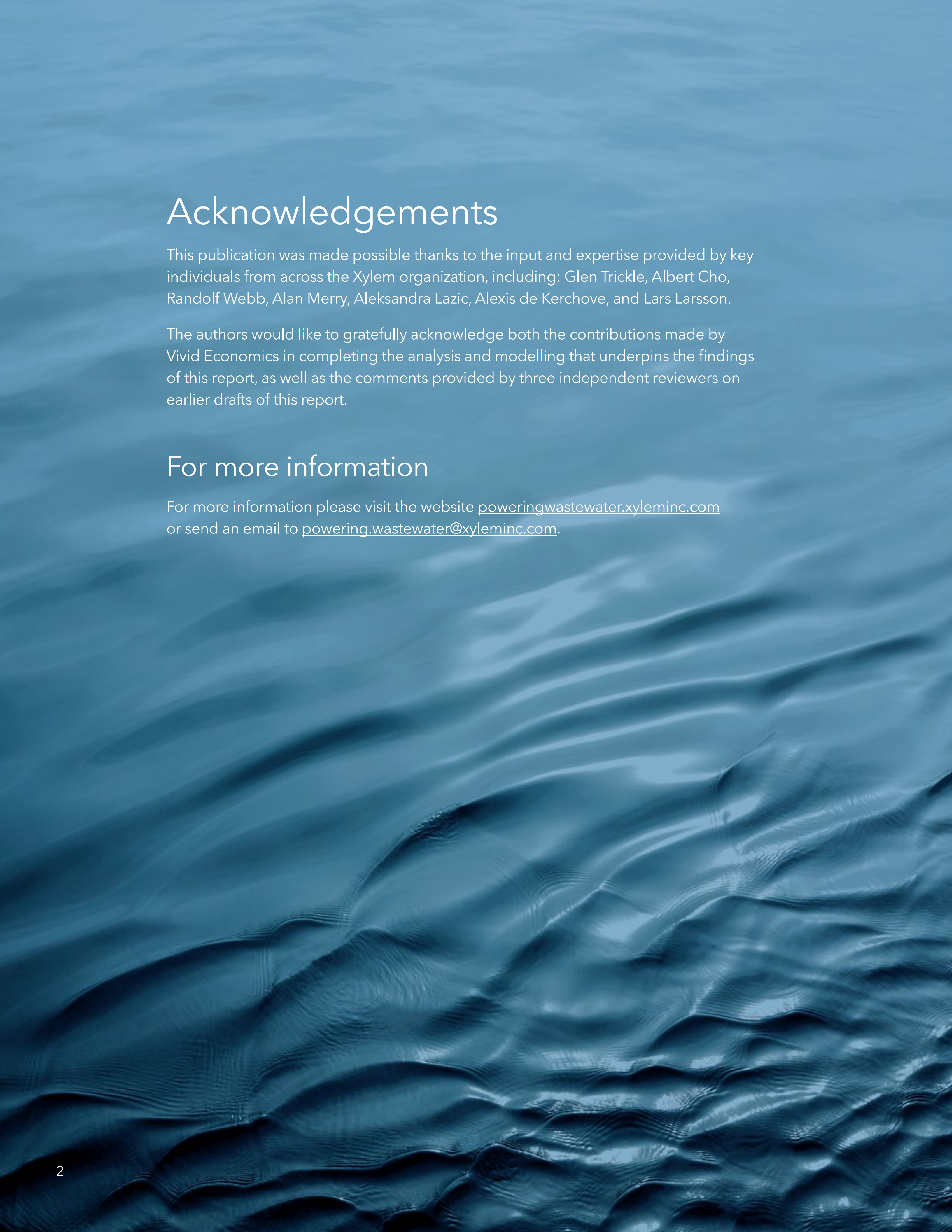
Powering the Wastewater Renaissance

ENERGY EFFICIENCY AND EMISSIONS REDUCTION IN WASTEWATER MANAGEMENT

xylem
Let's Solve Water



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For more information

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Abbreviations

CO_2, CO_2e	Carbon dioxide, an amount of another greenhouse gas with the same global warming potential as one unit of carbon dioxide
CH_4	Methane
FAO	Food and Agriculture Organization
IEA	International Energy Agency
IRR	Internal rate of return
MACC	Marginal abatement cost curve
Mt	Million metric tons
NO_3	Nitrate
N_2O	Nitrous oxide
NPV	Net present value
OECD	Organization for Economic Co-operation and Development
t	One metric ton
TWh	Terawatt-hour (or 10^{12} watt-hours)
USD	United States Dollars
US EPA	United States Environmental Protection Agency

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Letter from Xylem's President and CEO

As the world grapples with the challenges of climate change, resource scarcity and economic development for a growing population, new solutions are needed to meet today's urgent needs while building a sustainable future. It is incumbent on all of us – individuals, private businesses, non-government organizations (NGO), academia and governments – to work together to scope and solve these challenges on a sector-by-sector basis.

This report is Xylem's initial contribution to the debate. As a global water technology provider, we confront the linkages between water, climate and sustainable development every day. Climate change is expected to increase the variability of water supplies, increasing exposure to extreme weather events such as droughts and floods. Meanwhile, extending water and sanitation services to the billions who lack them today – and maintaining the systems that exist in the developed world – will require major investments and ongoing maintenance. And as governments seek to achieve significant reductions in emissions of greenhouse gases, they will need to drive substantial increases in energy efficiency in nearly every sector. Water infrastructure sits at the confluence of these agendas and presents a compelling opportunity to advance both the global mitigation and adaptation agendas.

Increasing energy efficiency across the water sector is an important place to start. This report set out to assess abatement potential from energy efficiency in the wastewater sector, focusing on levers that involve existing, proven technologies. The conclusion: nearly half of the electricity-related emissions in wastewater management can be abated at a negative or neutral cost. This translates to a potential global volume of 44 million metric tons of CO_2e that could be abated annually at zero or negative cost. The results are global in nature and apply both to upgrades of existing infrastructure in the United States and Europe and to development of new infrastructure in rapidly industrializing countries such as China.

This study demonstrates that pragmatic solutions exist today to mitigate a substantial portion of the harmful emissions generated by inefficient wastewater operations. Importantly, this reduction can be accomplished while simultaneously lowering the total cost of operations. What's missing is the enabling framework to incentivize investment and accelerate widespread adoption of these advanced, sustainable solutions.

The report also suggests that the time to act is now, since infrastructure decisions made today can have consequences for decades. Policy makers have a fundamental role in setting clear targets for emissions abatement and this report provides a strong, fact based foundation for the wastewater sector. But policy and regulation are only one piece of the puzzle. Engagement by the private sector – from financial services companies to wastewater technology providers – will also be vital to unleashing the full potential of low-carbon investment and innovation.

At Xylem, we look forward to working with colleagues in the water sector and across industries, with academics and innovators, NGOs and the financial community to develop new ideas and creative partnerships to advance adoption of these and other sustainable solutions. We hope you'll join us.

Patrick Decker
President and CEO
Xylem Inc.

Executive Summary

Nearly 50% of electricity-related emissions from the global wastewater sector could be abated at negative cost by investing in readily available technologies

This report investigates greenhouse gas abatement opportunities from energy efficiency in the wastewater sector. The results of the analysis are compelling:

- Almost **50% of electricity-related emissions from the wastewater sector** in the three regions studied (the U.S., Europe and China) can be abated with existing technologies. Nearly 95% of this abatement can be achieved at zero or negative cost, where savings from energy efficiency would exceed spending on the abatement measure.
- China has the most to gain in terms of both investment returns and emissions abatement, as nearly **100% of the abatement opportunities examined would be at zero or negative cost,** and the total **abatement potential is nearly 13 Mt CO_2e annually.**
- Extrapolating the volume of abatement in the three core regions studied to produce a global abatement volume for wastewater electricity use suggests that the potential **global volume of negative cost abatement is nearly 44 Mt CO_2e annually.**
- These financial and abatement results are relatively insensitive to the future carbon price scenarios and to the investment discount rate, suggesting that unlocking significant emissions abatement in the wastewater sector is **not dependent on technology development, but is solely a matter of accelerating adoption of existing high efficiency technologies.**

This study assesses 18 distinct electricity-related emissions abatement opportunities across three core regions: the United States, Europe, and China. A summary of the results by region can be found in Table 1. For each of the abatement opportunities, the concepts of marginal abatement cost curve (MACC) and internal rate of return (IRR) provide insight into the financial attractiveness of the opportunities, the overall emissions abatement potential, and the sensitivity of these investments to the key levers of carbon pricing and investor discount rates. This approach identifies low-cost ways to reduce greenhouse gas emissions, while acknowledging the political and financial barriers to adoption; a perspective which we believe is of interest to the wastewater industry and all stakeholders in the climate change debate, including non-governmental organizations, financial institutions, academics, and policy makers.

Table 1.

Over 50% of current wastewater electricity emissions, totalling nearly 44 Mt CO_2e, can be readily abated, and around 95% of this can be achieved at zero or negative cost

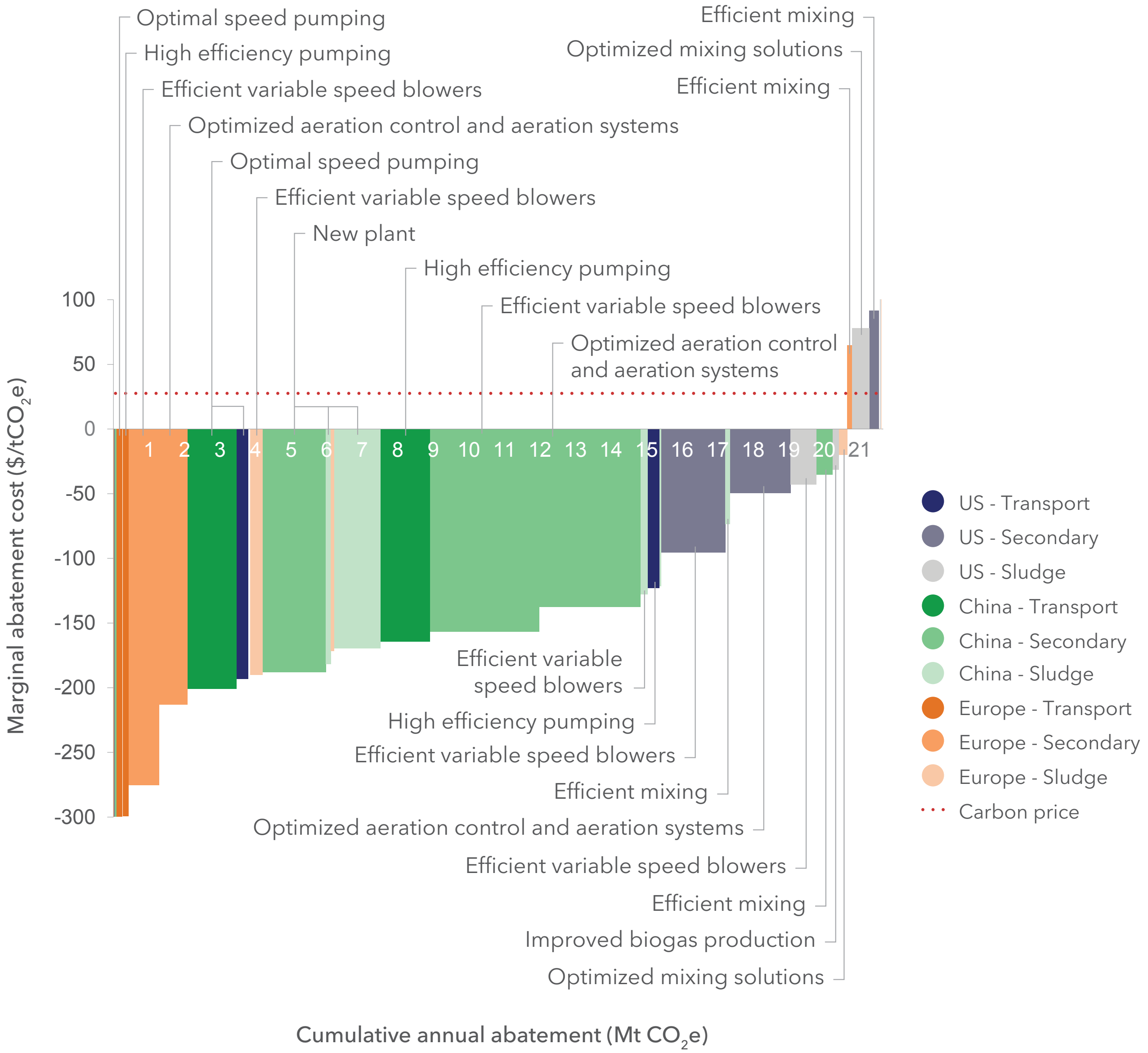
Variable	2015 wastewater electricity emissions (Mt CO_2e)	Modelled abatement (Mt CO_2e)	Abatement as a share of 2015 emissions (%)	Negative cost abatement (Mt CO_2e)	Negative cost abatement share (%)
United States	15.5	6.0	38%	5.1	86%
Europe	8.5	2.8	33%	2.6	94%
China	21.8	12.9	59%	12.9	100%
Three regions studied combined	45.9	21.7	47%	20.6	95%
Rest of the world	40.5	24.5	60%	23.3	95%
Global total	86.3	46.1	53%	43.9	95%

Note: *Abatement costs estimated using a 5.5% real discount rate. Rest of the world estimates based on a global extrapolation, as outlined in the Appendix.*

A combined MACC for the three core regions illustrates that the largest and lowest cost abatement options are in wastewater transport and secondary treatment. Geographically, the volume of abatement is greatest in China, reflecting its high and growing volume of wastewater treatment and its emissions-intensive electricity supply. Abatement is typically negative cost in all regions, but is lower cost in Europe and China than in the United States. This is due to the relatively low price of electricity in the United States which decreases the financial benefit of reducing electricity use in the region.

Figure 1.

The three regions combined offer over 20 Mt CO_2e of potential zero or negative cost abatement, with China in particular offering a high volume of low cost abatement

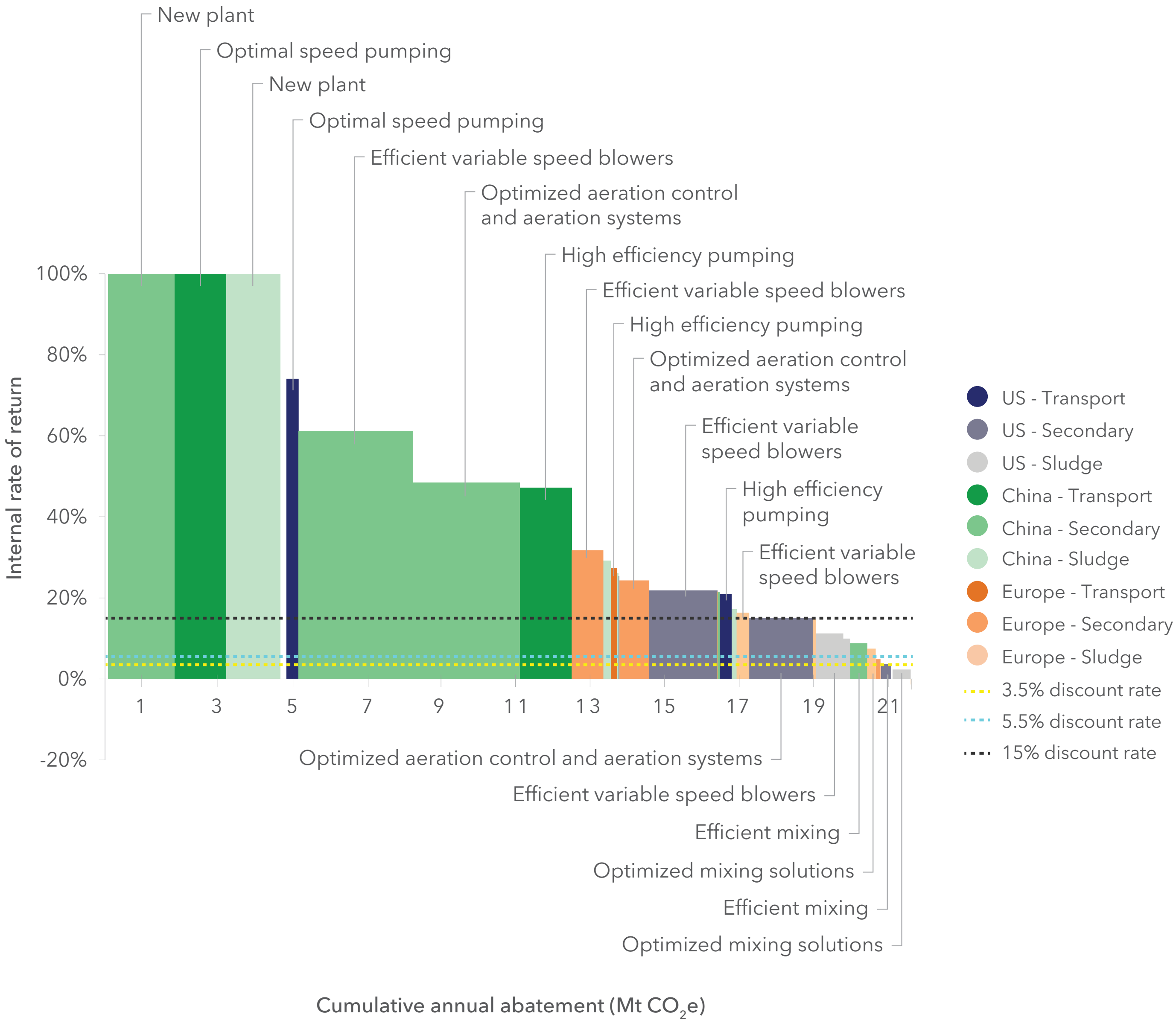


Note: *Abatement costs are presented within a range between \$200/ton CO_2e and -\$200/ton CO_2e to avoid distorting the presentation of the chart. Tertiary abatement categories omitted due to small size being invisible at the scale presented. The carbon price presented is the mid-range assumption of \$30/ton CO_2e. Numbers presented based on the mid-range discount rate assumption of 5.5%.*

Furthermore, analysis of the internal rates of return associated with each abatement opportunity indicates that there are strong returns to energy efficiency investments in all three regions, with wastewater transport and secondary treatment improvements proving to be the most attractive. Even if a high real discount rate of 15% is applied and a carbon price of \$30/ton CO_2e is assumed, nearly 19 Mt CO_2e of abatement could be achieved through profitable investments.

Figure 2.

