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Wastewater to Energy Processes: a Technical Note for Utility Managers in EAP countries

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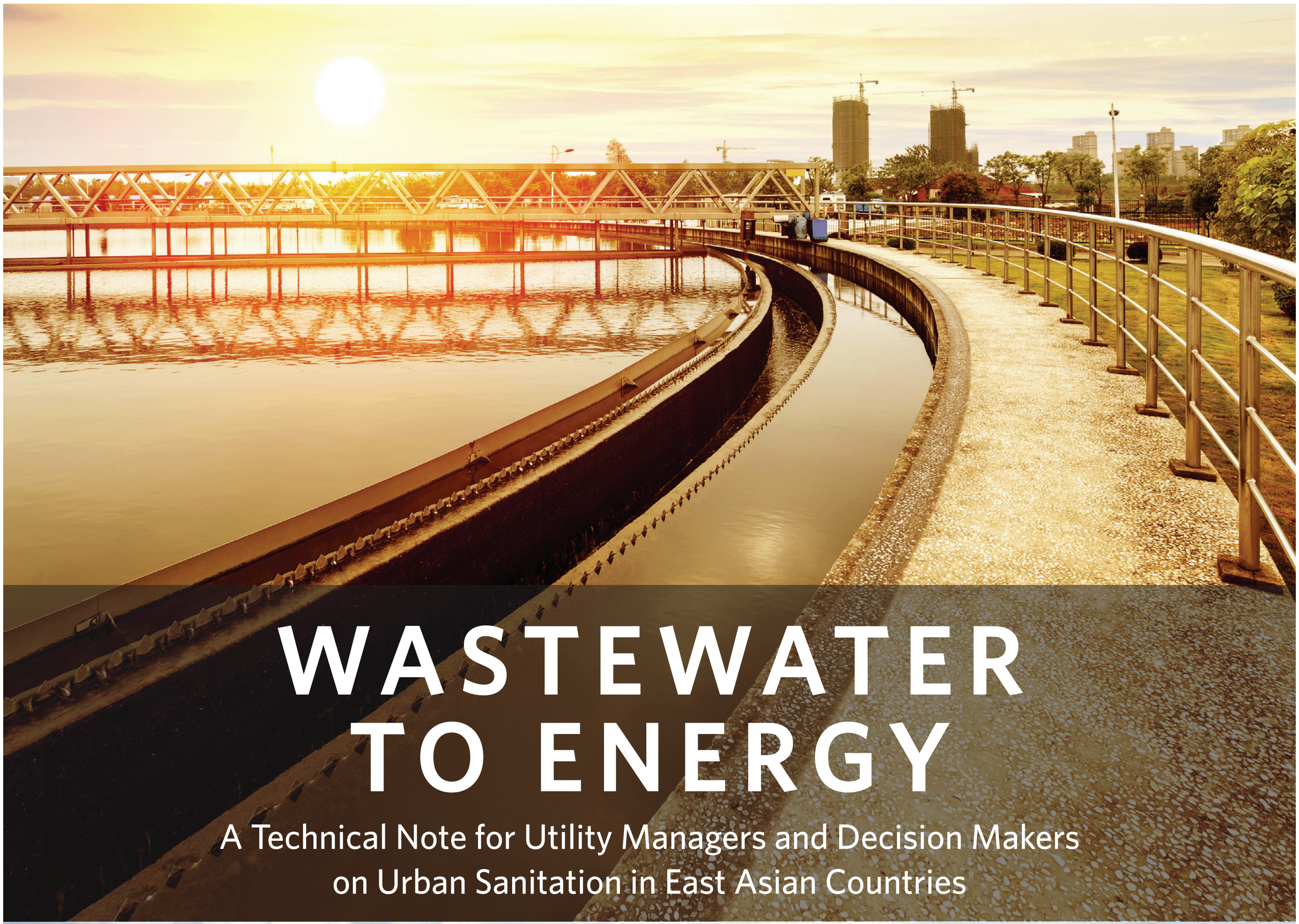

WASTEWATER TO ENERGY

A Technical Note for Utility Managers and Decision Makers on Urban Sanitation in East Asian Countries

January 2015

WORLD BANK GROUP
Water

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FOREWORD

The East Asia Urban Sanitation Review: A Call for Action (World Bank 2013) highlighted the importance of improving collection, treatment, and disposal of human waste in cost-effective ways in East Asian cities. It also recommended the systematic exploration of opportunities to use wastewater as a resource for the production of energy at treatment facilities and an increased emphasis on this approach, together with others, such as the generation of biosolids from sludge, as parts of a climate-smart sanitation strategy.

This technical note explores in greater depth the production of energy in wastewater treatment plants as an option to save costs in the operation of these facilities. This is relevant for two reasons. First, in East Asia, where urban populations have been growing rapidly and becoming increasingly dense, an exclusive reliance on onsite sanitation services is not possible, which presents a clear need to invest in infrastructure to collect and treat wastewater. This infrastructure is expensive to build and run; however, identifying smart cost-saving measures can help relieve the burden of utilities that struggle to expand wastewater collection and treatment services in a financially sustainable manner.

Second, research has traditionally focused on energy efficiency measures and energy generation with respect to wastewater treatment technologies that are energy intensive and work well in the cold climates usually found in developed countries. This leaves a knowledge gap that needs to be bridged to inform utility managers in developing countries about the factors that need to be in place for the adoption of options like "wastewater to energy," particularly applied to low-cost treatment options and conditions in warm developing climates.

With the urban wastewater sector in its early stages of development in many East Asian countries, the World Bank Group is committed to working with these countries to promote informed decisions and find innovative, cost-effective solutions that will contribute to improving the environmental conditions of rapidly growing cities and expanding sanitation services to increasing numbers of people, including the poor.

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The task team leader for producing this report was Victor Vazquez, and the sector managers were Charles Feinstein and Ousmane Dione. The main author was Konrad Buchauer (consultant). Main technical inputs were provided by Daniel Nolasco and Amit Pramanik (consultants) and the following staff from the World Bank and the Water and Sanitation Program (WSP): Sudipto Sarkar, Iain Menzies, Hung Duy Le, Sing Cho, Irma Setiono, Demilour Reyes Ignacio, Carmen Yee-Batista, Alexander Danilenko, and Christopher Ancheta. Mara Baranson and Lisa Ferraro Parmelee also made important contributions. The peer reviewers for this work were Kartik Chandran (Columbia University), Tim Shea (CH2MHill), Feng Liu, Peter Johansen, Satheesh Kumar, Manuel Mariño, and the East Asia WSP team at the World Bank.

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The report contains three parts, namely, the Main Report, Technical Annex and Assessment Tool. Only the Main Report is printed. The full report is available through the GP Water website at www.worldbank.org/water.

ACRONYMS AND ABBREVIATIONS

ABR	anaerobic baffled reactor
AD	anaerobic digestion
AeP	(mechanically) aerated pond
AFR	Africa (World Bank region)
ANEEL	*Agencia Nacional de Energia Eléctrica, Brazil*
AP	anaerobic pond
ASE	Alliance to Save Energy
AT	aeration tank
BAR	baffled anaerobic reactors
BOD5	five-day biochemical oxygen demand
CAP	covered anaerobic pond
CAPEX	capital expenditure (=investment cost)
CAS	conventional activated sludge
CDM	Clean Development Mechanism
CH4	methane
CHP	combined heat and power
CO_2e	CO_2 equivalent
COD	chemical oxygen demand
COPASA	*Companhia de Saneamento de Minas Gerais*
CW	constructed wetland
DBO	design-build-operate contract
DS	dry solids
DWA	German Association for Water, Wastewater, and Waste
EA	extended aeration (=activated sludge system with simultaneous aerobic sludge stabilization)
EAP	East Asia Pacific (World Bank region)
ECA	Europe and Central Asia (World Bank region)
ENACAL	*Empresa Nicaragüense de Acueductos y Alcantarillados*
ESMAP	Energy Sector Management Assistance Program
EU ETS	European Union Emissions Trading System
FOG	fat, oil, and grease
FST	final sedimentation tank
FY	fiscal year
GHG	greenhouse gas
GRP	glass fiber reinforced pipe
IBRD	International Bank for Reconstruction and Development
IDB	Inter-American Development Bank
IWA	International Water Association
KfW	*Kreditanstalt für Wiederaufbau*
LAC	Latin America and Caribbean (World Bank region)
MBBR	moving bed bioreactor
MBR	membrane bioreactor
MDG	Millennium Development Goals

MENA	Middle East and North Africa (World Bank region)
MGD, mgd	million US gallons per day (1 MGD = 3.7853 MLD)
MLD, mld	million liters per day (1 MLD = 1,000 m^3/d)
MLSS	mixed liquor suspended solids
N	nitrogen
NH_4	ammonia
NO_3	nitrate
O&M	operation and maintenance
OPEX	operation and maintenance expenditure (=O&M cost)
P	phosphorus
PAC	poly-aluminum-chloride
PE	population equivalent
PE_{60}	population equivalent, based on 1 PE_{60} = 60 $gBOD_5$ per capita per day
PE_{110}	population equivalent, based on 1 PE_{110} = 110 gCOD/cap/d
PE_{120}	population equivalent, based on 1 PE_{120} = 120 gCOD/cap/d
PS	primary sludge
PST	primary sedimentation tank
SAR	South Asia (World Bank region)
SBR	sequencing batch reactor
SST	secondary sedimentation tank
STP	sewage treatment plant
TF	trickling filter
TSS	total suspended solids
UASB	upflow anaerobic sludge blanket
USAID	U.S. Agency for International Development
USD	ultrasound sludge disintegration
VDS	volatile dry solids
VS	volatile solids
VSS	volatile suspended solids
WAS	waste activated sludge (also called secondary sludge)
WEF	Water Environment Federation
WERF	Water Environment Research Foundation
WSP	waste stabilization pond
WWTF	wastewater treatment facility
WWTP	wastewater treatment plant

Currency equivalents

Exchange Rates used in this report

AUD 1.5 (Australia) = EUR 1.0

R$ 2.5 (Brazil) = EUR 1.0

C$ 30.0 (Nicaragua) = EUR 1.0

US$ 1.35 (USA) = EUR 1.0

EXECUTIVE SUMMARY

Sanitation services in many East Asian cities struggle to keep pace with rapid urban growth. The East Asia Urban Sanitation Review (World Bank 2013) showed the enormous challenges the sanitation sector faces in most urban areas in the region, primarily excessive dependence on defective onsite sanitation in cities with high population densities and persistently low wastewater collection and treatment coverage levels (1 percent, 4 percent, and 10 percent in Indonesia, the Philippines, and Vietnam, respectively).

In addition to upgrading existing onsite sanitation services, the growing population densities necessitate expanding collection networks and building sustainable treatment plants that prevent the accumulation of wastewater in the numerous waterways and canals crossing the cities' packed neighborhoods. Plans to invest in scaled-up urban sanitation services and expanded wastewater collection and treatment infrastructure are already in place. For instance, in Vietnam alone, more than thirty new wastewater treatment plants are to be built in the coming years.

Meanwhile, existing wastewater utilities in East Asia are struggling to perform. The high expense of operating modern sewerage collection networks and, more in particular, wastewater treatment plants is often an obstacle to expanding and improving services for a sector that usually has low cost recovery rates and depends on unpredictable government transfers. Utilities tend to reduce costs where they can, most notably by saving on maintenance and electricity supply. The result is deteriorating treatment efficiencies, shortened lifespans for facilities, which often fall into disuse, and wasted investments. In Indonesia, for instance, only 47 percent of the treatment capacity installed in the 1990s is being used today (World Bank 2013).

In short, cost efficiency in the operation and maintenance (O&M) of treatment plants is essential. It can be achieved in three ways:

- By implementing effective and realistic energy efficiency processes.
- By selecting appropriate treatment technologies that are generally low-energy consumers.
- By generating electricity onsite from biogas resulting from anaerobic digestion of sludge or wastewater.

Work conducted by the Energy Sector Management Assistance Program (ESMAP) and the Water Environment Foundation (WEF) in 2012 focused on energy efficiency in operations. This technical note builds on that contribution and shows that, with a series of enabling factors in place, considerable savings can also be realized by adopting energy generation in low-cost treatment technologies, which will contribute to putting utilities in a better financial position to improve their service provision.

Also taken into consideration is a paradigm shift in the way wastewater is considered by society. Previously seen as a costly "problem," nowadays it is increasingly treated as a resource that can raise returns on investments. The potential for resource recovery from wastewater is wide, with the following options among the most common:

- Treated wastewater as a water resource for applications in agriculture, industry, aquaculture, urban and recreational uses, groundwater recharge, or drinking water supply
- Wastewater/sludge as a nutrient resource, from which phosphorus and nitrogen can be extracted and sold
- Sludge as an agricultural resource, whose fertilizing effects and soil improvement functions also give it an important role to play in the mitigation of greenhouse gas (GHG) emissions
- Wastewater/sludge as a renewable energy resource, whose use also helps reduce GHG emissions

The focus in this technical note is on the last aspect, paying attention not only to lower operation and maintenance expenditure on wastewater treatment, but also to a reduction in the carbon footprint of sludge management. A comprehensive comparison of energy recovery options with respect to different treatment schemes, particularly from the perspective of developing countries in warm climates, is absent from the specialized literature.

Objectives of the Technical Note

This technical note is directed to technical decision makers and utility managers in developing countries in East Asia Pacific (EAP). Its purpose is to facilitate learning on how to achieve significant savings in the operation of wastewater treatment plants (WWTPs) through the selection of appropriate treatment technologies and the utilization of financially viable wastewater-to-energy potentials and to explain the factors that need to be considered when investing in these processes. To these ends, the technical note does the following:

- It aims to fill a knowledge gap in the topic of energy generation in wastewater treatment plants with a focus on low-cost treatment options suitable for developing countries.
- It builds on the East Asia Urban Sanitation Review, conducted by the World Bank in 2013, which provided an overall assessment of the main challenges in the urban sanitation sector in Indonesia, the Philippines, and Vietnam. While this technical note likewise focuses mainly on these countries, many of its conclusions and recommendations could be applied to other countries with similar conditions and challenges.
- It provides an opportunity for the many EAP cities with low coverage of centralized sanitation services that plan to expand wastewater infrastructure to “get it right” in the first place by learning from existing practical experience and knowledge of how to keep O&M cost low from the investment stage.
- It provides the following in its explanation of how to generate energy from wastewater:
  - Evidence on the relevance of energy costs in the operation of WWTPs
  - Evidence on the potential savings from combining the adoption of smart treatment technologies with investment in energy recovery
  - Examples of best practices in the sector
  - A rapid assessment tool for conducting a preliminary evaluation of the viability of energy recovery options
  - Typical constraints and enabling factors that need to be considered when deciding on wastewater-to-energy investments

Methodology

The study is divided into three main sections. Section I presents the results of a comprehensive desk review describing the problem of utilities dealing with high operation costs in wastewater treatment plants, the link between energy consumption and the type of technology used for treatment, and the potential for energy generation.

Section II summarizes the findings from a series of case studies presenting a wide range of wastewater-to-energy options that could be considered in developing countries, paying particular attention to the characteristics of EAP countries (see table 1). The case studies cover all major biogas generation technologies that should be considered in warm climate countries like those in the region. Among them are typical technologies commonly used in developed countries, including examples from Europe, and technical developments appropriate for developing or transition countries. The analysis of the case studies looks into energy consumption at the WWTP, biogas quantities and characteristics, the potential for electricity generation, operation capacity needs, safety concerns, institutional aspects, greenhouse gas (GHG) reduction, co-financing through carbon trading mechanisms, cost-related aspects of capital expenditures (CAPEX), operational expenditures (OPEX), and overall financial viability.

Table 1: Case Studies Analyzed in this Technical Note

Case study	Biogas from wastewater treatment	Biogas from sludge treatment	Location of case study
1. CAS + sludge digestion	—	X	Europe
2. TF + sludge digestion	—	X	Nicaragua
3. UASB	X	—	Brazil
4. Covered anaerobic ponds	X	—	Bolivia, Australia
5. Co-digestion of organic waste	—	X	Europe
6. Ultrasound sludge disintegration	—	X	Europe

Note: CAS = conventional activated sludge; TF = trickling filter; UASB = upflow anaerobic sludge blanket.

Finally, section III draws conclusions from the previous sections to identify existing constraints that need to be addressed and factors that need to be in place when considering investments in energy generation at WWTPs.

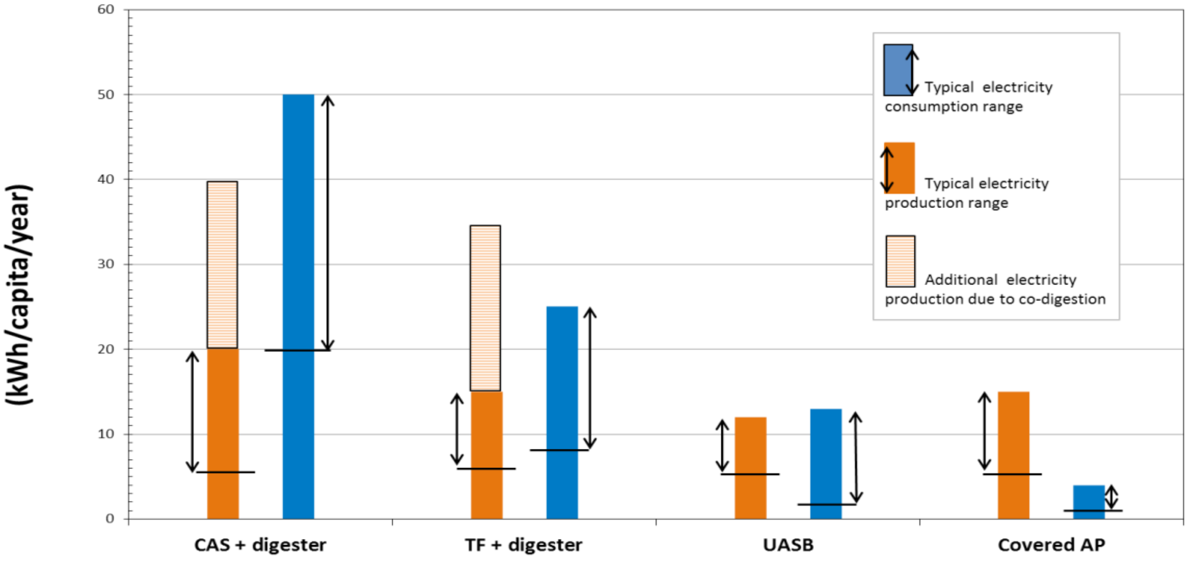
Key Findings from the Desk Review and Case Studies

The first of the key findings discussed in sections I and II of this technical note is that the electricity produced by wastewater-to-energy facilities can be sufficient to achieve substantial cost reductions at well-functioning WWTPs. Both the desk review and case studies show that a WWTP's OPEX structure depends mainly on the selected technology and on various parameters influenced by local conditions. Electricity cost is an important operational expenditure, contributing up to 50 percent of the WWTP's total OPEX. Existing cases indicate this percentage will be even higher in EAP than in Europe or the United States.

It is important to highlight that wastewater to energy does not compromise treated water quality. The overarching goal of all WWTPs, which is wastewater treatment that complies with locally prevailing standards, is usually not constrained by wastewater to energy. Only in cases where sludge digesters are used and no nutrient emission standards exist does wastewater to energy imply a slight increase in effluent nutrient emissions.

The case studies analyze the electricity consumption and potential for electricity production from biogas at WWTPs. The summary in figure 2 shows that the various wastewater treatment technologies differ significantly in energy consumption, while the same technologies are more similar in their potential to generate electricity. The cost-saving potential in absolute terms of biogas utilization is, thus, similar for all technologies. In relative terms, though, the potential is higher for technologies with low energy consumption, where the OPEX levels are already low. These technologies may even become energy independent, which not only has financial benefits but improves operational safety due to reduced dependence on public power supply.[1]

Figure 2: Electricity Consumption versus Production of Different Technologies



Notes: kWh/capita/y x 16.67 = kWh/kg BOD_5/y.

CAS = conventional activated sludge; TF = trickling filter; UASB = upflow anaerobic sludge blanket; AP = anaerobic pond.

The cost of generating electricity from biogas is low and usually competitive with the unit cost of electricity from the public grid. Large biogas facilities can generate electric power at US$0.02/kWh,[2] whereas the cost to purchase power in EAP countries ranges from US$0.06 to US$0.22/kWh.

A series of factors needs to be considered to assess the overall viability of investments in wastewater-to-energy projects. Table 2 summarizes the commonly found barriers and the factors that may make it possible to overcome them.

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[1] Although the utilization of biogas can also generate considerable quantities of thermal energy, heat is in low demand in warm climate countries. This technical note focuses, therefore, on electricity, which has a higher economic value.

[2] These results are based on life cycle assessments of CAPEX and OPEX of all installations typically required for this practice, including biogas treatment.

