Capital Cost Comparison of Waste-to-Energy (WTE), Facilities in China and the U.S.

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EXECUTIVE SUMMARY

Waste-to-Energy (WtE) is a technology that has seen a major rise in the last decade as China has been looking for methods for handling its population boom and related rapid increase in waste generation rates. Chinese companies have been able to construct WtE facilities at about one third of the capital cost as facilities in the U.S. and Europe. This thesis seeks to compare regulatory, technological, and financial factors that affect capital costs of WtE development around the world, focusing on China and the U.S.

The findings of this research show that the capital cost difference between Chinese and U.S. WtE facilities are largely due to China's unique level of governmental support, faster municipal approval than in other countries, cost savings on labor, and rapid development of in-country component manufacturing and construction capabilities. China has been able to construct WtE facilities at the average rate of $250 per annual ton capacity while U.S. facilities are constructed at a much higher cost rate at an average of $840 per annual ton capacity.

In addition, within each country, increased restrictions on emissions have led to noticeable increases in the capital cost of WtE facilities. In the U.S., this essentially stopped the pursuit of new WtE construction after 1995 with the exception of one new facility in 2015, while in China, companies have adapted to new regulations and shown reduced costs over time after a regulation-induced cost increase.

Chinese companies have shown interest in pursuing WtE projects outside of China, with two projects in Vietnam and Ethiopia including involvement from Chinese companies. These facilities are being built at roughly a 40% greater cost (i.e. $350 per annual ton capacity) than that of a Chinese company building a WtE facility within China. A greater escalation factor can be expected if Chinese companies pursue WtE projects in the U.S. or Europe due to increased labor costs, greater regulatory hurdles, and increased distance from component manufacturing locations. However, it is expected that there should be a cost benefit from the Chinese model of standardized designs (i.e. reproducing previous facility designs) and economies of scale.

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1 INTRODUCTION

Waste-to-energy (WtE), otherwise known as energy-from-waste (EfW), is a term used to describe the process of combusting waste materials to generate electricity and/or heat. Modern WtE facilities are a much more advanced form of energy recovery technology than incineration plants, as they generally use advanced emissions controls systems to prevent the escape of post-combustion fly ash and harmful gases. In general, WtE facilities are designed as part of larger city-wide or state/county/district-level waste management systems as an alternative to landfilling. Under waste management best practices, they are built to manage waste that cannot be otherwise reused or recycled in their communities. In general, WtE facilities are a costly investment for private investors and municipalities, easily costing in the ten to hundreds of millions of U.S. dollars equivalent. This thesis seeks to explore differences in cost to build facilities based on geographic region, as well as whether WtE technology benefits from learning curve behavior.

2 METHODOLOGY

The technology of combusting waste to generate energy for use in the form of electricity and heat has been used globally for many decades. There are a large number of technologies employed in the building of these facilities, as well as complex and changing regulatory conditions affecting WtE facilities in various regions and countries around the world. To gain a generally understanding of the global conditions for WtE, a literature review was conducted for current knowledge of WtE developments around the world to identify trends in facility planning, construction, and financing. To understand whether trends such as regulatory conditions, government support, and technological learning have a real impact on the cost to build WtE facilities, cost data was gathered from WtE facilities. This data was gathered through papers, reports, news websites, open-access government records, municipalities, and anonymized interviews with key industry professionals such as WtE facility managers, waste management planners for municipalities, and business development staff. In addition, these interviews also aimed on obtaining waste management professional and expert opinions on major influences to WtE facilities and markets.

3 THE CURRENT STATUS OF WASTE MANAGEMENT

3.1 WASTE MANAGEMENT AROUND THE WORLD

Waste management is a complex topic that is handled in different ways around the world based on available local resources, technologies, and intensity of community initiatives. Waste is constantly evolving based on the resources and products used by a community. For example, as a country becomes wealthier, there is often an increase in manufactured goods used by the population, thereby both increasing the total waste generation rate and contributing to more complex waste compositions. When waste is responsibly managed, communities tend to be much healthier due to reduced exposure from toxins, disease, and dangerous materials. As communities generate more waste, proper waste management strategies become ever more important. This is especially true in the current century, when ever-increasing populations and urbanization require efficient use of land area and mismanagement of large volumes of waste lead to environmental degradation. Communities must decide the best methods of handling these issues. More often, responsible waste management solutions are in the form of innovative reuse, recycling, and energy recovery schemes, rather than utilizing large tracks of land for landfill.

3.1.1 Waste Generation Rates

The World Bank conducted a study in 2012 that estimated global municipal solid waste (MSW) generation rates to be about 1.3 billion tons per year in urban areas. By 2025, this MSW generation rate will be about 2.2 billion tons per year. Greater levels of waste generation are generally correlated with larger income levels and greater levels of urbanization (The World Bank, 2012).