Rates of return are strongest in China, and nearly 19 Mt CO$_2$e of abatement could be unlocked across all three regions with an investment hurdle rate of 15% in real terms



Note: *Project IRRs are presented in a range below 100% to avoid distorting the presentation of the chart. Horizontal lines represent each discount rate assumption applied in the MACC sensitivity analysis, 3.5%, 5.5% and 15%. Numbers presented based on the mid-range carbon price assumption of \$30/ton CO$_2$e.*

The key finding of this study is that unlocking significant emissions abatement in the wastewater sector does not require new technologies or an aggressive carbon pricing policy; it requires accelerated adoption and reinvestment in existing high efficiency technologies. The sensitivity analysis detailed in the body of the report indicates that the vast majority of the available abatement is not dependent on policy settings that impose a cost of carbon on electricity supply, nor highly sensitive to the discount rate chosen. Thus the primary barriers to adoption are awareness of the opportunity and willingness to adopt existing solutions that have a higher initial capital cost, and a lower ongoing operating cost.

Two policy and finance levers can accelerate adoption of efficient wastewater technologies: assistance with financing, and new energy efficiency standards. First, given that energy-efficient solutions generally come with a higher initial capital cost, innovative financing through public or private structures could provide the tools needed to facilitate increased adoption. Second, increasing the energy efficiency standards of wastewater equipment through regulatory mandates will ensure more broad-based adoption. Standards requiring adoption of high efficiency pumping equipment are already due to commence in Europe and the United States, and similar regulations could be extended to related equipment as well as other geographies.

The opportunity is globally significant. In the United States and Europe, financing implementation of these technologies to unlock energy efficiency improvements would decrease operating costs and could even unlock new sources of capital to support the badly needed renewal of wastewater infrastructure. In China – and by extension, many other rapidly industrializing countries facing installation of large volumes of new wastewater treatment plants over the coming years – adoption of high efficiency technologies represents an economically attractive opportunity to avoid lock-in of costly and wasteful infrastructure. This finding applies even more strongly to improving the design efficiency of planned infrastructure projects that have not yet been constructed. Cumulatively, for the investments examined in this study, the net present value of Chinese investments with a positive economic return examined in this study exceeds $25 billion. Including Europe and the United States this total reaches $40 billion. Note that this return is the positive economic return from the investment in excess of any costs incurred. Now is the time for the industry and all stakeholders in the climate change agenda to work together to overcome these barriers to adopting high efficiency wastewater treatment technologies, which will result in greater productivity of wastewater operations, and a meaningful step forward in tackling climate change.

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1 Introduction

1.1 Objectives

The wastewater sector generates greenhouse gas emissions in two main ways: through fugitive emissions from the breakdown of organic materials in wastewater, and through electricity-related emissions associated with energy consumed in the treatment and transport of the wastewater. Identifying low-cost ways to reduce these emissions is of interest to both the wastewater industry and to stakeholders in global climate policy. This study uses the concepts of the marginal abatement cost curve (MACC) and the internal rate of return (IRR) to examine the attractiveness of investments and the sensitivity of these investments to carbon prices and investor discount rates.

1.2 Scope

This study focuses primarily on energy efficiency-related wastewater abatement options. It does so because abatement of fugitive emissions is typically more costly, capital-intensive, and driven by water quality requirements as opposed to abatement considerations. The hypothesis underlying this study is that energy efficiency investments can offer low-cost abatement potential in the wastewater sector – as is commonly seen in sectors such as buildings and appliances – resulting in “no regrets” opportunities for emissions reduction while enhancing the productivity of the global wastewater sector.

Three major wastewater markets are included in this analysis: the mature markets of the United States and Europe, and the rapidly growing market in China. In the United States and Europe, the study focuses on abatement from replacement of existing equipment, reflecting the broad coverage of existing infrastructure and the slow rate of construction of new treatment facilities. In China, abatement from both the replacement of existing equipment and the construction of new treatment facilities is estimated based on the hypothesis that abatement from adopting more efficient practices in new facilities could be substantial given rapid growth of wastewater infrastructure.

In total, this study examines 18 distinct electricity-related emissions abatement opportunities across the wastewater treatment process. Each of these opportunities provides a means of achieving abatement from reducing or altering electricity use.

1.3 Methodology

The modelling in this study brings together a series of inputs to assess the comparative attractiveness of emissions abatement opportunities in two closely related ways.

- **The abatement cost approach.** The cost of achieving emissions abatement (on the basis of dollars per ton of CO_2-equivalents) is estimated by calculating the net present value of the investment over its life and dividing it by the discounted volume of emissions abatement achieved over its life. When the abatement cost of each opportunity is sorted in increasing order and presented on a chart this is known as a 'marginal abatement cost curve', or MACC.

$$\text{Marginal Abatement Cost (\$/t } CO_2e) = \frac{\text{Net Present Value of Savings}}{\text{Net Present Value of GHG Abatement}}$$

Where,

$$\text{Net present Value of Savings (\$)} = \frac{\sum \text{(Equipment Cost – Operating Cost Savings – Energy Cost Savings)}}{\text{(1- Discount Rate)}^{\text{Equipment Life}}}$$

$$\text{Net present Value of GHG Abatement (t } CO_2e) = \frac{\sum \text{(GHG Emissions Abated by New Equipment)}}{\text{(1- Discount Rate)}^{\text{Equipment Life}}}$$

- **The internal rate of return approach.** The IRR is the discount rate that would give an investment a net present value of zero and is calculated using data on costs and savings over the lifetime of the investment. As in the construction of a MACC, the IRRs of each abatement option can be sorted in decreasing order and presented as an IRR curve.

Other than discount rates and carbon prices, all other assumptions used in both approaches are identical. The assumptions used and the modelling approach are described in further detail in Section 2, Section 3, and the Appendix.

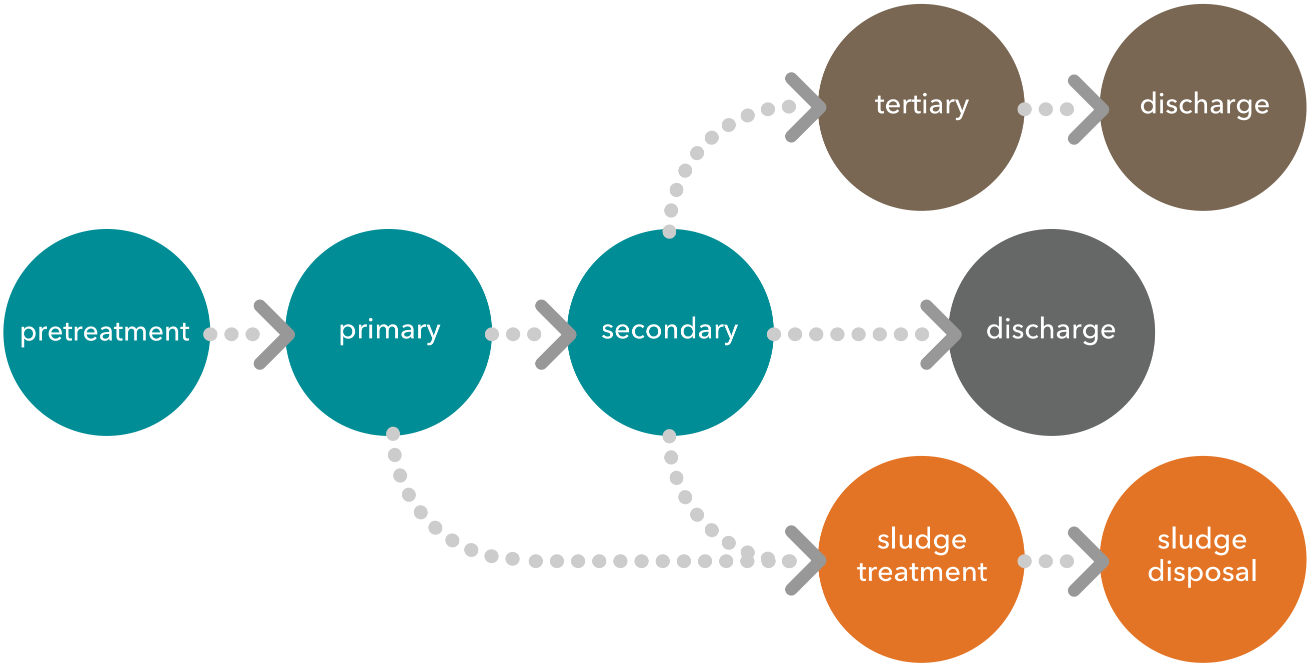
2 Emissions and abatement in the wastewater sector

2.1 Introduction to the wastewater sector

The wastewater sector includes the collection, treatment and discharge of wastewater from both household and industrial sources. In most cases, this wastewater is collected and transported to centralized treatment facilities where wastewater undergoes a range of processes during which contaminants are broken down and removed from the wastewater stream and the treated effluent can be returned to a water body or directly reused. Some wastewater is not collected and centrally treated, but instead is treated on-site in septic tanks or latrines, or is discharged directly to a water body without treatment.

Figure 3.

Stages of wastewater treatment



These treatment stages are normally sequential rather than substitutes for each other. For example, wastewater that undergoes primary treatment can then undergo secondary and further treatment stages. Likewise, wastewater that undergoes secondary treatment typically must have undergone primary treatment. It should be noted, however, that the framework described above is illustrative; there exists a broad variety of treatment processes that can be assembled to treat wastewater.

Wastewater treatment involves one or more of the following steps as outlined in Figure 3.

- **Pumping,** to assist in the transport of wastewater from its initial collection point to a treatment point.
- **Pretreatment,** involving basic processes such as screening wastewater for large solid constituents.
- **Primary treatment,** which involves settling of the wastewater (also known as sedimentation) to physically separate suspended solids from wastewater, further removing organic matter.
- **Secondary treatment,** which involves further treatment (e.g. aeration and introduction of activated sludge) to reduce biodegradable organic materials that would create a demand for oxygen in receiving streams or water bodies, plus nutrients such as nitrogen and phosphorus in the wastewater.
- **Tertiary treatment,** which can involve a range of treatments including filtration to remove residual particulate matter (solids) and nutrients, which may be followed by disinfection and/or advanced processes to inactivate pathogens or complex organics such as pharmaceuticals.
- **Discharge,** where the treated wastewater effluent is discharged back into a water body or aquifer.

- **Sludge treatment,** also known as excess sludge treatment, which involves breaking down organic matter contained in sludge by-products and/or the dewatering of sludge to reduce its weight for transport and disposal.
- **Sludge disposal,** where the residual sludge is used as a fertilizer, incinerated or disposed of in a landfill.

2.2 Wastewater sector emissions

The wastewater sector creates greenhouse gas emissions in two ways: directly through fugitive emissions from chemical changes to the wastewater stream (e.g. decomposition), and indirectly through emissions from energy inputs to transport and treat the wastewater.

Fugitive emissions principally consist of methane (CH_4), nitrous oxide (N_2O) and some carbon dioxide (CO_2). Methane results from the anaerobic decomposition (i.e. in the absence of oxygen) of organic matter in wastewater and sludge by-products. Nitrous oxide results from degradation of various nitrogen-containing substances in wastewater to nitrates (NO_3) through an aerobic process known as nitrification and subsequently to nitrogen gas (N_2) through a process known as denitrification that occurs in anoxic conditions where no free oxygen is present. The principal nitrogen-containing waste materials are urea, ammonia and proteins. Nitrous oxide can result from both processes and its control is complex (Doorn et al., 2006).

Energy-related emissions mostly include CO_2 derived from fossil fuel-based power generation processes, as electricity is a key energy input for wastewater transport and treatment. The relatively high energy-intensity of wastewater treatment and the prevalent use of fossil fuels for electricity generation mean that energy-related emissions from wastewater are material. The level of these emissions will vary depending on the emissions-intensity of electricity supply in a given location, the nature of wastewater treatment applied and the degree of pumping required to support the transport of wastewater to final treatment sites.

Fugitive emissions from untreated wastewater or wastewater treated on-site – where wastewater breaks down anaerobically in a septic tank, latrine, stagnant sewer, or when released as effluent – typically are very high. However, since these wastewater streams receive little or no treatment and are often not transported long distances, the energy input and associated emissions is very low. Conversely, well-managed centralized wastewater treatment systems do not typically result in high fugitive emissions, as organic matter is either broken down aerobically or, if it is broken down anaerobically, the methane is sometimes captured and combusted. Nitrous oxide emissions are also low when controlled nitrification and denitrification systems are applied. However, these systems require substantial energy inputs, resulting in material energy-related emissions, and they are complex to manage as the plant's loading varies. These patterns of emissions associated with different levels of wastewater treatment are summarized in Table 2.

Table 2.

The volume and nature of emissions from wastewater vary depending on the level and nature of treatment

Treatment stage	Fugitive emissions	Energy-related emissions
Wastewater treated on site	**High CH_4:** Substantial emissions in septic tanks or latrines where organic matter breaks down anaerobically.	**Low CO_2:** Minimal electricity-related emissions resulting from operating electric pumps.
Wastewater not treated and discharged to a water body	**High N_2O:** Resulting from degradation of nitrogen-containing compounds in effluent. **Low CH_4:** Likely to be minimal unless river or lake is oxygen-deficient.	**Low CO_2:** Minimal electricity-related emissions resulting from operating electric pumps.

Treatment stage	Fugitive emissions	Energy-related emissions
Wastewater collected and stored in a stagnant sewer or lagoon	**High CH_4:** Substantial emissions in stagnant sewers or shallow lagoons where organic matter breaks down anaerobically.	**Low CO_2:** Minimal electricity-related emissions resulting from operating electric pumps.
Wastewater transport	**Negligible emissions:** Minimal degradation of wastewater effluent resulting in negligible fugitive emissions.	**High CO_2:** Electricity-related emissions resulting from operating electric pumps.
Primary treatment	**Negligible emissions:** Minimal degradation of wastewater effluent resulting in negligible fugitive emissions.	**Low CO_2:** Some electricity-related emissions resulting from operating electric pumps.
Secondary treatment	**Low CH_4:** Emissions likely to be minimal if secondary system is not-overloaded as aerobic decomposition of organic matter will result only in CO_2 emissions of 'biogenic' origin. **Low N_2O:** Emissions result from nitrification and denitrification processes, with the majority of the nitrogen content of the wastewater being converted to the non-greenhouse gas, N_2.	**High CO_2:** Electricity-related emissions resulting from operating electric pumps and other electrical equipment. This equipment typically includes equipment to blow air into the treatment mix to ensure full aerobic decomposition.
Tertiary treatment	**Negligible emissions:** Nearly all biological degradation has already taken place resulting in negligible fugitive emissions.	**Medium CO_2:** Some electricity-related emissions resulting from operating electrical equipment, such as ozone producing machines and disinfection equipment.
Primary and secondary waste sludge treatment and dewatering	**Low CH_4:** Unless emissions are not captured from anaerobic process. Aerobic sludge treatment produces CO_2 and negligible CH_4. Anaerobic sludge treatment produces substantial volumes of CH_4 but this can be readily captured and combusted.	**High CO_2:** Electricity-related emissions result from operating electric pumps and other electrical equipment, such as heat to allow anaerobic digestion to occur at a sufficient temperature. When CH_4 is captured from the anaerobic process, this can be used to offset other energy inputs and associated emissions.
Sludge disposal	**Low CH_4:** Land disposal of sludge results in aerobic breakdown of remaining organic matter and therefore minimal CH_4 emissions. Landfill disposal can result in partial anaerobic decomposition and therefore CH_4 emissions as well as CO_2.	**Low CO_2:** Some energy and emissions associated with transporting sludge.

The analysis in Table 2 suggests that methane emissions can be reduced in properly managed centralized wastewater treatment plants. A further source of methane emissions is from treatment through septic tanks, which remains the most economical form of wastewater treatment for many small or distributed sources of wastewater, such as rural households. Table 3 summarizes data and analysis from a range of studies on electricity-related emissions and fugitive emissions for wastewater.

Table 3.

Electricity related emissions are substantial but are smaller overall than fugitive emissions

Variable	Unit	United States	Europe	China	Source
Electricity used in wastewater treatment	TWh	30	~28	16	US from Electric Power Research Institute & Water Research Foundation, 2013. Europe based on Water 2020, n.d. China from Danilenko et al., 2012
Wastewater treatment electricity emissions	Mt CO_2e	15	10	12	US and Europe based on Vivid calculation using electricity estimates above and IEA emissions intensities. China from Danilenko et al., 2012
Wastewater methane emissions	Mt CO_2e	25	19	132	US EPA
Wastewater nitrous oxide emissions	Mt CO_2e	5	3	17	US EPA
Total wastewater sector emissions	Mt CO_2e	45	32	161	Calculation
Share of wastewater emissions from electricity	%	33%	31%	7%	Calculation (electricity emissions in row 2 divided by total emissions in row 5)
Population	million people	316	507	1,357	World Bank population data
Emissions per unit of population	kgCO_2e/person	142	63	119	Calculation

Note: *European electricity use in wastewater is marked as approximate as it is drawn from an approximate share of Western European electricity used in wastewater treatment.*

While electricity-related emissions from wastewater are small relative to fugitive emissions in each of the countries studied – particularly China – the absolute volume of electricity and emissions involved is material. Moreover, while fugitive emissions in China were substantial in 2010 – reflecting high volumes of untreated wastewater – the rapid growth of wastewater treatment is likely to have changed the overall picture substantially. With this, wastewater treatment consumes a small but non-trivial portion of total electricity generation in a range of countries. For example, the Electric Power Research Institute and Water Research Foundation estimate that it consumed around 0.8% of US electricity supply in 2011, while a collaborative research network on European wastewater treatment estimates the equivalent percentage for Western Europe to be approximately 1% (Electric Power Research Institute & Water Research Foundation, 2013; Water 2020, n.d.).

2.3 Fugitive emissions in the wastewater sector

Past analyses of abatement opportunities in the wastewater sector have focused on fugitive emissions given their volume relative to electricity emissions. However, the most prominent analysis of fugitive emissions, by the US EPA, indicates that abating this emissions class from the wastewater sector is generally very expensive. To illustrate this, approximate abatement volumes at different price points and over different timeframes from this study are shown in Table 4. While this analysis was based only on visual identification of data points from a chart, it clearly illustrates the high cost of abating fugitive emissions.

Table 4.

Approximately a quarter of fugitive emissions abatement is available at a cost of less than $100 per ton of carbon dioxide equivalent

Year	Variable	Abatement available at less than $100/ton CO_2e	Abatement available at less than $800/ton CO_2e	Total abatement volume
2010	Abatement volume (Mt CO_2e)	19	30	Not reported
2010	Share of total abatement (%)	N/A	N/A	N/A
2020	Abatement volume (Mt CO_2e)	35	65	138
2020	Share of total abatement (%)	25%	47%	100%
2030	Abatement volume (Mt CO_2e)	60	110	218
2030	Share of total abatement (%)	28%	50%	100%

Note: *The US EPA abatement analysis focuses only on methane emissions and ignores nitrous oxide emissions. based on US EPA, 2013*

The high cost of abating fugitive emissions indicates that this class of emissions will not be a key opportunity for climate policy, and is more likely to be driven by wastewater regulations focused on addressing water quality challenges. For example, tighter effluent quality standards could require higher levels of wastewater treatment, which could in turn reduce fugitive emissions. However, additional processing would also increase electricity emissions.