BARRIER	ENABLING FACTORS
A SIZE OF THE PLANT	
Plant size can be a barrier to wastewater-to-energy projects, as **investments are usually only beneficial above certain minimum capacity thresholds** for wastewater treatment and, therefore, sludge generation. These thresholds are around 10,000 PE$_{60}$,* or 2,000 cubic meters per day (m^3/day) in developed countries. *Population equivalent, based on 1 PE$_{60}$ = 60 gBOD$_5$/capita/day.	A preliminary assessment for conditions in EAP countries showed the threshold in this region may vary between 10,000 and 100,000 PE$_{60}$ (2,000–20,000 m^3/d). A **case-by-case analysis is required** to determine the real threshold in each case. The tool included in this technical note can be used for that purpose.
B WASTEWATER DILUTION	
The most common technical barrier to wastewater-to-energy projects is wastewater dilution, a problem particularly common in many EAP cities where wastewater reaching the plants has low pollution concentrations. Hence, **the conditions in EAP may reduce the potential for biogas and energy generation**.	A **case-specific analysis,** for which the assessment tool provided by this technical note may prove helpful, **should become the standard approach**. A key indicator worth considering is the average influent total suspended solids concentration (TSS). If **TSS is $\leq$ 80 milligrams per litre (mg/L)**, then neither sludge digesters (lacking primary sludge) nor anaerobic wastewater technologies (requiring large volumes) are attractive. Yet, even under these conditions, **co-digestion** of organic feedstock or fecal sludge could make wastewater to energy viable.
C UNINFORMED DECISIONS	
Uninformed technical decisions are frequent in the countries considered here and can be attributed to (a) a lack of comprehensive information on all options for wastewater to energy; (b) a tendency to "copy and paste" technologies used in other countries, thus ignoring low-cost treatment technologies better suited to warm climates; (c) a preference for "cutting-edge" technologies; and (d) too much emphasis on CAPEX and less concern about OPEX.	Introducing holistic **technology benchmarking** to the sector will allow operators to learn from the best performers. Both average performance and benchmarks will usually improve over time. **The knowledge gap can be closed** through publications like this technical note, pilot plants, workshops, the regular exchange of operational experiences among different WWTPs, and operator training.
D INSUFFICIENT OPERATOR TRAINING	
Operators are not always well trained and informed about regular operating routines and even less so about troubleshooting techniques and necessary conditions for adequate biogas system functioning.	**Providing regular, good quality training** will ensure that operators understand potential problems and have the means for process control and intervention. An interesting option may be **involving the private sector by subcontracting out energy generation** as a separate operation unit within the WWTP, thus eliminating the need for operator training for this specialized task.

BARRIER	ENABLING FACTORS
E INADEQUATE O&M AND SAFETY ISSUES	
A utility should not invest in waste-to-energy options at its WWTPs if it follows a practice of **undermaintaining the existing facilities**. Failures of wastewater-to-energy options in existing WWTPs are often caused by insufficient maintenance, slow procurement of spare parts, or unwillingness to involve specialized third parties.	**Maintenance** of the WWTP **should be understood as an essential expenditure** that helps reduce total life cycle cost rather than an expenditure that should be minimized. Proper instruments for asset management should be in place.
Safety issues are also a common concern among practitioners in the sector. Risks usually only arise, however, in cases of inappropriate design, material quality issues, or ignorance of simple O&M precautions. Problems may also arise if power supply is unreliable.	Wastewater-to-energy technologies are not complicated to operate, and **safety and operation risks are low** if (a) projects are properly designed (wastewater + sludge + biogas); (b) specifications in the bidding documents are tailored to needs; and (c) operational protocols developed for these technologies are followed. **Design-build-operate (DBO) contracts** for the complete WWTP, including the biogas component, can be an attractive option. If **public power supply** is needed but considered unreliable, then additional backup systems or smart biogas and power management strategies are indispensable.
F REGULATORY FRAMEWORK	
Power companies may add barriers to the production and use of electricity in wastewater treatment plants. In cases where a power surplus is produced at the plant, electricity cannot be stored inexpensively, and flaring biogas is a waste of resources.	Generally, it is recommended that electricity from biogas be used onsite at the WWTP to cover its own operation needs. For electricity surpluses, **a clear tariff policy that includes the option of supplying bioelectricity to the public grid** is needed to make wastewater to energy viable.
A lack of a clear regulatory framework for co-digestion could be a problem, particularly if responsibilities for collection and disposal are not clearly distributed among the waste producer, the waste collector, and the entity responsible for final disposal.	The institutional tasks and responsibilities governing the collection and disposal of various wastes need to be clarified while still allowing the **necessary flexibility for co-digestion** of sludge and waste and the subsequent disposal or reuse of the digested mixed product. It is helpful **for wastewater utilities to have contracts directly** with other utilities, private collection companies, and/or waste producers.
The required effluent quality has implications for both the energy consumption and the electricity generation potential of WWTPs. The stricter the effluent standards, the lower the coverage ratio for electricity (production versus consumption) will be. Strict standards thus not only increase CAPEX (because installations are larger), but also OPEX.	In countries where treatment levels are as low as in EAP, **the first priority should be installing facilities that remove the bulk of the organic pollution**. Nutrient removal may only be introduced at a later stage, where environmentally justified. A sensible approach should allow for (a) **more lenient standards for small WWTPs**, since their environmental impacts are small as well and (b) **stricter standards for large WWTPs only where the recipient water is indeed sensitive** to the discharges.

BARRIER	ENABLING FACTORS
G SUBSIDIZED ELECTRICITY COST	
Subsidies that reduce unit costs of electric power can prove a major obstacle to energy recovery from renewable resources. The decision to undertake an energy recovery project is based mostly on an assessment of its financial viability. Thus, the more subsidized the cost of electricity is, the less attractive the investment in energy recovery will be.	**Subsidies** to electricity **should be minimized** as much as possible.
H ECONOMIC AND FINANCIAL ANALYSIS	
Utilities or municipal departments responsible for wastewater operations usually have little margin for financial maneuvering, which implies **difficulty in obtaining financing** for wastewater-to-energy investments. They also may have other priorities, given their limited capital resources. The economic analysis for this type of investment is often limited to requirements for a short, predetermined payback period.	Reduced OPEX could have positive effects on cash flows and free funds for vital investments at given points in time. **Decision makers should perform more comprehensive cost-benefit analysis** by calculating net present values, operational savings, and potential gains in cash flows. **Considering alternative sources of funding** is also advisable.
The present **low price level of carbon credits** renders most wastewater-to-energy projects unattractive for Clean Development Mechanism (CDM) application.	Many facilities are nevertheless interested in **quantifying greenhouse gas (GHG) emission reductions achieved** as proof of environmental stewardship.

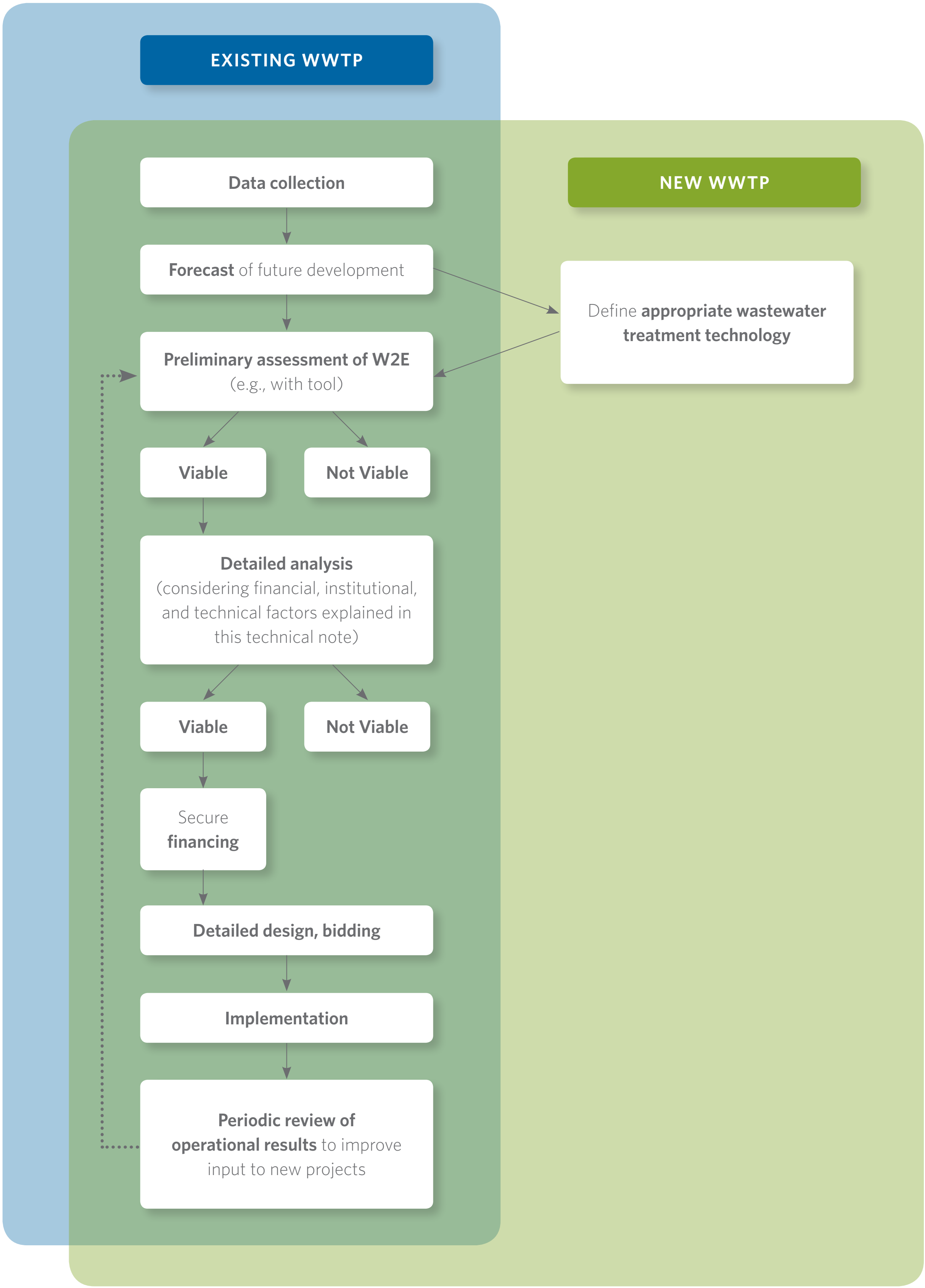
The Way Forward: A Wastewater-to-Energy Preliminary Assessment Tool

Since project-specific analysis is usually indispensable, this technical note presents in section II a simple assessment tool developed in spreadsheet format. This tool allows a quick preliminary quantification of OPEX-related implications of wastewater-to-energy facilities, as well as preliminary design of its major components. The CAPEX estimation and combined life cycle assessment remain up to the user, since they depend on a multitude of local factors that defy simple generalizations.

Also presented is an example of the tool's application, based on a specific WWTP in the Philippines. The assessment considers different influent characteristics, drawing conclusions on the viability of biogas generation in each case.

Finally, figure 4 summarizes the main actions recommended for successful wastewater-to-energy projects.

Figure 4: Guidance on Decision Making and Required Actions for Wastewater-to-Energy Projects



SECTION I: CONTEXT AND PROBLEM STATEMENT

1. Background in East Asia Pacific Countries

Wastewater collection and treatment levels in the rapidly growing cities of the East Asia Pacific (EAP) region are low, and providing adequate sanitation services in these areas is a serious challenge. As table I-1 shows for some typical cases, many of these cities, where land availability is a constraint, are dealing with increasing urban population densities.[3]

Table I-1: Typical Growth Characteristics of Cities in EAP Countries

Country	City	Population 2010	Population increase since 2000 (%)	Population density in 2010 (per sq. km)	Population density increase since 2000 (%)
Indonesia	Garut	1,136,926	70	24,749	26
	Jepara	515,777	70	10,783	23
	Tasikmalaya	1,594,737	50	17,090	26
Philippines	Angeles City	683,176	61	3,678	17
	Cebu	1,527,407	50	9,461	14
	Manila	16,521,948	35	12,958	9
Vietnam	Hanoi	5,642,882	60	6,634	10
	Hai Phong	1,221,115	49	6,144	21
	Da Nang	869,178	55	9,870	10

Source: World Bank 2014.

Most such cities have traditionally relied on onsite sanitation services, characterized by large numbers of septic tanks (usually poorly constructed), informal desludging services, and unsafe disposal of waste (World Bank 2013c). While improving septage management is necessary, the right strategy to adopt when urban densities are so high is to progressively extend sewerage systems to collect wastewater from households. As shown by figure I-1 and table I-2, the areas covered by centralized wastewater collection and treatment services in EAP are still too small. The consequences are cities packed with people living along waterways and open canals polluted with wastewater, with the resultant risk to public health.

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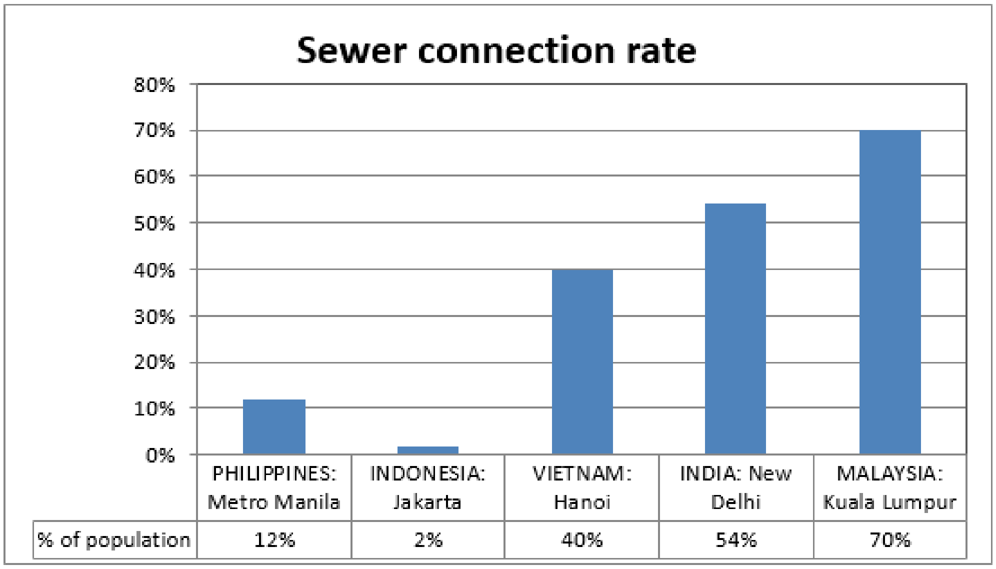
[3] This is often not the case in some cities in China, where urban population densities remain stable or even decline, despite the high population growth rates

Figure I-1: Sewer Connection Rates of Selected Cities in Indonesia, the Philippines, and Vietnam, as Compared to Other Asian Cities



Source: World Bank 2013, Siemens AG, 2011.

Large Investments Will Be Required to Tackle the Existing Sanitation Deficit. Most cities in EAP have plans or are already implementing projects to expand and upgrade centralized collection and treatment services. For instance, in Vietnam alone, where seventeen WWTPs are currently in operation, more than thirty are in the pipeline or under construction (World Bank 2013c). Indonesia is planning to construct area-wide sewage systems in forty medium-sized cities, and in Metro Manila, Philippines, the two concessionaires are or will be undertaking ambitious wastewater collection and treatment projects to comply with a 2008 Supreme Court mandate to improve the water quality of Manila Bay. Table I-2 shows that more than 90 percent of the wastewater/septage (representing 176 million out of a total of 194 million urban people) is not collected or treated in these three countries.

Table I-2: Summary Status of Urban Wastewater and Septage Management in EAP Countries

	Indonesia	Philippines	Vietnam
Total urban population	110 million	61 million	23 million
	194 million		
Urban population without wastewater/ septage treatment	105 million	51 million	20 million
Wastewater treated	1%	4%	10%
Septage treated	4%	10%	4%
	176 million		

Source: World Bank 2013c.

Urban populations are expected to increase in these countries by more than 50 percent by 2025, and sanitation investments needed to connect them to sewerage and treatment systems are estimated at US$74 billion (World Bank 2013c).

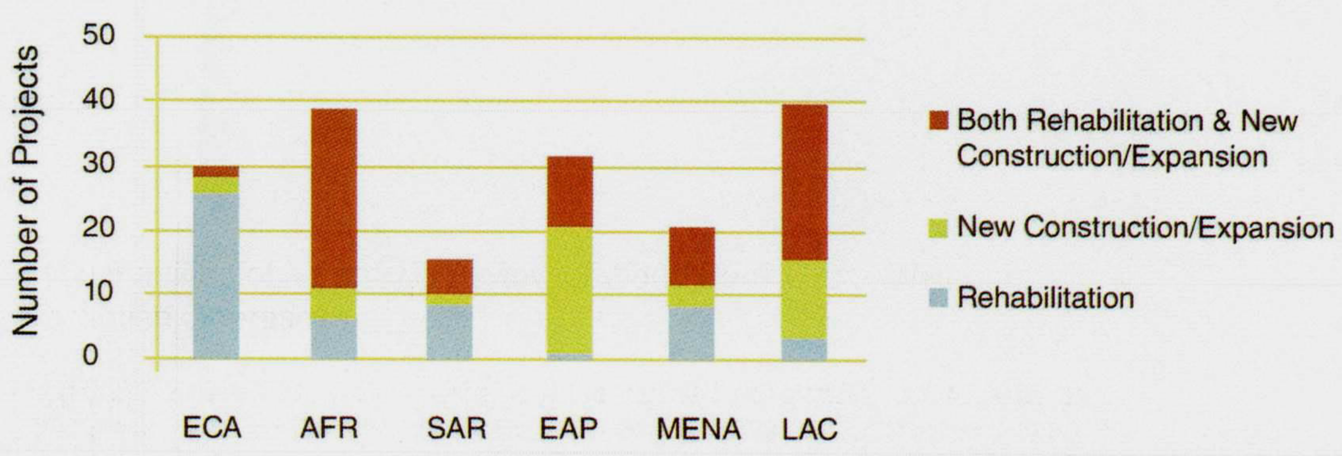
The Existing Wastewater Utilities in the Region Often Struggle to Perform. Sustainability of wastewater treatment facilities is usually a major challenge. Departments responsible for wastewater collection and treatment often have to deal with low levels of cost recovery and inadequate operation and maintenance (O&M) budgets resulting from low tariffs, low tariff collection rates, low household connection rates to sewers, or some combination of these.

This problem is aggravated by the high costs associated with operating WWTPs, which, in many cases, use inadequate and/or unnecessarily expensive technologies. This problem is commonly found in many developing countries, where decision makers tend to install "cutting-edge technologies" used in developed countries, even when they are not necessary or affordable (Libhaber et al. 2012) or are in places where stable and reliable sources of energy (electricity or gas) do not exist.

Consequently, utilities usually undermaintain the plants and networks to cut costs, thus reducing the life cycle of these structures or the efficiency of their operations. Under these circumstances, the optimized utilization of scarce funds and smart investment in low OPEX technologies are essential.

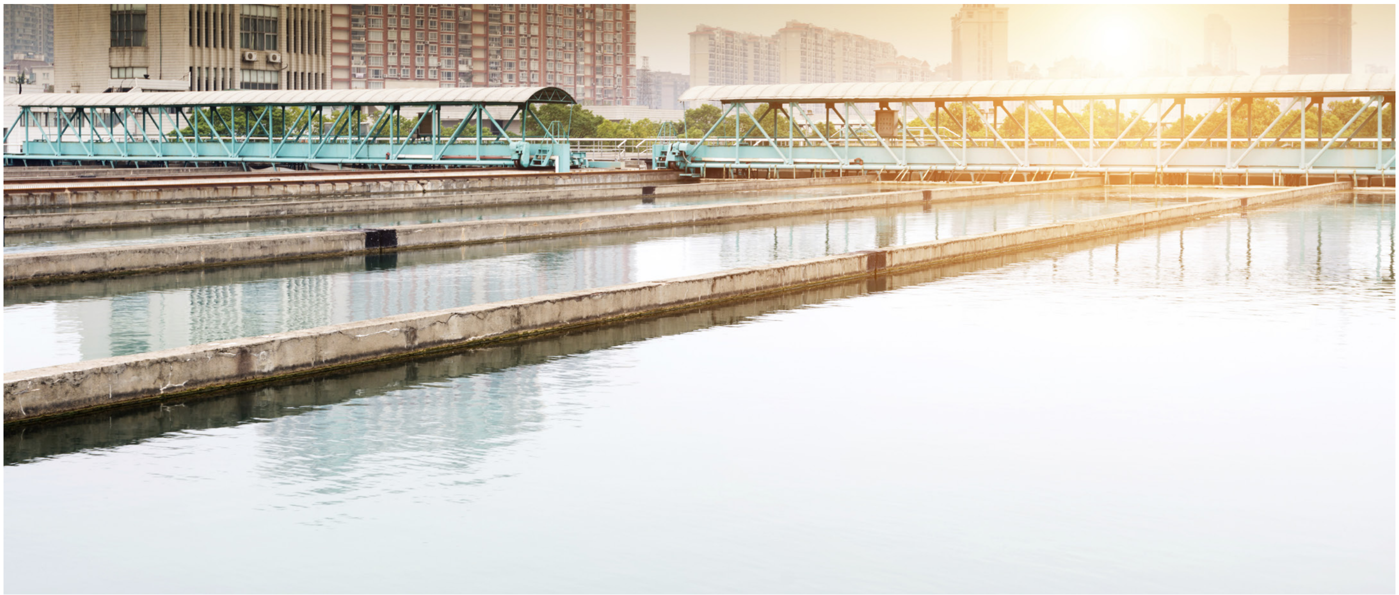
Energy Efficiency in Water and Wastewater Utilities: Ongoing Initiatives in EAP and Other Regions. In 2012, to help water and wastewater utilities reduce their operating costs and contribute to cost efficiency and the overall sustainability of investments in them, the Energy Sector Management Assistance Program (ESMAP), administered by the World Bank, published a "Primer on Energy Efficiency for Municipal Water and Wastewater Utilities," providing strategies for implementing energy efficiency measures in water and wastewater utilities. A key measure mentioned in the report was the production of energy from anaerobic sludge digestion in WWTPs. A portfolio review of all World Bank–funded projects in fiscal years 2000–2010 pointed to EAP as the region with the most new construction and expansions in urban water and sanitation (see figure I-2). Energy efficiency considerations were applied to only about 10 percent of projects in this period, leaving considerable work still to be done in energy efficiency projects and improvements.