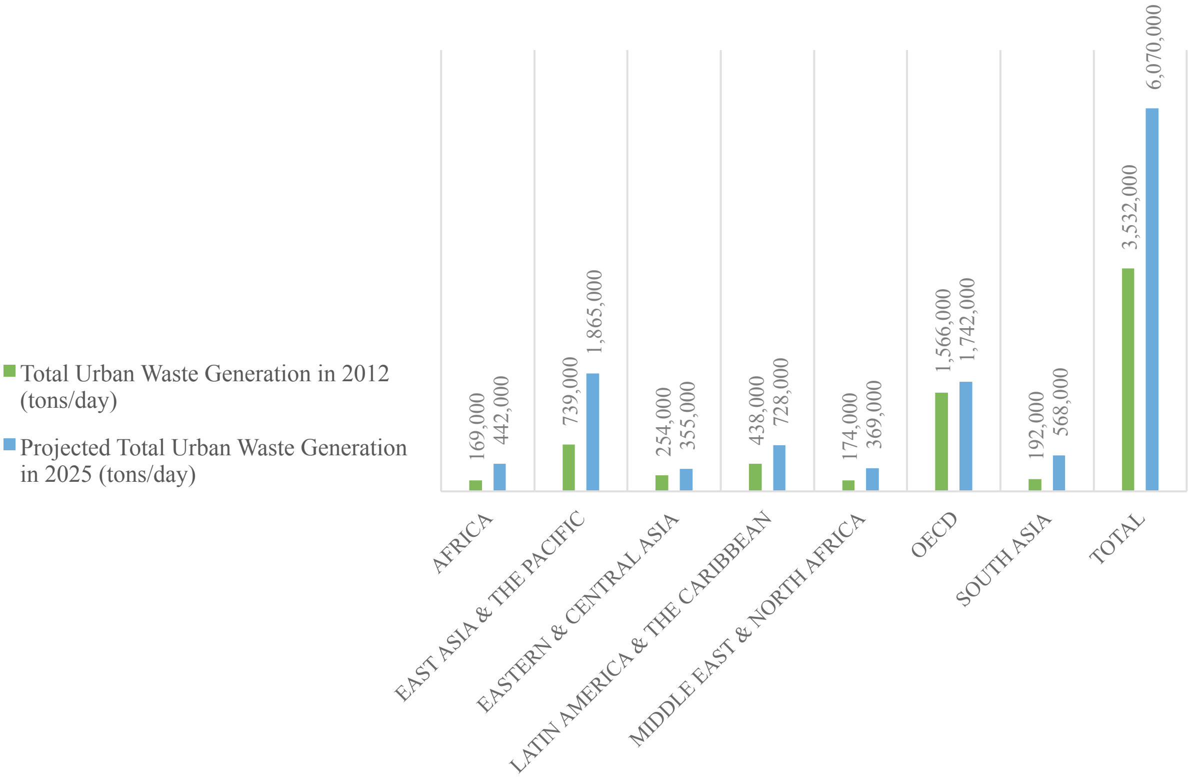

Figure 1: Total Global Urban Waste Generation Rates (The World Bank, 2012)

3.1.2 Waste Composition

Half of the composition of global MSW is estimated to be food waste. This is because generally low- and middle-income countries produce food waste ranging from 40-85% of their total waste streams. As income levels increase, so do the paper, plastic, glass, and metal fractions in the waste stream due to the increase in manufactured goods used by the population.

Table 1: Total MSW Generation (by material), Global, 2012 (The World Bank, 2012)

Paper (%)	Glass (%)	Metal (%)	Plastic (%)	Organic (%)	Other (%)
17	5	4	10	46	18

3.1.3 Disposal Methods

Waste can be handled in many ways by a given community. In general, waste management experts and professionals adhere to a waste management hierarchy that presents best practices in the field of waste management. This hierarchy, shown in Figure 2, prioritizes the reduction and reuse of waste where possible. Where waste is unavoidable, it should be recycled or composted to give the material new value. When recycling and composting are not viable solutions, responsible energy recovery methods, such as WtE, should be used. Lastly, the leftovers that have no better treatment solution are discarded into landfills.

Figure 2: Waste Management Hierarchy (United States Environmental Protection Agency, 2017)

Around the world, landfilling is currently the most popular waste management option, even though it is not the most sustainable based on the waste management hierarchy. This is because landfilling is a waste management strategy that is straightforward and cheap. However, more often, communities are seeing the benefit of reducing waste, recycling, composting, and WtE.

Not only are these strategies more environmentally responsible, but they often tap into valuable commodity markets.

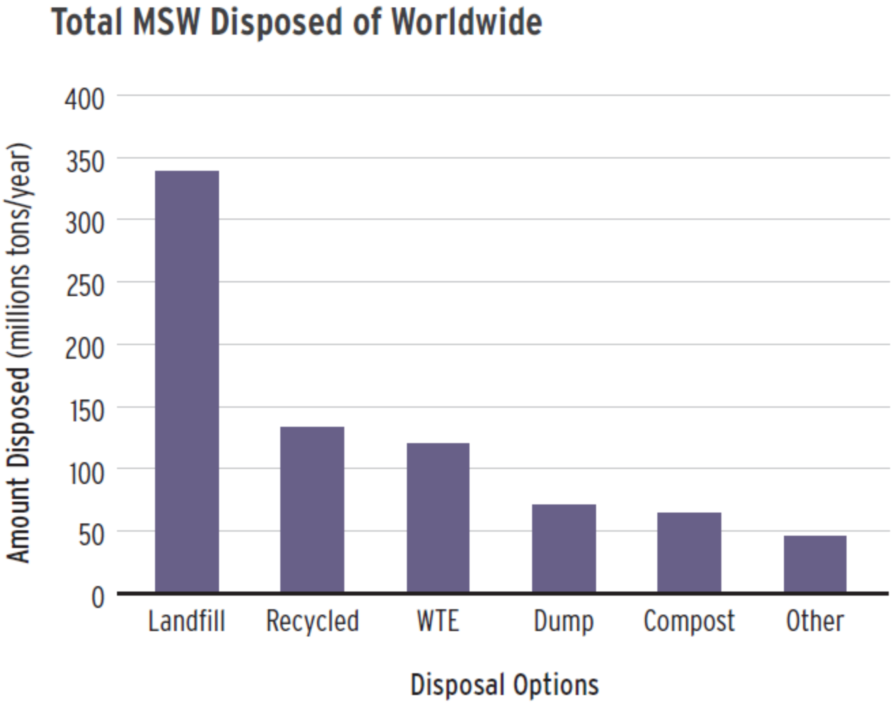

Figure 3: Total Urban MSW Disposed of Worldwide (The World Bank, 2012)

Based on Figure 3, there is room for improvement in transitioning away from landfills and dumps and towards recycling, composting, and WtE. Roughly half of the world's waste is sent to landfill or a dump. Even though almost half of the world's waste is composed of organics, less than one tenth of the world's waste is composted. In general, the high amount of recyclable and organic material in the world's waste streams as shown in the global waste composition values indicate that there are plenty of opportunities for the implementation of more sustainable waste management strategies instead of throwing valuable materials into a hole in the ground.

3.1.4 Waste-to-Energy Adoption

Globally, WtE has been developed mostly throughout Europe, the U.S., and East Asia. Some facilities also exist in countries such as Australia, Canada, India, Singapore, Thailand, and others to a lesser extent (D-Waste, 2017). In Europe, Japan, and South Korea, improved reuse, recycling, and energy recovery have been pursued primarily due to land constraints that have made landfilling operations expensive and difficult to site. Landfilling is also discouraged in these countries because of the negative environmental impact of waste disposal. In China, WtE has seen an upswing in the last decade as the national government has identified WtE as one solution to the country's increasing waste production rates and decreasing landfill space (Gosens, Kåberger, & Wang, 2017). The U.S. saw a rise in WtE facility construction following the Public Utilities Regulatory Policies Act (PURPA) enacted in 1978 (The National Museum of American History, 2017). This uptake in facility construction lasted until 1995, when the second-to-last facility was built in the U.S. (Energy Recovery Council, 2016).