2.4 Electricity-related emissions in the wastewater sector

The US EPA's analysis suggests that electricity-related emissions in the wastewater sector might provide more economically attractive abatement options than fugitive emissions. As electricity use in wastewater is significant, there would appear to be significant scope for more efficient equipment to reduce electricity inputs to the treatment process, thereby reducing greenhouse gas emissions. Therefore, rather than seeking to quantify all wastewater sector abatement options, this study provides a comprehensive review of energy efficiency related abatement opportunities.

This study evaluates abatement potential by estimating electricity use associated with the 'baseline' technology for treatment within the major elements of the wastewater treatment cycle, and an alternative 'improved' technology whose costs and performance can be well characterized. Replacement of the baseline technology with the improved technology reduces electricity inputs for the same level of wastewater treatment, but will involve different capital costs relative to the baseline technology. The economic cost of this abatement will depend heavily on the relative size of the capital cost increment for the improved technology relative to the volume of electricity saved; the latter drives both the degree of electricity cost savings and the volume of abatement. Changes to non-electricity operating costs also affect this equation given that improved technologies generally result in lower maintenance and therefore lower operating costs.

Implicitly this approach takes the level of wastewater treatment as fixed in both the baseline and improved scenario. The analysis can account for the potential increased levels of wastewater treatment, either through treating previously untreated wastewater or by adding additional treatment stages. In these cases, abatement is calculated as the difference in emissions between a baseline scenario where the new treatment occurs with standard technology and an alternative scenario where it occurs with improved technology. The change in emissions from a circumstance without the new treatment to one where the treatment is present is not considered; this is excluded on the logic set out in Section 2.3, that increases in wastewater treatment will be driven by water quality considerations rather than a desire to reduce greenhouse gas emissions.

This analysis identified 18 distinct interventions to achieve abatement by reducing or altering electricity use. All but one intervention improves the energy efficiency of equipment in the treatment process. These improvements cover all stages of the wastewater treatment cycle presented in Table 2 except pretreatment and primary treatment. One source of abatement involves improving the yield of biogas from anaerobic decomposition of sludge, which increases potential energy production of, and reduces net energy input to, the process. For simplicity, this energy production was assumed to offset electricity use, and therefore can be analyzed in an equivalent manner to the other electricity-efficiency sources of abatement. The 18 sources of abatement are summarized in Table 5.

Table 5.

This study assesses the cost and abatement potential of 18 abatement opportunities

Code	Abatement option	Treatment stage	Brief description
1	High efficiency pumping	Transport	Use of sustained high efficiency non-clog pumps
2	Optimal speed pumping	Transport	Use of variable speed pumps, allowing the pump to operate at its optimal efficiency
3	High efficiency pumping	Secondary	Use of sustained high efficiency non-clog pumps for in-plant pumping
4	Efficient variable speed blowers	Secondary	Use of efficient blowers to aerate wastewater during the secondary treatment stage
5	Optimized aeration control and aeration systems	Secondary	Use of intelligent optimized control systems and fine bubble aeration to reduce energy consumption in activated sludge process
6	Efficient mixing	Secondary	Use of highly efficient treatment mixing and process control within the activated sludge secondary treatment process
7	High efficiency pumping – aerobic sludge	Sludge	Use of sustained high efficiency non-clog pumps for in-plant pumping
8	Efficient variable speed blowers	Sludge	Use of efficient blowers and intelligent control in aerobic sludge treatment
9	Optimized mixing solutions	Sludge	Use of intelligent optimized control systems to reduce energy consumption in aerobic sludge process
10	High efficiency pumping – anaerobic sludge	Sludge	Use of sustained high efficiency non-clog pumps for in-plant pumping
11	Improved biogas production	Sludge	Enhancing the production of biogas (methane) during anaerobic digestion, allowing greater energy production
12	High efficiency pumping	Tertiary	Use of sustained high efficiency non-clog pumps for in-plant pumping

Code	Abatement option	Treatment stage	Brief description
13	Air scour efficiency	Tertiary	Improving air scour blower efficiency to provide energy savings
14	Filter control	Tertiary	Filtration system control to maximize filter runs while minimizing power costs that deliver energy and water efficiency
15	More efficient optimized new plant – secondary	Secondary	New secondary treatment plant where more efficient equipment and processes (abatement options 3 to 6) are all adopted in place of their less efficient alternatives
16	More efficient optimized new plant – tertiary	Tertiary	New tertiary treatment plant where more efficient equipment and processes (abatement options 12 to 14) are all adopted in place of their less efficient alternatives
17	More efficient optimized new plant – aerobic digestion	Sludge	New aerobic sludge treatment plant where more efficient equipment and processes (abatement options 7 to 9) are all adopted in place of their less efficient alternatives
18	More efficient optimized new plant – anaerobic digestion	Sludge	New anaerobic plant where sludge digester, more efficient pumping (abatement option 10) and improved biogas production (abatement option 11) are adopted in place of their less efficient alternatives

The electricity consumption of each stage of treatment, and hence the scope for abatement, has been estimated using a simplifying assumption that all treatment plants utilize conventional activated sludge (CAS) processes. The analysis allows for both anaerobic and aerobic digestion of the surplus sludge produced by these plants, dependent on plant size. The conventional activated sludge process is widely used in the US and Europe, though it is less common in China, where anaerobic-anoxic-oxic (AAO) treatment and advanced oxidation (AO) treatment has become more common. Initial comparison of the abatement opportunity from energy efficiency for CAS and AAO/AO suggests that our CAS assumption results in a conservative estimate, but a natural refinement of this study would be to introduce specific estimates for these two processes and to apply them to China's sector.

3 Modelling results

3.1 Model overview

The modelling in this study brings together a series of inputs to assess the attractiveness of the abatement opportunities in three core regions. The attractiveness of these abatement opportunities and the associated investments can be assessed in two closely related ways, the marginal abatement cost approach (MACC), and the internal rate of return (IRR) approach. Both approaches are summarized in Section 1.3.

All assumptions used in both approaches are identical, except the discount rates and carbon prices. The relationship of these inputs – and of the MACC and IRR approaches – are summarized in Table 6.

Table 6.

The abatement cost and internal rate of return approaches use essentially the same inputs

Input or output	Abatement cost approach	Internal rate of return approach
Discount rate	✓	✗
Carbon price	✗	✓
Changes to capital costs, operating costs and energy inputs due to wastewater transport and treatment process improvements	✓	✓
Wastewater treatment volumes	✓	✓
Electricity emissions intensity and prices	✓	✓
Core output	Abatement cost ($ per ton of abatement)	Discount rate at which the NPV of the improvement is zero (i.e. the IRR)

Noting the importance associated with both carbon price and discount rate assumptions, this study also uses a sensitivity analysis to encompass a range of outcomes. The range of assumptions adopted under each approach is presented in Table 7. Please note that the range adopted is not symmetrical around the mid-range assumption as extremely high values are possible for the high assumption, whereas the low assumption is bounded by zero. The upper estimate of the carbon price is set at $125/ton CO_2e to reflect the carbon price prevailing in Organization for Economic Co-operation and Development countries in 2035 in the most stringent emissions reduction scenario in the IEA's 2013 World Energy Outlook modelling analysis. The upper estimate for the real discount rate broadly represents a high equity hurdle rate and could be considered as a conservative rule of thumb for identifying investments that have a strong business case. All other key assumptions, including wastewater treatment volumes, capital and operating costs for baseline and improved investments, and electricity emissions intensities and prices, are detailed in the Appendix. All abatement options are assessed over an assumed investment life of 20 years.

Table 7.

Carbon price and discount rate assumptions

Variable	Units	Relevant approach	Low assumption	Mid-range assumption	High assumption
Real discount rate	%	Abatement cost approach	3.5%	5.5%	15%
Carbon price	Real 2015 USD	IRR approach	$0	$30	$125

Note: *Carbon prices are held constant in real terms, adjusting for inflation, over the full period of analysis.*

As discussed above in Section 2.4 the two scenarios analyzed here are a 'baseline' scenario, where relatively low to moderate efficiency existing equipment is replaced at the end of its life with similar quality equipment, and an 'improved' scenario where higher efficiency equipment is adopted instead. In all elements of the wastewater treatment process except transport, all existing equipment is assumed to be replaced at the end of its life with a more efficient alternative. Similarly, in the case of a new plant, the baseline equipment adopted was also assumed to be of the less efficient variety. In the case of transport, a share of existing pumping equipment in the United States and Europe was assumed to already be efficient and therefore not able to be replaced with a more efficient alternative. For China, pumps were assumed to be of the less efficient variety in the baseline scenario, based on literature suggesting that users have a general preference for lower capital cost equipment (Lu, 2014). These assumptions are detailed in the Appendix in Table 14.

Traditionally, a MACC is presented as a static snapshot of abatement opportunities at a point in time but this approach has been modified in two key ways:

- First, new plant abatement was scaled on the basis of expected volumes of growth in secondary treatment over the next five years in China only (this was assumed to be zero for the United States and Europe). This was considered to be an appropriately conservative way to reflect the abatement potential in wastewater treatment infrastructure construction over the coming years. In China, new plants may be built in smaller towns and villages as they receive enhanced wastewater treatment as well as in cities experiencing population and economic growth.
- Second, improvements to existing plant were costed as end-of-life replacement. Here, the assumption is that relatively inefficient equipment is replaced with either a similarly inefficient new item or an efficient alternative. The abatement volume and cost modelled in this study sums all these end-of-life replacements, as if they occur immediately, which is unrealistic given the approximately twenty-year life of the relevant equipment. This approach generates the total volume of abatement available by replacing the existing stock with highly-efficient equipment at the end of its life. However, the fact that the emissions intensity of electricity supply is likely to decline over time means that this approach may slightly over-estimate the volume, and under-estimate the unit cost, of abatement measures.

3.2 Results of MACC analysis

The MACC analysis for each region studied indicates a substantial volume of potential negative cost abatement opportunities. As illustrated in Table 8, it can be seen that the mature markets of the United States and Europe can abate over 33% of their 2015 electricity-related emissions with nearly 90% of these abatement actions being zero or negative cost. China can cut nearly 60% of projected electricity-related emissions in the wastewater sector with abatement actions of zero or negative cost. In combination the three regions offer over 20 million tons of CO_2e of economically attractive annual abatement from reduced electricity use in wastewater treatment.

The proportion in China is high because rapid growth in wastewater treatment capacity over time means that the abatement potential is large relative to emissions today. The portion of current emissions abated in Europe is lower than in the United States due to the more rapid decline in emissions intensity of electricity supply in Europe, over time, using assumptions based on the International Energy Agency's World Energy Outlook (OECD/IEA, 2013). As electricity supply decarbonizes, the volume of future abatement available from energy efficiency shrinks.

Table 8.

Over 50% of current wastewater electricity emissions, totalling nearly 44 Mt CO_2e, can be readily abated, and about 95% of this can be achieved at zero or negative cost

Variable	2015 wastewater electricity emissions (Mt CO_2e)	Modelled abatement (Mt CO_2e)	Abatement as a share of 2015 electricity emissions (%)	Negative cost abatement (Mt CO_2e)	Negative cost abatement share (%)
United States	15.5	6.0	38%	5.1	86%
Europe	8.5	2.8	33%	2.6	94%
China	21.8	12.9	59%	12.9	100%
Regions studied	45.9	21.7	53%	20.6	95%
Rest of the world	40.5	24.5	60%	23.3	95%
Global total	86.3	46.1	53%	43.9	95%

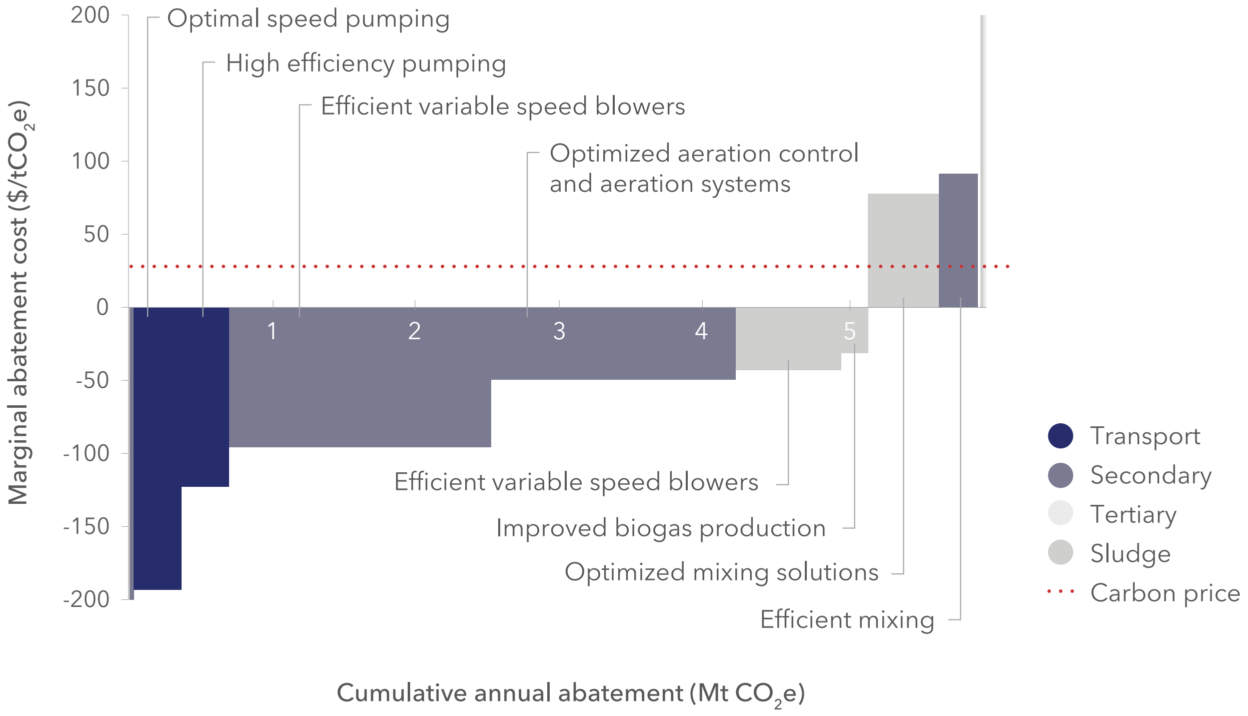
Note: *Rest of the world estimates based on a global extrapolation, as outlined in the Appendix. Total emissions estimates differ from those in Table 3 as those estimates were for earlier years (2011 for the US and 2010 for China and Europe). Negative cost abatement in China is slightly lower than, but rounds up to, 100%.*

Extrapolating globally, this analysis indicates that 47% of expected wastewater electricity emissions in 2020 are covered within the core study regions and periods. If the 53% of wastewater electricity emissions from other world regions are included, and assuming that abatement is taken up in proportion to emissions, there is potential global abatement of 46 Mt CO_2e. Further, if the ratio of negative cost abatement to total abatement is similar in the rest of the world to the regions studied, the negative cost abatement potential reaches nearly 44 Mt CO_2e.

The MACCs for the United States, Europe and China are presented in Figure 4, Figure 5 and Figure 6 respectively; please note that the Europe MACC uses a slightly different scale on the y-axis.

Figure 4.

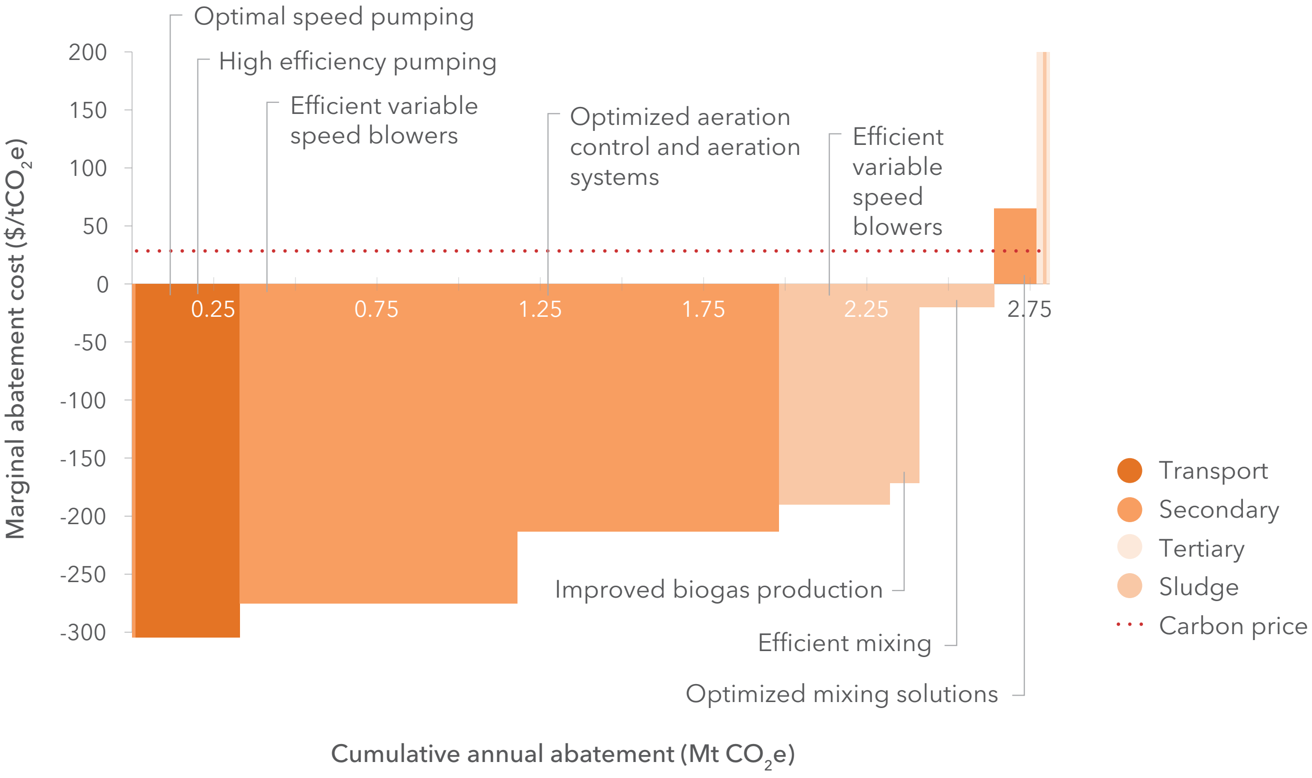
The United States wastewater sector can abate over 5 Mt CO_2e of electricity-related emissions at zero or negative cost, representing almost 40% of current electricity-related emissions



Note: *Abatement costs are presented within a range between \$200/ton CO_2e and -\$200/ton CO_2e to avoid distorting the presentation of the chart. The carbon price presented is the mid-range assumption of \$30/ton CO_2e. Numbers presented based on the mid-range discount rate assumption of 5.5%.*

Figure 5.

