biogeneric, these CO_2 emissions are not counted in the total GHG emissions reported (IPCC 2006). This is in line with the European renewable resource directive (Directive 2009/28/EC), which counts

Table C-1 | **GHG Accounting for Different Sludge Treatment Methods**

Sludge Treatment Method	GHG Emission Accounting
Xiangyang project (Thermal hydrolysis and anaerobic digestion)	• Emissions from fuel (coal) used during two-month start of treatment system • Avoided emissions from use of biogas to fulfill energy requirements of project • Avoided emissions from use of CNG to replace gasoline in municipal taxis • Avoided emissions because transportation of sludge to disposal site is not required (sludge treatment occurs directly next to WWTP) • GHG emissions reduction from carbon sequestration by trees planted
Landfill	• Emissions from fuel used for dehydrating sludge from 80% moisture content to 60% moisture content. (If 300 metric tons of sludge are treated each day, daily gas use is 10,500 m^3) • Emissions of CH_4 due to naturally occurring anaerobic digestion of sludge in landfill • Emissions from transportation of sludge to landfill (If distance is 50 km, the annual transportation emissions will be 276 metric tons CO_2e) (MoT 2016)[a]
Incineration	• Emissions from fuel used for dehydrating sludge from 80% moisture content to 30% moisture content[b] (If 300 metric tons of sludge are treated each day, daily gas use is 14,980 m^3) (Wang et al. 2009) • Emissions from N_2O produced during incineration process • Emissions from transportation of sludge to incinerator (If distance is 50 km, the annual transportation emissions will be 276 metric tons CO_2e)

Notes: a) according to the Ministry of Transport, the coal consumption of transport corporations is 1.9 kg coal/100 ton per km. The emission factor of coal is 2.69 $kgCO_2/kg$; b) self-maintaining incineration can happen after drying sludge to 30% moisture content.

Figure C-1 | **Boundary of GHG Accounting for Different Sludge Treatment Methods**



Note: Because the Xiangyang project is constructed beside the WWTP, the transportation emissions of sludge are ignored in the GHG emissions calculation in this study.

GHG emissions as zero when biogas is used to replace gasoline for vehicles. Additionally, both the U.S. eGRID (the Emissions and Generation Resource Integrated Database of the U.S. EPA) and the United Kingdom Defra acknowledge that emissions from biogas combustion for power generation are zero. China also has similar standards for GHG accounting; methane emissions from biomass combustion are counted in the total emissions, but CO_2 emissions are not (NDRC 2011).

GHG Emissions Comparison

Figure C-2 (the Sankey diagram) compares the carbon balance, carbon migration, and GHG emissions of the Xiangyang project with the other treatment methods (landfilling and incineration).

Figure C-2 | **Carbon Balance and Carbon Emissions Comparison Between the Xiangyang Project and Other Treatment Methods**