In some countries, such as in the U.S., proposals for new WtE facility construction are put under high levels of community and regulatory scrutiny due to associations with historical incineration facilities. Incineration facilities also combust materials for energy or to reduce material volume, but do not use emissions controls systems and thus pollute the communities near which they are sited. Due to negative associations such as this, many industry experts believe that WtE will have limited capacity for growth in areas in which there is not already strong political leadership in favor of WtE. However, it should be acknowledged that based on current available technologies for reuse and recycling, WtE is necessary to avoid the landfilling of post-recycling residue. Indeed, the world's leading countries in terms of sustainable waste management have accepted WtE as a must-have to avoid or minimize the use of landfills (Earth Engineering Center and Inter-American Development Bank, 2013).

3.2 WASTE MANAGEMENT IN CHINA

3.2.1 Governmental Entities and Regulatory Conditions

On a national scale, environmental issues in China including waste management and renewable energy are managed by the Ministry of Environmental Protection (MEP). The MEP publishes a plan every five years which sets the country's environmental goals and expectations. In the National 13th Five-Year Plan for the Protection of Ecological Environment (2016-2020), it states that China's "waste incineration rate is expected to reach 40% by 2020" (Ministry of Environmental Protection of the People's Republic of China, 2016). This indicates a strong commitment to continue China's growth in the WtE sector, even prior to focusing on improving China's formal recycling infrastructure.

The Chinese government backs up their political support of WtE with subsidies, feed-in tariffs, and quicker permit processing times. A prior review of Chinese WtE showed that the capital investment cost of building a WtE plant in China is about $45,000-95,000 (300,000-600,000 RMB) per daily ton of processing capacity (Ji, et al., 2016). This study estimated that initial building costs mainly included "equipment (50%), installation (15%), civil construction (25%), and design (10%)." Facilities get a 70-250 RMB per ton subsidy from the government. The government-enforced feed-in tariff ensures that WtE facilities can sell their excess electricity back to the grid at a higher price (0.65 RMB per kWh) than for coal-fired plants (0.4-0.5 RMB per kWh) (Ji, et al., 2016). Subsidies and feed-in tariffs, as well as income from scrap metal collected from post-combustion residue, have made WtE investments favorable in many cities in China and has fueled a rise in WtE facility construction.

Even with such an aggressive growth schedule for WtE facilities in China, the MEP is aware of the need to keep emissions low. Regulation GB 18485-2014 sets emissions standards for Chinese WtE plants. For dioxins and mercury, some of WtE's most damaging emissions for human health, emissions standards are set equivalent to EU2000/EU2010 regulatory levels. Emissions standards for other substances lag behind EU standards, but have seen improvements since GB 18485-2001 (Ji, et al., 2016). See section 5.2 Waste-to-Energy Technology Requirements and Regulatory Impact: Air Pollution Control for more details on regulatory emissions standards.

3.2.2 Waste Generation Rates

China generated 172 million tons of MSW in 2013, but that number has been steadily climbing thanks to China's fast-growing economy. Estimates show the country's waste generation rate to increase by 8-10% per year, thereby exceeding 323 million tons of MSW generated per year by 2020 and 480 million tons per year by 2030 (Yang, Zhang, Chen, Shao, & He, 2012). China's population growth and increasing economic output have been strong drivers for their rapidly increasing waste generation rates.

3.2.3 Waste Composition

Waste composition varies between cities, but in most studied cities, food waste makes up the largest proportion of MSW. Food waste has a high moisture content and low calorific value, making it difficult to use the MSW in many cities as a fuel source for WtE without pre-treatment or using fossil fuels to boost the calorific value of the mixture.

Table 2: Composition Ranges of MSW in Different Cities in China, 2007-2014 (Ji, et al., 2016)

	Paper (%)	Plastic (%)	Textiles (%)	Wood (%)	Food (%)	Non-Combustable (%)
Low	2.4	5.4	1.2	0	37.8	1.4
High	24.3	28.2	20.4	5.9	77.2	20.5

3.2.4 Disposal Methods

China has seen a large growth in the amount of MSW that it generates over time. This has put significant strain on the country's landfills, leading to government initiatives to invest in WtE technologies to preserve landfill capacity and potentially to eventually eliminate some landfills. The country has a strong informal recycling sector, making it difficult to determine the exact percentage of recycling that occurs. However, Chinese officials have shown interest in improving its formal recycling sector over time, which could offer additional opportunity to capture waste before it is sent to landfill.

Table 3: Post-Recycling MSW Treatment in China, 2003-2015 (Zhang, Huang, Xu, & Gong, 2015) (National Bureau of Statistics of China, 2018)

	Landfill			Waste-to-Energy			Other		
Year	Number of Facilities	Amount Disposed (million tons/year)	Ratio[1] (%)	Number of Facilities	Amount Treated (million tons/year)	Ratio[1] (%)	Number of Facilities	Amount Treated (million tons/year)	Ratio[1] (%)
2003	457	64.0	85	47	3.7	5	70	7.2	10
2004	444	68.9	85	54	4.5	9	61	7.3	6
2005	356	68.6	86	67	7.9	10	46	3.5	4
2006	324	64.1	82	69	11.4	15	20	2.9	4
2007	366	76.3	82	66	14.4	15	17	2.5	3
2008	407	84.2	83	74	15.7	15	14	1.7	2
2009	447	89.0	80	93	20.2	18	16	1.8	2
2010	498	96.0	79	104	23.2	19	11	1.8	2
2011	547	100.6	77	109	26.0	20	21	4.3	3
2012	540	105.1	73	138	35.8	25	23	3.9	3
2013	580	104.9	68	166	46.3	30	19	2.7	2
2014	604	107.4	66	188	53.3	33	26	3.2	2
2015	640	114.8	64	220	61.8	34	30	3.5	2

1 – Ratios may not add to 100% due to rounding.

As seen in Table 3, in the 12 years between 2003 and 2015, China has built 173 new WtE facilities. In the years of 2011-2015, over 20 facilities were completed each year. In addition, reports have shown that over 100 more facilities are already under construction or being planned in the country (Standaert, 2017). Due to the increase in WtE facilities, even though the total tons of waste sent to landfill is still increasing, the overall ratio in decreasing. This is a major win for the WtE industry in China. However, it is important to continue to keep in mind the best practices waste management hierarchy as China looks forward in planning sustainable waste management strategies.

3.3 WASTE MANAGEMENT IN THE U.S.

3.3.1 Government Entities and Regulatory Conditions

The federal regulation of waste management in the U.S. falls primarily under the U.S. Environmental Protection Agency (EPA). The EPA is also in charge of overseeing regulations for the emission of substances to water and air. In addition, WtE facilities are subject to a number of state and local regulations. In general, experts have noted that one of the greatest barriers to WtE facility construction in the U.S. is the length of time, difficulty, and cost of obtaining numerous permits from municipalities, leading to planning times to up to a decade before facility construction can begin.