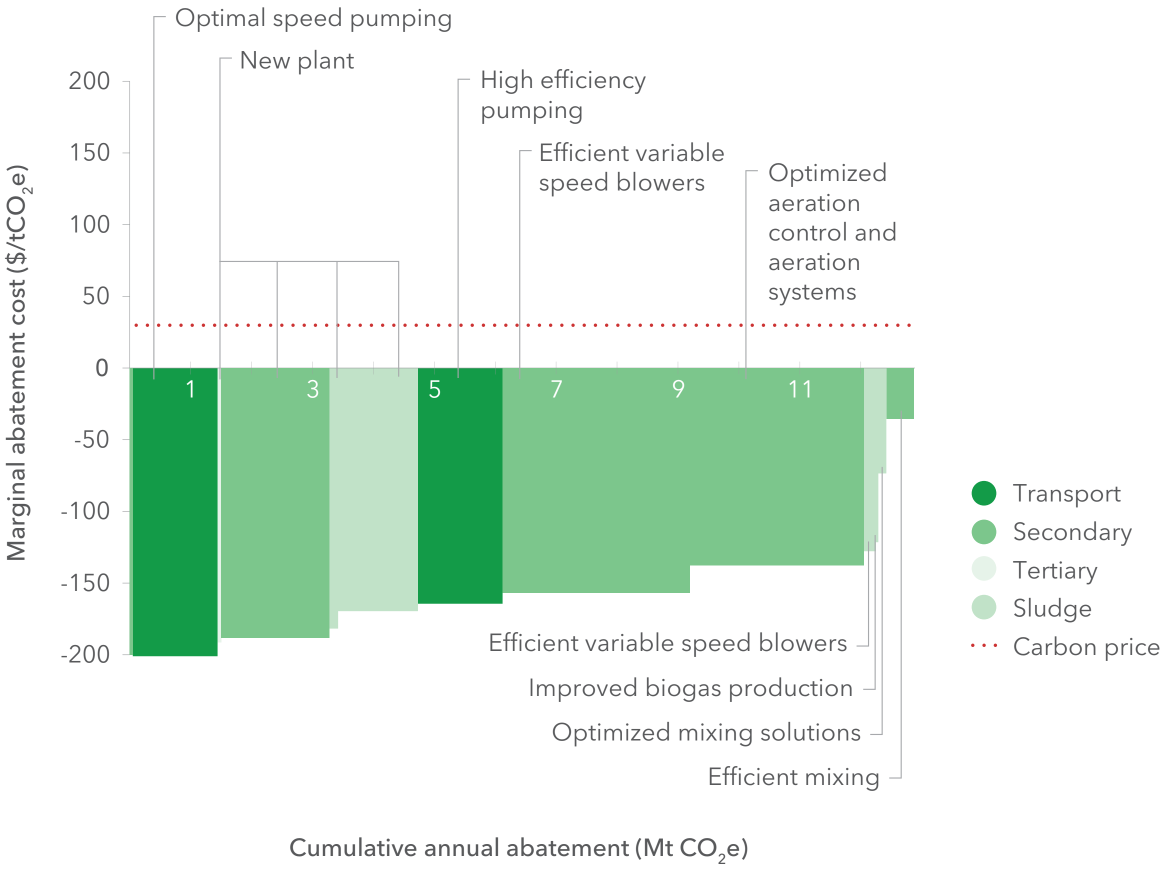
The European wastewater sector can abate more than 2.5 Mt CO_2e of electricity-related emissions at zero or negative cost, representing more than 30% of current electricity-related emissions



Note: *Abatement costs are presented within a range between \$200/ton CO_2e and -\$300/ton CO_2e to avoid distorting the presentation of the chart. The carbon price presented is the mid-range assumption of \$30/ton CO_2e. Numbers presented based on the mid-range discount rate assumption of 5.5%.*

Figure 6.

The Chinese wastewater sector can abate more than 12 Mt CO_2e of electricity-related emissions at zero or negative cost, representing almost 60% of current electricity-related emissions



Note: *Abatement costs are presented within a range between $200/ton CO_2e and -$200/ton CO_2e to avoid distorting the presentation of the chart. The carbon price presented is the mid-range assumption of $30/ton CO_2e. Numbers presented based on the mid-range discount rate assumption of 5.5%.*

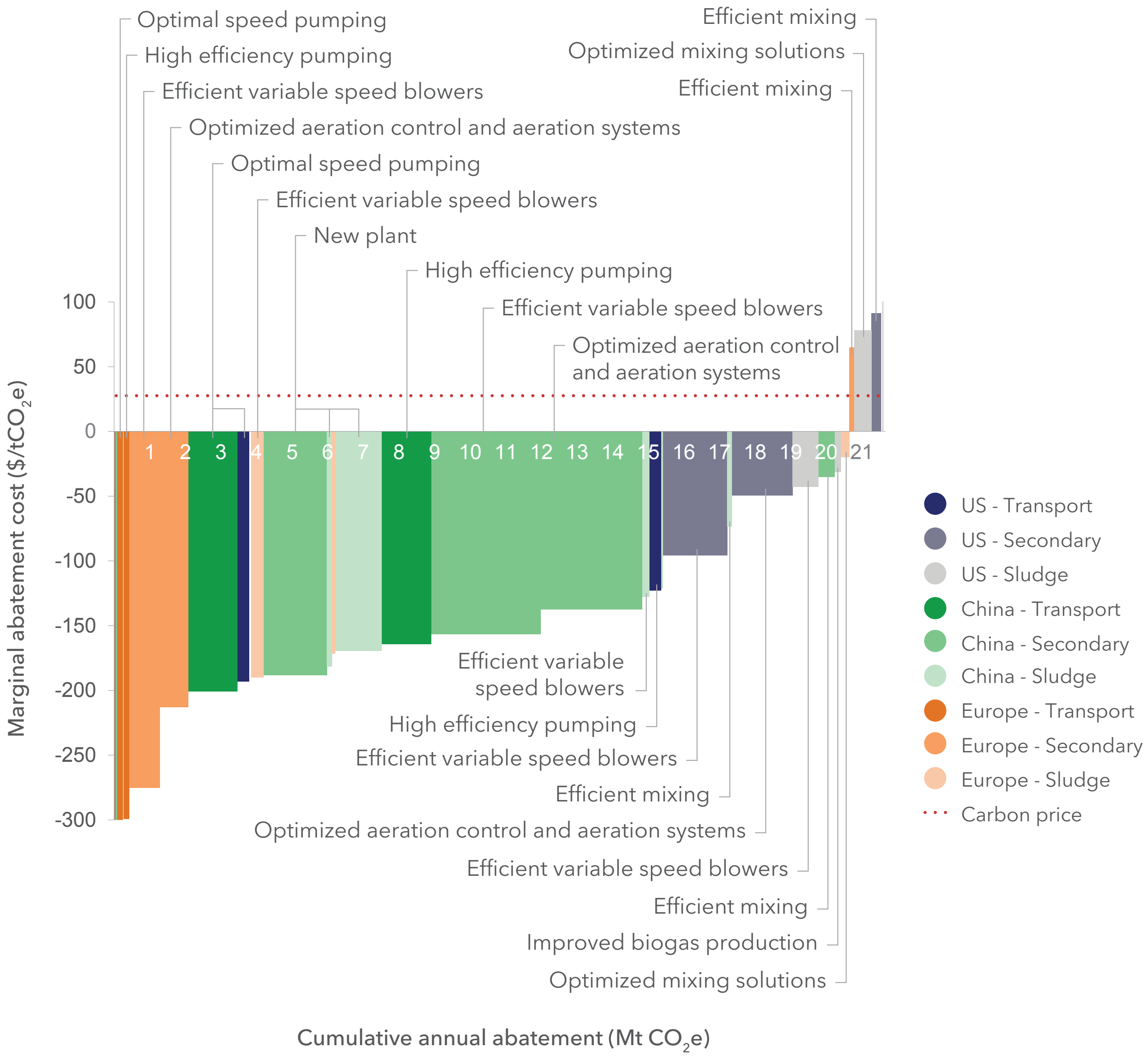
Some of the lowest cost abatement in China is from new plants. When constructing new treatment facilities, the adoption of more efficient secondary, sludge, or tertiary treatment equipment is a very economically efficient way to reduce emissions. The substantial volume of abatement from new plants gives the Chinese MACC a broader base of negative cost abatement potential than the MACCs for Europe and the United States. Rates of new plant construction in Europe and the US are extremely low compared with the rapid expansion occurring in China, so European and US new plant build has been excluded from this analysis for simplicity. By contrast, China's Five Year Plan forecasts construction of wastewater capacity of approximately 17 billion cubic meters per year between 2016 and 2020, which is a one-third increase on present treatment levels.

The combined MACC for all three regions gives an indication of the relative cost and magnitude of abatement in each region. Figure 7 illustrates the relatively small volume of European abatement compared to that in China, driven by Europe's relatively small absolute volume of wastewater treatment and low electricity emissions intensity.

European abatement is often found to be lower cost than in China or the United States. Counter-intuitively, this occurs in part because of the low emissions intensity of electricity supply in Europe. This means that for a given electricity cost saving, the volume of abatement is relatively small. In turn, when the project net present value is divided by the volume of abatement, the saving per unit of abatement is high.

Figure 7.

The three regions combined offer over 20 Mt CO_2e of potential zero or negative cost abatement, with China in particular offering a high volume of low cost abatement



Note: *Abatement costs are presented within a range between $200/ton CO_2e and -$200/ton CO_2e to avoid distorting the presentation of the chart. Tertiary abatement categories omitted due to small size being invisible at the scale presented. The carbon price presented is the mid-range assumption of $30/ton CO_2e. Numbers presented based on the mid-range discount rate assumption of 5.5%.*

The largest sources of abatement across the three countries are efficient variable speed blowers and optimized aeration systems within the secondary treatment stage. Each of these offers abatement of more than 5 Mt CO_2e annually if fully adopted. Collectively the secondary treatment stage offers the largest share of potential abatement, at 64% of the total. Within transport, the options of introducing high efficiency pumps and optimal speed pumps each offers almost 2 Mt CO_2e, and are the next largest sources of abatement. New secondary and aerobic sludge plants in China and efficient variable speed blowers for aerobic sludge treatment each offer in excess of 1 Mt CO_2e. The volume of abatement offered by each of the 18 abatement options across the three regions studied is summarized in Table 9.

Table 9.

Secondary treatment stages offer well over half of the potential abatement for the regions studied

Abatement option	Treatment stage	Abatement (Mt CO_2e)				Share of total
		US	Europe	China	Total	
High efficiency pumping	Transport	0.3	0.2	1.4	1.9	9%
Optimal speed pumping	Transport	0.3	0.2	1.4	1.9	9%
High efficiency pumping	Secondary	0.0	0.0	0.1	0.1	0%
Efficient variable speed blowers	Secondary	1.8	0.9	3.1	5.7	26%
Optimized aeration control and aeration systems	Secondary	1.7	0.8	2.9	5.4	25%
Efficient mixing	Secondary	0.3	0.1	0.5	0.9	4%
High efficiency pumping - aerobic sludge	Sludge	0.0	0.0	0.0	0.0	0%
Efficient variable speed blowers	Sludge	0.7	0.3	0.2	1.3	6%
Optimized mixing solutions	Sludge	0.5	0.2	0.1	0.9	4%
High efficiency pumping - anaerobic sludge	Sludge	0.0	0.0	0.0	0.0	0%
Improved biogas production	Sludge	0.2	0.1	0.0	0.3	1%
High efficiency pumping	Tertiary	0.0	0.0	0.0	0.1	0%
Air scour efficiency	Tertiary	0.0	0.0	0.0	0.0	0%
Filter control	Tertiary	0.0	0.0	0.0	0.0	0%
More efficient optimized new plant - secondary	Secondary	0.0	0.0	1.8	1.8	8%

Abatement option	Treatment stage	Abatement (Mt CO_2e)				Share of total
		US	Europe	China	Total	
More efficient optimized new plant – tertiary	Tertiary	0.0	0.0	0.1	0.1	0%
More efficient optimized new plant – aerobic sludge	Sludge	0.0	0.0	1.3	1.3	6%
More efficient optimized new plant – anaerobic sludge	Sludge	0.0	0.0	0.1	0.1	1%
All	Transport	0.7	0.3	2.8	3.8	17%
All	Secondary	3.8	1.8	8.2	13.8	64%
All	Tertiary	0.1	0.0	0.1	0.2	1%
All	Sludge	1.4	0.7	1.8	3.9	18%
Total	All	6.0	2.8	12.9	21.7	100%

3.3 Results of IRR analysis

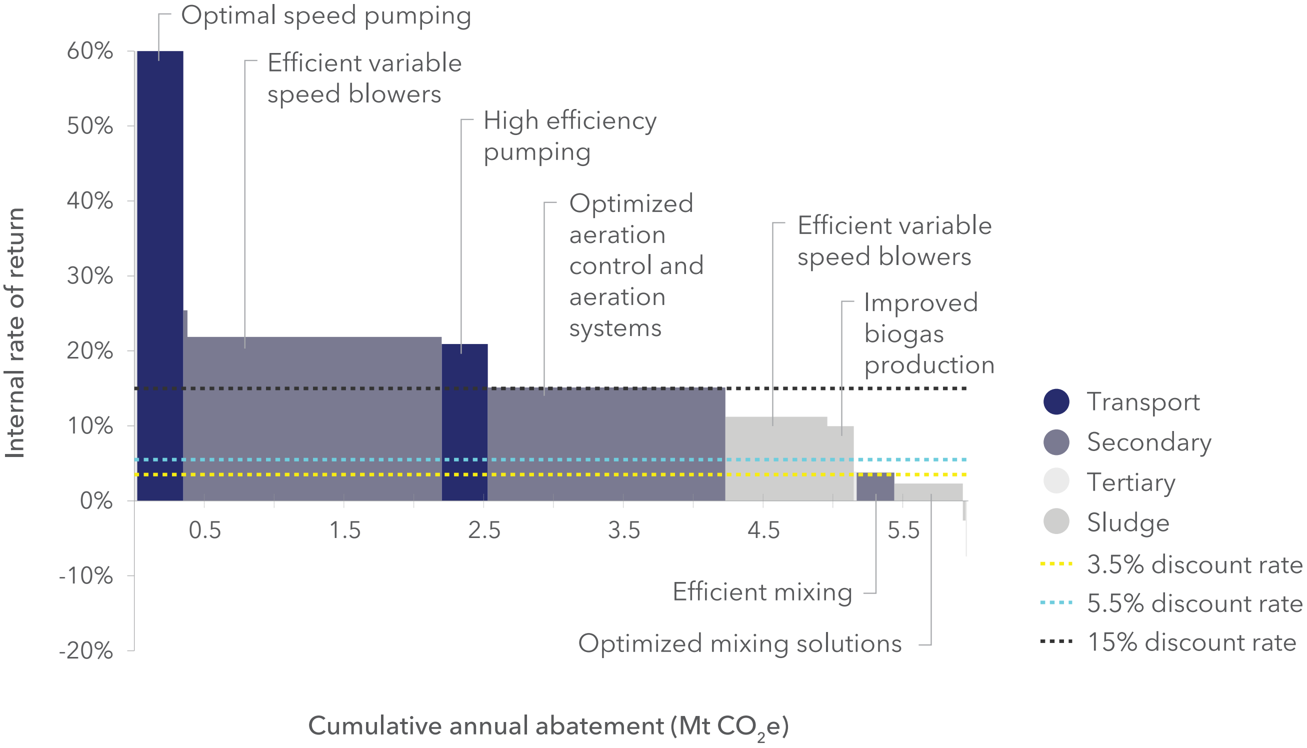
As the IRR curves present the same underlying information as the MACCs, the results on the charts are similar. The key difference is that strong investment returns are signified by a high IRR, as opposed to a low cost of abatement. Similarities between the MACCs and IRR curves include:

- Attractive returns from transport pumping improvements, secondary blower efficiency, treatment blower upgrades for aerobic sludge and improved biogas production for anaerobic sludge in all regions;
- Attractive returns from investments in higher-efficiency equipment in new plant investments in China; and
- Substantial abatement potential in China, exceeding that in the United States which in turn exceeds that in Europe.

A notable aspect of these charts is that almost all of the abatement potential in China offers an IRR of more than 15% in real terms. The IRR curves for the United States, Europe and China are presented in Figure 8, Figure 9 and Figure 10, respectively. Please note that the Chinese MACC uses a slightly different scale on the y-axis due to the prevailing high IRRs in that region.

Figure 8.

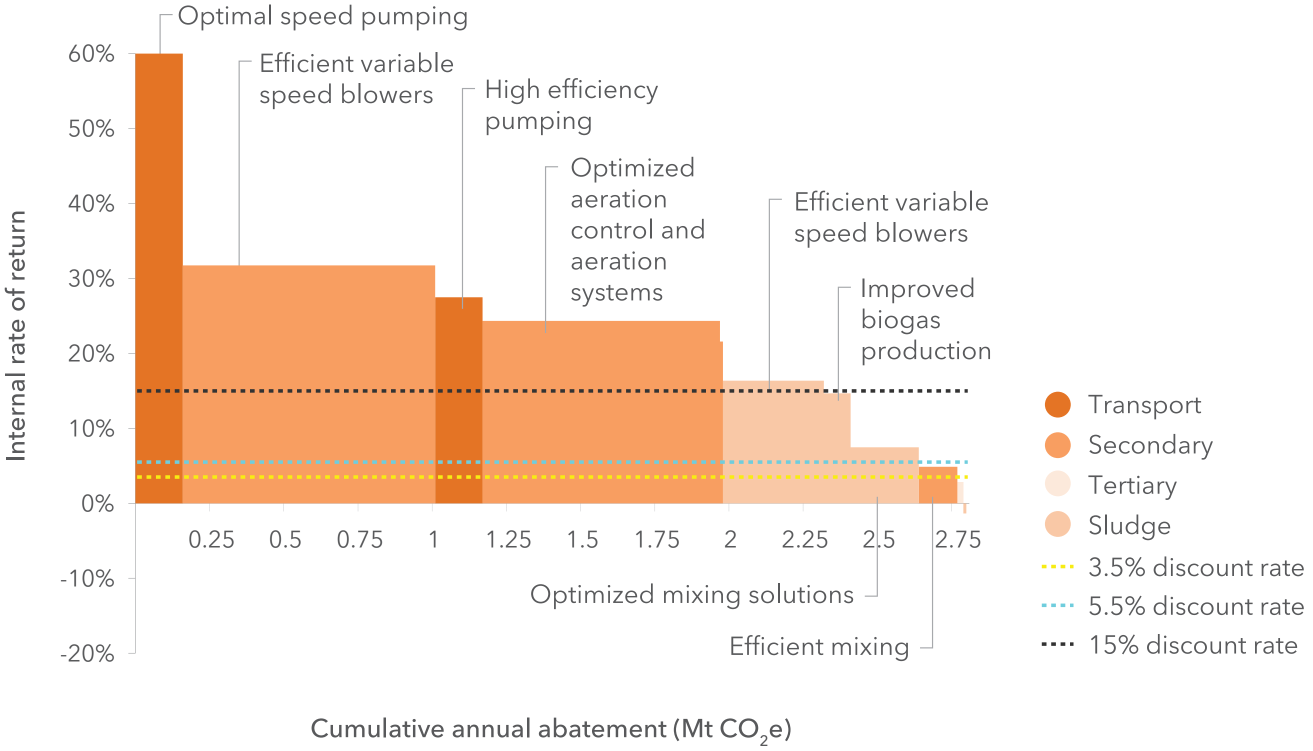
Blower efficiency, aeration control and transport pumping investments have very strong IRRs in the United States, with other investments offering slightly less attractive returns



Note: *Project IRRs are presented in a range below 60% to avoid distorting the presentation of the chart. Numbers presented based on the mid-range carbon price assumption of $30/ton* CO_2e*.*

Figure 9.