Figure I-2: Regional Orientation on Rehabilitation and/or New Construction/Expansion in 178 World Bank–funded Water and Sanitation Projects during FY2000–2010



Source: ESMAP 2012.

Note: ECA = Europe and Central Asia; AFR = Africa; SAR = South Asia; EAP = East Asia Pacific; MENA = Middle East and North Africa; LAC = Latin America and Caribbean.



In other regions, efforts to improve energy efficiency in the water and sanitation sector are ongoing. The Watergy program, conducted by the Alliance to Save Energy (ASE), is funded by the U.S. Agency for International Development (USAID) and currently operates in Brazil, India, Mexico, the Philippines, South Africa, and Sri Lanka (ESMAP 2012). In Latin America and the Caribbean (LAC), initiatives are being carried out by the Inter-American Development Bank (IDB). The World Bank also continues to support efforts to improve energy efficiency in LAC water utilities in collaboration with ESMAP and the Water Partnership Program (WPP), as well as with external partners, such as utility associations and nongovernmental organizations (NGOs).

2. Objective of the Technical Note

The objective of this technical note is to inform utility managers and technical decision makers in East Asian countries about appropriate technologies available for wastewater treatment with energy recovery processes. It aims to explain how, with consideration of specific local conditions and a series of required enabling factors, wastewater-to-energy technologies can reduce operational expenditures (O&M costs or OPEX) of wastewater treatment plants and thus improve the long-term sustainability of the investments.

This technical note also intends to fill a gap in the existing literature by providing a comprehensive picture of energy generation applied to all available wastewater treatment technologies, with special focus on the interests of developing countries, and more particularly those in the East Asia Pacific region. A review of a number of case studies will provide experience-based data and lessons learned from large-scale projects that can reliably be applied in similar contexts. Most of the content and recommendations made here will be valid in other developing regions, as well.

With regard to energy, this technical note focuses on electricity generation, since it is usually more valuable from a financial perspective than thermal or heat energy, which can also be generated from wastewater. This analysis concentrates on centralized wastewater treatment plants where investment in energy recovery technologies can be financially viable and recommended.

3.Electricity Consumption in Wastewater Treatment Operations

Electricity consumption at WWPTs can be analyzed both from the utility's perspective and from a larger macroeconomic perspective at the national level.

Electricity Consumption at WWTPs from a Macroeconomic Perspective

The cost of electricity is a major component of the total OPEX of most urban WWTPs. Potential electricity savings can be very relevant from the utility's perspective and, if aggregated at the national level, can also contribute to a country's hitting renewable energy targets. Box I-1 provides relevant data from the wastewater sector in Germany and the United States, where the sector is fully developed and covers the entire urban population.

BOX I-1. MACROECONOMIC ENERGY PERSPECTIVE OF WWTPS IN GERMANY AND THE UNITED STATES

According to the German Association for Water, Wastewater, and Waste, the existing German WWTPs (approximately 10,000 facilities) consume a total of 4.2 million MWh/y, equal to the emission of about 2.36 million tons of CO_{2e} per year based on CO_2 emissions from fossil fuels consumed for electricity generation of 562 g CO_{2e}/kWh (DWA 2013b). Assuming an average electricity cost of US$0.20/kWh for WWTPs, this is a cost item of US$840 million per year. Based on the total national electricity consumption of over 500 million MWh/y, WWTPs thus consume somewhat less than 1 percent of the country's total electricity. Nevertheless, WWTP consumption represents about 20 percent of the electricity consumed by municipal utilities, such as schools, hospitals, water supply, solid waste management, public lighting, traffic, administration, and so forth (UBA 2008).

Data from the United States indicate that "the 16,000 publicly owned U.S. [WWTPs] consume significant quantities of electrical energy, estimated to be approximately between 1–4 percent of total energy production varying regionally, or approximately 40 million megawatts per year (MWh/year). At the average U.S. electrical price (September 2009) of US$0.0718 /kilowatt-hour (kWh), this amounts to US$2.8 billion being spent on electrical power for wastewater treatment country-wide in 2009" (WERF 2010b).

This technical note estimated the electricity requirements for WWTPs in Indonesia, the Philippines, and Vietnam. This analysis determined the additional energy required to provide wastewater treatment coverage services to the urban population who already have access to improved latrines but whose wastewater is not being properly collected and treated. Several scenarios for future development have been created, using different treatment technologies with different energy consumption requirements: activated sludge (high energy consumption), trickling filters (medium), and upflow anaerobic sludge blankets (UASBs; low consumption). In addition, each scenario is considered with and without biogas utilization. Where biogas utilization is considered, the expected power production is based on very conservative assumptions to reflect the reduced power potential under country-specific conditions, such as wastewater dilution or existence of large numbers of septic tanks.

The assessment found that an increase in wastewater treatment coverage levels to serve the population with access to improved sanitation would produce an increase in the total power consumption in Indonesia, the Philippines, and Vietnam combined from 0 to 7.6 million MWh/y. This range corresponds with an increase of 0–2.5 percent in energy production and US$0–500 million/y[4] in energy cost, depending on the process technology selected and whether or not biogas utilization is considered.

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[4] Based on a power unit cost typically between US$0.06 and US$0.22/kWh (Indonesia US$0.12/kWh; Philippines US$0.22/kWh; Vietnam US$0.06/kWh). The value of 0 would correspond to a hypothetical situation where all the future WWTPs were using low-cost technologies and incorporating energy generation. The cited electricity unit cost values were taken from PWC (2011) for Indonesia, private information (2013) received from Maynilad for the Philippines, and data from SCE (2013) for Vietnam.

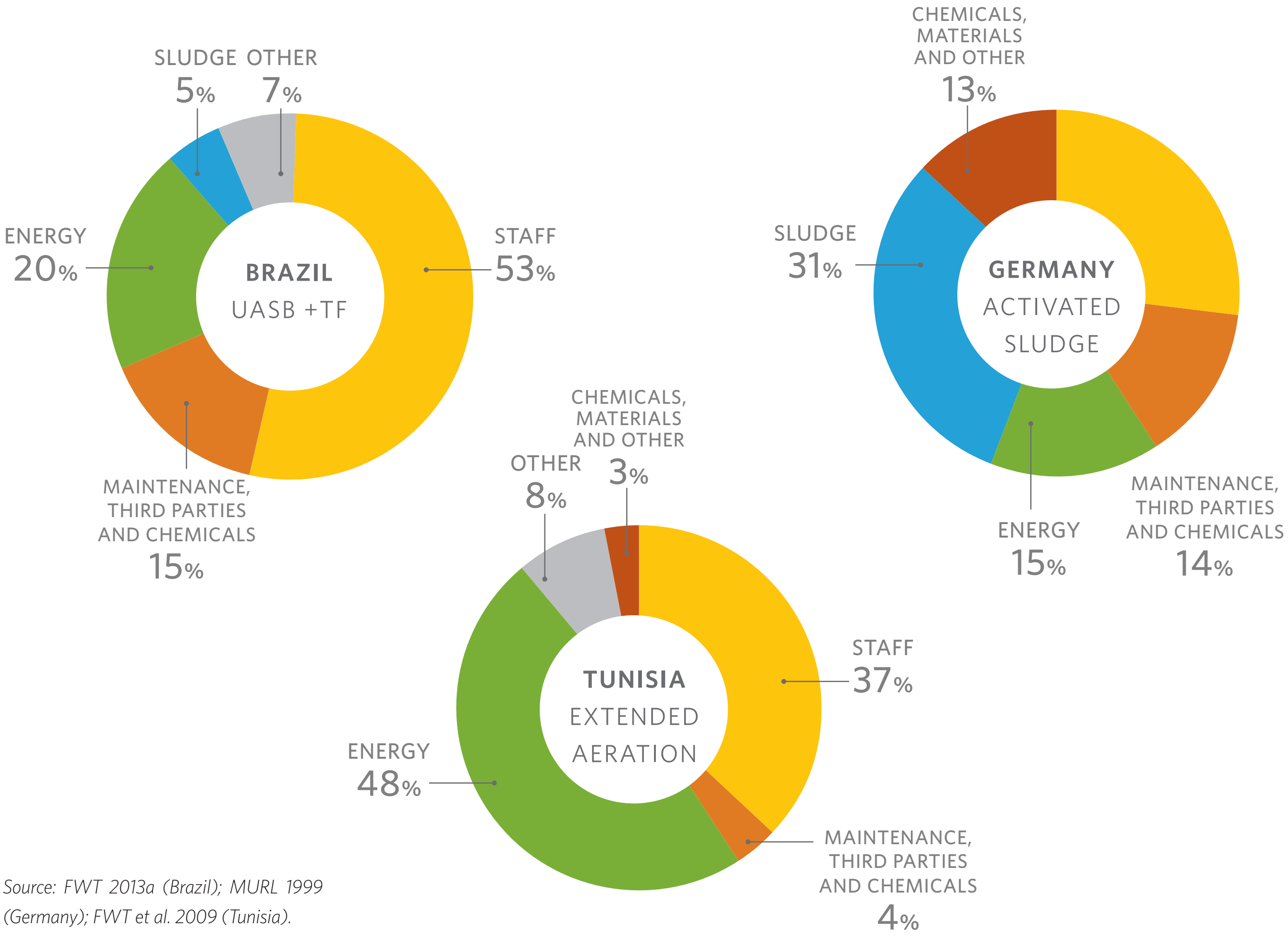
Putting the electricity generation potential from biogas at WWTPs into perspective with the production of electricity from renewable sources in EAP countries, this source can amount to as much as 10 percent of total electricity from renewables in Indonesia and about 5 percent in the Philippines and Vietnam.

Electricity Costs from the Utility's Point of View

A WWTP's OPEX structure depends mainly on the selected treatment technology and on various parameters influenced by the local context. Of particular interest for a utility operating WWTPs are the main components of its overall operational cost, the structure of which is strongly influenced by the treatment technology. Furthermore, the relative contribution of electricity to the overall cost also depends on the unit cost for personnel, the disposal/reuse cost for sludge (biosolids), or the quantity of chemicals employed in treatment.

Figure I-3 presents examples of OPEX structures for different technologies in countries in different regions.

Figure I-3: Comparison of Typical OPEX Structures at WWTPs with Different Technologies in Different Regions—Brazil, Germany and Tunisia



Source: FWT 2013a (Brazil); MURL 1999 (Germany); FWT et al. 2009 (Tunisia).

Electricity cost makes up about 15–50 percent of total OPEX in the examples in figure I-3. Similar values are cited in ESMAP (2012), which found the electricity cost of water and wastewater utilities usually varies from 5 to 30 percent and can be 40 percent or more in some countries. This share is reported to be generally on the higher side in developing countries.

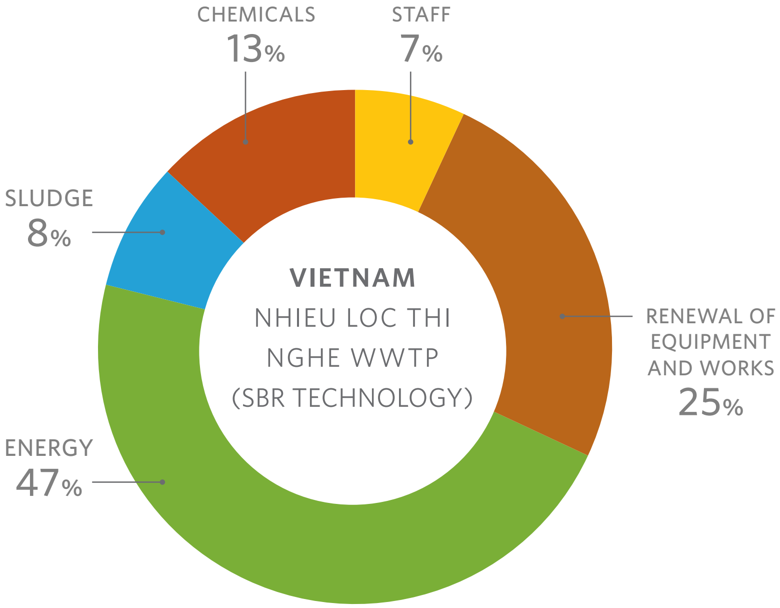
In the case of Germany, the percentage of electricity cost is relatively low because of several other expensive cost components, such as the cost of staff, of maintenance, which is subject to strict protocols, and of sludge disposal/reuse, which is expensive. In Brazil, the electricity cost is low for other reasons, such as the selection of anaerobic process technology, which requires no energy for aeration, and the low unit power cost relative to Germany. In Tunisia, electricity for aeration is clearly the most significant cost component, as staff costs are relatively low, and sludge disposal costs almost nothing.

Per capita electricity costs can vary widely, depending on country and technology. In the above three cases, they fluctuate within the following ranges (based on 2014 costs): Germany (CAS): ≈US\$5–10/PE_{60}/y (benchmarks ≈US\$3–5/PE_{60}/y); Brazil (UASB): ≈US\$0.5–2.0/PE_{60}/y; and Tunisia (EA): ≈US\$1–2/PE_{60}/y. These figures are valid for medium and large WWTPs. For very small WWTPs, the price variation can even double due to the implications of economies of scale, lower efficiency of installations, less sophisticated automation, and lower staff skills.

Electricity cost as a percentage of total OPEX of WWTPs in East Asia Pacific is expected to be at the upper end of these ranges. Actual operating costs for large WWTPs in East Asia Pacific are difficult to estimate, as cost information is only available for some small WWTPs with capacity barely above one million liters per day (1 MLD). These plants are not representative of the larger WWTPs, where biogas utilization is indeed recommendable.

The future WWTP in Ho Chi Minh City's District 2 in Vietnam will be more representative of the cost structure of future medium and large WWTPs in

Figure I-4: OPEX Structure at Nhieu Loc Thi Nghe WWTP in Ho Chi Minh City, Vietnam, Based on SBR Technology, 2015



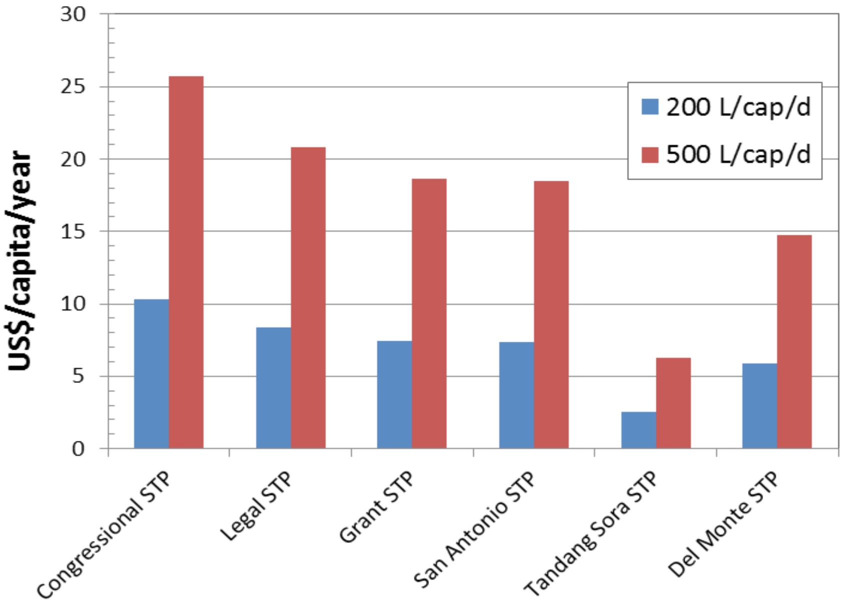
Source: SCE 2013.

the region. It is designed for a capacity of 480 MLD to serve a projected population of 1.4 million when it starts operation in 2020. For the recommended process technology (sequencing batch reactor, or SBR), the cost structure in 2015 was calculated in the feasibility study conducted for the project (SCE 2013) and is presented in figure I-4.

As the figure shows, energy cost makes up almost 50 percent of the total OPEX of the Nhieu Loc Thi Nghe WWTP, which would be equivalent to an absolute electricity cost of US$2.77 million/year in 2015. This is on the upper end of the range found for other countries discussed here. The high electric power cost is, in part, associated with strong wastewater dilution, with wastewater pumping contributing 30 percent of the total. However, as the price of electricity is low in Vietnam (US$0.06/kWh), it is expected that the share of energy cost compared with the total OPEX for similar plants will be higher in other countries with higher electricity prices. Even in places with less wastewater dilution, power unit cost and the choice of process technology are the main factors determining the cost of electricity as a percentage of total OPEX.

The actual electricity costs of several newly built WWTPs in Metro Manila, Philippines, are presented in figure I-5. These facilities, with design capacities between 0.5 and 4 MLD, are all based on conventional activated sludge (CAS) or moving bed bioreactor (MBBR) technologies; only Tandang Sora STP is running a different technology (STM-Aerotor). The available data refer to the actual annual cost of electricity and annual wastewater flows for 2013. Due to wastewater dilution—caused by a combination of factors, such as sewers intercepting wastewater from traditional open drainage canals, high groundwater tables, and seasonally heavy tropical rains—per capita specific flow rates are higher in Metro Manila than they are in other regions. The assessment assumes a flow range of 200–500 L/capita/day entering a typical WWTP under these conditions.

Figure I-5: Actual Capita Specific Power Cost at Selected WWTPs in Metro Manila, Philippines, 2013



Source: Data provided by MWSI, Metro Manila.

The capita-specific power cost ranges from US$5 to US$25/cap/y for activated sludge and MBBR technologies for only the electricity needed for wastewater treatment. Electricity costs at these plants were also found to comprise nearly 50 percent of the total OPEX of the treatment process.

Energy Requirements of Different Treatment Technologies

A desk review was conducted for this technical note to collect data on energy requirements at WWTPs for different plant sizes and treatment technologies. While the topic is not covered extensively in most traditional sanitation handbooks, this trend is changing, and awareness is increasing worldwide of the need to lower the operating costs of wastewater infrastructure, since proper operations require high tariffs and subsidies.

Consequently, more and more technical publications, mostly focused on developed countries, have been comparing in detail the energy needs of different technologies. Germany recently presented a systematic comparison of the energy consumption of technologies used at about 2,500 German WWTPs (DWA 2013a; DWA 2014). The results are summarized in table I-3 and figure I-6.

Table I-3: Median Electricity Consumption for Different Treatment Technologies and WWTP Design Size Categories

Plant design size category (SC)	Median electricity consumption in kWh/PE_{60}/y (number of WWTPs)						
	CAS	EA[5]	SBR	TF	WSP	AeP	CW
SC1	—	**65.2** (184)	**92.8** (45)	**53.2** (65)	**23.8** (45)	**41.5** (44)	**19.1** (26)
SC2	—	**44.2** (476)	**44.4** (46)	**22.7** (119)	—	**35.6** (123)	—
SC3	**37.9** (37)	**39.4** (269)	**50.2** (19)	**24.7** (28)	—	—	—
SC4	**33.8** (509)	**36.2** (345)	**35.2** (27)	**26.5** (15)	—	—	—
SC5	**31.9** (114)	—	—	—	—	—	—

Source: DWA 2013a, DWA 2014.

Notes: kWh/PE_{60}/y x 16.67 = kWh/kg BOD_5/y.

SC1 = 0–999 PE_{60}; SC2 = 1,000–5,000 PE_{60}; SC3 = 5,001–10,000 PE_{60}; SC4 = 10,001–100,000 PE_{60}; SC5 = >100,000 PE_{60}.[6] CAS = conventional activated sludge; EA = extended aeration; SBR = sequencing batch reactor; TF = trickling filter; WSP = waste stabilization pond; AeP = aerated pond; CW = constructed wetland.