Due to the nature of WtE as both a tactic for waste management and a means of electricity and heat generation, it is also subject to regulations enforced by the Federal Energy Regulatory Commission (FERC). When the 95th U.S. Congress enacted PURPA in 1978, WtE companies were able to sign contracts with municipalities that allowed electricity generated by WtE facilities to be sold to the grid at a favorable set price. This protected WtE facilities from energy price market fluctuations for the generally 20-25 year lengths of their PURPA contracts. This encouraged many companies to build WtE facilities in the 1980s and early 1990s. However, only one WtE facility has been built in the U.S. since 1995, and the PURPA contracts for most of the facilities of the 1980s have expired. Contract expirations have also coincided with a strong dip in electricity sale prices due to the rise of cheap natural gas, making it difficult for many of these older facilities to stay in business.

Another major regulatory shift for the WtE industry was the passing of the Clean Air Act in 1990, which set Maximum Achievable Control Technology (MACT) standards for Large Municipal Waste Combustors (MWC) (i.e. WtE facilities). These standards are updated as better technologies are developed and were revised in both 1995 and 2006 (United States Environmental Protection Agency, 2016). After the 1991 MACT standards began being enforced, older facilities had to pay for retrofits such as replacing electrostatic precipitators with baghouses and updating their acid gas control systems. Difficulties in complying with these regulations as well as falling electricity sale prices has caused the closure of many facilities over time.

Lastly, unlike many European countries, the U.S. does not to the same extent use government regulation to artificially increase the price of landfilling waste. The average nationwide tipping fee at landfills is $51.82 per ton for 2017 with the highest tipping fees in the Northeast where land for landfilling is scarcer (Environmental Research & Education Foundation, 2017). In comparison, WtE facility tipping fees are generally higher in the $60-110 range. Thus, price competition from landfills prevent many municipalities from seeing WtE as a better option.

3.3.2 Waste Generation Rates

The total waste generation rate for the U.S. is estimated by different sources at 258 million tons of municipal solid waste in 2014 (United States Environmental Protection Agency, 2017), at 347 million tons in 2013 (Environmental Research & Education Foundation, 2016), and at 389 million tons in 2011 by the Columbia University Earth Engineering Center (EEC) (Shin, 2014). The substantial differences in these waste generation estimates are due to the methodologies used by each group. For example, the Environmental Research & Education Foundation (EREF) report identified more treatment facilities than previously estimated (Szczepanski, 2016). Some methodology differences between the EPA and EEC studies are discussed in detail in the EEC report.

3.3.3 Waste Composition

For the percentage composition of MSW in the U.S., the U.S. EPA values are provided in Table 4. These values were used as the EPA study provided the most accessible and comprehensive waste composition data of the three studies. The waste profile of the U.S. is reflective of its higher per capita income levels than much of the rest of the world. It has a lower amount of organics waste (34.4% including wood, yard trimmings, and food waste) than the global average. However, the U.S. produces a higher than average amount of potentially recyclable waste such as paper, metal, and plastic.

Table 4: Total MSW Generation (by material), U.S., 2014 (United States Environmental Protection Agency, 2017)

Paper & Paperboard (%)	Glass (%)	Metal (%)	Plastic (%)	Rubber, Leather, & Textiles (%)	Wood (%)	Yard Trimmings (%)	Food (%)	Other (%)
26.6	4.4	9.0	12.9	9.5	6.2	13.3	14.9	3.2

3.3.4 Disposal Methods

The disposal data from the EEC study is provided in Table 5. In the U.S., landfilling is by far the most popular option for waste disposal due to the amount of available land. Landfilling also often comes at a cheaper price than other waste disposal options, including WtE. However, this means that the U.S. has plenty of potential to treat waste using alternatives to landfill. The ratio of potentially recyclable and compostable material is far greater than the ratio currently being recycled or composted. In addition, with 64% of the waste stream material in the U.S. sent to landfill, there should be locations were WtE can be a more beneficial alternative and more effective use of land.

Table 5: Management of MSW, U.S., 2011 (Shin, 2014)

	Landfill		Waste-to-Energy			Recycled		Composted	
Year	Amount Disposed (million tons/year)	Ratio[1] (%)	Number of Facilities	Amount Treated (million tons/year)	Ratio[1] (%)	Amount Treated (million tons/year)	Ratio[1] (%)	Amount Treated (million tons/year)	Ratio[1] (%)
2011[2]	247.0	64	85	29.5	8	87.8	23	24.6	6

1 – Ratios may not add to 100% due to rounding.

4 WASTE-TO-ENERGY FINANCING STRUCTURES

Waste-to-Energy projects are financed through various blends of debt and equity and public versus private investment. In the U.S., most facilities are built with financial backing from municipal bonds, which is a form of debt security that has a low risk of defaulting. A few facilities with private partners also opt to partially finance facilities with private equity, but this is a less common practice. In addition, some facilities are able to acquire a small portion of grant funding by governmental or multilateral organizations. From media-based observations of one Chinese WtE company, the opposite ratio of debt versus equity is used in Chinese WtE investments. This Chinese company finances its WtE projects with a 50-90% equity fraction with the remainder provided by the partnering municipality.

Due to the large capital expenditures needed to fund WtE projects and the specific expertise needed to design, construct, and operate these facilities, the majority of WtE projects are pursued as public-private partnerships (PPPs). Under a PPP, a private company specializing in WtE is often requested by a municipality to design and build a given facility to the municipalities needs and specifications.

Waste-to-Energy facilities pursued under a PPP generally have a Build-Operate-Transfer (BOT) ownership/operational structure. The contracted private company designs, builds, and operates the facility for a contracted period of time (ex. 20-25 years), usually taking responsibility for maintenance and operational costs for the facility (World Bank Group, 2016). Revenue is collected through sales of electricity to the utility or government entity, tip fees charged to waste haulers (both public and private) who drop waste off at the facility, and sales of scrap metals and sometimes ash material. After the contracted period is over, ownership and operational responsibilities of the facility are transferred to the contracting government entity. Occasionally, Build-Own-Operate (BOO) structures are pursued where the private company owns the project and does not transfer the facility at the end of the contract term (Thomson Reuters, 2010).