Thermal Hydrolysis + Anaerobic Digestion

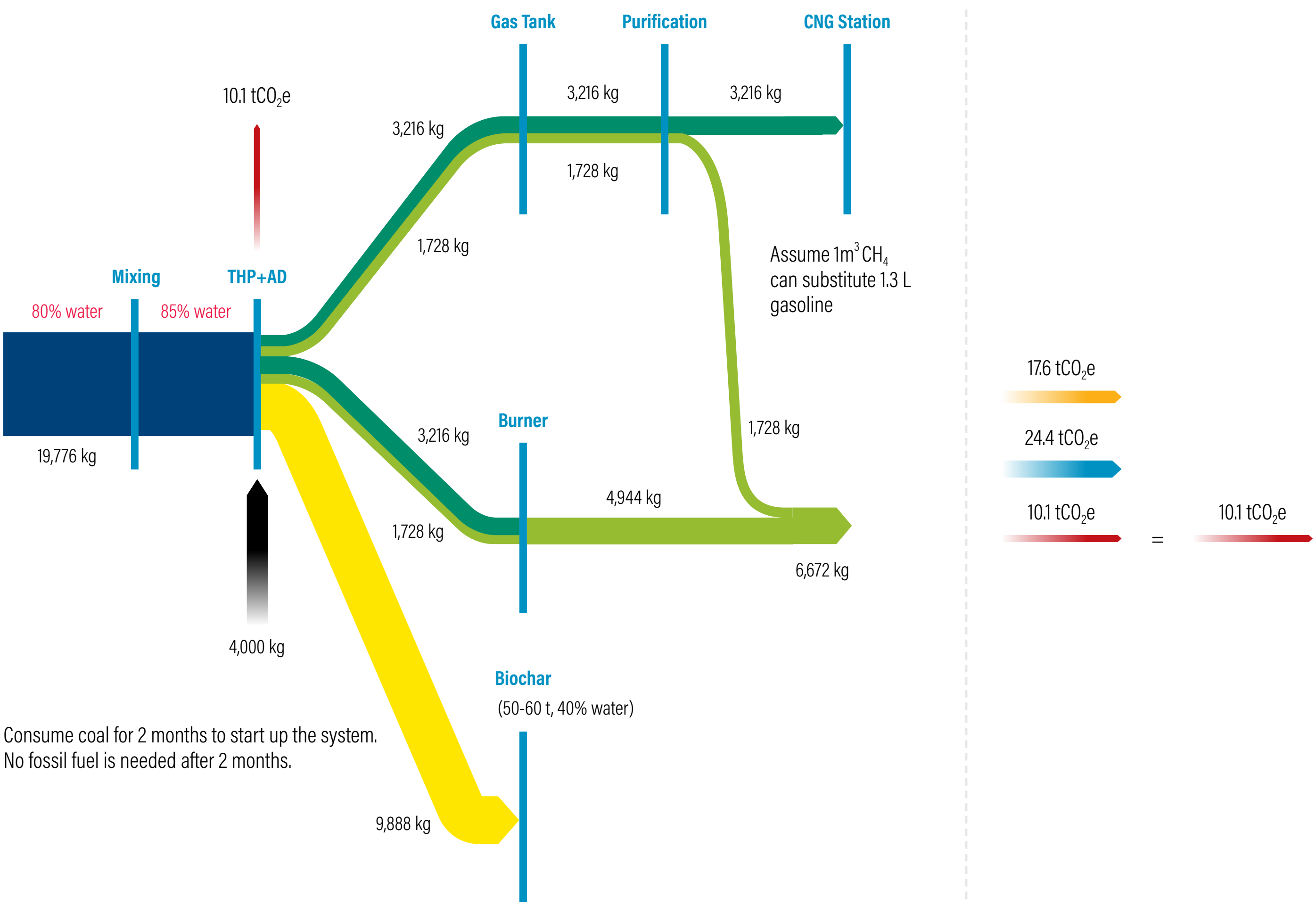
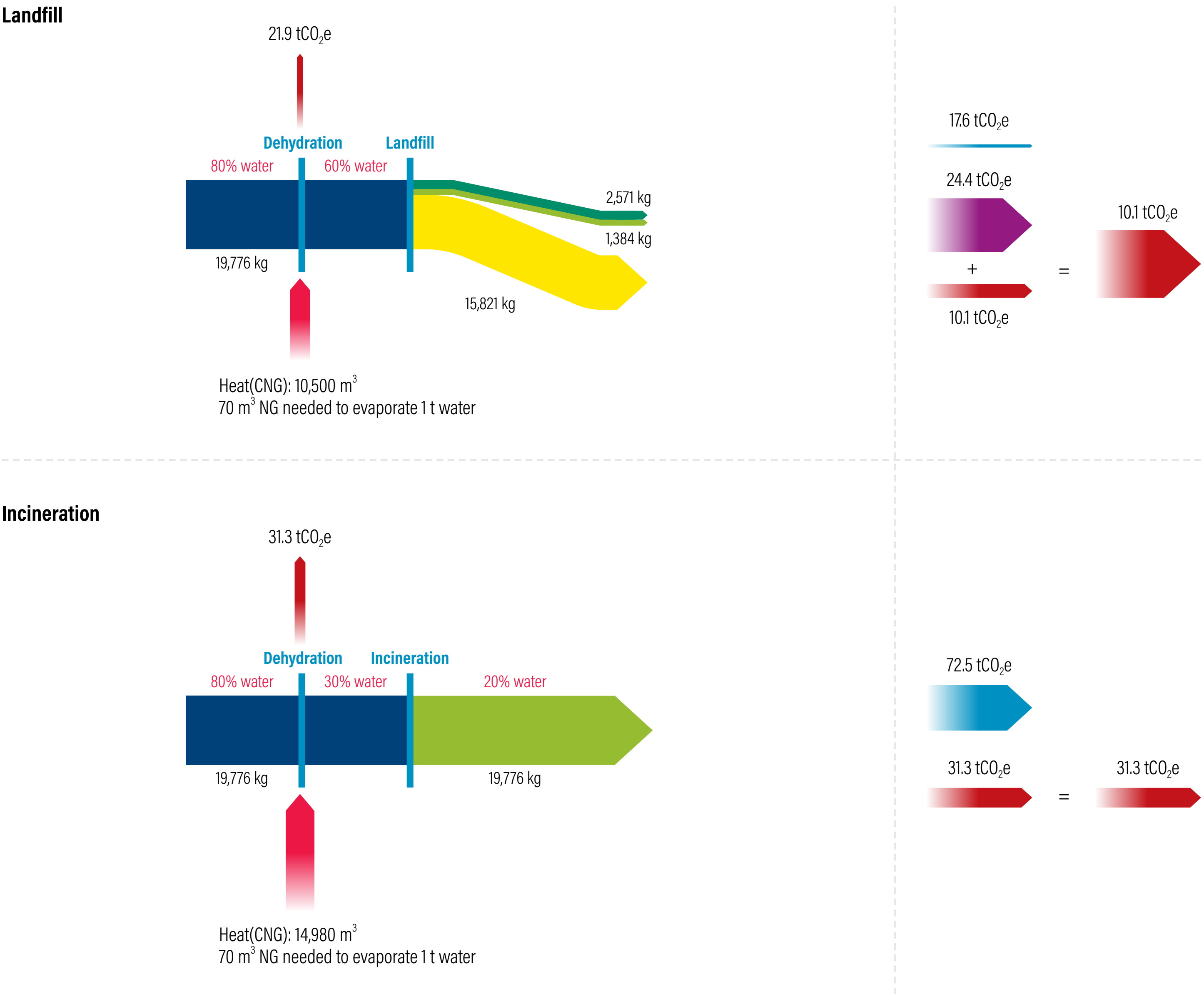