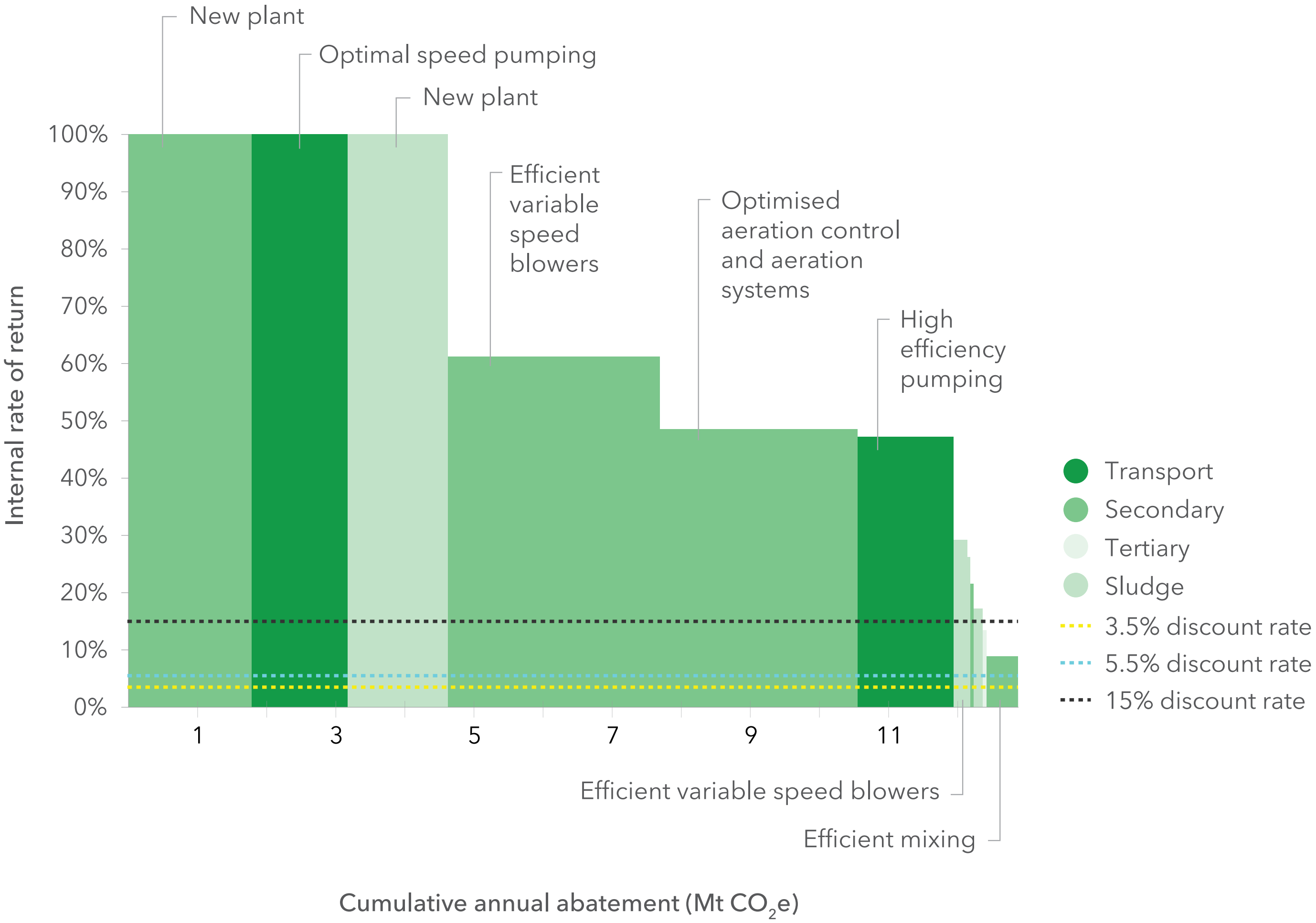
A broad range of investments in Europe offer IRRs in excess of 15% in real terms, representing highly attractive abatement options of more than 2 Mt CO_2e



Note: *Project IRRs are presented in a range below 60% to avoid distorting the presentation of the chart. Numbers presented based on the mid-range carbon price assumption of \$30/ton* CO_2e.

Figure 10.

Almost all investments in China offer IRRs in excess of 15% in real terms, representing highly attractive abatement options of more than 12 Mt CO_2e

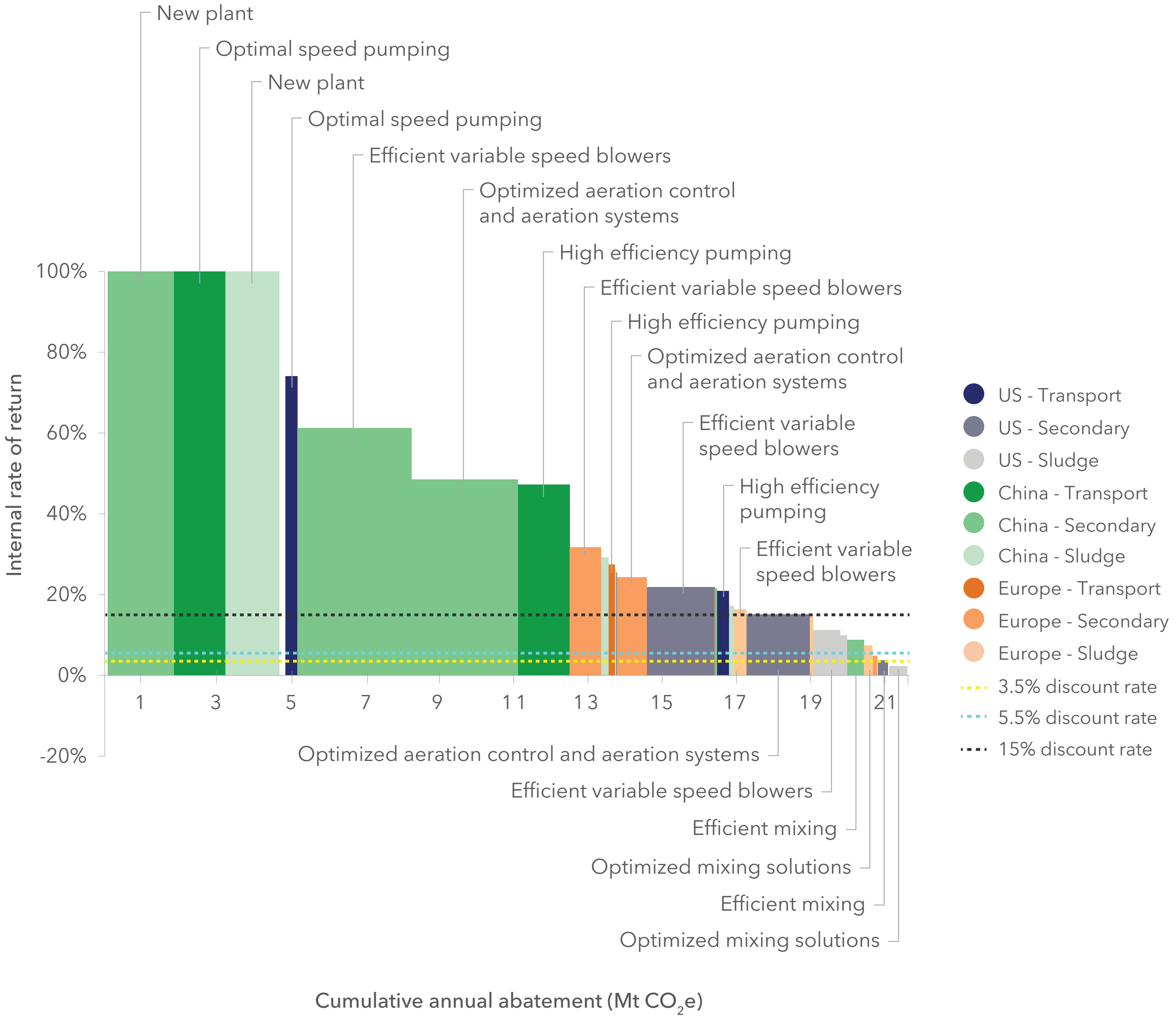


Note: *Project IRRs are presented in a range below 100% to avoid distorting the presentation of the chart. Numbers presented based on the mid-range carbon price assumption of $30/ton CO_2e.*

The combined IRR curve in Figure 11 illustrates the strong investment case in all regions and particularly in China and Europe. It is notable that 19 Mt CO_2e of abatement can be achieved through projects with a real internal rate of return of 15% or higher.

Figure 11.

Rates of return are strongest in China, and nearly 19 Mt CO_2e of abatement could be unlocked across all three regions with an investment hurdle rate of 15% real terms



Note: *Project IRRs are presented in a range below 100% to avoid distorting the presentation of the chart. Horizontal lines represent each discount rate assumption applied in the MACC sensitivity analysis, 3.5%, 5.5% and 15%. Numbers presented based on the mid-range carbon price assumption of $30/ton CO_2e.*

An alternative metric of project profitability is the net present value of the investment per unit of water it delivers. This metric could be interpreted as the change in the levelized cost of the relevant treatment stage between the improved and the baseline investment; a positive number indicates that the improved investment option is financially superior and investing in the improved equipment will earn the investor a profit. Calculations below use the mid-range discount rate assumption of 5.5% and are exclusive of any carbon price.

Table 10.

Normalized investment net present values per unit of water indicate strong investment returns for a range of abatement options

Abatement option	Treatment stage	Normalized investment net present values per unit of water (US cents per m^3)		
		US	Europe	China
High efficiency pumping	Transport	0.29	0.47	0.57
Optimal speed pumping	Transport	0.46	0.64	0.70
High efficiency pumping	Secondary	0.10	0.08	0.06
Efficient variable speed blowers	Secondary	0.41	0.77	0.97
Optimized aeration control and aeration systems	Secondary	0.20	0.55	0.80
Efficient mixing	Secondary	-0.06	-0.03	0.03
High efficiency pumping - aerobic sludge	Sludge	-0.02	-0.02	-0.01
Efficient variable speed blowers	Sludge	0.10	0.28	0.41
Optimized mixing solutions	Sludge	-0.12	0.02	0.16
High efficiency pumping - anaerobic sludge	Sludge	-0.03	-0.03	-0.03
Improved biogas production	Sludge	0.06	0.22	0.34
High efficiency pumping	Tertiary	-0.02	-0.03	-0.02
Air scour efficiency	Tertiary	-0.08	-0.09	-0.06
Filter control	Tertiary	-0.07	-0.06	-0.04
More efficient optimized new plant - secondary	Secondary	0.00	0.00	2.14
More efficient optimized new plant – tertiary	Tertiary	0.06	0.04	0.05
More efficient optimized new plant – aerobic sludge	Sludge	0.00	0.93	0.00
More efficient optimized new plant – anaerobic sludge	Sludge	0.00	0.51	0.00

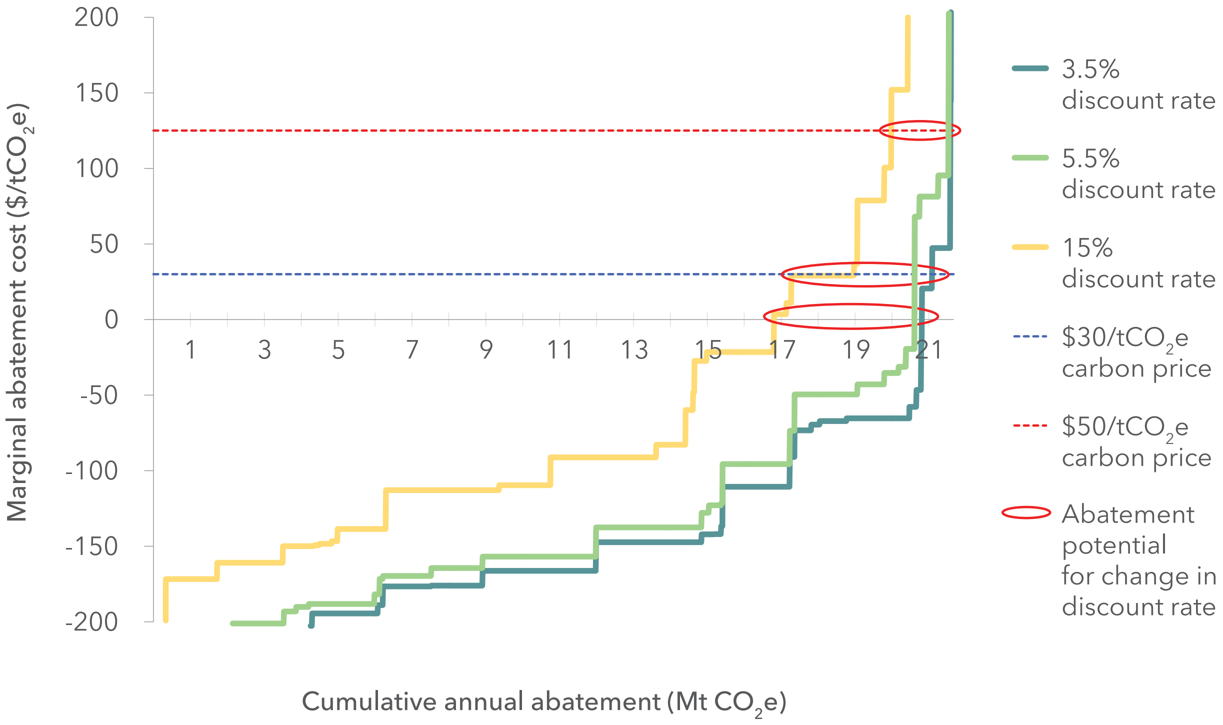
Note: *Positive values indicate that the project is profitable at the prevailing discount rate. Calculations above assume a 5.5% discount rate and a no carbon price. Normalized investment net present values per unit of water are calculated as the investment net present value divided by the total volume delivered over the project lifetime, discounted to its net present value in 2015. The value of the investment is equal to if a payment of this level were made on each unit of water delivered over the project's lifetime.*

3.4 Sensitivity analysis

The combined MACCs or IRR curves for all three regions show that the total volume of abatement does not change greatly within a plausible range of discount rate assumptions, see Figure 12. A MACC illustrates the volume of abatement on the x-axis that would be available at a carbon price equal to or lower than the relevant value on the y-axis. The length of the red hoops illustrates the potential change in abatement that would result from changing the discount rate, for a fixed carbon price.

Figure 12.

The investment case is only weakly sensitive to discount rate assumptions, particularly if carbon prices are higher

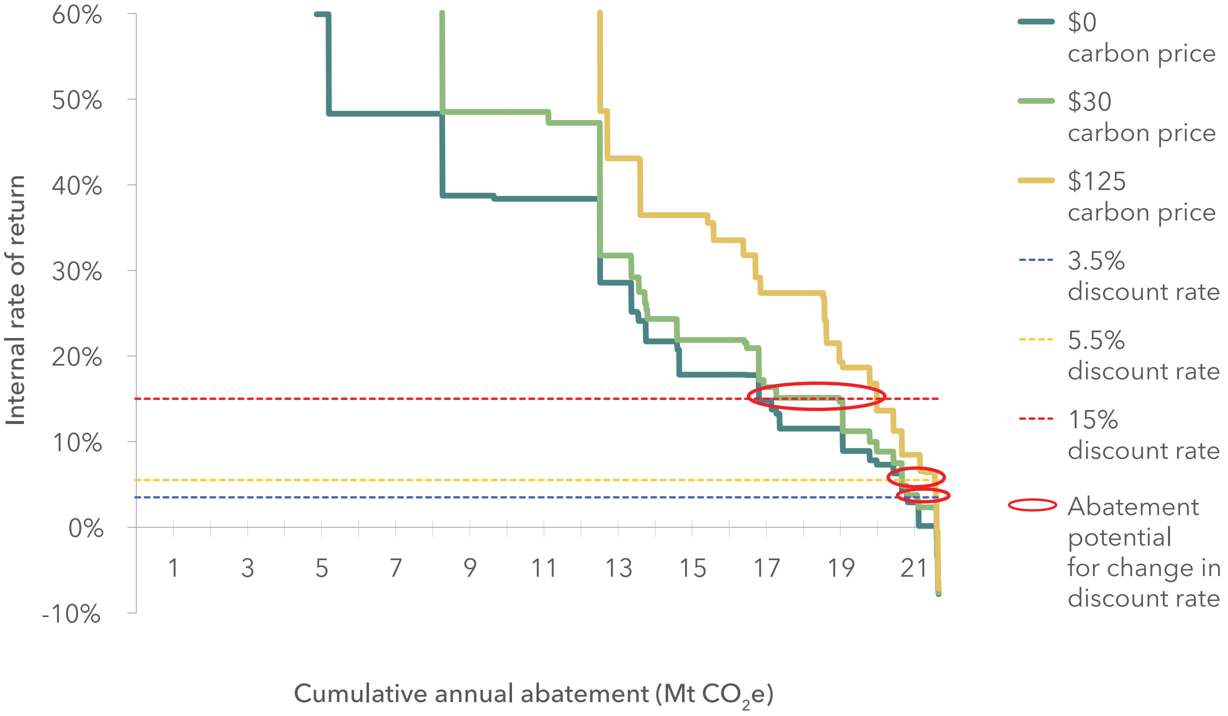


Note: *The red circles indicate the variability in the abatement volume that would occur if the discount rate was varied between the low and high assumptions.*

Combined IRR curves for all three regions across three carbon price assumptions indicate that project returns are not highly sensitive to carbon prices. These curves are provided in Figure 13. While returns are clearly superior under the higher carbon price assumption, the total volume of abatement that is viable at a given discount rate does not change greatly with the carbon price. This is illustrated by the width of the red hoops, which show the change in the volume of potential abatement due to a change in a carbon price, holding the discount rate fixed. The overall sensitivity of the volume of abatement to changing discount rate and carbon price assumptions is summarized in Table 11.