When facilities were being built in the 1980s and early 1990s in the U.S., companies made Power Purchase Agreements with government utilities that set electricity prices for these WtE facilities for the next 20-25 years. This lowered the risk for WtE investments during this period as this meant that revenues from electricity would not be subject to market fluctuations for most years of the facility's operations. The Chinese government offers a similar incentive for current WtE projects where the government utility purchases electricity from WtE facilities at a set price. This price is higher than that paid to other facilities such as coal power plants.

5 WASTE-TO-ENERGY TECHNOLOGY REQUIREMENTS AND REGULATORY IMPACT

Modern WtE facilities use many advanced technologies for the purpose of facility operations, storing and processing waste, combusting waste, recovering energy, capturing metals, and controlling emissions. Facilities undergo regular maintenance to ensure that they maintain optimal operating conditions, and occasionally, updates such as improved monitoring systems or better machinery components are added as technology improves over the decades that a facility is in operation. In addition, when improved emissions regulations are enacted in a given country, region, state, or municipality, existing facilities may have to update their emissions controls systems and new facilities have to integrate new technologies into their designs. The inclusion of new technologies is often costly and also dependent on the facility's original design's ability to adapt to needed updates. When a facility cannot adapt to new regulatory or market conditions, it is under risk of shutting down.

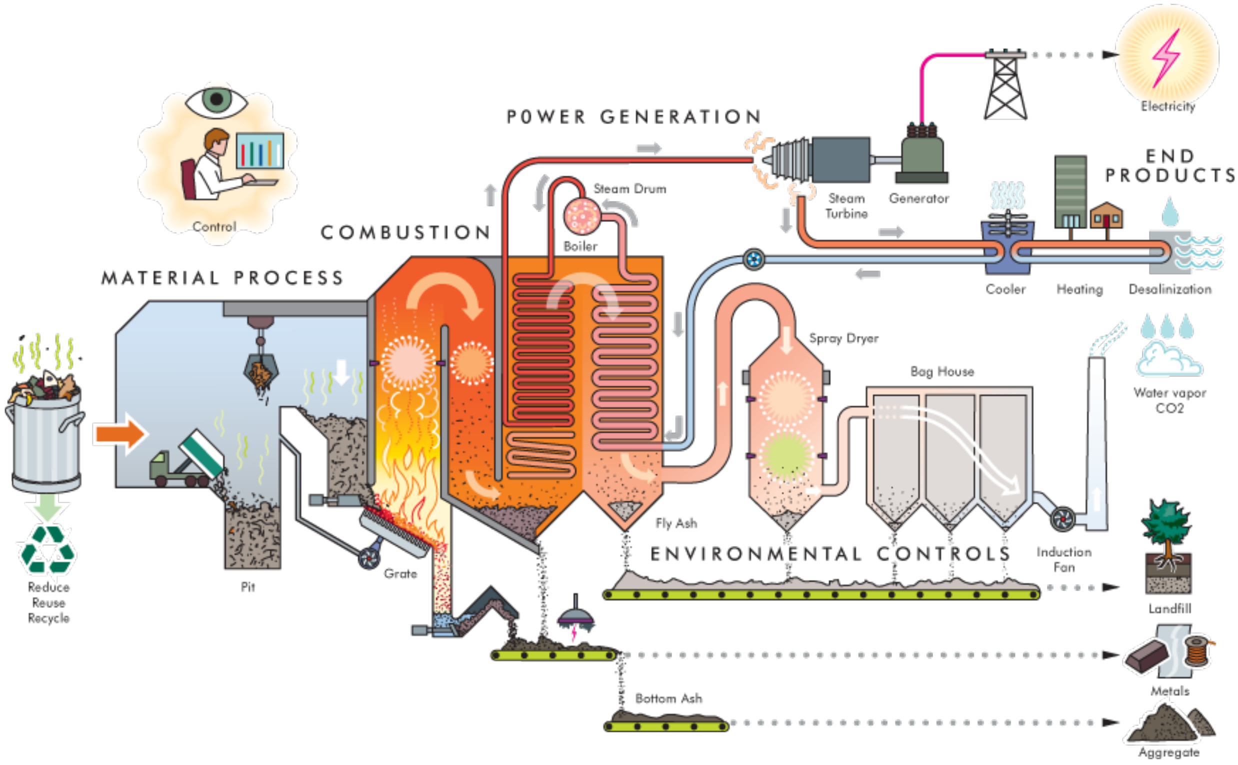

Figure 4: Artistic Rendition of a Waste-to-Energy Combustion Plant (National Energy Education Development Program, 2017)

The schematic in Figure 4 shows the general components of a WtE facility. There is a tipping hall with a bunker/pit where trucks drop off their waste. This waste is mixed and deposited into a feed hopper via a large crane claw. The waste enters the combustion unit, which is often either a moving grate (MG) furnace or a circulating fluidized bed (CFB) furnace. The heat produced from the furnace interacts with a boiler to produce steam. This steam turns a steam turbine to produce electricity which is then sold to the grid. In some cases, the low-pressure steam left over after electricity generation is used for heating for other industrial facilities or for residential district heating. After the waste has been combusted, the bottom ash residue exits at the base of the furnace and the fly ash and flue gases rise upward where they will be treated via the facility's emissions controls systems. Magnets and eddy currents are often used to recover the value of the scrap metals in the bottom ash. The residual bottom ash can be used as aggregate for concrete, asphalt, and other construction material (a common practice in Europe) or as landfill cover (a common practice in the U.S.). The emissions controls systems for fly ash and flue gas treatment include a series of steps that reduce temperature, particulate matter, dioxins, NO_x, SO_x, HCl, CO, heavy metals, and other pollutants to the maximum extent possible before the air exits as cleaned water vapor from the facility smokestack. All WtE facilities have a controls system and dedicated staff that monitor facility conditions to ensure proper operations during year-round operations and during facility maintenance periods.

5.1 COMBUSTION TECHNOLOGY

One of the primary differences between different forms of WtE facilities is the technology used to convert waste into energy. The most popular technology used worldwide is the moving grate furnace, followed by the circulating fluidized bed furnace (Morin, 2014). The popularity of the MG furnace can be attributed to its ease of operation, level of technological understanding, high plant availability, comparatively low personnel requirements, and relative ease of training new personnel (Bourtsalas, 2016). A number of other technologies are used, as seen in Table 6. In general, less developed technologies, such as gasification and pyrolysis (not shown in Table 6), can only currently be built at a much higher price per ton of processing capacity than many municipalities can afford due to increased complexity and lower levels of development of the technology. The feedstock for all listed facilities range from different levels of unprocessed MSW to processed MSW. Some facilities accept refuse-derived fuel (RDF), which is a form of processed MSW that has an improved calorific value for better combustion over unprocessed as received MSW. In addition, some facilities opt to install shredders and leachate bunkers to increase the surface area and reduce moisture content of the incoming waste to increase the MSW's calorific value. These two pre-processing practices are pursued in China where high percentages of food waste content result in low caloric values for as received MSW.