Figure C-2 | **Carbon Balance and Carbon Emissions Comparison Between the Xiangyang Project and Other Treatment Methods (continued)**



- C (Feedstock) [kg]
- C (CO_2) [kg]
- C (Solid) [kg]
- C (CH_4) [kg]
- Heat(CNG) [m^3]
- CO_2 emission [tCO_2e]
- CH_4 emission (biogas) [tCO_2e]
- CO_2 substitute [tCO_2e]
- CO_2 emission (biogas) [tCO_2e]
- Coal [kg]

Feed: 300 tons mixture of sludge and kitchen waste (200 tons sludge and 100 tons kitchen waste). The feed for landfill and incineration is the same with digestion.
Moisture Content: 80%
Carbon Content: 44%
Decomposition Rate of Degradable Organic Carbon: 50%
Composition of Biogas: CH_4/CO_2: 6.5/3.5
GWP (CH_4)=25
Emission Factor (Gasoline): 2.26 $kgCO_2$/L
Emission Factor (Natural Gas): 2.09 CO_2/m^3
Emission Factor (Coal): 2.53 $kgCO_2$/kg
Emission Factor (Center China Grid): 7.0629 tCO_2e/10MWh
Note: The carbon balance calculation was the average daily estimate according to the potential of carbon flow.

Avoided CO_2 emissions from gasoline due to the use of CNG

CO_2 emissions of the project

CH_4 emissions from landfill

CO_2 emissions from biogas

APPENDIX D. SOCIAL COST OF CARBON OF SLUDGE-TO-ENERGY APPROACH

The social cost of carbon (SC-CO_2) can be used as a tool for deciding policies, where priority is given to decisions and policies that have favorable outcomes for the environment and society, based on quantified results called "climate benefits" (Interagency Working Group of the U.S. Government 2013). The process of calculating these climate benefits helps quantify the economic value of social outcomes, both within and outside the scope of the project, so that options can be weighed based on their relative outcomes.