Figure 13.

Project economics are only weakly sensitive to carbon price assumptions, particularly at a relatively low discount rate



Note: *Three discount rates are represented through the horizontal red dashed lines at 3.5%, 5.5% and 15%. The circles represent the variability in abatement volumes that would occur in moving from low to high carbon price assumptions.*

Table 11.

The total abatement volume varies by 5% to 19%, if carbon price or discount rate assumptions are varied across a plausible range

Total abatement volume (Mt CO_2e)	Discount rate assumption			Sensitivity (holding carbon price constant)	
Carbon price	**3.5%**	**5.5%**	**15%**	**Absolute sensitivity**	**Relative sensitivity**
$0/t$CO_2e$	21	21	17	4	19%
$30/t$CO_2e$	21	21	19	2	10%
$125/t$CO_2e$	22	22	20	2	9%
Absolute sensitivity	1	1	3		
Relative sensitivity	5%	5%	15%		

Overall, this analysis indicates that the underlying economics of investment options in the wastewater sector are robust and not dependent on policy settings such as the establishment of a carbon pricing regime, or commercial settings, such as an investor's chosen discount rate. Section 4 discusses in more detail some reasons why such attractive investment options may not be taken up widely at present, and explains why policies to support increased uptake are justified.

4 Conclusions

4.1 Significance of findings

This study examined 18 distinct electricity-related abatement opportunities across three core regions resulting in key insights into the emissions abatement opportunity in the wastewater sector.

Almost 50% of wastewater sector electricity emissions in the regions studied can be readily abated with existing technologies, with approximately 95% of this abatement achievable at zero or negative cost. The potential global volume of negative cost abatement is substantial, at approximately 44 Mt CO_2e annually. The energy efficiency opportunities can unlock substantial abatement under current market conditions using available technology. They require the widespread adoption of high efficiency pumps and aerators, variable speed drivers, and monitoring and control systems among other technologies.

The rapidly growing wastewater market of China and other growing countries provide enormous investment opportunities. The net present value of Chinese investments with a positive economic return examined in this study exceeds $25 billion, in which increases to approximately $40 billion when Europe and the United States are included. These positive economic returns could in turn be the capital pool to power the badly needed upgrades to our wastewater and water infrastructure.

The full abatement and investment returns modelled here will take time to achieve as they are reliant on progressive replacement of existing equipment at the end of its operating life. For simplicity these investments have been modelled and summed as if they occurred today. An ongoing multi-year program of investment is required to unlock the full potential of the wastewater sector to reduce electricity use and the associated greenhouse gas emissions.

Abatement in the wastewater sector does not require new technologies or carbon pricing policies, but is a matter of adoption. The majority of the available abatement options are not dependent on new technology development or new policy settings that impose a cost of carbon on electricity supply, nor highly sensitive to the discount rate chosen. Energy efficiency measures such as those available today in the wastewater sector should be targeted as a matter of priority due to their low cost and immediate availability.

Given that the wastewater sector is energy-intensive and the financial returns for increasing energy efficiency are so strong, a non-price barrier may exist in many cases to prevent adoption. Many installers of wastewater treatment equipment, particularly municipalities, are averse to adopting higher capital cost equipment even when the lifecycle cost of this equipment is lower than cheaper, less efficient alternatives (Lu, 2014). Other non-price barriers may also exist. We recommend investigation of these barriers and how to remove them.

4.2 Recommendations

Two levers appear to be most relevant to accelerate the adoption of abatement measures: assistance with financing and regulations to mandate uptake of energy efficient equipment in wastewater management.

Regulations requiring the adoption of high efficiency pumping equipment are already due to commence in Europe and the United States; similar regulations could be extended to other items of equipment or other jurisdictions. The substantially negative cost of these abatement opportunities indicates that such regulations would be welfare enhancing, provided any genuine financing or other barriers to adoption can be overcome.

Innovative financing may help to unlock abatement in the wastewater sector. Innovative financing mechanisms can resolve the barrier that many users of wastewater treatment equipment face, where the higher upfront cost of more advanced and efficient equipment deters them from this choice, despite its lower lifecycle cost.

Many financing solutions to unlock negative cost abatement options do not rely on policy intervention. Municipalities and other users of wastewater equipment can finance their own balance sheets to fund investment in equipment or, alternatively, equipment providers could package a financing solution, such as leasing, using their own balance sheet or external financing.

In certain cases, the external benefits from energy efficiency in the wastewater sector justify the use of public assistance. Where strong abatement objectives are in place, unlocking low-cost abatement through public assistance can reduce the amount of higher cost abatement required elsewhere in the economy; the benefits of this will be broadly felt beyond the wastewater sector. If municipalities or other providers of wastewater treatment are themselves credit constrained, public assistance can unlock clearly productive investments with low risk, while preventing scarce capital of the municipalities from being diverted from other necessary investments.

We encourage the wastewater sector and policy makers to overcome these barriers, invest in the productivity of wastewater operations, and take a significant step forward in tackling climate change.

4.3 Next steps

This report is intended to be a stepping stone to a better understanding of the emissions abatement opportunity in the wastewater sector, as well as in the broader water sector. Moving forward there are many potential avenues for either deepening the understanding of the topic through additional research, or broadening the impact of the existing research by forming new coalitions and working groups to advance actionable solutions.

Refine the assumptions used in this analysis to deepen the understanding of the wastewater treatment processes, the regional variations in these processes, and how these variables drive the abatement opportunities. There are a handful of assumptions made in this analysis and we encourage researchers to further analyze these assumptions to develop an understanding – and an estimate – that is at a more granular level of detail. For example, we encourage further analysis to estimate the abatement amounts and costs for energy efficiency measures applied to anaerobic-anoxic-oxic and advanced oxidation treatment processes and how this compares to our assumption to use conventional activated sludge as the representative family of processes.

Form a working group focused on specific regions or countries to deepen the understanding of the drivers of emissions abatement opportunities and the specific actions that can be taken. Forming a multi-stakeholder working group – which could include participants from academia, the private sector, and the public sector – will provide the expertise and network to deepen our understanding of the factors that are underlying the numerical analysis performed in this report which will better inform the actions that can be taken to accelerate emissions abatement in the wastewater sector.

Explore the feasibility of introducing specific new policy instruments and standards for the wastewater sector. Policies, such as encouraging transparency of energy efficiency performance in wastewater treatment plants, and instruments such as carbon pricing can significantly accelerate emissions abatement in the wastewater sector. However, the second-order implications of these actions need to be fully understood and we recommend a deeper analysis on a shortlist of potential actions.

Improve global data sources on wastewater plant performance parameters, including process types, capacities, throughput, energy consumption, location, and effluent quality. Robust and accurate data sets are key to developing a technical understanding which is the foundation for building effective policies. Monitoring is also critical to ensuring such policies are successful. We encourage the forming of a working group to define the path to the creation of such a database.

Conduct field work to identify the nature and severity of barriers to adoption of efficient equipment during existing plant maintenance, retrofit and new construction. Carry out a survey of asset operators, owners and funders to understand whether barriers are present relating to access to information, short-termism in selecting options including capital and operating budget trade-offs, and availability of suitable products. Develop and test policy options to address the barriers that are identified.

Again, we encourage all stakeholder groups interested in the topic of emissions abatement in the wastewater sector to continue to drive this research forward. This study definitively demonstrates that the opportunity to significantly reduce greenhouse gas emissions from the electricity inputs to wastewater sector operations exists today. Now is the time for the industry and policy makers to work together to overcome the barriers to adoption, which will result in greater productivity of wastewater operations, and a meaningful step forward in tackling climate change.

Appendix

Wastewater flows

Emissions and potential abatement in the wastewater sector are dependent on both wastewater flow volumes and energy inputs per unit of wastewater treated. It is necessary to estimate the total wastewater flow volumes in the regions of interest. The Food and Agriculture Organization's (FAO's) AQUASTAT database provides an estimate of treated wastewater flows for most countries of interest. However, this data is not available for all countries, nor for a consistent year. Accordingly, some manipulation of the AQUASTAT data is required to derive consistent estimates for 2015 wastewater treatment volumes for all countries of interest. The process involved adjusting for population growth between the latest AQUASTAT observation and 2015, and allowing for growth in wastewater treatment per capita. Vivid Economics' analysis of AQUASTAT data indicated that developed countries typically only experience 0.7% growth in wastewater treatment per capita, while upper middle income countries experience 8.7% and lower middle income countries experience 9%. The upper middle income rate of growth was applied to calculate wastewater treatment flows in Romania, Bulgaria and Hungary, while the lower middle income rate was applied in China. The full assumptions for wastewater flows in 2015 are set out in Table 12, with the new build assumption for China also included.

Table 12.

Wastewater flow assumptions

Country	Treated wastewater (10^9 m^3/year) - observed	Observation year	Population growth since observation	Assumed growth in wastewater treatment per capita	2015 treated wastewater assumption (10^9 m^3/year)	Population (2015, millions)	Treated wastewater per capita (10^3 m^3/year/ capita)	Adopted 2015 wastewater assumption (10^9 m^3/year)
US	40.89	2008	0.8%	0.7%	45.32	320.8	141.28	45.3
China (existing)	48.06	2014	0.6%	9.0%	52.73	1,374.6	38.36	52.7
China (new build)	16.7	2015-2020						16.7
China (total including new build)		To 2020						69.4
Austria	1.899	2010	0.4%	0.7%	2.01	8.5	235.22	2.01
Estonia	0.19	2009	-0.3%	0.7%	0.19	1.3	148.54	0.19
France	3.77	2008	0.5%	0.7%	4.09	66.5	61.54	4.09
Germany	5.183	2007	-0.3%	0.7%	5.35	80.2	66.67	5.35
Greece	0.566	2007	-0.2%	0.7%	0.59	11.0	53.65	0.59

Country	Treated wastewater (10^9 m^3/year) – observed	Observation year	Population growth since observation	Assumed growth in wastewater treatment per capita	2015 treated wastewater assumption (10^9 m^3/year)	Population (2015, millions)	Treated wastewater per capita (10^3 m^3/year/ capita)	Adopted 2015 wastewater assumption (10^9 m^3/year)
Portugal	0.27	2009	-0.2%	0.7%	0.28	10.4	26.65	0.28
Ireland	0.54	2010	0.6%	0.7%	0.58	4.7	122.67	0.58
Italy	3.902	2007	0.4%	0.7%	4.26	60.3	70.65	4.26
Malta						0.4	70.65	0.03
Luxembourg	0.04	2008	1.9%	0.7%	0.05	0.6	86.01	0.05
Netherlands	1.875	2010	0.3%	0.7%	1.97	16.8	116.90	1.97
Belgium						11.3	116.90	1.32
Denmark						5.7	116.90	0.66
Poland	1.356	2011	0.0%	0.7%	1.39	38.5	36.20	1.39
Czech Republic						10.6	36.20	0.38
Slovak Republic						5.4	36.20	0.20
Slovenia	0.126	2010	0.2%	0.7%	0.13	2.1	63.72	0.13
Spain	3.16	2004	0.8%	0.7%	3.74	47.0	79.57	3.74
Sweden	0.436	2010	0.7%	0.7%	0.47	9.7	48.16	0.47
Finland						5.5	48.16	0.26
United Kingdom	4.048	2011	0.6%	0.7%	4.27	64.9	65.82	4.27
Cyprus	0.023	2010	1.1%	0.7%	0.03	1.2	22.20	0.03
Lithuania	0.128	2009	-1.2%	0.7%	0.13	2.9	43.65	0.13
Latvia	0.128	2009	-1.2%	0.7%	0.13	2.0	64.46	0.13
Romania	0.373	2011	-0.4%	8.7%	0.51	19.9	25.81	0.51

Country	Treated wastewater (10^9 m^3/year) – observed	Observation year	Population growth since observation	Assumed growth in wastewater treatment per capita	2015 treated wastewater assumption (10^9 m^3/year)	Population (2015, millions)	Treated wastewater per capita (10^3 m^3/year/ capita)	Adopted 2015 wastewater assumption (10^9 m^3/year)
Bulgaria						7.2	25.81	0.18
Hungary						9.8	25.81	0.25
Croatia	0.209	2011	-0.4%	0.7%	0.22	4.2	51.35	4.2
Europe (sum)								33.7

Source: *Wastewater flows based on FAO AQUASTAT; Population data from the World Bank; China new build assumption based on the Chinese Government's Five Year Plan (2015-2020).*

Further assumptions are required to estimate the total volume of wastewater by treatment stage. The absolute volumes above were adjusted based on flow shares for primary, secondary and tertiary treatment. Except for the Chinese assumption, these shares were derived from OECD data with adjustments to allow for untreated wastewater, and are detailed in Table 13.

Table 13.

Wastewater treatment share assumptions

Country	Share with primary only	Share with primary and secondary	Share with primary, secondary and tertiary	Adjustment
US	2%	44%	54%	-
China	0%	80%	20%	Vivid assumption; tertiary treatment rates conservatively estimated to be low
Austria	0%	1%	99%	-
Belgium	0%	13%	87%	-
Czech Republic	0%	10%	90%	-
Denmark	1%	2%	97%	-
Estonia	1%	9%	91%	-
Finland	0%	0%	100%	-
France	0%	47%	53%	-

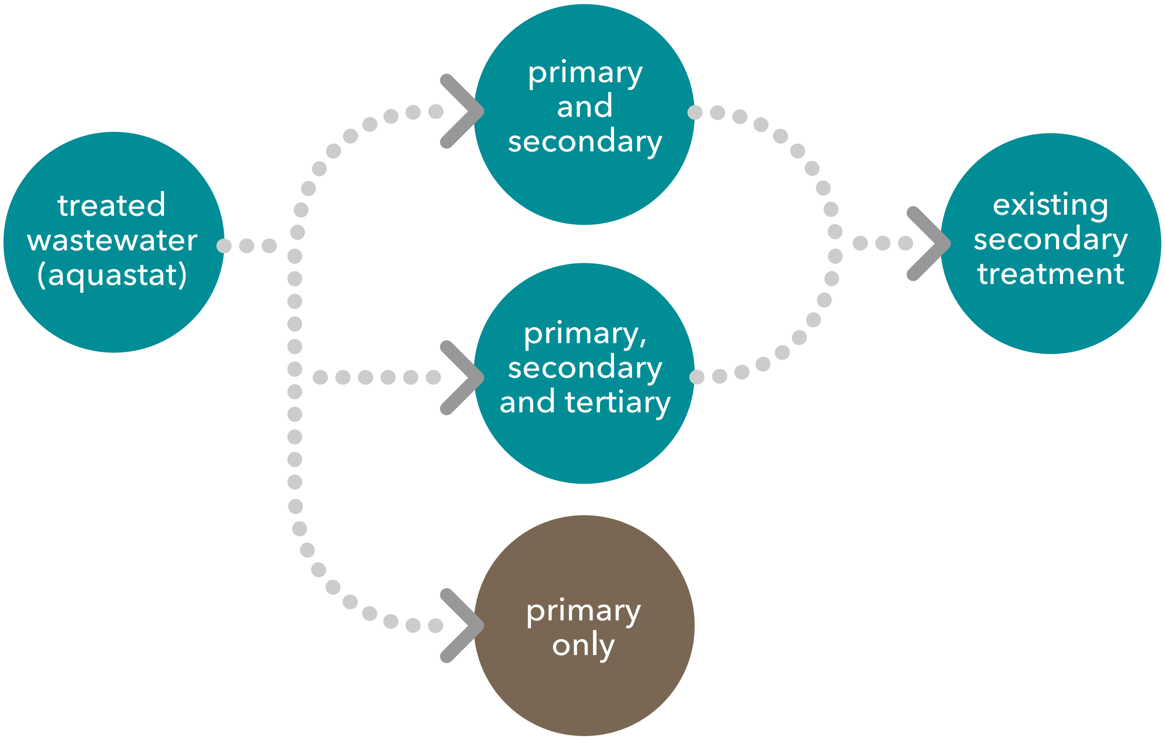
Country	Share with primary only	Share with primary and secondary	Share with primary, secondary and tertiary	Adjustment
Germany	0%	3%	97%	-
Greece	0%	7%	93%	-
Hungary	2%	47%	51%	-
Iceland	97%	2%	2%	-
Ireland	2%	76%	22%	-
Italy	6%	39%	55%	-
Luxembourg	2%	28%	70%	-
Netherlands	0%	1%	99%	-
Poland	0%	20%	79%	-
Slovak	0%	10%	90%	Using Czech Republic's data
Slovenia	1%	63%	36%	-
Spain	1%	35%	64%	-
Sweden	0%	5%	95%	-
United Kingdom	0%	50%	50%	-
Cyprus	0%	7%	93%	Using Greece's data
Malta	6%	39%	55%	Using Italy's data
Lithuania	1%	9%	91%	Using Estonia's data
Latvia	1%	9%	91%	Using Estonia's data
Bulgaria	0%	20%	79%	Using Poland's data
Croatia	0%	20%	79%	Using Poland's data
Romania	0%	20%	79%	Using Poland's data
Europe (implied share)	1%	26%	73%	

Source: *Total flows based on FAO AQUASTAT with adjustments by Vivid Economics; treatment shares based on OECD except China.*

The assumptions in Table 13 were used to estimate both the total volume of treated wastewater and the volume receiving secondary treatment. This is shown schematically in Figure 14.

Figure 14.