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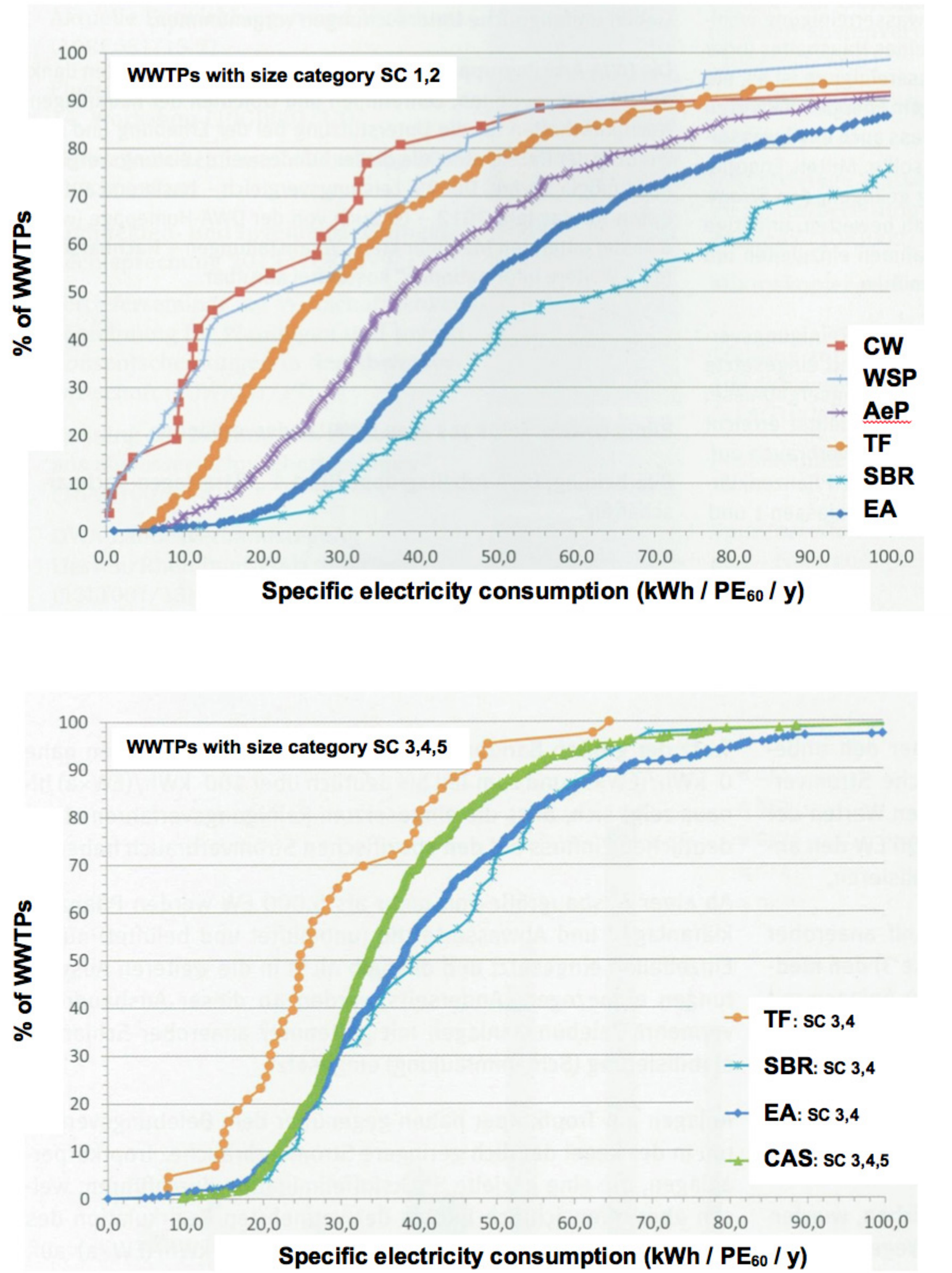
[5] Data from German EA plants show energy consumption 5–10 percent higher than with CAS. This difference is less than what might be expected, indicating an in-depth analysis beyond the scope of this study is needed.

[6] It is common practice in many European countries to define WWTP design sizes according to their incoming pollution loads (expressed as PE), while in other countries (particularly English-speaking ones), design size is often defined according to flow rate (expressed as MLD or MGD). In Germany, when BOD_5 load is used, 1 population equivalent (PE) is defined as 60 g BOD_5 /PE/d; when COD is used, 1 PE is defined as 120 (sometimes also 110) g COD/PE/d. To indicate the reference, PE is indexed with the number used. PE_{xy} should not be confused with actual (physical) population numbers Depending on lifestyle, use of in-sink grinders, type of wastewater collection system (combined or separate), and so forth, the actual per capita pollution load emission reaching a WWTP can vary considerably from region to region, typically within 30-80 g BOD_5 /cap/d, and need not be exactly 60 g/cap/d.

Figure I-6: Germany—Specific Electricity Consumption (Statistical Distribution) for Different Treatment Technologies and WWTP Design Size Categories



Source: DWA 2013a, DWA 2014.

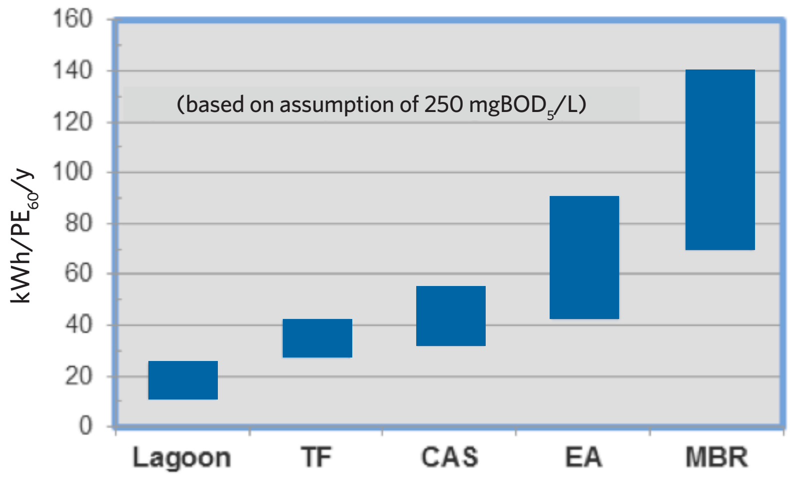
Note: $kWh/PE_{60}/y \times 16.67 = kWh/kg\ BOD_5/y$.

Three main conclusions can be derived from this analysis:

- In general, the smaller a specific WWTP design size, the higher the energy consumption per capita. Medium and large WWTPs >5,000 PE$_{60}$ rarely exceed a consumption of 50 kWh/PE$_{60}$/y.
- The different technologies differ greatly in energy consumption.
- Benchmarks on energy consumption per capita, set at the fifth percentile, range from ≈1 kWh/PE$_{60}$/y for low-energy technologies in small plants, such as constructed wetlands (CW) or waste stabilization ponds (WSP), to ≈10 kWh/PE$_{60}$/y for trickling filters, and they can go up to ≈20 kWh/PE$_{60}$/y for high-energy technologies, such as CAS, SBR, or extended aeration (EA).

In the United States, analysis of the energy consumption of existing wastewater treatment technologies (WERF 2010b) has produced data similar to those from Germany, showing a wide range of energy requirements for different treatment technologies (see figure I-7)[7].

Figure I-7: Specific Electricity Consumption for Different Treatment Technologies in the United States, Related to Unit Pollution Load



Source: WERF 2010b.

Note: kWh/PE$_{120}$/y x 16.67 = kWh/kg BOD$_5$/y.

No overview of the energy consumption of different WWTP technologies is available for the EAP region. Generally, it is expected that consumption patterns for the same technologies will be similar to or higher than those observed in Germany and the United States, in the case of inadequate maintenance, instrumentation, and control systems.

Energy Efficiency Improvement

Since the vast majority of energy assessments relate to CAS only, reliable energy benchmark values are only available for this technology, while existing information for other processes is limited. The high energy consumption of the CAS process has itself become relevant only in the last ten to fifteen years. While sporadic attempts to optimize energy needs were made earlier in various places in Australia, Canada,

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[7] WERF reports unit energy consumption related to flow rate MGD instead of pollution load PE. To allow for direct comparison, figure 3-6 presents the reported values converted to PE.

Europe, and the United States, a more systematic and structured approach to energy optimization at WWTPs is a recent phenomenon.

A summary description of the strategies applied and results achieved from energy optimization at WWTPs in Europe and the United States is presented in annex 1, which also contains state of the art energy benchmarks and target values. The major findings of this assessment are as follows:

- Energy cost at optimized CAS plants can be reduced by an average of 30–50 percent in developed countries.
- About one-third of cost saving is, on average, achieved through improved efficiency of installations and operation; the rest comes from energy generation from biogas.
- Energy optimization is usually financially attractive for WWTPs because annualized life cycle cost (derived from OPEX and CAPEX) can be reduced.

Of all possible approaches to reducing energy costs in WWTPs, this technical note focuses on energy generation.

4. Wastewater Treatment: From Necessary Evil to a Source of Beneficial Products

For most of the last century, wastewater treatment was considered a necessary evil, seen exclusively as a "problem" that required considerable investment, with little thought devoted to O&M costs. Laws addressed the need to protect the environment and the public, promoting public health by mitigating the negative impacts of untreated wastewater. Increasingly strict environmental regulations drove the development of improved treatment processes and better effluent quality. Initial requirements for mechanical treatment of wastewater evolved to include more efficient removal of carbon compounds, enhanced removal of nutrients, and disinfection. Lately, the removal of micropollutants has become a hot topic in some regions.

This constant need to build new facilities and/or upgrade existing ones implied very large investments. CAS proved to be the main technology of choice, since it was applicable to most effluent standards, it worked well in cold climates, and it provided much flexibility for well-trained operators.

Nowadays, a real paradigm shift is taking place, with wastewater increasingly seen and treated as a resource. Key terms like climate change, carbon footprint, green technologies, sustainability, and energy and resource recovery feature prominently in discussions, both at the specialist level and in public opinion forums. The water, organic, nutrient, and energy content of wastewater can be put to beneficial use. The former "waste sludge" produced from wastewater treatment, when treated to certain specified levels, now becomes "biosolids," whose nutrient and calorific content make them valuable as fertilizer or a source of energy.

BOX I-2: CHANGES IN TERMINOLOGY

Changes in terminology observed in literature, laws, and regulations regarding wastewater are clear indicators of the paradigm shift to considering and treating it as a resource. A typical example is "discharge criteria for treated wastewater," now referred to as "environmental protection laws." Also notable are the professional organizations in the wastewater sector that have changed their names. The trade association of water quality professionals in the US, for instance, began as the Federation of Sewage Works Associations in 1928, changed its name to the Federation of Sewage and Industrial Wastes Associations in 1950 and to the Water Pollution Control Federation in 1960, and finally became the Water Environment Federation (WEF) in 1991.

The following are the main resources derived from wastewater and sludge:

- *Treated wastewater as a water resource:* Treating and recycling wastewater can help mitigate the impacts of water scarcity in the many regions of the world that are becoming increasingly water stressed. This does not necessarily mean recycling wastewater to drinking-water quality. Rather, industrial reuse, irrigation reuse, aquaculture, non-irrigation urban uses, environmental and recreational uses, and groundwater recharge are all increasingly interesting options for water recycling.
- *Wastewater/treated sludge as a nutrient resource:* The primary macro nutrients that can be extracted from wastewater and sludge are nitrogen and phosphorus. The commercial focus of recent years has been particularly on phosphorus, since it is a limited mineral resource that is essential in agriculture and for life on

the planet. Also critical is the world's dependence on a small number of countries with phosphorus resources, mainly China, Morocco, Russia, and the United States. Furthermore, the financial feasibility of developing this resource is improving for larger WWTPs, with several technologies now commercially available that can extract phosphorus from wastewater sludge and help control potential deposition problems in pipes, pumps, and digesters or from ash incinerators. The phosphorus products produced can then be marketed.

The situation for nitrogen recovery is different. The most common method of nitrogen production uses energy-intensive industrial processes to produce ammonia fertilizer from air. The extraction of nitrogen from wastewater or sludge is much more expensive. Currently, the focus is on exploring more energy- and cost-efficient removal of nitrogen from wastewater, and not so much on the recovery of nitrogen as a product.

- *Sludge as an agricultural resource:* The beneficial properties of treated sludge as a fertilizer—its soil amendment, moisture retention, and soil improvement qualities—are well established. This traditional view has now been supplemented, however, by an interesting application for sludge in

agriculture not considered in previous years: it plays an important role in the mitigation of greenhouse gas (GHG) emission effects. Not only does treated sludge offset energy-intensive production of chemical fertilizers; it also replenishes soil organic carbon subjected to climate change–induced wind and water erosion (WEF et al. 2013b).

A 2012 analysis by ADB of various sludge management options in China came to the conclusion that the combined effects of anaerobic digestion and land application of properly treated sludge produced the smallest carbon footprints of all sludge management options. The largest carbon footprints resulted from direct landfilling without landfill gas management. Consequently, the study recommended closing the nutrient cycle by applying sludge to agricultural reuse after proper treatment, including anaerobic digestion with biogas utilization. Where this is not possible, the next best recommendation is energy recovery through digestion, followed by dewatering and incineration with heat recovery.

Agricultural applications for sludge may be limited for a number of reasons:

- Concern about the heavy metal content in sludge if pretreatment requirements for industrial dischargers are inadequate, particularly in urban areas
- The emerging challenge of organic pollutants in sludge, the uncertainties about which may be prompting various developed countries to phase out its use in agriculture
- The potential limitations on available land for agricultural reuse in urban environments
- The possibility that public opinion will turn against them, which is usually due to concerns about odor and food safety

- *Wastewater/sludge as a renewable energy resource:* Many WWTPs worldwide already implement energy recovery from wastewater and sludge, with three methods being the most common: through anaerobic sludge digestion, through anaerobic wastewater treatment, and through sludge incineration. Of these, the least desirable is the third, as from a financial perspective, the electricity generated from biogas in anaerobic sludge digestion and anaerobic wastewater treatment is worth more than the extra thermal energy generated from incineration of undigested sludge.

Murray and others (2008) analyzed a wide range of sludge treatment options, including dewatering, lime addition, mesophilic anaerobic digestion, heat drying, incineration, and various combinations of these. A life cycle assessment led them to conclude that “anaerobic digestion is generally the optimal treatment” (Murray at al. 2008). While the authors based their analysis on a specific case study of four large WWTPs in Chengdu, China, they maintained that the outcome should be representative for many other WWTPs worldwide.

Since the energy produced is, in any case, a renewable form of energy, all these energy recovery options can help reduce GHG emissions.

5. Renewable Energy Generation at WWTPs

The focus on energy resource recovery via biogas generation from wastewater/sludge should be seen as just one among a wide range of resource recovery options. The biogas-centered approach of this technical note is justified for various reasons:

- Reduction of OPEX of wastewater treatment provides financial relief to wastewater utilities.
- The approach implies a reduction of the carbon footprint for sludge management.
- Closing the nutrient cycle by land application of digested sludge is an attractive option that allows the further utilization of resource benefits from wastewater.
- A comprehensive comparison of different schemes to recover energy from wastewater/sludge is still absent from the specialized literature, particularly from the perspective of developing countries with warm climates. The energy attention so far has been almost exclusively on CAS systems with digesters. Closing this knowledge gap is considered important, too.

Therefore, if the right factors are in place, it is possible to recover energy in urban WWTPs by building on practical experience nowadays available in energy optimization and recovery in wastewater treatment, a field in which significant improvements have been made in recent years. Twenty years ago, a typical WWTP producing 30 percent of its electric energy from biogas was doing well, in a specialist's perception. Today, it is possible to achieve reductions in energy consumption of 50 percent, on average.

At the same time, energy production from renewable biogas, generated from a WWTP's wastewater and biosolids, can be enhanced through various means. One increasingly popular option is co-digestion of organic waste in sludge digesters. This "add-on" can contribute to achieving a positive energy balance, with the WWTP's annual electricity production exceeding its annual consumption. The effect on nutrient loading also has to be considered if there are nutrient effluent standards. The practice has become a widespread standard in Central Europe and is drawing increased attention in Japan, Singapore, South Korea, and the United States. Case study 5 in this technical note focuses on this technology.

BOX I-3: THE FUTURE OF WWTPS?

The current enthusiasm for energy generation at WWTPs goes beyond achieving energy balance. Some utilities have started considering WWTPs as energy production centers. One example is the Swiss Morgental WWTP, which currently produces some 50 percent of the 1.4 million kWh of electric power it consumes annually from its own biogas from sludge digestion (Strässle 2012). In 2012, the city council decided to install an energy park at the WWTP. It will feature more efficient biogas utilization installations, a hydropower station for wastewater, heat exchangers in the sewers to utilize its thermal energy, a biomass incinerator for wood chips, a new photovoltaic plant, and co-digestion of organic waste from households in the WWTP's sludge digesters. The future WWTP/energy park is expected to produce some 10 million kWh/y—equivalent to seven times the electricity it consumes—and will deliver 22 million kWh/y in thermal energy to be used for district heating. All this will come at an economically viable and attractive cost and will have a positive carbon impact. While this may be an extremely ambitious scheme from a developed country that might not be easily implemented in other countries, it does indicate the direction in which the sector is heading.

Technologies for Renewable Energy Generation via Biogas from Wastewater

The various options for introducing renewable energy generation at WWTPs can be classified as follows:

- Energy from anaerobic sludge or wastewater treatment:
  - Anaerobic digestion of sludge from wastewater treatment
  - Co-digestion of energy-rich organic waste materials in sludge digesters
  - Anaerobic wastewater treatment
- Other sources of energy:
  - Electricity from hydropower from a plant's influent or effluent
  - Electricity and thermal energy captured from solar radiation at facilities
  - Electricity captured from wind power at facilities
  - Thermal energy and/or electricity from sludge incineration

- Heating or cooling energy collected from the wastewater's thermal energy

This technical note focuses on the first family of options: sludge and wastewater anaerobic digestion for biogas production.

The Use of Biogas from Human Waste as a Resource

Knowledge about biogas formation from anaerobic digestion of human waste is not new. The first improved sludge digesters were already constructed in the 1920s, and in Southeast Asia today, household digesters are widespread at technically small scales. Box I-4 provides a brief overview of the historical background of the use of biogas from human waste.

BOX I-4: BRIEF HISTORY OF BIOGAS FROM HUMAN WASTE AS A RESOURCE

That a combustible gas is generated when organic waste is allowed to rot in piles has been known for centuries, and that this gas is rich in methane became clear at the beginning of the nineteenth century. In the 1860s, the Frenchman John Louis Mouras came up with the idea of a large, deep sedimentation tank for wastewater to prolong the intervals of sludge removal. This idea of a "*fosse* Mouras" (Mouras pit) was subsequently taken up by an Englishman, Donald Cameron, who in 1895 constructed an improved version, calling it a "septic tank." Already in some of the first installations of that type, the generated biogas was used for heating and lighting (Abbasi et al. 2012).

Just a decade later, in 1906, the German sanitary engineer Karl Imhoff proposed the so-called "Imhoff tank," with two separated compartments. The upper compartment is used for the sedimentation of raw wastewater, and from it the sludge glides into a lower sludge digestion compartment. In the Imhoff tank, biogas is usually not collected and is released to the open air (Roediger et al. 1990). Although the Imhoff tank is a robust and simple installation, it has some disadvantages, particularly its deep foundation, the absence of sludge mixing, and no heating. Lack of mixing and heating reduces the rate of biogas production.

These problems were overcome with separate sludge digestion reactors, complete with mixers and heating, which were first constructed in Germany and the United States in the 1920s (Roediger et al. 1990). This concept has been further improved over the years and is still being applied for anaerobic sludge digestion. As improved reactor shapes, mixing systems, and heating systems have sprung up over time, some of the earlier technical developments have been phased out, while others have continued to evolve.

Southeast Asia and East Asia Pacific are among the regions where these processes have grown in popularity; Bangladesh, China, India, Nepal, Pakistan, and Vietnam have been using household biogas plants for decades (Abbasi et al. 2012). China in particular stands out because of the sheer number of its digesters, located mostly in rural areas. Today, over 25 million households are using biogas in China, accounting for over 10 percent of all rural households. The number of large-scale digesters (over 300 m^3) has also been increasing rapidly. By the end of 2012, over 20,000 large anaerobic digesters were in operation in China, representing about 30 percent of the total number worldwide (Ren 2013). These large digesters predominantly feed on waste from livestock, poultry farms, and food industries.

During the last decade, interest in household digesters has been growing in South American countries. Biogas produced by these systems is usually used for cooking, thereby replacing firewood, which preserves the environment through reduced deforestation, decreases household expenditures on fuel and/or fertilizer, and reduces the workload of the women and children who collect the firewood (Ferrer et al. 2013).

Sludge Digesters for Renewable Energy Generation at WWTPs

Anaerobic sludge digestion has become a standard WWTP component in developed countries, where anaerobic digesters are a state of the art element of many WWTPs with design capacities above about 10,000–20,000 PE_{60} (1–2 MLD). Digesters serve several purposes: the destruction of organic matter reduces the need for expensive disposal of sludge quantities by about 30 percent, reduces the sludge's potential for the emission of bad odors, and reduces the pathogen content of the biomass; and the generated biogas can be used to produce energy. Anaerobic sludge digestion is still not common in developing countries, however. To date, of the three countries on which this study focuses, only one—Vietnam—has a single sludge digester, located at Yen So WWTP (200 MLD).