Methodology for Calculating the Social Cost of Carbon

The integrated assessment models (Interagency Working Group of the U.S. Government 2013) are used to develop SC-CO_2 estimates. Table D-1 presents the current SC-CO_2 estimates for certain years.

Table D-1 | Annual SC—CO_2 Values: 2010-2050 (2007 dollar/metric ton CO_2)

Year	Discount Rate		
	5% Avg	3% Avg	2.5% Avg
2010	10	31	50
2011	11	31	50
2012	11	31	50
2013	11	31	50
2014	11	31	50
2015	11	36	56
2016	11	36	56
2017	11	36	56
2018	12	36	56
2019	12	36	56
2020	12	42	62
2021	12	42	62
2022	13	42	62
2023	13	42	62
2024	13	42	62
2025	14	46	68
2026	14	46	68
2027	15	46	68
2028	15	46	68
2029	15	46	68
2030	16	50	73
2031	16	50	73
2032	17	50	73
2033	17	50	73
2034	18	50	73
2035	18	55	78
2036	19	55	78
2037	19	55	78
2038	20	55	78
2039	20	55	78
2040	21	60	84

Climate Benefit at the Project Level

Source of Carbon Emissions Reductions

There are three sources of carbon emissions savings: use of biogas produced on-site as energy to replace fossil fuel (such as coal), substitution of gasoline with CNG in local taxis, and carbon sequestration from the trees cultivated in biochar. Table D-2 summarizes the carbon emissions reductions of the project by source.

Economic value of carbon reductions for the life cycle of entire project (21 years)

If only the carbon emissions reduced during the sludge treatment stage are considered, the climate benefits range from 6.9 to 43 million USD, as of 2011 (Table D-3).

If the carbon emissions reduced by substituting gasoline with CNG are also included, the climate benefits increase to between 34 and 216 million USD, as of 2011 (Table D-4).

If the carbon emissions offset by tree cultivation are also included, the climate benefits range from 42 to 260 million USD, as of 2011 (Table D-5).

Table D-2 | **Sources of Carbon Emissions Reduction**

Carbon Savings	Reason for Carbon Savings	Daily Reduction (metric tons/day)
Sludge treatment	Biogas produced in treatment replaces fossil fuels for project operation	134,033[a]
Substitute gasoline with CNG	Purified biogas (CNG) replaces gasoline	140,000
Tree saplings	Planted trees result in carbon sequestration	750,000[b]
Total		1,024,033

Note: a) the Xiangyang project uses 9,230 m^3 biogas to meet the daily energy need for the system operation. This figure is calculated based on the estimation that the caloric value of 1 m^3 biogas is approximately equal to 0.714 kg coal and the emission factor of 1 kg coal is 2.69 kg CO_2/kg coal; b) carbon sequestration assumed not to occur until two years after planting.

Table D-3 | **Value of Carbon Reduction from Sludge Treatment Stage Only (2011 USD)**

Social Discount Rate	2.5%	3%	5%
SC-CO_2 (2.5%)	$9,151,520	$8,302,778	$6,924,571
SC-CO_2 (3%)	$28,746,013	$2,005,714	$21,754,688
SC-CO_2 (5%)	$43,225,311	$39,288,173	$32,875,486

Table D-4 | **Value of Carbon Reduction Including Fuel Substitution (in 2011 USD)**

Social Discount Rate	2.5%	3%	5%
SC-CO_2 (2.5%)	$45,653,312	$41,419,272	$34,543,942
SC-CO_2 (3%)	$143,402,476	$130,126,580	$108,525,524
SC-CO_2 (5%)	$215,633,961	$195,993,136	$164,002,779

Table D-5 | **Value of Carbon Reduction Including Fuel Substitution and Carbon Sink from Tree Cultivation (2011 USD)**

Social Discount Rate	2.5%	3%	5%
SC-CO_2 (2.5%)	$54,961,268	$49,863,978	$41,586,882
SC-CO_2 (3%)	$172,639,874	$156,657,242	$130,652,087
SC-CO_2 (5%)	$259,598,167	$235,952,901	$197,440,239