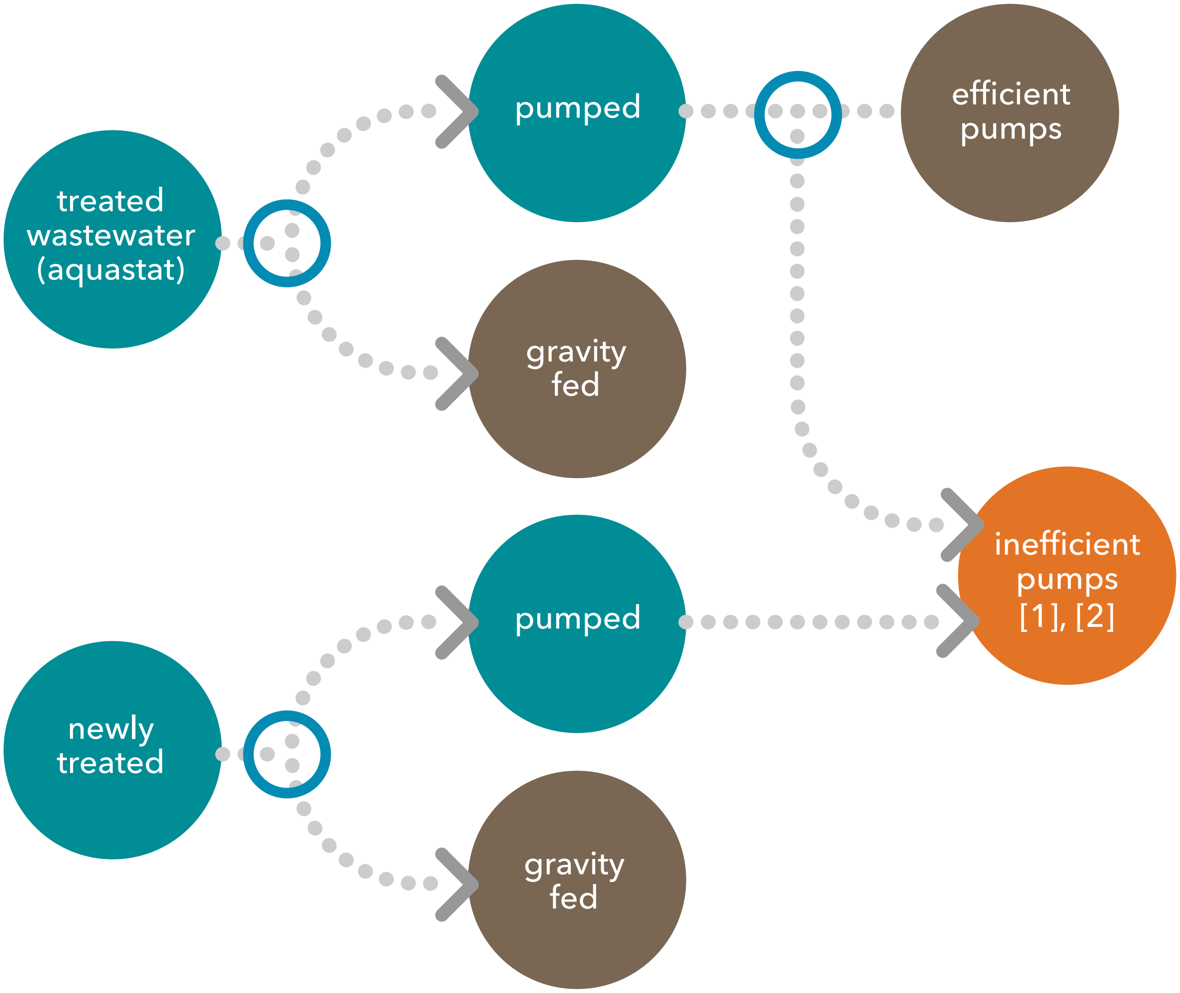
The total wastewater flow is slightly greater than the volume receiving secondary treatment, as a small proportion of wastewater receives only primary treatment



The total volume of treated wastewater estimated in Table 13, including that with primary treatment only, was assumed to be transported for treatment. In some cases this wastewater is gravity fed rather than pumped and energy input is minimal. In further cases, the pumps used for transport would be highly efficient already and would not offer the potential for substantial further abatement. Figure 15 schematically shows the estimated portion of the total wastewater flow, plus newly treated flows in China, for which pumping efficiency could be improved, while the share parameters assumed in allocating the flow to each category are provided in Table 14.

Figure 15.

Only wastewater flows that are pumped and that do not currently use efficient pumps offer the opportunity for abatement in the transport phase



Note: *Numbers in square brackets indicate the code of the abatement opportunities applicable to that volume of wastewater flow. Each of the blue circles indicates a share assumption, as detailed above.*

Table 14.

Assumptions used to estimate flows with potential for improved pumping efficiency

Share assumption	US	Europe	China	Source(s)
Share of treated wastewater that is pumped	50%	50%	50%	Vivid Economics analysis of total wastewater energy load in US and China; residual after removing estimated treatment load attributed to transport. Europe assumed to be equal to the US and China
Share of newly treated wastewater that is pumped	50%	50%	50%	As above
Share of transport pumping that uses efficient pumps	35%	35%	0%	US and Europe estimates based on Xylem analysis; China assumption adopted by Vivid

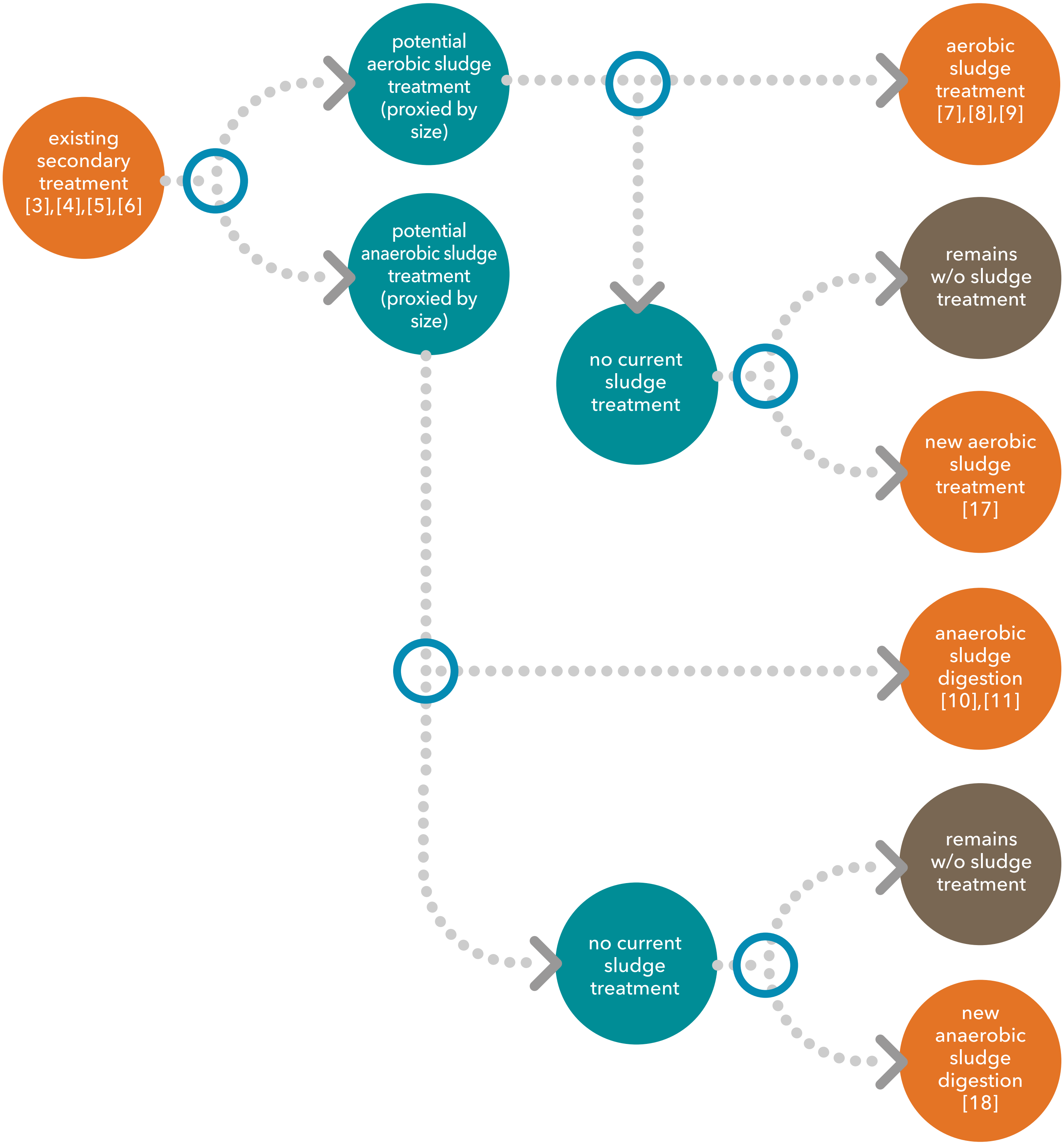
For the purpose of this analysis all wastewater that undergoes secondary treatment was assumed to go through the same process. This process is a conventional activated sludge process, which introduces oxygen to the sewage mixture to break down the organic matter present. This process produces ‘waste activated sludge’, which gives the process its name. This excess sludge must be further broken down in one of two ways. Aerobic sludge treatment further breaks down remaining organic matter without creating methane. By contrast, anaerobic digestion of the sludge produces methane but this is typically captured and combusted for energy production. The simplifying assumption that all secondary treatment is conventional activated sludge accurately reflects the treatment processes in the US and Europe, but is less representative of treatment in China. A natural refinement of this study would be to introduce other treatments such as anaerobic-anoxic-oxic treatment, used in China, and to assess marginal abatement costs specifically for these processes.

For the purpose of this study, larger plants are assumed to adopt anaerobic sludge digestion, whilst smaller plants are assumed to use aerobic sludge treatment. Larger plants have economies of scale that lead to the adoption of anaerobic sludge digestion equipment; this has a higher capital cost but generates methane that can be captured and used for energy production. The size cut off adopted was at a flow rate of 100 million gallons per day rated treatment capacity. A promising refinement of this study would be to combine this size variation with information on plant energy efficiency from benchmarking studies such as the analysis of 2,800 wastewater treatment plants in China, recently published by the World Resources Institute.

Not all sludge generated by the secondary treatment is treated, with studies indicating that this proportion is quite low in China. This must be taken into account in estimating abatement potential from both existing and new sludge treatment processes. The logic flow used to estimate the wastewater flows is set out schematically in Figure 16, while the logic for newly treated wastewater (applicable to China only) is set out in Figure 17. The parameters used to estimate the values for each region are set out in Table 15.

Figure 16.

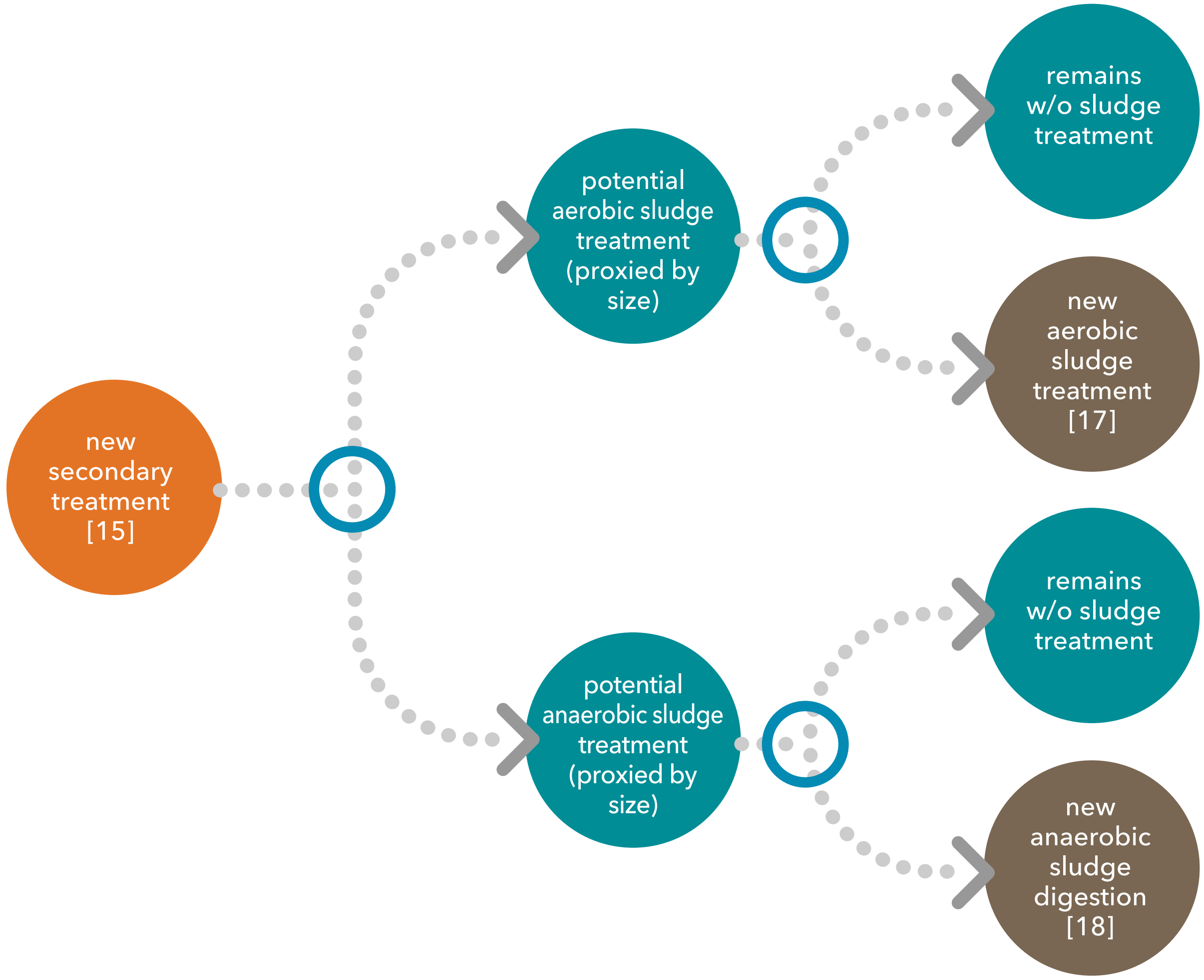
Sludge treatment is assumed in to aerobic in relatively small plants and anaerobic in relatively large plants



Note: *Numbers in square brackets indicate the code of the abatement opportunities applicable to that volume of wastewater flow. Each of the blue circles indicates a share assumption, as detailed above.*

Figure 17.

Where new secondary treatment occurs, any subsequent sludge treatment may be either aerobic or anaerobic



Note: *Numbers in square brackets indicate the code of the abatement opportunities applicable to that volume of wastewater flow. Each of the blue circles indicates a share assumption, as detailed above.*

Table 15.

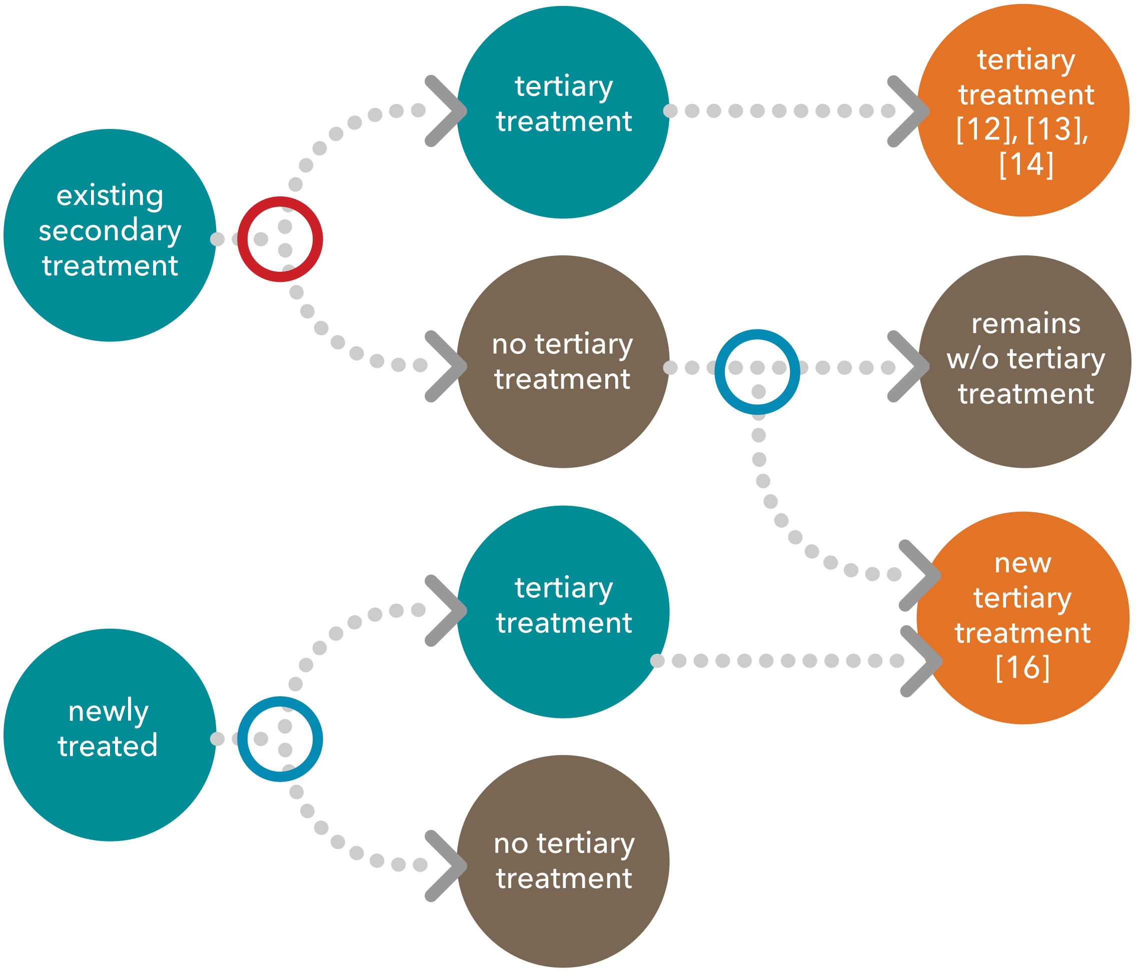
Assumptions used to estimate flows with potential for improved secondary and sludge treatment

Share assumption	US	Europe	China	Source(s)
Share of existing sludge treatment that uses aerobic processes (proxied by plant size)	77%	77%	83%	Xylem analysis for the US; US estimate adopted for Europe; China estimate based on Vivid analysis of data in Guo, Ma, Qu, Li, & Wang (2012)
Share of new sludge treatment that uses aerobic processes (proxied by plant size)	77%	77%	83%	As above
Share of sludge that does not receive treatment	0%	0%	85%	US and Europe assumptions based on Xylem expert judgement; China estimate based on Vivid analysis of data in Guo, Ma, Qu, Li, & Wang (2012)
Share of currently untreated sludge that receives new aerobic treatment	N/A	N/A	50%	Chinese assumption chosen by Vivid Economics to ensure a realistic but conservative abatement estimate
Share of currently untreated sludge that receives new anaerobic treatment (digestion)	N/A	N/A	50%	Chinese assumption chosen by Vivid Economics to ensure a realistic but conservative abatement estimate
Share of sludge from new secondary treatment in relatively small plants that receives aerobic treatment	N/A	N/A	50%	Chinese assumption chosen by Vivid Economics to ensure a realistic but conservative abatement estimate

The final schematic in Figure 18 addresses the fact that not all wastewater that goes through secondary treatment will also receive tertiary treatment. The share of wastewater that does or does not receive tertiary treatment presently is determined for each country using the data in Table 13. For newly treated wastewater (relevant to China only) and wastewater that does not presently receive tertiary treatment, Vivid conservatively assumed, for all regions, that 50% of this wastewater may receive tertiary treatment in the future.