Furthermore, even though many WWTPs in Europe and the United States feature sludge digesters, the potential to generate electricity from biogas is not exploited fully, which leaves room for increased power generation. Detailed information on the use of sludge digesters and the potential for renewable energy production from biogas in Europe and the United States, as well as the expected electricity consumption and generation potentials at future WWTPs in Indonesia, the Philippines, and Vietnam, are provided in annex 2.

Quantification of Renewable Energy Generation Potential at WWTPs

Utilities in developed countries are pursuing energy efficiency improvement to reduce OPEX and present a greener image in a number of ways:

- By enhancing energy savings at all stages of wastewater and sludge treatment through optimized process selection, infrastructure, instrumentation, and control
- By implementing various means of maximizing electricity production from biogas:
  - Co-digestion of waste sludge, food waste, FOG (fats, oils, and grease), and industrial organic wastes
  - Adoption of new hydrolysis technologies to release cell liquor from the sludge's micro-organisms prior to its digestion, thereby increasing biogas production further (for example, Cambi[8] and ultrasound sludge treatment, among others)
  - Building of high-efficiency and low-maintenance combined heat and power (CHP) installations for the conversion of biogas into electric energy (for example, co-generation with improved efficiencies and micro turbines)[9]
  - Improved infrastructure for improved mixing and temperature combinations at the anaerobic reactor level (for example, digestion at mesophilic [around 35°C] and thermophilic [around 50°C] temperature levels)

Although some developing countries are paying more attention to anaerobic wastewater treatment technologies, biogas utilization and low-energy wastewater technologies are generally underdeveloped. While Europe and the United States overwhelmingly rely on activated sludge technologies, which work well in cold winter temperatures, developing countries

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[8] At Blue Plains WWTP in Washington, DC, the world's largest Cambi plant is currently being installed by the local utility (DC Water).

[9] There are several options to produce electricity from biogas: fuel cells, Stirling motor, direct drive engines, co-generation or microturbines. Evaluations of these options show that the combined production of electricity and heat (CHP) through co-generation or microturbines usually results as the most economical option for biogas reuse at WWTPs. This has become the common international standard approach at WWTPs, which is also applied in all case studies of this technical note. More details on these options are provided in annex 3, case study 1.

have the opportunity to select technologies that may be better suited to their specific conditions. The following are the most notable signs of movement in this direction:

- Increased numbers of anaerobic wastewater treatment technologies, such as upflow anaerobic sludge blanket (UASB) reactors, baffled anaerobic reactors (BAR), and covered anaerobic ponds
- Utilization by a few facilities of the biogas they produce
- Revitalization of other low-energy technologies, such as trickling filters and constructed wetlands, among others, and various combinations of these

All of these are, however, either regionally limited or taking place in small numbers. The sharing of knowledge about the advantages, specific requirements, realistic large-scale operation results, operators' skills, and cost features associated with these developments would increase their appeal and spur their wider adoption.

One way of finding novel approaches other than CAS is to look at recent international awards won by WWTP technologies in developing countries[10]. The awards provide important incentive for technological development, and they indicate the direction in which the future of energy efficiency is heading.

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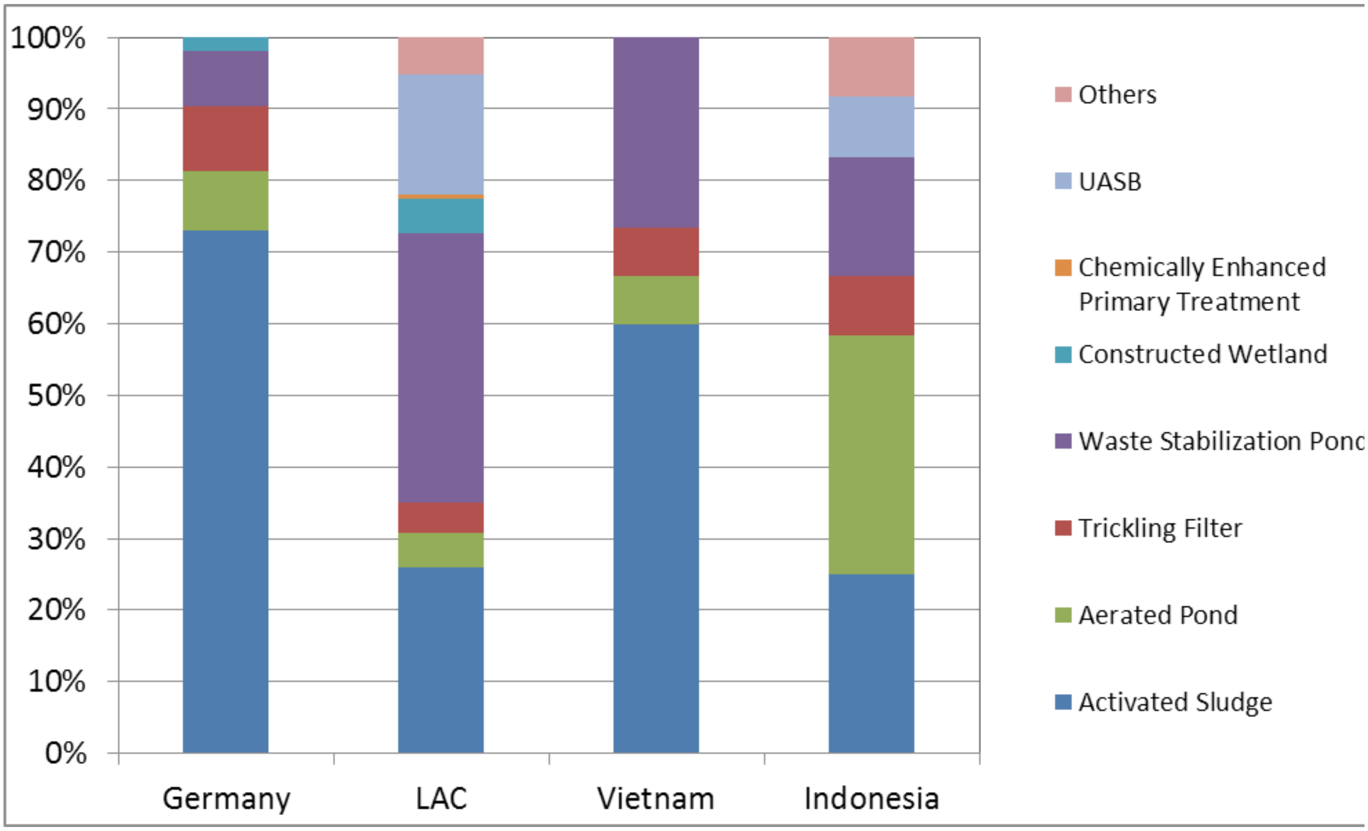
[10] The IWA Projects Innovation Awards chose as the winner of its Global Honor Awards in 2013 a WWTP in Batumi, Georgia, that combines anaerobic ponds with trickling filters. This decision was justified by the "extremely low investment cost" and "low power consumption . . . [representing] less than 50 percent of [that of] any process technology." (IWA 2013). In biosolids treatment, a solar sludge drying facility in Managua, Nicaragua, was nominated for the Global Water Award 2010 in the category of Environmental Contribution of the Year on the basis that "low-cost, low-energy systems such as this are going to be an important part of the solution in developing countries." At the time of startup, this facility was the largest of its kind worldwide. Since then, a proliferation of similar and even larger plants in warm climate countries has been observed.

The Specific Conditions in EAP Regarding Renewable Energy Generation

The current trend in WWTP technologies in EAP points in a direction similar to that taken by other countries (see figure I-8). Since waste stabilization ponds (WSPs) or aerated ponds require large areas, they are usually not feasible in urban environments, so CAS systems are usually preferred.

Figure I-8: Distribution of Wastewater Treatment Technologies in Germany, LAC, Vietnam, and Indonesia



Source: DWA 2013a (Germany); Noyola et al. 2012 (Latin America and Caribbean [LAC]); World Bank 2013f (Vietnam); World Bank 2013d (Indonesia).

China, where the great majority of WWTPs use CAS technology, is one example of this trend. CAS systems are well suited for meeting required treatment levels, but they have high CAPEX and OPEX, which stresses the financial situation of sanitation utilities. Although potentially interesting alternatives for urban WWTPs in warm climate countries, such as trickling filters and UASB, do exist, their numbers are relatively modest.

Impact of wastewater dilution and large numbers of septic tanks. A rather unique feature of EAP countries is their high levels of wastewater dilution—that is, the low concentrations of pollutants in their wastewater. In a wastewater treatment plant, dilution increases pumping costs, requires larger settling tanks, and reduces treatment efficiencies. Dilution is a common problem in many areas around the world, but there are not many regions where it is as severe as in EAP.

When very low concentrations of suspended solids are found in influent wastewater, a primary sedimentation tank (PST) is not necessary[11]. This matters in terms of biogas production because the sludge coming out of PSTs is richer in volatiles that produce biogas. If PSTs are not needed, sludge will only be an output of the biological treatment process. The activated sludge coming out of this process has less biogas potential than that coming from PSTs, so overall biogas production is significantly reduced.

Wastewater dilution is usually caused by a combination of factors frequently found in the EAP region, such as the use of combined sewers that intercept wastewater from traditional open or poorly constructed drainage canals, seasonally heavy tropical rains, and high groundwater tables infiltrating the sewers. In the wet season, wastewater concentrations may be very low, sometimes even below the required treatment standards, putting the need for wastewater treatment into question. In addition, septic tanks in urban areas are very common in the region. While these onsite systems may be in bad physical shape and/or poorly maintained, they still succeed in retaining a large percentage of the solids usually present in wastewater, thus contributing to the dilution problem.

Dilution has additional impacts on process technology for wastewater treatment. Technologies in which the main treatment unit is designed based on retention time criteria (for instance, UASB or anaerobic ponds) require reactors with larger volumes if the wastewater is diluted. If these larger reactors are expensive to build, the whole technology becomes less attractive. Other technologies might be less affected by diluted wastewater. For instance, CAS and trickling filters, being designed on total biochemical oxygen demand (BOD) load criteria, will require the same reactor volumes, with or without dilution.

Assessment of measures to address the dilution problem is beyond the scope of this technical note, but some actions to consider were suggested in the East Asia Urban Sanitation Review (World Bank 2013):

- Conduct robust analysis when designing sewerage networks, and consider separate systems for new development areas.[12]
- Minimize the runoff and, therefore, the infiltration flows in combined systems by introducing measures that favor natural infiltration in the soil.
- Maximize the number of household connections, progressively eliminating septic tanks for new construction where sewerage networks and treatment plants are in place.

The consequences of the phenomenon of wastewater dilution are still not well understood, however. A thorough analysis of actual wastewater concentrations and its consideration in process design are very important to producing optimal designs and correct OPEX forecasts. Although dilution is generally recognized as a problem affecting wastewater-to-energy potential, project-specific conditions do

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[11] In a situation with no dilution problem, the TSS in a typical PST effluent would normally be ≈80 (50–150) mg TSS/L, based on TSS efficiencies of 50–75 percent, and a conventional raw wastewater influent concentration of some 200–300 mg TSS/L. Consequently, if influents already have less than about 80 mg TSS/L, a PST is usually not recommendable.

[12] The Vietnam Urban Wastewater Review (World Bank 2013) shows the significant difference between influent concentrations of pollutants in separate versus combined sewerage collection networks.

matter, and a case-specific analysis based on sound data is always recommended.

Impact of required treatment standards. As also highlighted in the EAP Urban Sanitation Review (World Bank 2013c), stricter effluent standards lead to increased cost in terms of both CAPEX and OPEX. This is usually justified by the environmental capacity of the receiving waters, although it is not always the case. Effluent standards can be categorized at three levels, depending on the level of environmental protection required:

1. Normal values for carbon parameters and phosphorus. These are BOD5 <15–50 mg/L, COD <50–150 mg/L, TSS <15–40 mg/L, P <5 mg/L, with no requirements on nitrogen (N).
2. Nitrogen removal requirements. These usually imply imposing limits on ammonia, and even on total nitrogen, which usually increases cost through various effects:
   - Less costly technologies become inappropriate because they cannot deliver the required N quality, and more costly technologies must be used.
   - Larger reactor volumes are required.
   - Operation and maintenance of larger and more sophisticated technologies becomes more costly.
   - The potential for electricity generation from biogas decreases because a higher percentage of organic material is oxidized in the treatment process.
3. Requirements for even lower levels of BOD, chemical oxygen demand (COD), total suspended solids (TSS), and phosphorus (P). These imply additional and more costly treatment stages. Usually the biogas potential is just marginally affected, as long as the preceding main treatment stages remain unchanged. But, generally, additional treatment stages imply increased electricity consumption, thus reducing the electricity coverage through power from biogas. Consequently, the economic and environmental advantages and disadvantages of pursuing more ambitious standards must be carefully considered.

Feed-in tariffs. Regulations for power supply to the public grid already exist in many East Asian countries for various renewable energy sources, such as landfill gas or power from biomass. Energy from sludge biogas is, therefore, not expected to encounter obstacles if power surpluses are to be supplied to the grid in the future.

SECTION II: CASE STUDIES AND ASSESSMENT TOOL METHODOLOGY

6. Methodology

In this section, six large-scale case studies are analyzed in detail, covering all of the wastewater-to-energy options appropriate for East Asia Pacific.

Although a wide range of wastewater treatment technologies exists, just a few are suited for biogas generation. Figure II-1 presents a summary of the main biological wastewater treatment systems. Those used for biogas generation from municipal wastewater are highlighted in bold.

Figure II-1: Summary Description of Main Biological Wastewater Treatment Systems and Their Use for Biogas Generation from Municipal Wastewater

WASTE STABILIZATION PONDS

- Facultative pond
- **Anaerobic—facultative pond**
- Facultative aerated pond
- Aerated lagoon—sedimentation pond
- High-rate pond
- Maturation pond

LAND DISPOSAL

- Slow-rate system
- Rapid infiltration
- Subsurface infiltration
- Overland flow

CONSTRUCTED WETLANDS

- Surface flow
- Subsurface flow

ANAEROBIC SYSTEMS

- **UASB (upflow anaerobic sludge blanket)**
- Anaerobic filter
- Anaerobic reactor—post-treatment

ACTIVATED SLUDGE

- **CAS (conventional activated sludge)**
- EA (extended aeration)
- **SBR (sequencing batch reactor)**
- **AS (activated sludge) with biological N removal**
- **AS with biological N + P removal**

AEROBIC BIOFILM REACTORS

- **Low-rate trickling filter**
- **High-rate trickling filter**
- Submerged aerated biofilter

Source: Sperling and Chernicharo 2005.

The main biological wastewater treatment systems typically used to produce biogas from wastewater/sludge fall into four groups: waste stabilization ponds, anaerobic systems, activated sludge, and trickling filters.

This technical note presents practical experiences with wastewater-to-energy options through a detailed analysis of the six case studies listed in table II-1.

Table II-1: Biogas Production Technologies Analyzed in this Technical Note

Case study		Biogas from		Location of case study
		wastewater treatment	sludge treatment	
1	CAS + sludge digestion	—	X	Europe
2	TF + sludge digestion	—	X	Nicaragua
3	UASB	X	—	Brazil
4	Covered anaerobic ponds	X	—	Bolivia, Australia
5	Co-digestion of organic waste	—	X	Europe
6	Ultrasound sludge disintegration	—	X	Europe

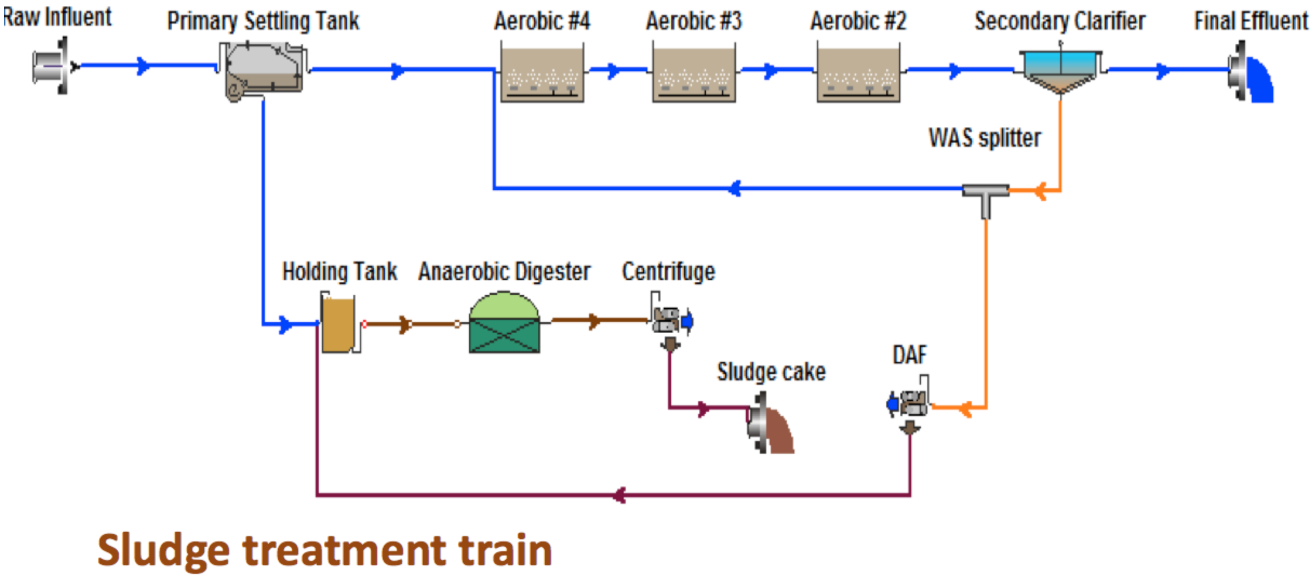
The analysis looks into the energy consumption of the wastewater treatment technologies, biogas quantities and characteristics, the potential for electricity generation, operation capacity needs, safety concerns, institutional aspects, GHG reduction, co-financing options through carbon trading mechanisms, and cost-related aspects (CAPEX, OPEX, and overall financial viability).

Based on the analysis, a simple assessment tool has been developed in spreadsheet format and is presented in section II, subsection 8 below. This tool permits quick, preliminary quantification of energy efficiency. The user will need to insert data regarding specific local conditions to obtain results that quantify such aspects as energy consumption, biogas potential, electricity coverage ratio, preliminary design of major wastewater-to-energy components, and overall impact on OPEX. This tool is expected to facilitate understanding of the viability of energy generation and the preselection of appropriate options for wastewater treatment, specifically in urban areas of warm climate countries.

7. Main Findings from the Analysis of Case Studies

The technologies assessed can be grouped into those producing biogas directly in the wastewater treatment train and those based on installations in the sludge treatment train. The wastewater and sludge treatment trains are identified in figure II-2, which represents a typical conventional activated sludge (CAS) plant with anaerobic digestion of sludge. In this case, the two sources of sludge to treat are removed from the bottom of the primary settling tank (primary activated sludge) and from the bottom of the secondary clarifier (waste activated sludge, or WAS).

Figure II-2: Wastewater and Sludge Treatment Trains of a Typical CAS Plant



Source: authors

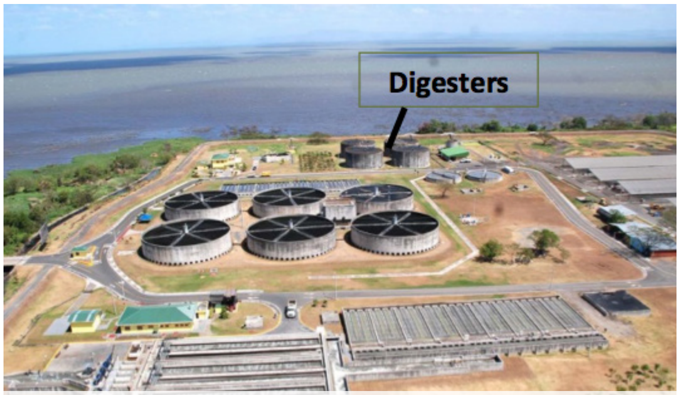
In sludge treatment applications, the centerpiece is always an anaerobic digester, which is a closed reactor in which the temperature is usually controlled through a heating system (in cold climate countries) and the sludge is partly decomposed into biogas and other subproducts. What can be expected from the digester depends on the conditions inside the reactor and what is being fed into it. Since conditions are controlled and feed sludge characteristics are similar worldwide, experiences with these systems can be applied to any location. Consequently, most of the case studies involving digesters (1, 5, and 6) are based on data from Europe and the United States, where a great deal of practical experience and data are available. Case study 2 shows an example of one digester from a warm climate country that is operated without heating.

In addition, wastewater treatment itself can be used for biogas production when using anaerobic systems (such as anaerobic lagoons or UASBs). This approach works particularly well in warm climates, as the case studies show.