LIST OF ABBREVIATIONS

3E	Environment, Energy, and Economic Benefits
AD	Anaerobic digestion
ANNAMOX	Anaerobic Ammonia Oxidation Method
BOO	Build-operate-own
C	Carbon
CH_4	Methane gas
China Exim Bank	Export-Import Bank of China
CNG	Compressed natural gas
CNY	Chinese Yuan
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CPI	Consumer price index
Defra	The Department of Environment, Food and Rural Affairs of the United Kingdom
eGRID	The Emissions and Generation Resource Integrated Database
EPA	Environment Protection Agency of the United States
EU	European Union
GDP	Gross domestic product
GGE	Gasoline gallon equivalent
GHG	Greenhouse gas
GMI	Global Methane Initiative
GWP	Global warming potential
HC	Hydrocarbon
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
MFA	Material flow analysis
MoHURD	Ministry of Housing and Urban-Rural Development
MoT	Ministry of Transport
N	Nitrogen
NDRC	National Development and Reform Commission
NG	Natural gas
NH_4^+	Ammonium
NO_x	Nitrogen oxides
P	Phosphorus
POPs	Persistent organic pollutants
PPP	Public-private partnership
$SC\text{-}CO_2$	Social cost of carbon
SLCP	Short-lived climate pollutant
SSI	Sewage sludge incinerator
THP	Thermal hydrolysis process
TN	Total nitrogen
TP	Total phosphorus
USD	U.S. dollar
WBCSD	World Business Council for Sustainable Development
WRI	World Resources Institute
WWTP	Wastewater treatment plant

ENDNOTES

1. Estimated based on the data from "The 12th Five-Year Plan for Municipal Wastewater Treatment and Reclaimed Water Facilities." The plan set a target for a wastewater treatment capacity of 170 million m^3/day, a wastewater treatment ratio of 85%, and a loading rate of wastewater treatment plants above 75%.

2. Reports related to environmental issues resulting from sludge pollution in cities, such as Wuxi at http://special.caixin.com/2013-07-23/100559337.html; Beijing at http://news.xinhuanet.com/2010-10/23/c_12692064.htm, http://special.caixin.com/2013-07-23/100559337.html; and http://bj.people.com.cn/n2/2016/0517/c82840-28345214.html; Shanghai at http://www.people.com.cn/; Guangzhou at http://epaper.southcn.com/nfdaily/html/2011-09/15/content_7006581.htm; Nanjing at http://leaders.people.com.cn/n/2013/0419/c58278-21200271.html.

3. As per the Climate and Clean Air Coalition definition: SLCPs are agents that have a relatively short lifetime in the atmosphere—from a few days to a few decades—and a warming influence on climate. Besides CO_2, the most significant contributors to the human enhancement of the global greenhouse effect are the SLCPs (such as black carbon, CH_4, and tropospheric ozone).

4. According to the American Council for an Energy-Efficiency Economy, municipal water supply and wastewater treatment systems are among the most energy-intensive sectors. See: http://aceee.org/topics/water-and-wastewater.

5. MFA refers to the systematic analysis of material flows and storage in a certain domain. By analyzing the material input, storage, and output, the balance of material can be illustrated. MFA is a tool for decision making in the fields of resource, environmental, and waste management.

6. According to the China Statistical Bureau, the average exchange rate between CNY and USD in 2015 was 1 USD = 6.2284 CNY. See: http://finance.sina.com.cn/roll/2016-02-29/doc-ifxpvzah8377214.shtml.

7. Thermal hydrolysis breaks down extracellular polymeric substances, macromolecular organic matter, and microbial cell walls; these processes increase the biodegradability, mobility of material, and capacity utilization of anaerobic digesters. Thermal hydrolysis destroys pathogens in the sludge, making it exceed the stringent requirements for land application, and can increase the yield of biogas. Finally, thermal hydrolysis decreases the moisture content of slurry for better reclamation. The temperature ranges from 60–270°C; high-temperature thermal hydrolysis is above 130°C while low-temperature thermal hydrolysis is below 130°C. Studies have shown that the ideal temperature for thermal hydrolysis is 170°C, at which the total chemical oxygen demand (TCOD) increases from 38.11% to 56.78% and the biogas yield increases from 160 ml to 250 ml.

8. Anaerobic digestion is the use of facultative bacteria and anaerobic bacteria for anaerobic biochemical reactions; the bacteria stabilize sewage sludge by decomposing the organic matter. Anaerobic digestion can be classified as high-temperature (55 + 2°C, residence time of 10–15 days) or medium-temperature (35 + 2°C, residence time of more than 20 days).