Table 6: Feedstock, Energy Product, and Total Capacity of Existing WtE Technologies (Earth Engineering Center and Inter-American Development Bank, 2013)

WtE Process	Feedstock	Energy Product	Estimated Annual Capacity (million tons)	Regions Where Applied
Moving Grate Combustion	As Received MSW	High Pressure Steam	<168	Europe, Asia, North America
Circulating Fluidized Bed	Shredded MSW or RDF	High Pressure Steam	>11	Europe, China
RDF to Grate Combustion	Shredded and Sorted MSW	High Pressure Steam	>5	Europe, U.S.A.
Mechanical Biological Treatment	Shredded and Bioreacted MSW	RDF	>5	Europe
Rotary Kiln Combustion	As Received MSW	High Pressure Steam	>2	Europe, Japan, U.S.A.
Energy Answers Process (SEMASS)	Shredded MSW	High Pressure Steam	>1	U.S.A.
Directing Smelting	RDF	High Pressure Steam	>0.9	Japan
Ebara Fluidized Bed	Shredded MSW or RDF	High Pressure Steam	>0.8	Portugal, Japan
Themoselect Gasification	As Received MSW	Syngas	>0.8	Japan
Bubbling Fluidized Bed	Shredded MSW or RDF	High Pressure Steam	>0.2	U.S.A.
Plasma-Assisted Gasification	Shredded MSW	Syngas	>0.2	France, Japan, Canada
	Global WtE Capacity		<195	

5.2 AIR POLLUTION CONTROL

As discussed in 3.1.4 Waste Management Around the World Waste-to-Energy Adoption, countries in Europe, the U.S., China, Japan, and other countries have air emissions regulations that restrict the emissions allowed to be emitted by WtE facilities. In the U.S., these restrictions are even stricter than those enforced for coal-fired power plants, metal smelters, and cement plants (Earth Engineering Center and Inter-American Development Bank, 2013). Table 7 gives an overview of some emissions standards for WtE facilities around the world. Generally, the European Union has the strictest standards. The latest revision to the Chinese emissions standards for WtE facilities has adopted the European Union's limits for dioxin and mercury emissions. However, the remaining limits are not as stringent. Even so, some Chinese companies have chosen to build their facilities to follow to European Union emissions standards as an adherence to best practices, potentially in anticipation of future tightening of emissions regulations, and in good faith to the communities in which they operate (China Everbright International Ltd., 2017).

Table 7: Emissions Standards for Waste-to-Energy in China, the U.S., and the European Union

Pollutants	Units	China (GB 18485-2014)[1]	United States (71 FR 27324)[2]	European Union (EU 2010/75/EU)[3]
Last Update	-	2014	2006	2010
Particulate Matter	mg/m^3	30	20	10
HCl	mg/m^3	60	~37 [4]	10
HF	mg/m^3	-	-	1
SO_x	mg/m^3	100	~79 [4]	50
NO_x	mg/m^3	300	~282-470 [4,5]	200
CO	mg/m^3	100	~57-286 [4,5]	50
TOC	mg/m^3	-	-	10
Hg	mg/m^3	0.05	0.05	0.05

Pollutants	Units	China (GB 18485-2014)[1]	United States (71 FR 27324)[2]	European Union (EU 2010/75/EU)[3]
Cd	mg/m^3	0.1	0.01	0.05
Pb	mg/m^3	1	0.14	≤0.5
Other heavy metals	mg/m^3	-	-	≤0.5
Dioxins	$ng\text{-}TEQ/m^3$	0.1	0.1	0.1
Blackness	Ringelman	1	-	-

1 – (Ji, et al., 2016)
2 – (United States Environmental Protection Agency, 2006)
3 – (The European Parliament and the Council of the European Union, 2010)
4 – Values for U.S. HCl, SO_x, NO_x, and CO emissions standards are given in EPA regulatory rules in units of ppm. The values in Table 7 are converted to mg/m^3. The molecular weights of SO_2 and NO_2 are used for SO_x and NO_x conversion.
5 – Actual limit is dependent on technologies used by the facility. Values fall within the ranges given.

Based on a survey of known capital costs of WtE facilities, there appears to be a slight effect of emissions regulation implementation on capital costs. This is due to the fact that the implementation of new emissions regulations generally means stricter environmental standards requiring updated emissions control equipment.

The last updates to the Chinese emissions standards were in 2001 and 2014 (Ji, et al., 2016). Leading up until the 2014 emissions regulation, it is likely that Chinese companies anticipated the required changes to comply with the new emissions laws. Therefore, new best practices were tested and implemented in newly constructed facilities, raising the cost of building facilities leading up to 2014. After 2014, facility costs start to drop, potentially as companies are learning cost reduction strategies and are able to utilize labor and resources more efficiently.