Since O&M practices and cost data from one location should not be applied to another without background analysis, this technical note takes into account the specific conditions existing in EAP countries when assessing the case studies. The photos presented in figure II-3 give some indication of the physical appearance of the installations in the case studies, which are summarized here and documented in more detail in annex 3.

Figure II-3: Wastewater and Sludge Treatment Trains of a Typical CAS Plant

CS #1: Heated sludge digesters of different shapes (Europe), used for digesting sludge from CAS



CS #2: Unheated sludge digesters (Nicaragua), at a trickling filter plant

CS #3: UASB and trickling filter plants (Brazil)

CS #4: Covered ponds (Bolivia)

CS #5: Co-digestion of organic feedstock (Europe)

CS #6: Ultrasound disintegration of sludge (Europe)

Wastewater Influent and Effluent

All of the case studies present normal-strength raw wastewater. Carbon removal is always required, but nutrient removal is not. Table II-2 summarizes the wastewater characteristics of case studies 1–4. Case studies 5 and 6 are not included, since wastewater characteristics are not directly relevant for these technologies.

Table II-2: Average Influent and Effluent Wastewater Characteristics of Case Studies

			Case Study #1:	**Case Study #2:**	**Case Study #3:**	**Case Study #4:**	
			CAS+digestion	**TF+digestion**	**UASB**	**Covered Anaerobic Ponds**	
			Central Europe	**Nicaragua**	**Brazil**	**Bolivia**	**Australia**
WWTPs (nr.)		nr.	6,823	1	22	4	2
Pop.Equivalents	avg. actual	PE_{60}	n.a.	447,000	62,417	802,000	4,569,000
	max. actual	PE_{60}	n.a.	606,000	577,917	1,023,000	4,994,000
WASTEWATER QUANTITY							
Specific wastewater production		L / PE_{60} /d	201	225	220	147	105
WASTEWATER QUALITY							
COD	Influent	mg/L	602	505	697	946	1,009
	Effluent	mg/L	35	101	194	197	32
	Elimination	%	94	80	72	79	97
BOD_5	Influent	mg/L	255	248	297	407	571
	Effluent	mg/L	5	28	62	60	4
	Elimination	%	98	89	76	85	99
N_{total}	Influent	mg/L	47	28	n.a.	92	73
	Effluent	mg/L	9	18	41	66	21
	Elimination	%	81	37	n.a.	28	72
NH_4-N	Effluent	mg/L	1	n.a.	38	2	5
NO_3-N	Effluent	mg/L	6	n.a.	1	0	15
P_{total}	Influent	mg/L	8	4	7	15	11
	Effluent	mg/L	0.7	1.7	4.5	4.4	9.0
	Elimination	%	91	54	33	71	14

Notes: 1 cap = 60 g BOD_5/d in Central Europe and Australia; 46.5 g BOD_5/d in Nicaragua; 54 g BOD_5/d in Brazil; and 40 g BOD_5/d in Bolivia.

1 PE_{60} = 1.0 cap in Central Europe and Australia; 1.29 cap in Nicaragua; 1.11 cap in Brazil; and 1.5 cap in Bolivia.

L/PE_{60}/d = L/cap/d in Central Europe and Australia; x 1.0 (1.29; 1.11; 1.50) in Bolivia, Brazil, and Nicaragua respectively.

The following points can be highlighted:

- Most influent concentrations represent normal-strength wastewater conditions. Only case study 4 includes plants with lower specific wastewater production and consequently higher influent concentrations.
- Case studies 1, 5, and 6, in Europe, feature enhanced nutrient (N + P) removal.
- All other cases describe systems with only carbon removal. Only the Australian pond + CAS system of case study 4 is also performing enhanced N removal.
- In case studies 1, 2, 5, and 6, with sludge digesters, an increased nutrient load enters wastewater treatment due to increased N and P concentrations in the filtrate from sludge dewatering after digestion. Therefore only where effluent regulations do not require nutrient removal (case study 2) there will be an increase in the nutrient load discharged to the environment. The return loads of N and P typically amount to less than 20 percent and less than 10 percent of influent loads, respectively. The overall increase in nutrient emissions of WWTPs with wastewater-to-energy systems under such

conditions is still small compared to other nutrient emissions to the aquatic environment (for example, diffuse entries via surface runoff and/or through groundwater fed from septic tanks and agriculture, industries, improper waste disposal, and so on).

- When applying case study results to EAP conditions, diluted wastewater and nutrient removal requirements are very important factors to consider, and a case-specific analysis is recommended.

Biogas Production and Potential for Energy Generation

The case studies confirm that CAS technology usually cannot achieve full electricity coverage from digester biogas, and that other technologies with generally lower electricity consumption, such as trickling filters, UASB, and covered anaerobic ponds, can. The case of co-digestion demonstrates that this option is an efficient instrument to further increase biogas in sludge digesters, so if all the generated biogas can be put to good use, the financial benefits are substantial.

Table II-3 summarizes both the biogas production and subsequent power generation potential found in case studies 1–5, as compared to the power consumption of the respective technologies or installations. Results show that different required wastewater treatment levels (that is, considering carbon and nitrogen elimination) do have an impact on energy production.

Table II-3: Biogas and Power Generation Potential of Case Studies, Compared to Power Consumption

	Case study 1:	**Case study 2:**	**Case study 3:**	**Case study 4:**		**Case study 5:**
	CAS + digestion	**TF + digestion**	**UASB**	**Covered anaerobic ponds**		**Co-digestion**
	Central Europe	Nicaragua	Brazil	Bolivia	Australia	Central Europe
Biogas production						
- N elimination (L/PE$_{60}$/d)	20-23	—	—	—	—	17.5 (sludge) + 30 (waste)
- C elimination (L/PE$_{60}$/d)	24-29	16	13	25	13	—
Power generation from biogas						
- N elimination (kWh/PE$_{60}$/year)	15-18	—	—	—	—	11 (sludge) + 19 (waste)
- C elimination (kWh/PE$_{60}$/year)	18-22	11	9	15	13	—
Power consumption						
- N elimination (kWh/PE$_{60}$/year)	37	—	—	—	16 ****	25
- C elimination (kWh/PE$_{60}$/year)	25	9-10	6 (29)*	<4 ***	—	—
- Electricity coverage from biogas	35-80%**	115%	150% (40%)*	>300%***	50-70%	110%

Large (small) WWTPs.

***Depending on electric efficiencies of all WWTP installations.*

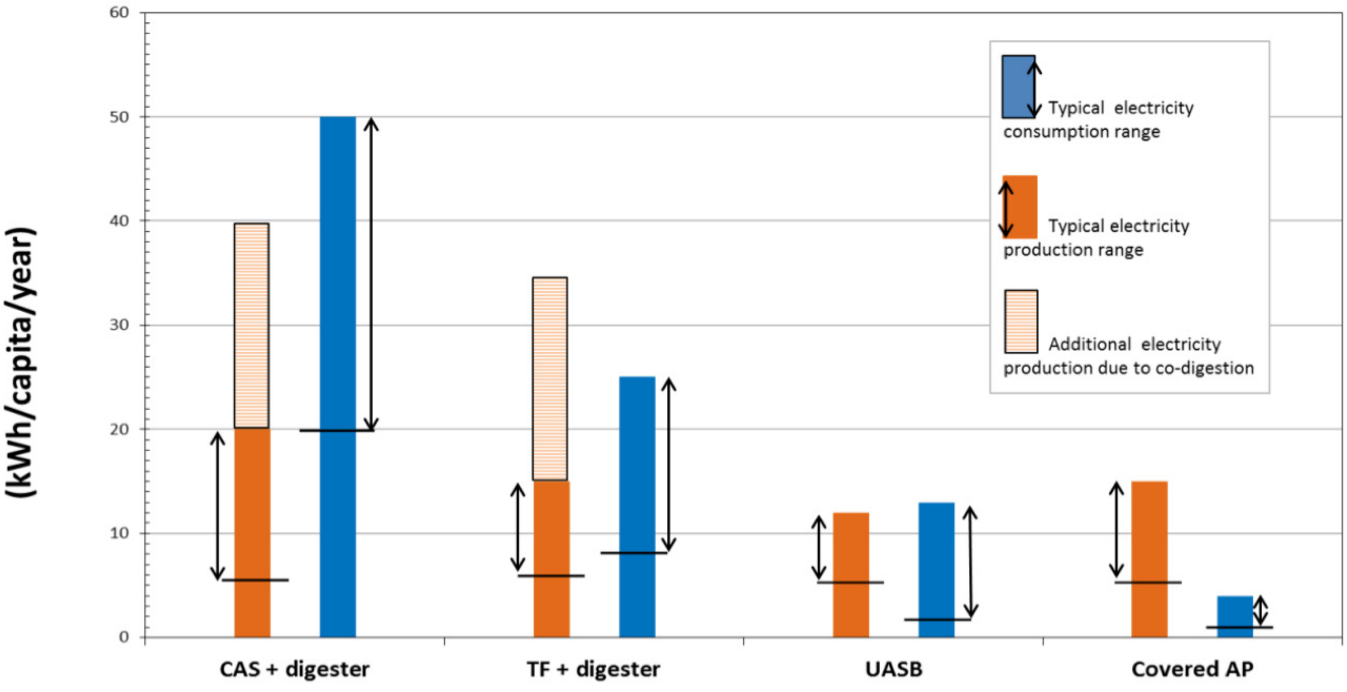
****Estimate.*

*****Including downstream CAS systems.*

Note: L/PE$_{60}$/d x 16.67 = L/kg BOD$_5$/d; kWh/PE$_{60}$/y x 16.67 = kWh/kg BOD$_5$/y.

Figure II-4, derived from the analysis of all the case studies, provides a broader picture of the ranges of electricity consumption and production within which the various technologies usually operate. Four of the case studies relate to different wastewater technologies (CAS, TF, UASB, and covered AP), and the fifth (co-digestion) can optionally be added to CAS and TF.

Figure II-4: Electricity Consumption versus Production of Different Technologies



Note: kWh/capita/y x 16.67 = kWh/kg BOD$_5$/y. CAS = conventional activated sludge; TF = trickling filter; UASB = upflow anaerobic sludge blanket; AP = anaerobic pond.

The following observations can be made:

- **Power consumption** *(blue bars in figure II-4):*
  - The case studies confirm that CAS is the frontrunner in terms of high energy consumption, with a power requirement range of 20–50 kWh/cap/y. TF requires only 8–25 kWh/cap/y, equal to about 35–50 percent of the energy CAS needs to operate. UASB requires about 2–13 kWh/cap/y, equal to 10–30 percent, and covered APs require 1–4 kWh/cap/y, equal to 5–10 percent of CAS's energy requirements.
  - The power consumption ranges, at their respective upper ends, also include requirements for enhanced nutrient removal for all technologies except covered APs. If APs did, indeed, require enhanced nutrient removal, additional treatment stages would be needed, which were not included in the case studies.
- **Power production from biogas** *(orange bars in figure II-4):*
  - The CAS + digester in case study 1 produces about 20–40 percent more electricity from biogas than other technologies.

  - While the most efficient means of increasing power production is co-digestion, using it is only possible with those technologies that feature separate sludge digesters. Depending on the quantity and quality of the extra feedstock, doubling the biogas/power generation from sludge alone can be feasible with the existing sludge installations.
  - Ultrasound sludge disintegration (USD) is a simple way to increase biogas/power generation further, but more than a net increase of 10–15 percent should not be expected. This option is only applicable to CAS + digester.
- **Electricity consumption coverage through power production from biogas at the plant:**
  - The CAS + digester case study shows that enabling full electricity coverage is usually not possible for this technology.[13]
  - In the cases with TFs + digester and UASBs, full electricity coverage can be achieved more easily if primary sedimentation tanks are included in the treatment train, wastewater treatment standards are limited to carbon removal and nitrification, sludge treatment is limited to thickening, digestion, and mechanical dewatering (no thermal drying or incineration), and the sludge digesters are properly mixed and operated at mesophilic temperatures of about 30–35°C.
  - Similarly, covered APs can always achieve full electricity coverage if only carbon removal is required and polishing ponds are sufficient to meet the effluent criteria. If stricter carbon standards and/or nitrification are required, a combination of covered APs with TFs will still be able to achieve full electricity coverage. Yet if additional denitrification is required as well, or if additional energy-intensive installations have to be operated, the electric power from the biogas can be insufficient to cover all these needs.

EAP countries may be able to enhance existing CAS systems with digesters for biogas production, with a potential to cover 20–80 percent of total power requirements through power generation onsite, depending on the local circumstances. The extent of the coverage primarily depends on wastewater and installation characteristics. The remaining power gap is still the largest of all analyzed technologies if co-digestion is not considered.

If figure II-4 is amended to show the effects of wastewater dilution, the energy consumption values will be in the upper range, and the energy production will be in the lower range indicated. The only means to counter this trend are (a) elimination or reduction of the underlying causes and (b) application of co-digestion to the greatest extent possible, as described in case study 5.

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[13] A few exceptions are characterized by very low energy consumption at benchmark level and optimum installations for biogas production and utilization.

Operation Capacity Needs and Biogas Safety

Table II-4 summarizes all the factors that can cause concern in the operation of the respective biogas and electricity generation systems in each of the case studies.

Table II-4: Possible Types of Concerns and Relevance for the Technologies Analyzed

CONCERNS	Case study 1: CAS + digestion	Case study 2: TF + digestion	Case study 3: UASB	Case study 4: Covered anaerobic ponds	Case study 5: Co-digestion
Safety concerns	YES	YES	YES	YES	(no change)
Digester foaming	YES	YES	—	—	(no change)
Deposits in the digester	YES	YES	YES	YES	YES
Insufficient biogas treatment	YES	YES	YES	YES	(no change)
Scum formation	—	—	YES	—	—

These concerns are discussed in depth in the annexes. Problems only arise if these factors are not properly considered at the design stage, in the specifications of the bidding documents, or in daily O&M. If they are properly handled, though, no sustained negative consequences are anticipated. Addressing these factors is not costly, nor does it require a great deal of knowledge.

Institutional Aspects Related to the Case Studies

The wastewater-to-energy components in the case studies were usually not incorporated out of a particular interest in energy production per se, but rather to find the least costly solutions to treat wastewater and sludge or, in case study 1, to stabilize and minimize sludge quantities, since the cost of sludge disposal in Europe and the United States is very high.

Case studies 2, 3, and 4 were selected because they combined competitive CAPEX with low electricity consumption. But in none of these cases was energy production from biogas included right from the start. Biogas utilization was deemed unattractive for financial reasons, due to operation concerns, or because its benefits were not well understood. Only in recent years, with increasing electricity costs and high OPEX, has interest emerged in options for biogas utilization in CHP.

Also notable is that, although the private sector is often involved in O&M tasks in many wastewater-to-energy projects in Europe and the United States, none of the case studies from elsewhere involves the private sector in the operation of CHP for energy generation. Below are summarized the institutional aspects of the case studies; a more detailed analysis of each case is provided in annex 3.

Regulatory framework. As shown in case studies 1 and 5, the utilization of electricity from biogas is explicitly regulated in Europe; however, this is not true in the other cases. In those where power surpluses are produced, transferring electricity to the public grid is usually an objective (case studies 2, 3, and 4), since storing it is too expensive to be considered. Alternatives, such as supplying the biogas to natural gas pipelines or producing biofuel, are technically possible but not common practice because they are not financially attractive. The low feed-in tariffs to the public grid in all the case studies provide little incentive for wastewater utilities to transfer their surplus electricity (see table II-6, below).

Case study 5, on co-digestion, shows the feedstock supply is just sufficient to cover 100 percent of the WWTP's own power needs. Surpluses are intentionally avoided. In this case it was interesting to see well-defined institutional arrangements in place, where collection and pretreatment of the organic waste is carried out by a private company that made all the necessary investments, whereas the wastewater utility receives the sludge free of charge.

A smart option found in case studies 3 and 4 (Brazil and Bolivia) is to supply electricity to the public grid and withdraw the same electricity at a different site, paying a reasonable grid transmission fee only. Large utilities that operate several WWTPs, not all of them producing electricity, and even water supply facilities find this option attractive. This innovative policy was, indeed, the main enabling factor for the utilities to start considering investments in energy generation at their WWTPs.

Know-how. While developed countries base many of their decisions on wastewater to energy on analysis of benchmarking data, this approach is unknown in other countries, where local specialists are usually quite hesitant to promote wastewater-to-energy projects because they are unfamiliar with many of the technical matters involved. Apart from rare exceptions, such as in Brazil, the technology is incorporated mostly by projects with international co-financing.

While access to financing would appear to be a major obstacle for wastewater to energy in developed countries (WERF 2012a; ESMAP 2012), the findings of the case studies did not confirm this. Rather, the main obstacles were low electricity unit cost and lack of knowledge, as shown by case studies 2, 3, and 4. It can be concluded, however, from case studies 1, 5, and 6 that European utilities already opt for investing in energy generation if the investment can be paid back within the average lifespan of the required installations, which is typically about fifteen years. Utilities in these cases are particularly keen to present a "green image" to the public. This trend has also been detected in other countries, yet it is still not translated into a decisive impact on decision making in case studies 2, 3, and 4.

GHG Reduction and Co-financing through Carbon Trading

All the case studies were analyzed according to their potential for GHG reduction, taking into consideration co-financing from CDM. Following the approach usually taken by these utilities, the potential reduction in CO_{2e} is calculated from the combined effects of (a) the amount of electricity generation from fossil fuels that is being replaced by electricity from renewable sources and (b) the reduction of emissions of methane, a GHG twenty-one times stronger than CO_2. Not included in this assessment are the effects of nitrous oxide (N_2O), which can play an important role in nutrient removal (WERF 2012b). N_2O is subject to ongoing research activities. However, quantifications of its effects for any process technology are still under discussion.

Table II-5: GHG Reduction Results of Case Studies

GHG reduction	CASE STUDY 1: CAS + digestion		CASE STUDY 2: TF + digestion	CASE STUDY 3: UASB	CASE STUDY 4: Covered anaerobic ponds	
	Germany	Austria			Santa Cruz	Melbourne
GHG reduction						
tons CO_{2e}/y	n.a.	n.a.	2,350	1,100	65,392	302,019
kg CO_{2e}/PE_{60}/y	7	3	5	1	82	66
kg $CO_{2e}/kgBOD_5$	0.3	0.1	0.2	0.04	3.7	3.0
kg CO_{2e}/cap/y	7	3	4	1	54	66
Aspects considered						
GHG reduction by electric power generation	YES	YES	YES	YES	YES	YES
GHG reduction by methane emission reduction	n.a.	n.a.	n.a.	n.a.	YES	YES

Source: Geyer and Lengyel 2008.

Note: Data for case study 1 are based on an electricity production of 16 kWh/PE_{60}/y, which is an average yield in case of N elimination (see annex 3).

The case study assessments show that the present low price of carbon credits renders most wastewater-to-energy projects unattractive for carbon trading. Table II-5 summarizes the GHG reduction results from the case studies.

The case studies have major differences in terms of GHG reduction. Case study 4 (covered anaerobic ponds) achieves most reductions by eliminating CH_4 (methane) emissions when the anaerobic ponds are covered. Technologies that already collect biogas as an intrinsic part of the treatment process, such as CAS, TF, or UASB, cannot claim the elimination of the CH_4 generated at the plant under generally accepted carbon trading schemes.

Case study 1 shows that the price of carbon credits is as low as US$6.80/t$CO_{2e}$ in the European Union Emissions Trading System (EU ETS). Prices are not substantially higher at other trading places, either, which reduces the attractiveness of this financing option. Applying these unit prices to any of the other case studies produces absolute prices that are lower than the cost of preparing those carbon trading projects, particularly if only the electricity generation can be claimed.[14]

Energy Costs and Viability of Investment in Biogas Utilization

Table II-6 summarizes the electricity feed-in and purchase tariffs of the case studies.