9. The global warming potential of a gas refers to the cumulative radiative forcing—both direct and indirect effects—integrated over a period of time from the emission of a unit mass of gas relative to the reference gas (CO_2).

10. When calculating the greenhouse gas emissions of CH_4, this paper uses a GWP of 25 for CH_4.

11. According to research by the California Air Resources Board (CARB), a CNG-fueled vehicle emits 20–29% less GHG than a comparable gasoline- or diesel-fueled vehicle, on a well-to-wheel basis. https://www.ngvamerica.org/natural-gas/environmental-benefits/.

12. In the container seedling method, trees are planted in containers that have had biochar added to the soil. In containers, the trees can be moved easily, hence the name "mobile forest." Traditionally, transplantation of saplings can partially break the trees' roots and, during transportation, they may face soil and water shortages. These issues result in a survival of only about 50% of saplings, a significant economic loss. "Mobile forests," by contrast, are cultivated in pots that can be easily transported without damage to roots or soil or water shortages; this increases the survival rate to at least 98% of saplings.

13. According to the Beijing Energy Conservation Center, it is estimated that one tree can absorb 18.3 kg CO_2 in a year. See: http://www.beec.gov.cn/kpzs/408.jhtml.

14. In 2010, the TN and TP concentration of livestock manure was 8.5 mg/L and 1.8 mg/L in China.

15. Provided by the operator of Chengdu no.1 sludge incineration project.

16. Calculated based on the central parity rate released by the People's Bank of China, the average exchange rate was 1 USD = 6.8958 CNY in January 2017. This exchange rate is used to calculate the economic benefit of the project unless otherwise specified.

17. In 2014, the NDRC published "Notice on Cancelling Price Adjustment Fund for Coal, Oil and Natural Gas" to cancel the collection of price adjustment of these three types of energy since December 2014.

18. The profit from trees is directly related to the type of trees that are planted. Taking camphor as an example, the cost to plant one tree is approximately 100 CNY (15 USD), including the costs of the container, tree sapling, irrigation, labor, and cost of sales. In the Xiangyang project, trees are planted at landfills to restore the environment of the landfill; the cost for land can be ignored. In the actual market, each camphor tree (two years after planting) can be sold at the price of 300 CNY (50 USD). The profit received for each camphor planted is 200 CNY (29 USD). If tree saplings are planted on farmland, the rent for the land will be 1,000 CNY/year (145 USD/year).

19. Calculated based on the central parity rate released by the People's Bank of China, the average exchange rate was 1 USD = 6.4588 CNY in 2011.

20. The subsidy (254 CNY/ton, 37 USD/metric ton) is made up of three parts: a sludge treatment subsidy of 219 CNY/metric ton (32 USD/metric ton); an upfront investment in equipment (14 million CNY) divided by the total tons the equipment will eventually treat of 15CNY/ton (2.2 USD/metric ton); and a pre-treatment fee for accumulated sludge of 20 CNY/ton (3 USD/metric ton).

21. The SC-CO_2 is a measure, in dollars, of the long-term damage done by a ton of CO_2 emissions in a given year. See: https://www.epa.gov/climatechange/social-cost-carbon.

22. See Appendix D for detailed calculations of the social cost of carbon.

APPENDIX ENDNOTES

i. There are abundant nutrients in sludge. For example, one ton of dry sludge yields 100 kg ammonium sulfate, 100 kg calcium superphosphate, and 16 kg potassium sulfate. These products can be used in agriculture, forestry, greenhouses, and soil remediation.

ii. Factsheet of Kapusciska plant in Bydgoszcz, Poland. See: http://www.cambi.com/MediaSection/Files/Fact-Sheets/KAPUSCISKA-Bydgoszcz-Poland.

iii. Factsheet of Ringsend plant in Dublin, Ireland. See: http://www.cambi.com/MediaSection/Files/Fact-Sheets/RINGSEND-Dublin-Ireland.

iv. According to the ISO 14044, the system boundary for estimating GHG emissions of sludge-to-energy approach should be expanded to include the additional functions related to the co-products to avoid allocation of the system under the case of the multi-products system.

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