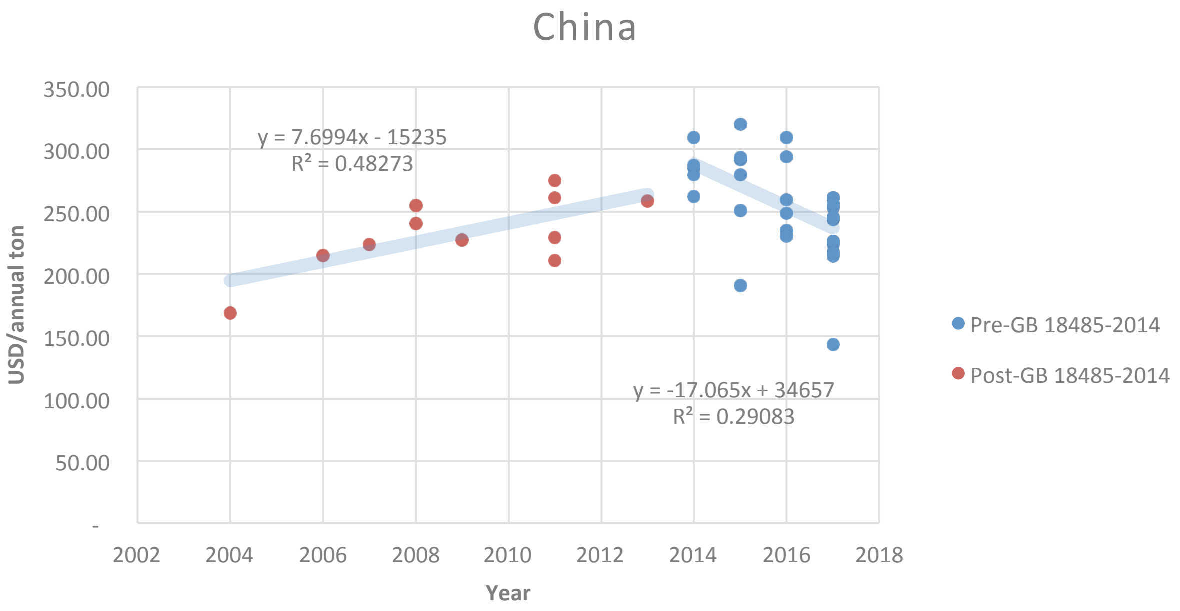

Figure 5: Cost to Build Chinese WtE Facilities Over Time, Converted to USD, Adjusted for Inflation (Survey of Waste-to-Energy Facilities, 2017)

In the U.S., emissions standards were updated in 1991, 1995, and 2006 (United States Environmental Protection Agency, 2016). The effect of implementing the MACT standards in 1991 was an overall increase in the cost of constructing a facility as more advanced and more expensive equipment was needed. The average inflation-adjusted price for building a facility before MACT standards was about $750 per annual ton of facility capacity. The price after MACT standards was about $1,050 per annual ton of facility capacity.

Facilities built before 1991 were required to be updated to comply with new standards. Not enough data was captured in surveys of U.S. WtE facilities to give a definitive cost for the necessary upgrades, especially as facility needs varied based on the performance and existing design of each unique facility. Reported ranges in the survey were $25-370 per annual ton of facility capacity to adopt new emissions controls technologies (Survey of Waste-to-Energy Facilities, 2017). However, values reported in the surveys and interviews could also have included costs for other expensive facility upgrades such as boiler replacement. In addition, the survey data is skewed for costs of facilities that currently still exist and may not include enough already-closed facilities that may have been priced out of the market.

By the 1995 emissions controls update, few companies were able to build new facilities as investments in WtE became less financially attractive. It was not until 2015 that a new WtE facility has been built in the U.S. with the latest technologies in emissions controls. Due to the abrupt halt of WtE development in the U.S. in the 1990s from stringent regulation and unfavorable market conditions, no learning curve behavior can be observed for U.S. facilities. In terms of a cost perspective, the facility built in 2015 is roughly around what is expected for a U.S. facility, but it is important to note that this facility uses much more advanced technologies for facility monitoring and emissions controls than its predecessors. It even includes both selective non-catalytic reduction (SNCR) and selective catalytic reduction (SCR) technologies for NO_x control to ensure emissions are far below regulatory limits. Most U.S. facilities only opt to use SNCR as it is a less costly option.

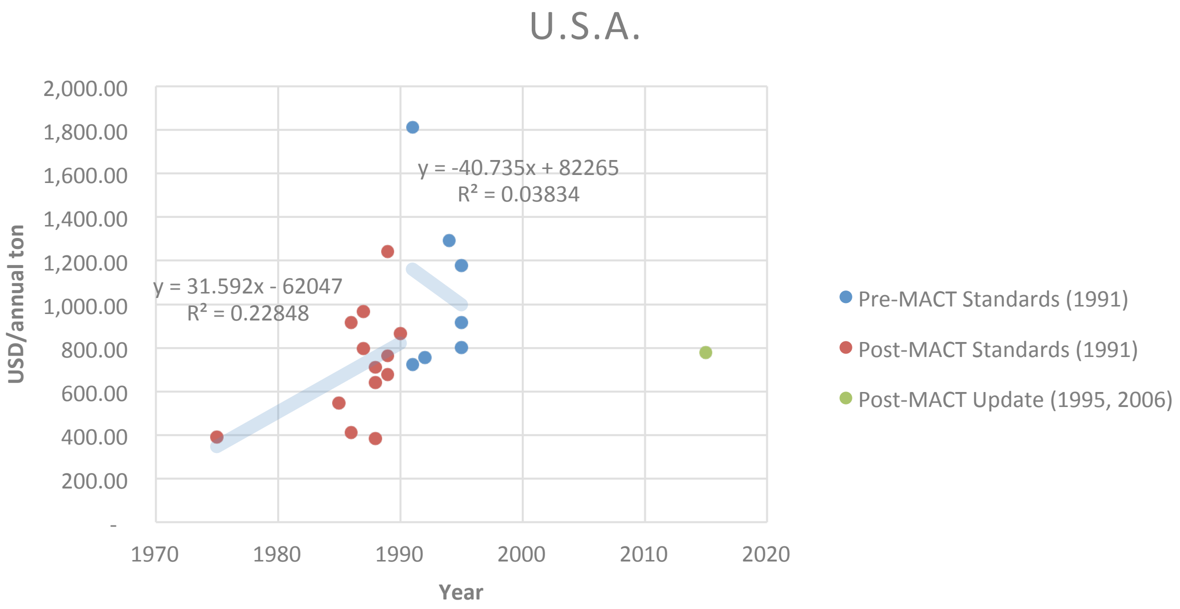

Figure 6: Cost to Build U.S. WtE Facilities Over Time, Adjusted for Inflation (Survey of Waste-to-Energy Facilities, 2017)

6 COST COMPARISONS ACROSS COUNTRIES

When looking at capital cost data found for WtE facilities around the world, it is also interesting to note that WtE facilities in China are much cheaper to build than in most other countries. After adjusting for exchange rates and inflation, the average capital cost for 60 Chinese WtE projects was $250 per annual ton capacity (range of $143-320 per annual ton). For comparison, after adjusting for inflation, the average initial capital cost of 21 U.S. facilities was $840 per annual ton capacity (range of $386-1,811) (Survey of Waste-to-Energy Facilities, 2017).