Table II-6: Feed-in Tariffs for Electricity Generated from Biogas at WWTPs, as Compared to Unit Power Cost for Electricity Purchases from the Public Grid

Country	Feed-in tariff	Electricity cost from public grid
	US$/kWh	US$/kWh
Australia	(=purchase cost minus small fee)	≈0.09
Austria	0.08	≈0.14
Bolivia	(only power transmission is targeted)	0.06
Brazil	(only power transmission is targeted)	0.25
Germany	0.08-0.09	≈0.20
Nicaragua	(not yet defined)	0.08

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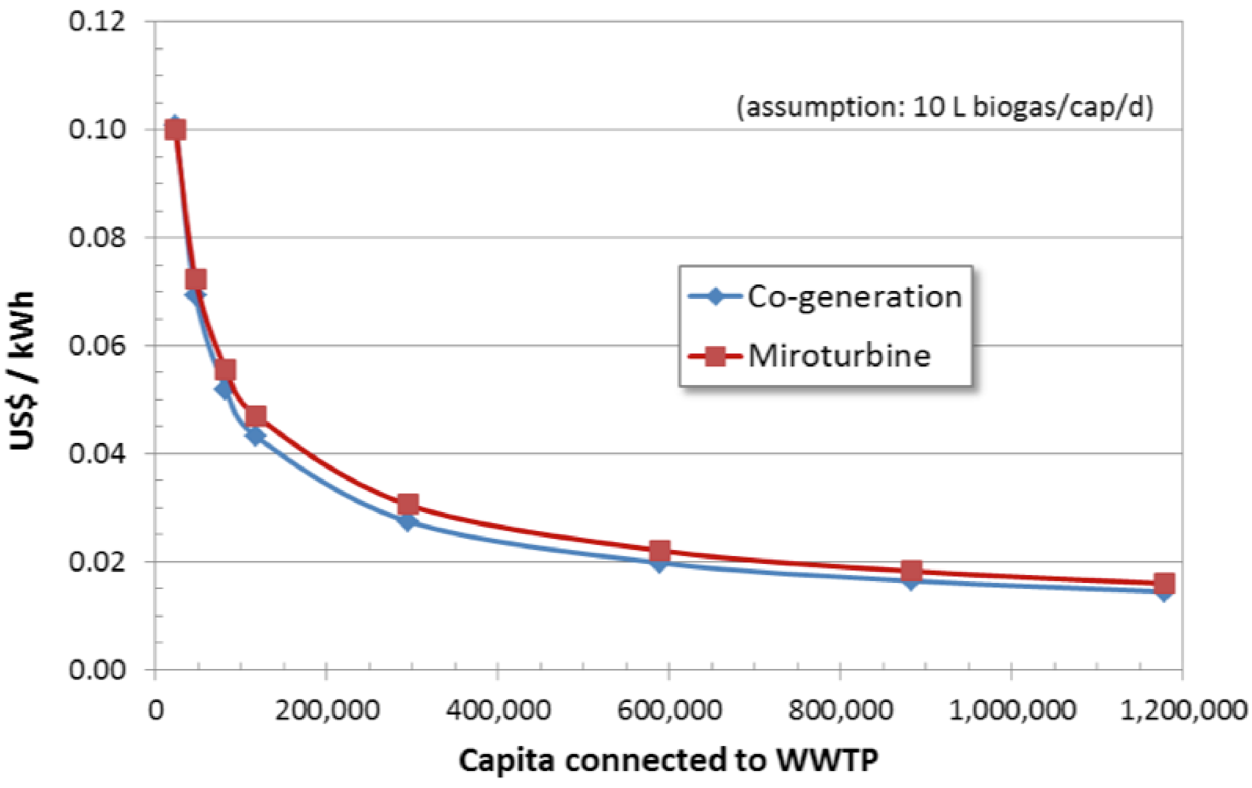
[14] A change would be possible if the price of carbon credits reflected the real costs. Annex 3, case study 1 indicates the real cost by presenting companies' "internal carbon price" per ton of CO_{2e} - about US$40 - which they use for planning purposes. If a price around this value were to materialize, CDM co-financing could become a much more appealing funding instrument, both in general and specifically for wastewater-to-energy projects in the future.

The electricity unit cost in the countries of the case studies ranges from US$0.06 to US$0.25/kWh—a ratio of four between the minimum and maximum electricity unit cost. This can have a decisive influence on overall financial viability, since the investment cost of the installations in question does not tend to vary that much.

Feed-in tariffs in many of the case studies are uncertain. In some of these cases, only a general agreement has been cleared with the power utility, without specific unit values for kWh supplied to the grid. In these cases, the feed-in tariff is expected to be lower than the retail price.[15]

The cost of generating electricity from biogas is generally lower than the above-cited unit cost of purchasing electricity from the grid. Figure II-5 presents the cost of electricity generation from biogas, based on life cycle cost assessment. These results are derived from CAPEX and OPEX information provided by Geyer and Lengyel (2008) for implemented projects of different sizes. The cost assumptions used in this analysis are on the conservative side. The life cycle cost calculation includes all installations typically required for biogas utilization, including gas treatment.[16]

Figure II-5: Total Life Cycle Cost of Electricity Generation from Biogas



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[15] In Austria and Germany, the feed-in tariff is regulated by law, and equals roughly 50 percent of the electricity unit purchase price.

[16] Further assumptions are a twelve-year lifespan of installations with an availability of about 90 percent, discount factor of 5 percent, and conservative biogas production assumptions (production of 10 L/cap/d, 62 percent methane, 30 percent electric efficiency of CHP). Similar total cost values are also cited in other sources (U.S. EPA CHP Partnership 2011).

Comparing these findings against the electricity tariff in Vietnam (US$0.06/kWh) suggests biogas utilization is viable for plant sizes larger than about 80,000 capita. With higher electricity unit costs, as in Indonesia (US$0.12/kWh) and the Philippines (US$0.22/kWh), smaller plants (less than 80,000 capita) can also be financially attractive; and, since the latter unit cost values are comparable to those in Europe, financial viability may be possible, as in Europe, for plants down to a minimum size of about 10,000 capita (see annex 3, case study 1). Taking also into account other possible cost components, such as improved preliminary treatment for efficient grit and screenings removal or power feed-in installations, minimum WWTP design sizes over a total range of about 10,000–100,000 capita may be realistic for financially viable wastewater-to-energy projects.

Table II-7 summarizes the financial viability of wastewater-to-energy projects for the case studies presented by looking at their respective payback periods under their specific local cost conditions.

Table II-7: Financial Viabilities of Case Studies

Case study	Payback period (y)	Observation
1 CAS + sludge digestion	<15	Relates to a wide set of cases with different base configurations. Generally, anaerobic sludge digesters, combined with biogas utilization in CHP, are considered financially viable in Central Europe for WWTPs with a design size larger than 10,000–20,000 PE_{60}. The larger a WWTP, the shorter the payback period.
2 TF + sludge digestion	≈10	Relates to the introduction of a biogas utilization project with CHP (microturbines).
3 UASB	≈7	Relates to the introduction of a biogas utilization project with CHP.
4 Covered anaerobic ponds in Santa Cruz (Bolivia)	≈10	Relates to the complete cost of covers + biogas utilization project with CHP. High value mainly due to low cost of electricity in Bolivia.
5 Co-digestion of organic waste	<1	Very low investment (pre-treatment of waste done by private company; at WWTP only minor adjustments are necessary, since infrastructure for sludge digestion and biogas management already exist); additional reduced OPEX.
6 Ultrasound sludge disintegration	≈5	Relates to complete cost involved.

All the presented wastewater-to-energy case studies are deemed financially viable by their respective utilities. Nonetheless, while in many developed countries these projects nowadays have become standard WWTP components—as, for example, in case studies 1, 4 (Australia), 5, and 6—they have not as yet been included in case studies 2, 3, and 4 (Bolivia).

8. Simple Assessment Tool

A simple tool has been developed to provide a quick and preliminary assessment of wastewater-to-energy projects. It is conceived as a first step, to be followed by more in-depth analysis. The tool can be used for the following:

- Estimation of the potential for biogas production with various wastewater-to-energy technologies
- Estimation of the electricity generation potential from that biogas
- Preliminary assessment of the electricity coverage that can be achieved with various WWTP treatment and wastewater-to-energy technologies
- Preliminary design of major components of a wastewater-to-energy project, such as required digester volume, required gas holder volume, and total CHP power requirements
- Estimation of the overall impact on OPEX of investing in energy generation technology

The tool does not provide a detailed cost–benefit analysis considering life cycle costs, as many factors influencing CAPEX depend on the particular situation in each plant. This type of analysis would be the natural next step after using the tool to deem wastewater to energy potentially viable.

Development of the Tool

The tool is based on a simple Excel spreadsheet calculation, containing two sheets:[17]

- **Sheet 1 ("Input and Results").** Sheet 1 consists of two parts:
  - *The upper part* of the sheet is where the user can insert the necessary input data, reflecting conditions of a specific project. The sheet also contains information on standard values, which can be utilized if project-specific input data are not known.
  - *The lower part* summarizes output results, facilitating the modification of input data and directly checking the impact on results without the need to switch between sheets.
- **Sheet 2 ("Details").** Sheet 2 includes the detailed calculations automatically made by the tool.

The following wastewater-to-energy technologies can be analyzed with this tool:

- **CAS + digestion** (+ optional co-digestion)
- **Trickling filter + digestion** (+ optional co-digestion)
- **UASB**
- **Covered anaerobic ponds**

Since this tool is intended for preliminary assessments only, it should not be used as a substitute for a feasibility study, pre-designs, or final designs.

Application of the Tool to a Specific Case Study

The assessment tool has been applied to the specific case of the Valenzuela Sewage Treatment Plant located in Metro Manila, Philippines, comparing results for actual influent characteristics with a range of realistic modifications. Results show the significant impact of project-specific wastewater characteristics on the viability of biogas generation at a WWTP.

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[17] Both sheets of the tool are open, so components or modifications can be added to it. A code provided as a footnote in both sheets can be applied by users to unlock cells that are initially protected to avoid unintentional changes.

The concessionaire responsible for this project is Maynilad Water Services, Inc. As of this writing, the design and construction of the WWTP were open to bids. Preliminary versions of the assessment tool were used in the preparation of the bidding documents to assess the feasibility of a wastewater-to-energy project. The results indicated the project would be feasible only if additional feedstock were co-digested, due to the effects of the heavy dilution and lack of solids in the raw wastewater. Consequently, the decision of including a wastewater-to-energy component was left open to bidders.

For the purposes of this report, the tool was applied to investigate the following scenarios for Valenzuela STP:

- **SCENARIO A: Very diluted wastewater + many septic tanks.** CAS + digester, based on actual influent data as analyzed in 2013:
  - Influent BOD_5 = 80 (55) mg/L in dry (rainy) season
  - Influent VSS = 0.3 x BOD_5 = 24 (17) mg/L in dry (rainy) season
  - Influent TSS = VSS / 0.7 = 34 (24) mg/L in dry (rainy) season
- SCENARIO B: Diluted wastewater + many septic tanks. CAS + digester, with the following (theoretical) changes:
  - Increased influent BOD_5 = 180 (155) mg/L in dry (rainy) season
  - Influent VSS = 0.3 x BOD_5 = 54 (47) mg/L in dry (rainy) season
  - Influent TSS = VSS / 0.7 = 77 (66) mg/L in dry (rainy) season
  - Introduction of primary sedimentation tank (PST)
  - Co-digestion of 5 m^3/d of fat, oil, and grease (FOG)

  - Installation of ultrasound sludge disintegration (USD)

- **SCENARIO C: Diluted wastewater.** CAS + digester, similar to scenario B but with additional changes of influent concentrations:
  - BOD_5, PST, co-digestion, USD: same as scenario B
  - Influent VSS = 0.7 x BOD_5 = 126 (109) mg/L in dry (rainy) season
  - Influent TSS = BOD_5 = 180 (155) mg/L in dry (rainy) season

All three scenarios are assessed with the same flow rate, which is 40 MLD in the dry season (five months a year) and 60 MLD in the rainy season (seven months a year), so all scenarios relate to a 60 MLD plant, but with different influent concentrations and technology components.

The focus of this example is exclusively on CAS + digester, since CAS and its variations are the selected technology in this case. The assessment tool is also providing results for trickling filter + digestion, UASB, and covered anaerobic ponds. While these results are not discussed in this example, the discussion may be relevant to other projects.

Table II-8 summarizes the electricity generation and coverage of the plant's total electricity consumption, as well as total OPEX savings for the three scenarios.

Table II-8: Key Results Taken from Exemplary Application of Assessment Tool to 60 MLD WWTP with CAS + Digestion Technology, for Three Scenarios

	Scenario A	Scenario B	Scenario C	
Electricity generation from biogas	264,981	1,222,604	2,239,332	kWh/year
Electricity coverage from biogas	12%	22%	40%	% of total consumption
Total OPEX saving	-25,083	-472,657	-729,645	US$/year

The results reveal how dependent biogas production is on specific project conditions. For the same plant capacity of 60 MLD, supposedly minor changes of influent characteristics—the introduction of co-digestion of small quantities of FOG and the application of ultrasound sludge disintegration technology—can increase biogas production almost tenfold.

Using the preliminary assessment generated by the tool, additional information was introduced to estimate CAPEX and assess financial viability. Table II-9 presents a basic CAPEX estimate for scenario C.

CAPEX was also calculated for the two other scenarios: in scenario B, it was US$3.4 million, and in scenario A, US$0.7 million[18].

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[18] These financial assessments are somewhat simplified: (a) for scenarios C and B, the CAPEX reduction caused by the reduced aeration tank volume has not yet been considered, so the financial appeal of these scenarios is actually higher; and (b) financing cost has not been taken into account.

Table II-9: CAPEX Estimate for Scenario C, Based on Results from Exemplary Application of Assessment Tool to 60 MLD WWTP with CAS + Digestion Technology

	Required		Unit cost (US$)	Cost (US$)
Primary sedimentation tank	2,000	m^3	300	600,000
Aeration tank volume saving	-40%		300	Not considered
Reception and dosing station for FOG	1	sum	50.000	50,000
Ultrasound sludge disintegration	1	sum	370,000	370,000
Anaerobic sludge digester incl. piping	3,231	m^3	600	1,938,631
Biogas holder	517	m^3	800	413,250
CHP	339	kW	1,500	508,204
Flare, gas piping	1	sum	100,000	100,000
Sludge holding tank after digester	40	m^3	400	16,000
Subtotal				**3,996,085**
Contingencies and engineering	20%			799,217
Total additional CAPEX				4,795,302

Conclusions:

- In **scenario C,** an investment of US$4.8 million leads to annual OPEX savings of US$0.73 million. Not including financing cost, the payback period of this investment is 6.6 years. Most likely, this is a **financially viable** investment.

- In **scenario B,** an investment of US$3.4 million leads to annual OPEX savings of US$0.47 million. Not including financing cost, the payback period of this investment is 7.2 years. Most likely, this is a **financially viable** investment.

- In **scenario A,** an investment of US$0.7 million leads to annual OPEX savings of US$0.025 million. Not including financing cost, the payback period of this investment is 28 years. This is **financially not viable**.

The conclusion of this preliminary assessment is that scenarios C and B deserve in-depth analysis of a wastewater-to-energy component, while scenario A should probably be ruled out.

This example also confirms the finding that once the wastewater is so diluted that a PST is not necessary, which is typically the case with TSS less than about 80 mg/L, sludge digestion (without co-digestion of extra feedstock) is not viable. But as soon as a PST is recommendable, the chances for a financially viable wastewater-to-energy project greatly increase.

SECTION III: LESSONS LEARNED AND RECOMMENDATIONS

9. Constraints and Enabling Factors

From the experience with the implementation of wastewater-to-energy processes captured in both the desk review and the case studies, it is possible to derive a series of lessons learned and recommendations, summarized below, in the form of typical constraints and enabling factors that need to be taken into account when considering these types of investments in EAP countries. Some of these recommendations are already described to by WERF (2012a) and Willis and Stone (2012).

Technical Aspects

The main technical aspects to consider when assessing wastewater-to-energy investments are the following:

Size. Not any plant size is suitable for waste-to-energy investments. A preliminary assessment for conditions in EAP countries showed that the threshold in this region may vary between 10,000 and 100,000 PE_{60} (2,000–20,000 m^3/d). A case-by-case analysis is required to determine the real threshold in each case. The tool included in this technical note can be used for that purpose.

Wastewater dilution. Wastewater dilution is perhaps the most important technical barrier to investment in wastewater to energy because it may lead to reduced biogas production and energy generation potential. For this reason, it is crucial to have a reliable set of data, with a time series long enough to capture seasonal variability in the concentration of relevant wastewater parameters, such as BOD_5, COD, and suspended solids. The tool presented in this technical note can provide useful information on the potential viability of energy generation options at a plant, to be followed by a case-specific analysis. In general terms, if TSS is less than about 80 milligrams per litre (mg/L), then neither sludge digesters (lacking primary sludge) nor anaerobic wastewater technologies (requiring large volumes) is attractive because of the consequent negative implications for the generation of biogas.

Yet even under these conditions, co-digestion of organic feedstock could make wastewater to energy viable. In EAP, investigating the potential of fecal sludge or other organic material such as food waste for co-digestion may also prove promising.

Effluent quality requirements. At present, effluent requirements are quite different from country to country in EAP. Whereas nutrient criteria are already in place in Vietnam, in the Philippines a discussion is ongoing about the introduction of such standards. Indonesia also does not apply nutrient standards at present. As explained in the previous section, the required effluent quality has implications for both the energy consumption and the electricity generation potential of WWTPs, as the stricter the effluent standards, the higher the consumption of electricity and the lower the electricity generation potential.

In countries where treatment levels are as low as in EAP, the first priority should be installing facilities that remove the bulk of the organic pollution. Nutrient removal should only be introduced later, where environmentally justified; effluent standards have been similarly approached stage-wise in other countries. A sensible approach should allow for (a) less strict standards for small WWTPs, since their environmental impacts are small as well, and (b) stricter standards for large WWTPs only where the recipient water is indeed sensitive to the discharges.

Co-digestion. Alternative feedstock (organic waste) can be used in addition to sludge to increase biogas production. When evaluating co-digestion, apart from other organic wastes (FOG, organic municipal

waste, food waste, industrial waste, and so on), it is also important to consider fecal sludge as a potential extra feedstock. Experience from Vietnam points to the possibility that fecal sludge may also be a suitable co-substrate if it is collected from appropriate sources.

Consolidation of solids handling. Consolidation of the solids handling of small plants at a larger, centralized facility is usually financially viable for small WWTPs that produce sludge after thickening. The extra sludge is delivered to a nearby medium-sized or large facility, where it is "co-digested" with the larger facility's own sludge.

Knowledge Aspects

The main knowledge constraints and enabling factors are related to the following aspects:

Informed decisions. Holistic technology benchmarking is missing from the wastewater sector in EAP countries, so decisions are frequently made without evidence from real operations, using data or experiences from contexts different from the local ones—a practice that leads to suboptimal solutions. Added to the lack of comprehensive information on all possible options for wastewater to energy is the sparseness of research applied to and published on low-cost options. The tendency is to "copy and paste" solutions from other countries that do not always consider the low-cost

technologies best suited to warm climates. Project owners sometimes prefer technologies that are "cutting edge" and place more emphasis on CAPEX than on OPEX.

While the resulting designs are not wrong per se, this knowledge gap can lead to projects that perform less than optimally, which may negatively affect their lifespans and even result in project failures.

The following are some of the most typical misconceptions and bad practices from a technical standpoint:

- Underestimation of the impacts of inefficient grit chambers, which result in undesired sand accumulation, particularly in anaerobic lagoons and digesters
- Underestimation of the negative impacts of inefficient screening on scum formation in UASB systems
- Lack of FOG removal prior to UASB, which contributes to scum formation in UASB, resulting in reduced performance
- Unrealistic biogas yield assumptions
- Lack of efficient and affordable biogas treatment
- Unrealistic O&M cost assumptions
- Suboptimal design of biogas-related installations
- Exaggerated safety concerns
- Lack of adequate mixing

For all these reasons, gradually introducing holistic technology benchmarking to the sector is important. Increased efforts to collect data should be the starting point for identifying and quantifying savings potentials in more efficient operations. Initiatives like the ibNet should be further promoted in the wastewater sector so operators can compare themselves to and learn from the best performers. This practice usually implies motivation to do better, and both average performance and benchmarks will improve over time. Particularly important is conducting research on how these processes can be applied in developing countries, and on how operational results from large-scale plants with energy generation compare to technologies without it.

Training of operators. Operators are not always well trained and informed, not only about regular operating routines, but also about troubleshooting techniques and necessary conditions for adequate biogas system functioning. Operators often do not understand potential problems, or they lack the means for process control and intervention. Training needs should be well identified and addressed, and training programs should target the understanding of potential problems and provide the means for process control and intervention. Involving the private sector by subcontracting energy generation as a separate operation unit within the WWTP is an interesting option to consider, eliminating the need for operator training for this specialized task. Most manufacturers of CHP offer this service at competitive cost.

Operation and maintenance. Undermaintaining has a negative impact on the efficiency of treatment systems and increases life cycle costs. A relatively minor financial savings on maintenance can result in considerably larger financial losses. This link between O&M and the lifespan of facilities is not always well understood at the time of making the investment and planning the operational arrangements.

Insufficient maintenance is often not so much a matter of negligence on the operator's side as it is hampered by a procurement system that is devised with little understanding of urgent maintenance needs. Procurement is often conducted with an eye toward saving money by bargaining with operators about the necessity of specific maintenance requirements.

Poor O&M can also be a consequence of inexperience. Some of the few existing sludge digesters in East Asia are suffering from problems associated with foaming and deposits in the digester. Presumably this is a typical consequence of inadequate preliminary treatment (screening and grit removal). To avoid such problems in the future, it may be worthwhile to consider DBO (design-build-operate) contracts for WWTPs with sludge digesters. With their use, experienced private companies in charge of the complete WWTP design and operation are expected to install proper components at all stages. As demonstrated by case study 2, this approach can work well.

In any case, a utility that follows a culture of undermaintaining the existing facilities should reverse this tendency before considering investment in energy generation solutions. Maintenance of the WWTP should be understood as an essential expenditure that helps reduce total life cycle cost rather than one that should be minimized. Asset management and/or maintenance plans need to be already in place at the planning stage. Again, considering the private sector for tasks related to O&M is an interesting option.