Figure 18.

The model estimates the level of tertiary treatment at the country level and allows for increases in tertiary treatment over time



Note: *Numbers in square brackets indicate the code of the abatement opportunities applicable to that volume of wastewater flow. Share assumptions for each blue circle are set at 50% for all countries and regions. The red circle represents a share assumption determined for each country on the basis of data in Table 13.*

Energy prices and emissions intensity

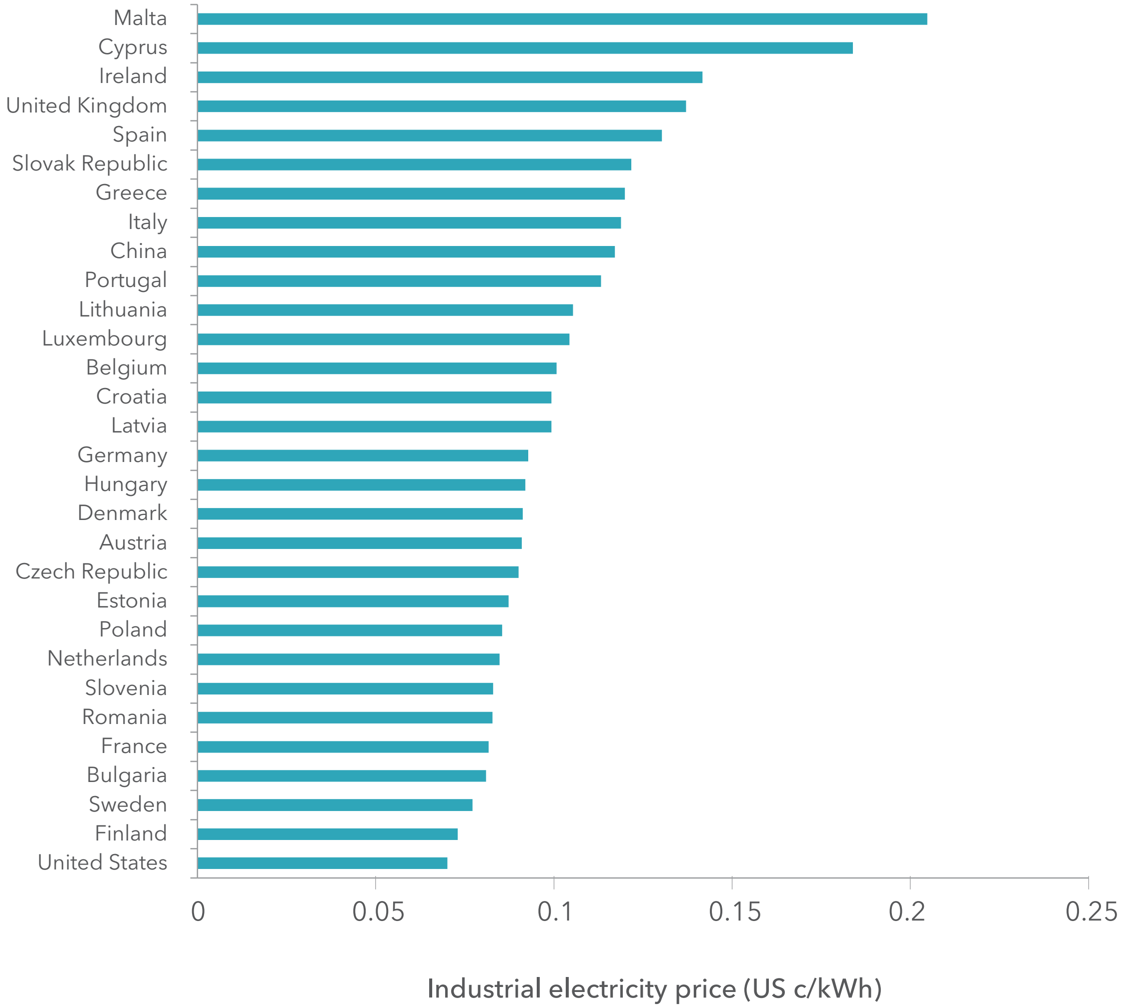
Electricity prices are an important determinant of the cost savings that result from process efficiency improvements in the wastewater sector. In all but one case the abatement modelled here results from electricity savings, and so the electricity price directly determines the associated energy cost saving. In the other case, enhanced biogas production in the anaerobic sludge digestion process, the increased volume of methane created is assumed to be turned into electricity and used to avoid electricity use elsewhere in the treatment process; in this way the electricity price again determines the volume of cost saving.

Electricity prices were generally adopted from Eurostat for European countries, with the US Energy Information Agency providing the US estimate and the OECD providing the Chinese estimate. All electricity price assumptions reflected prices for medium-sized industrial applications, which was the most appropriate and consistently available metric to apply to wastewater treatment plants. For simplicity and to ensure that the analysis is conservative, electricity prices were held constant in real terms over the term of the analysis. Starting electricity price assumptions for 2014 are illustrated in Figure 19.

Wedeco Duron UV installation in Chichester, UK.

Figure 19.

Electricity prices vary substantially by country

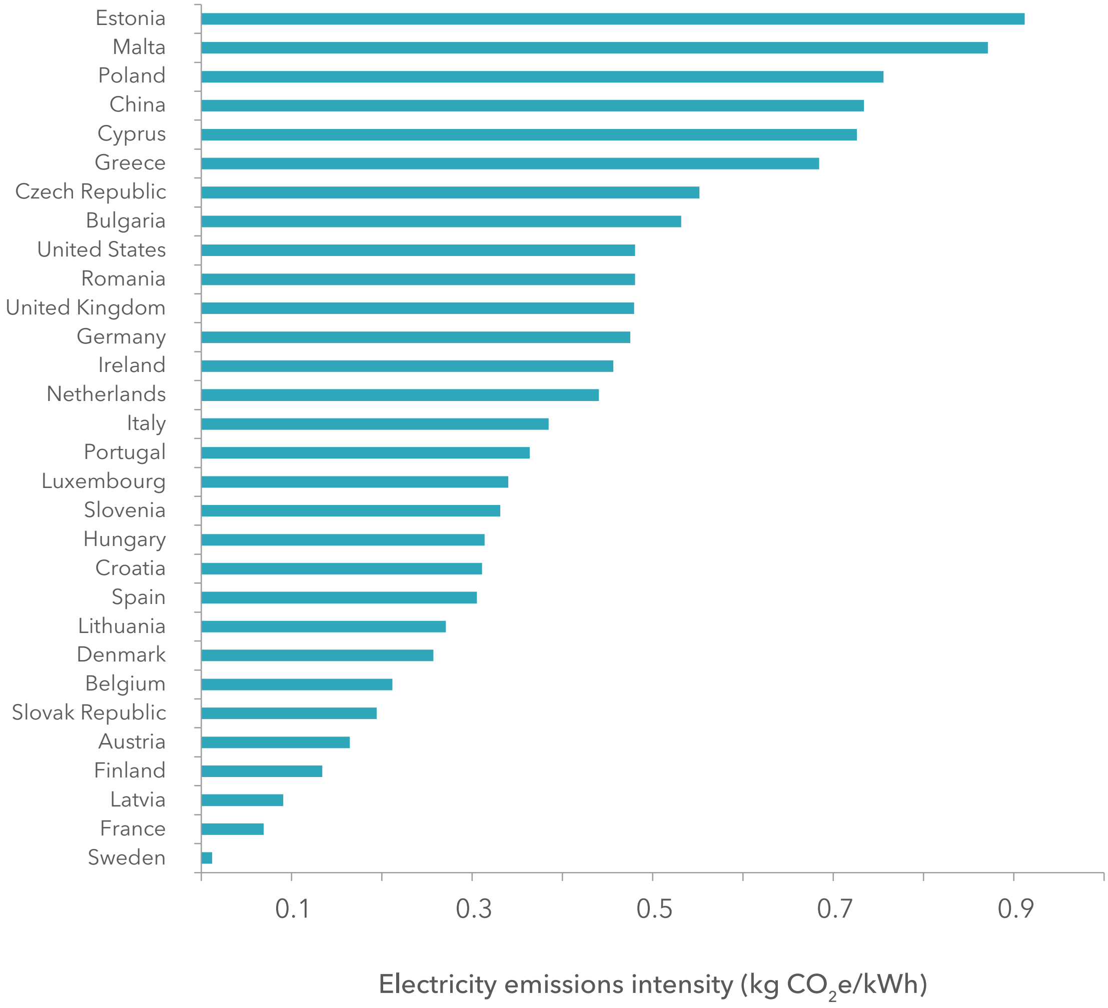


Source: *Eurostat, US EIA and OECD*

Electricity emissions intensity data was extracted from the International Energy Agency's (IEA's) database. Values for 2012 are summarized below. To allow for the likely decarbonisation of electricity supply over time, Vivid Economics analyzed the expected rate of reduction in electricity emissions intensity for the US, China and Europe in the IEA's World Energy Outlook 2013 over the period to 2035. These decline factors were applied to each national emissions intensity estimate over the period of analysis. The annual decline factors adopted were approximately 1.5% for the United States, approximately 2% for China and approximately 3% for Europe. The starting emissions intensity estimates for 2012 are presented in Figure 20.

Figure 20.

China and the United States had higher electricity emissions intensities in 2012 than most European countries



Source: *International Energy Agency*

Cost and efficiency data

Xylem provided capital cost, non-electricity operating cost and electricity use assumptions for both baseline and improved state for each of the eighteen wastewater abatement opportunities identified (see Table 5). These estimates were based on Xylem's estimate of the average efficiency and cost gains that would come from the upgrades to an average wastewater utility. In defining the 'average' efficiency gains for the 'average' utility, primary data from German utilities was used in combination with data sets from relevant literature as these utilities are often more advanced than most, resulting in lower efficiency gains than would come from less advanced utilities. This results in efficiency and cost estimates that are conservative and easily modified to be representative of the regions studied. Vivid Economics verified that application of these high level estimates to wastewater flow data gave overall electricity use estimates that are consistent with aggregate assumptions found in the literature.

This analysis confirmed the overall robustness of these assumptions. In general improved technologies have higher capital costs than standard alternatives, reflecting their higher quality. However, they are more energy efficient and, in general, incur lower non-energy operating costs due to better reliability and reduced maintenance costs.

Capital and non-electricity operating costs were further adjusted between countries based on estimates of wages and of construction costs. Wages were drawn from OECD data and compared to United States wage rates. The resulting index used to adjust 50% of the non-electricity operating cost relative to the core estimate, which was developed using Xylem's understanding of United States operating costs.

For capital costs, per unit construction costs for a series of building types were extracted from the Turner & Townshend capital cost survey for 2013 (Turner & Townshend, 2013). Data was available for the United States, China, Germany, Netherlands, Poland and the United Kingdom. Costs for other countries were indexed based on costs in the most comparable country. Fifty percent of the total construction cost was indexed based on these construction cost estimates, reflecting that a substantial portion of the total capital cost would be for equipment rather than civil works, and therefore would be relatively uniform by location.

Global extrapolation

The core study focuses on three regions: the United States, Europe and China. To give an indicative estimate of the potential global volume of abatement from energy efficiency in the wastewater sector, Vivid Economics has estimated the approximate portion of global wastewater electricity emissions that are covered by these three regions. Noting that a range of factors will vary between the regions inside and outside the core study, such as the shares of different treatment types and a range of cost factors, the approach taken here to account for these factors should give a strong indication of the potential scope of global abatement. Also, as the cost of abatement and incremental rate of return on different improvement options are heavily driven by the core capital and operating costs and the volume of the electricity saving, the pattern of significant volumes of negative cost abatement would be expected to recur in most regions.

The methodology for the global extrapolation is broadly as below:

- Analyze available wastewater flow data from the FAO's AQUASTAT database;
- Combine this with population data to examine trends in flows per capita over time in countries with different income classifications;
- Use these flow per capita estimates by country type and population estimates for 2015 to normalise all available AQUASTAT flow estimates to 2015 as a common base year;
- Use the implied 2015 flow per capita volumes for different regional and country groupings to estimate flows per capita for countries outside the AQUASTAT sample;
- Use 2015 population data to derive total flow estimates for all countries outside the AQUASTAT sample;
- Use US, European and Chinese levels of electricity input per unit of wastewater treated to estimate wastewater electricity use in all countries of interest, with developing countries adopting the Chinese figure and developed countries either the US or European figure depending on region of location;
- Use 2012 emissions intensity data from the IEA to weight the total wastewater treatment flow in each country in accordance with the likely emissions implied in its treatment;
- Calculate the portion of implied global wastewater electricity emissions that are within the scope of the study, that is United States and Europe emissions to 2015 and Chinese emissions to 2020, and the portion that is outside the study.

This methodology informed the calculations set out above in Table 12 that estimate 2015 wastewater flows for the in-study countries.

The rate of growth of wastewater flow per capita was based on the average annual rate of growth implicit in all countries that have two wastewater flow data points in the AQUASTAT database. There are 51 such countries, across four broad income classifications. The calculation was weighted by total population to ensure that outlying observations from small countries do not distort the average. The calculated annual rate of growth for each income classification is:

- 0.7% for high income OECD countries;
- 1.3% for high income non-OECD countries;
- 8.7% for upper middle income countries; and
- 9.0% for lower middle income countries.

No low income countries had two observations in the AQUASTAT database; therefore a 9.0% growth rate was also adopted for this grouping.

Once wastewater flows per capita were normalized to the common base year of 2015, the average flow per capita was calculated based on geographic region rather than income level, except for high income countries. This applied the logic that many countries in the same region have the same income classification, and different regions may have different water availability and therefore level of wastewater treatment. The regional and income group averages are set out below, expressed as cubic meters of treated wastewater per capita:

- 100 cubic meters of treated wastewater per capita for high income OECD countries;
- 47 for high income non-OECD countries;
- 56 for countries in Europe (non-OECD) and Central Asia;
- 33 for countries in East Asia and the Pacific;
- 30 for countries in Sub-Saharan Africa;
- 26 for countries in Latin America and the Caribbean;
- 25 for countries in the Middle East and North Africa;
- 5 for countries in South Asia.

The exceptions to these assumptions were European countries that were within the core study sample, that is, the 28 European Union countries. Where observations were not available for those countries, observations for treated wastewater per capita for similar and/or geographically close countries were adopted and used to estimate total flows, as shown in Table 12.

Once weighted by electricity input intensity and emissions intensity, this analysis indicated that 47% of global wastewater treatment electricity emissions were analyzed in the core study and 53% were outside the study. In turn this suggests that abatement volume estimates for the core study regions can be more than doubled to provide an indicative global abatement volume estimate.

Peer reviewer comments

To ensure methodological and analytical rigor, this paper was reviewed by several external experts with relevant technical knowledge. Each reviewer was asked to provide unbiased feedback on areas related to their domain expertise, including wastewater technology, energy efficiency, and environmental economics. These reviewers provided excellent and detailed feedback that improved this paper, and each reviewer consented to publication of the summary comments provided below.

"I think the economics work is well done and the report is well written. I have looked closely at a critical part of the spreadsheet, and I believe that the IRR calculations are correct, given the inputs. The results are plausible and reasonable, given the barriers to public works projects.

I confirm that the results are relatively insensitive to carbon price and discount rates, as the report says, but the results are sensitive to changes in electricity consumption from the selected technology and to electricity prices. Fortunately, a spot check of US electricity prices found the report's result to be conservative."

- **Stig Morling,**
  SWECO Environment

"I reviewed a draft of the report and tested both its analytical structure and its assumptions, focusing on China. The report adopts a logical framework supporting a comprehensive analysis. I challenged the assumptions made on the process composition in China, but ultimately decided that there is indeed a mix of processes in China including AAO (anaerobic-anoxic-oxic), OD (oxidation ditch), and CAS (conventional activated sludge). For the purpose of this paper, with its focus on the case for abatement investment globally, I agreed it was appropriate to treat all these processes as a family of options and to have CAS serve as a proxy, so long as this is clearly explained. Care is needed in assigning abatement potential between existing and new treatment plant, where new plant are generally of smaller scale. As a next step, I suggest a follow-up study that specifically focuses on China with more granular assumptions and tailoring of content towards Chinese stakeholders."

- **Lijin Zhong,**
  World Resources Institute

"I have examined the report and considered the engineering potential and costs for improvements in energy efficiency and emissions abatement generally. Drawing on my experience of many plant investigations, I believe the potential identified in the report is reasonable. Indeed, there will be circumstances in which greater savings are possible, for example, in the early life of new plant when loading is below design capacity and through system optimization beyond the options discussed in this report. The realization of these savings will be dependent on the skill and motivation of commissioning engineers and operational staff. Without dedicated, experienced staff, opportunities will be missed. This human factor is not taken into account in [this] assessment but it will be important in determining whether the abatement takes place. Furthermore, as the quality demanded of wastewater treatment works effluent evolves in the future, the opportunities for abatement will change. This could be examined through the use of scenarios of future quality standards if the work were to be extended.

My comments on the report concerned these points and some suggestions to improvement of the text, including addition of a list of abbreviations and glossary."

- **John F. Raffensperger,**
  Ph.D., The University of Chicago

Glossary

Abatement	Reduction in emissions
Abatement cost	The unit cost, in this report in USD, of abating one ton of carbon dioxide
Carbon price	The market value of a traded allowance to emit carbon dioxide, or the rate of a tax on carbon dioxide emissions
Discount rate	The return required on money over a year to make it worth not spending it the money this year but instead to wait until next year to receive it plus the return
Effluent	Wastewater discharged to sewer
Fugitive emissions	Emissions which escape and are not a product of combustion
Internal rate of return	The discount rate that would give an investment a net present value of zero
Levelized cost	Annuity giving the same present value as a schedule of costs
Marginal abatement cost curve	A set of ranked abatement measures placed in order of increasing unit abatement cost
Negative cost of abatement	Abatement with cost savings greater than expenditure
Organic	Substance made of carbon, hydrogen and oxygen, often of biological origin
Present value	The weighted sum of a series of costs (or benefits) over time where the weights are discount factors derived from the discount rate and the time when the cost (or benefit) occurs
Real discount rate	The discount rate adjusted for inflation

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Xylem |'zīləm|

1) The tissue in plants that brings water upward from the roots;
2) a leading global water technology company.

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