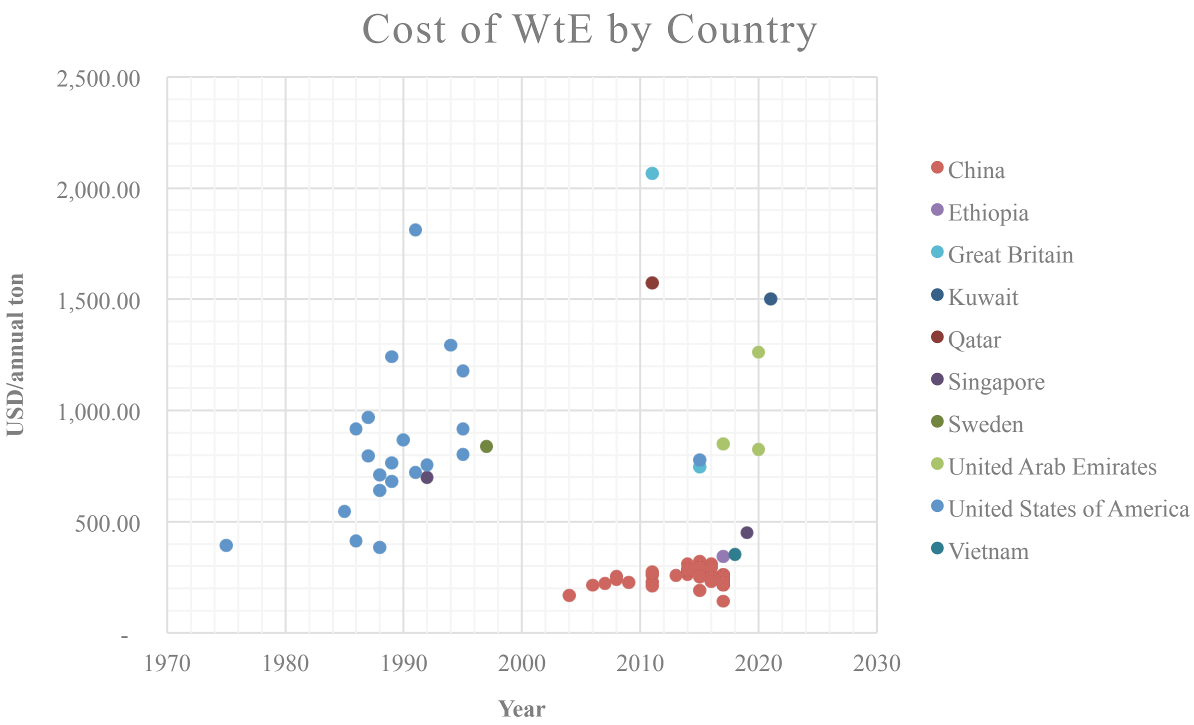

Figure 7: Cost to Build WtE Facilities Around the World Over Time, Adjusted for Exchange Rates and Inflation (Survey of Waste-to-Energy Facilities, 2017)

The capital cost for Chinese facilities compared to most of the rest of the world is almost a three-fold difference. The exception to this previous statement are two facilities located in Vietnam (at $353 per annual ton capacity) and Ethiopia (at $343 per annual ton capacity), both of which are projects led by or with participation from Chinese companies. Initially, this seems like an impossibly low capital cost value that is unheard of in the rest of the world. However, when comparing these price trends with trends in the transportation industry, specifically in automobile manufacturing and rail infrastructure, it can be observed that Chinese methods and resources provide a price advantage across sectors. The automotive and rail industries were used for comparison as both are technologically complicated and are resource intensive to construct, utilizing large amounts of skilled labor, metal (for cars and rail infrastructure), and concrete (for rail infrastructure).

In the car manufacturing industry, the average price of a car sold in China is \$20,805, whereas the average price of a car in the U.S. is \$34,537. When looking at only domestically produced cars, the average car price in China is \$15,706 (Automotive News, 2015). Taxes on cars in China and the U.S. are similar, with taxes in China at 7.5% in 2017 rising to 10% in 2018 (Spring & Cheng, 2017) and taxes in the U.S. at an average of 5.75% (Hall-Geisler, 2017). This means that due to a blend of cheaper resources, labor costs, process efficiency, regulatory differences, and market conditions, China is able to produce cars that sell for half the price as cars in the U.S.

In the rail industry, Chinese infrastructure projects are also pursued at roughly a third of the cost as similarly technologically complex rail projects in the U.S. and Europe. This has been attributed to lower labor and unit costs (for supplies), economies of scale, and the ability to reuse and amortize high-cost construction equipment across several projects. Due to national vigor in pursuing large scale rail projects, companies have been encouraged to quickly invest in competitive local resources, mechanization in construction and manufacturing processes, and design standardization. One example of the application of these methods is that Chinese companies were able to acquire a slab track manufacturing process from Germany, but decided to make the product locally benefitting from economies of scale for roughly two thirds of the cost (Ollivier, Sondhri, & Zhou, 2014). A similar method was used in the WtE industry in China where moving grate technology was acquired from Germany and was then adapted and produced in China at much lower price. The same version of the moving grate is being manufactured multiple times and is being used in several facilities, rather than designing and manufacturing a new moving grate unique to each individual facility. This process is being pursued for all major aspects of WtE facility components, including the air distribution, emissions controls, and automation systems (Waste Management World, 2015).

7 CONCLUSIONS

The research conducted in this thesis showed that the cost of WtE facilities is most dependent on regulatory conditions, government incentives, and the amount of customized design and manufacturing needed to construct a facility. Many experts have been impressed by the price and efficiency at which Chinese companies have pursued WtE over the course of the last decade with the average cost of facilities in China being $250 per annual ton capacity (range of $143-320). The average capital cost of U.S. facilities is about $840 per annual ton capacity (range of $386-1,811 over the last 30 years). Much of the cost difference can be attributed to very favorable regulatory conditions that support WtE investments and continued operation of WtE facilities as well as the benefit of Chinese ingenuity and the country's unique mass manufacturing capabilities. This knowledge is not likely to reduce permitting time needed in countries like the U.S. where municipalities are generally hesitant to pursue WtE and the regulatory process is not streamlined. However, Chinese companies have already shown that they are able to export their technology and facility designs to other nearby countries with a slight increase in the overall capital cost compared to facilities within China. Chinese companies are involved in the construction of two facilities in Vietnam and Ethiopia, both costing about $350 per ton annual capacity. This amounts to about a 40% increase in cost over constructing a Chinese plant in China, which is likely to account for transportation of materials, potential differences in labor costs, and contingencies for building and operating in a novel market. If municipalities were willing to partner with Chinese companies to take advantage of the manufacturing infrastructure and standardized design processes in place, substantial cost benefits could be achieved. The cost to build a new facility would be more than in Vietnam or Ethiopia due to the extended distance from the manufacturing source and labor costs, but perhaps a facility could be built around the lower end of the range in capital costs to build a U.S. facility. The other option would be to invest in a similar business model in which companies are able to almost completely reuse designs and equipment providers from previous facilities for application in a different municipality with similar waste needs. This would be more difficult to achieve in countries like the U.S. where only a little interest exists in WtE projects, but may be applied in parts of the world where there is higher interest.

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