Safety. While safety issues are a common concern among practitioners in the sector, risks usually only arise in cases of inappropriate design, questionable material quality, or ignorance of simple O&M precautions. Wastewater-to-energy technologies are not complicated to operate, and safety and operation risks are low if (a) designs are done properly (wastewater + sludge + biogas), (b) specifications in the bidding documents are tailored to the real needs, and (c) operational protocols developed for these technologies are properly followed.

Reliability of power supply. In situations where power supply from the public grid is not reliable, additional backup systems or smart biogas and power management strategies are indispensable.

Institutional Aspects

The main institutional aspects to consider are the following:

Regulatory framework to utilize electricity from biogas. WERF (2012a) and Willis and Stone (2012) report that many water and wastewater utilities run into problems with power utilities when they decide to start a biogas project. Sometimes power companies do not want the utilities to produce power onsite and threaten "that the plant [will] lose their eligibility for lower power rates and rebate programs."

In addition, while the priority for utilization of the electricity generated from biogas should always be onsite at the WWTP, in some cases a power surplus is produced. Energy generation at facilities with low electric power consumption, such as UASB plants or covered anaerobic ponds, can produce more electricity than the plant requires. If good financial use cannot be made of this surplus, simply flaring the biogas off may seem more attractive than investing in infrastructure to utilize it.

Subsidies that reduce the unit cost of electric power can prove a major obstacle to energy recovery from renewable resources. The decision to undertake an energy recovery project is mostly based on a financial assessment of its viability. The more subsidized the cost of electricity is, the less attractive the investment in energy recovery will be. After all, investments in energy generation from biogas are usually not subsidized and still have to compete with subsidized unit cost per kWh. Such a distortion of electricity prices through subsidies has a negative implication, regardless of whether the electricity from biogas is used at the WWTP or sold to the public grid.

Therefore, a clear tariff policy that includes the option for supplying bioelectricity to the public grid utilities will raise interest in investment in wastewater-to-energy technologies. High feed-in tariffs can facilitate the implementation of biogas projects, but the rules for this practice should be well defined.

Co-digestion. Since co-digestion is a relatively new practice, the rules and institutional arrangements that govern the use of organic solid waste at WWTPs may not be developed yet. Co-digestion implies collection of different types of organic waste, so responsibilities could fall under different utilities. Disagreements on who "owns" the waste and how it should be collected and transported could arise between the waste collector and the WWTP, so this must be clarified. Similarly, the rules that govern the disposal of the digested product from co-digestion need to be clear. Having contracts with other utilities or service providers (municipal departments or private companies) will be necessary to determine responsibilities and define implementation arrangements for co-digestion of organic waste at WWTPs.

Economic and Financial Aspects

According to a survey carried out by WERF (2012a) in Australia, Canada, and the United States, the most significant barriers to biogas use are economic. The following were the main findings of the survey:

- Utilities may have other priorities for limited capital resources than investing in biogas use. In particular, the ongoing challenges to rehabilitate and maintain existing infrastructure do not leave much room for new investments.

- The economic analysis conducted to determine the viability of a wastewater-to-energy project is often limited to a requirement for a predetermined, short payback period for the investment, neglecting such other factors as impact on cash flow, annual reduction in OPEX, or improved present worth.

- Paradoxically, small WWTPs with capacities of 2–10 MGD (≈20,000–100,000 PE_{60}) were found to overcome barriers with more creative approaches (for example, grants or carbon credits), while those between 10 and 25 MGD (≈100,000–300,000 PE_{60}), despite being more viable, were often ruled out for biogas utilization due to the larger investments needed and the difficulty of finding financing options.

Some of these situations are also found in EAP, where autonomous utilities are rare and usually constrained by low revenues from low tariffs in the sector due to little willingness to pay or to charge. Also, wastewater and water supply businesses are often not merged under a single utility, so no opportunity exists to cross-subsidize wastewater operations. Utilities also have a long list of challenges to deal with, such as extending coverage, reducing losses, connecting more households, and meeting effluent standards (World Bank 2013; ESMAP 2012). All these factors translate into little margin for financial maneuvering and, therefore, impose an important constraint on investing in energy generation.

For these reasons, potential gains from reduced OPEX can be interesting for financially weak utilities. Sound economic and financial analysis should be carried out to determine the impacts of investing in energy generation on reduced OPEX and overall performance of the utility. Only then will it be possible to place this option on the long list of priorities the utility may have.

Economic analysis should therefore be more comprehensive by considering net present value, net revenue, and operational savings. In particular, cash flow potential, especially over the long term, should be highlighted for decision makers, tying maximum acceptable payback periods to the average service life of the equipment, not to predefined periods.

In addition, it is important to consider all possible sources of funding, such as grants, low-interest loans, or state-supported financing.

Finally, the present low price level of carbon credits renders most wastewater-to-energy projects unattractive for Clean Development Mechanism (CDM) application. Nevertheless, many facilities are interested in quantifying greenhouse gas (GHG) emission reductions they have achieved as proof of environmental stewardship.

10. Road Map for Decision Making

Following the steps in the road map below may be helpful to managers of utilities in charge of running different WWTPs as they decide whether to invest in wastewater-to-energy solutions:

1. Collect data on flows and concentration of pollutants (BOD, COD, TSS, VSS, P, N).
2. Forecast future development in terms of extension of the collection network and new connections.
3. Conduct a preliminary assessment of wastewater to energy by, for example, using the tool developed in this technical note. Taking an unbiased look at all possible biogas options and not defining technologies prematurely is important for this purpose.
4. If viability looks promising, proceed to a more in-depth analysis, considering all institutional, technical, and financial factors explained in this technical note. The following are particularly important:
    - a Compare electricity consumption values of the project being evaluated with the reference numbers presented in this study. Check energy designs (consumption and production) using the assessment tool, which can be used to quantify the potential of various treatment alternatives for energy consumption and generation.
    - b Pursue a detailed financial analysis, including both CAPEX and OPEX projections in project evaluations. Insist on detailed OPEX structuring, with solid justification of underlying assumptions.
5. If viability is confirmed, proceed to financing, detailed design, bidding, and implementation.
6. Periodically review operational results to reassess and improve design parameters in future investments at other plants owned by the utility.

The same decision flow outlined above can be applied to new WWTPs, with the additional need to select the right technology for wastewater treatment. Among the different criteria to be assessed, the importance of low OPEX should be highlighted. Alternative technologies combined with biogas utilization offer a potential for strongly reduced electricity cost. These savings can make the decisive difference between operating a treatment plant in a sustainable manner or doing so suboptimally with negative implications on the lifespan of the investment.

References

Abbasi, T. et al. 2012. "A Brief History of Anaerobic digestion and Biogas. In Biogas Energy, Springer Briefs in Environmental Science 2." DOI 10.1007/978-1-4614-1040-9_2.

ADB (Asian Development Bank). 2012. "Promoting Beneficial Sewage Sludge Utilization in the People's Republic of China." 21.

ANEEL (Agencia Nacional de Anergia Eléctrica). 2012. Resolucao Normativa No. 482, (in Portuguese language).

ARAconsult. 2009. "Bäckerei Ruetz – Biogas aus Bäckereiabfällen (Bakery Ruetz - Biogas from Bakery Waste), (in German language)." 44.

ARAconsult. 2012. "Kläranlage Obervinschgau in Glurns: IST-Zustands-Erhebung (WWTP Glurns – Assessment of Actual Situation), (in German language)." June.

ARAconsult. 2013. "Programa DKTI da Copasa, Componente 2 – Eficiencia energética em ETEs (DKTI Programme: Component 2 – Energy efficiency at WWTPs), (in Portuguese language)." 91. June.

Asian Green City Index 2011. Siemens AG

ASUE (Arbeitsgemeinschaft für sparsamen und umweltfreundlichen Energieverbrauch e.V.). 2011. "BHKW-Kenndaten 2011 (Co-generation key data), (in German language)." 64, Berlin, Germany.

Baubüro, Syneco. 2012. "Co-Vergärung der Bioabfälle in der BZG Vinschgau (Co-fermentation of biowaste at WWTPs in Vinschgau, Northern Italy)." Umsetzungsprojekt und Vorprojekt. 71.

Bauerfeld, K., Dockhorn, T., and N. Dichtl. 2009. "Klärschlammbehandlung und –verwertung unter anderen klimatischen und sonstigen Randbedingungen (Sludge treatment under different climate and other conditions), (in German language)." Technical University Braunschweig.107. October.

Billmaier, K., et al. 2001."Anforderungen an die Co-Fermentation von biogenen Abfällen in Faulbehältern von Kläranlagen (Requirements fort he co-fermentation of biowaste in WWTP digesters), (in German language)". Merkblatt, Berichte zur Umwelt, Bd. 22. MUNLV: Düsseldorf.

BLFUW (Bundesministeriums für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft der Republik Österreich). 2001."Benchmarking in der Siedlungswasserwirtschaft (in German language). "

Braun, R. 2001. "Stand der Technik der Klärschlamm-Cofermentation in Europa (State of the art of co-fermentation in Europe). " IFA: Tulln.

Buchauer, K. 1996. "Biologische Hydrolyse zur Optimierung von Bio-P (Biological hydrolysis for optimization of enhanced biological phosphorus removal), (in German language)." 297. PhD thesis. University Innsbruck.

BUWAL (Bundesamt für Umwelt, Wald und Landschaft, Schweiz). 1994. "Energie in ARA – Energiesparmassnahmen in Abwasserreinigungsanlagen (in German language). " By E.A.Müller, R.Thommen, P.Stähli.

Cakir, F.Y., and M.K. Stenstrom. 2005. "Greenhouse Gas Production: A Comparison Between Aerobic and Anaerobic Wastewater Treatment Technology." Water Research, *39*. 4197-4203.

Callegari C. 2010: "Co-Fermentation Erfahrungsbericht – AWV Fritzens (Practical results from co-digestion at Fritzens WWTP), (in German language)." Proceedings of OWAV conference on sewage sludge. 23.

Cao,Y.S. 2011. "Mass flow and energy efficiency of municipal wastewater treatment plants." IWA Publishing. 111. 2011.

Casazza, R. 2010. "STEP d'Estavayer-le-Lac, Désintégration des boues, Evaluation intermédaire (Estavayer-le-Lac WWTP, Sludge disintegration, Intermediate evaluation), (in French language)." 5. March.

Chamy, M.R. 2013. "Anaerobic digestion to decrease the carbon footprint." Proceedings of 13th IWA World Congress on Anaerobic Digestion, Santiago de Compostela (Spain). 4. June 25-28.

Chen, C.L., et al. 2013. "Faeces and food waste co-digestion for development of decentralised urban resource recovery in Singapore". 13th IWA Conference on Anaerobic Digestion, Santiago de Compostela, Spain. 4.

Chernicharo, C.A.L., et al. 2012. "Anaerobic domestic wastewater treatment in Brazil: drawbacks, advances and perspectives." *Water 21*. 24-26, October.

Chernicharo, C.A.L., et al. 2013. "Current limitations and the necessary improvements in the anaerobic technology for domestic wastewater treatment." Proceedings of 13th IWA World Congress on Anaerobic Digestion, Santiago de Compostela (Spain). 4. June 25-28.

CIWEM, aquaenviro, SCI, United Utilities. 2013. "Activated sludge: past, present and future; One hundred years of activated sludge – a brief history." www.activatedsludgeconference.com.

CME (Carbon + Energy Markets). 2012. "Electricity Prices in Australia: An International Comparison." *A report to the Energy Users Association of Australia*. March.

DeGarie, C.J., et al. 2000. "Floating geomembrane covers for odour control and biogas collection and utilization in municipal lagoons." *Water Science and Technology*. 42, 10-11, 291-298.

Dengg, J. 2013. "Co-Vergärung auf der ARA Strass (Co-digestion at Strass WWTP), (in German language)." *KA-Betriebs-Info 2013 (43)*. 2113-2118. July.

Dohmann, M. and M. Schröder. 2011. "Energy in the Wastewater Disposal Sector – Historical View and Future Prospects (in German language)." *Korrespondenz Abwasser, Abfall (KA), (58) Nr.6*. 536-541.

DWA (German Association for Water, Wastewater and Waste).1996. "ATV-Handbuch Klärschlamm (ATV-Manual Sludge) (in German language)." 4th edition.729, ed. Ernst & Sohn. Berlin, Germany.

DWA (German Association for Water, Wastewater and Waste).2002. "Merkblatt ATV-DVWK-M363: Herkunft, Aufbereitung und Verwertung von Biogasen (DWA Advisory Leaflet M363: Origin, treatment and utilization of biogas), (in German language)." 66. August.

DWA (German Association for Water, Wastewater and Waste). 2003a. "DWA Advisory Leaflet M368E – Biological Stabilisation of Sewage Sludge."35. April.

DWA (German Association for Water, Wastewater and Waste). 2003b. "Merkblatt ATV-DVWK-M372: Technische Rahmenbedingungen für die Vergärung biogener Abfälle." *DWA Advisory Leaflet M372 – Technical conditions for co-digestion of organic waste (in German language)*. May.

DWA-BW (DWA Baden Württemberg) by P.Baumann, and M.Roth. 2008. "Senkung des Stromverbrauchs auf Kläranlagen. Leitfaden für das Betriebspersonal."4.

DWA (German Association for Water, Wastewater and Waste). 2009. "Energiebilanz der Desintegration, Arbeitsbericht der DWA-Arbeitsgruppe AK1-6 (Energy balance of disintegration, Report of DWA Working Group AK-1.6), (in German language)." *Korrespondenz Abwasser, Abfall (KA), (56) Nr.8*. 797-801.

DWA-BW (DWA Baden Württemberg). 2010. "Kennzahlenvergleiche Wasserversorgung und Abwasserbeseitigung in Baden-Württemberg - Ergebnisbericht für das Erhebungsjahr 2008 (Benchmarking of Water Supply and Sanitation in Baden-Württemberg – Results from 2008), (in German language)."

DWA (German Association for Water, Wastewater and Waste). 2011. "DWA Standard M361 – Aufbereitung von Biogas (Treatment of biogas), (in German language). " 3. October.

DWA (German Association for Water, Wastewater and Waste). 2013a. "25. Leistungsvergleich kommunaler Kläranlagen 2012 (in German language).".*Korrespondenz Abwasser, Abfall (KA), (60) Nr.10.* .889-896.

DWA (German Association for Water, Wastewater and Waste). 2013b. "Arbeitsblatt DWA-A 216 - Energiecheck und Energieanalyse – Instrumente zur Energieoptimierung von Abwasseranlagen (in German language) ." *DRAFT*. April.

DWA (German Association for Water, Wastewater and Waste). 2014. "25th Performance Comparison of Municipal Wastewater Treatment Plants in Germany.*" Korrespondenz Abwasser, Abfall (KA), International Special Edition.* 15-21.

EAWAG (Swiss Federal Institute of Aquatic Science and Technology) by E.Tilley, et al. 2008. "Compendium of Sanitation Systems and Technologies." 158.

Ebner, C. 2013. "In den Faulbehälter hineinschauen (Looking into a digester), (in German language)." *KA-Betriebs-Info 2013 (43)*. 2092-2094. April.

Economist. 2013. "Some firms are preparing for a carbon price that would make a big difference." *The Economist*. December 14.

Economist. 2014. "Worse than useless." *The Economist*. January 25.

Eder, B. 2007. "Die neue Generation der Desintegration (The new generation of disintegration), (in German language)." Proceedings of Kitzbüheler Wassersymposium, Kitzbühel. November 13-14.

Enviro-Consult & Sogreah China. 2007. "Design review and consultancy of sludge treatment, Shanghai Bailongang Municipal WWTP." 54.

ESMAP (Energy Sector Management Assistance Program). 2012. "A Primer on Energy Efficiency for Municipal Water and Wastewater Utilities." World Bank. February.

Felde, D., Staske, S., and R. Wilms. 2005. "Co-Vergärung von Fettabscheiderrückständen in Faulbehältern kommunaler Kläranlagen – Betriebserfahrungen (Co-fermentation of grease separator residues in digesters at municipal sewage treatment plants – Operating experiences), (in German language)." *Korrespondenz Abwasser, Abfall (KA), (52) Nr.10*. 1151-1156.

Ferrer I., Cadena E., Perez I., and M. Garfi. 2013. "Technical, economic and environmental assessment of household biogas digesters in developing countries." Proceedings of 13th World Congress on Anaerobic Digestion. Santiago de Compostela, Spain. June 25-28.

Frey, W. 2012. "Stand und Trends bei der Faulgasverwertung (State of the art and trends in biogas treatment), (in German language)." Technical University Vienna, Wiener Mitteilungen, Nr. 226. 173-202.

FWT. 2008. "Expertise sur la capitalisation de l'experience ONEP dans le domaine de l'epuration. Tâche 1: Diagnostic du fonctionnement des STEP et recommandation pour l'amélioration (in French language)." Financed by ONEP and KfW.

FWT, Comete. 2009. "Assistance Technique a L'exploitation des Stations D'epuration de Sousse Sud, de Bizerte et des Stations de la Vallee de Medjerdha, Rapport Définitif: Phase II: Elaboration des mesures d'amélioration de l'exploitation des STEPs, Rapport Récapitulatif (in French language)." Financed by ONAS and KfW.

FWT. 2013a. "Evaluación y análisis de datos ETEs (Evaluation and analysis of WWTP data). Presentation in the framework of the Project "Programa de Despoluição da Bacia Hidrográfica do Rio Paraopeba" (in Spanish language).". Financed by COPASA & KfW. By K.Buchauer. 107. August 3.

FWT. 2013b. "Medidas complementarias para la PTAS de Managua – Desarrollo de un perfil de proyecto (Complementary measures for Managua WWTP – Development of a project profile), (in Spanish language)." Final Report. ENACAL & KfW. June.

FWT K. Buchauer. 2013c. "Evaluación y análisis de datos ETEs (Evaluation and analysis of WWTP data), (in Spanish language)." March 8.

Geyer, W. and A. Lengyel. 2008. "BHKWs – Auslegung, Gesamtkosten und Optimierungsmöglichkeiten (Co-generation – Design, Cost and Optimization), (in German language). " OEWAV workshop Betriebsoptimierung von Kläranlagen (Operation optimization of WWTPs). Linz, Austria. May 21.

Ghetti F. 2013. "Proyecto de generación en las PTAR de Saguapac - Análisis de viabilidad y gestión para su implementación (Electricity production at Saguapac's WWTPs – Viability and management analysis for implementation), (in Spanish language)." 37.

Graf, P. 2008. " Benchmarking Abwasser Bayern: Projektvorstellung, Vorstellung der Ergebnisse 2006, Ausblick (Benchmarking of Sanitation in Bavaria: Project presentation, Results from 2006) (in German language)." Presentation at the Presseclub Nürnberg. July 23.

Graf, P. 2010. "Benchmarking Abwasser Bayern: Projektvorstellung, Vorstellung der Ergebnisse 2008 (Benchmarking of Sanitation in Bavaria, Project presentation, Results from 2008), (in German language)." April 28.

Gretzschel O., et al. 2012. "Sludge Digestion instead of Aerobic Stabilization – A Trend for the Future? Results of a Study that Assesses the Cost Effectiveness of Conversion from Aerobic Stabilization Plants to Digestion Plants, (in German language)." *Korrespondenz Abwasser, Abfall (KA), (59) Nr.12*. 1144-1152.

GWI (Global Water Intelligence). 2010. "The 2010 Global Water Awards: Full shortlist. Striving for the high watermark." *GWI, Volume 11, Issue 2*. 31-41. February.

Haandel van, A. and G. Lettinga. 1994. "Anaerobic sewage treatment." John Wiley & Sons Ltd, England. 226.

Heubeck S. and R.J. Craggs R.J. 2009. "Biogas recovery from a temperate climate covered anaerobic pond." Proceedings of IWA Conference on Waste Stabilization Ponds, Belo Horizonte. 8. April 26-30.

Heumer F. 2012. "Inspektion und Grundreinigung eines Faulbehälters (Inspection and cleaning of a digester), (in German language)." KA-Betriebs-Info 2012 (42), Nr.1. 1914-1918.

Hodgson, B. and P. Paspaliaris. 1996. "Melbourne Water's wastewater treatment lagoons: design modifications to reduce odours and enhance nutrient removal." Water Science and Technology, Vol 33. No 7. 157–164.

Huber, M.B., et al. 2007. "Untersuchungen zur Bäckereiabfall und Klärschlamm Co-Fermentation in einem vollautomatisierten 1 m3 Doppelversuchsreaktor (Experiments with bakery waste and sewage sludge co-fermentation in a 1 m3 reactor), (in German language)." Chemie-Ingenieur-Technik, 79/4, S.450-458.

Iacovidou, E., Ohandja, D.G., and N. Voulvoulis. 2012. "Food waste co-digestion with sewage sludge - Realising its potential in the UK." *Journal of Environmental Management (112)*. 267-274.

IEA (International Energy Agency). 2012. "CO_2 emissions from fuel combustion – Highlights." IEA Statistics.138. October.

IWA (International Water Association). 2013. "The 2013 IWA Project Innovation Awards – Development." *Executive Summary of Winners and Honour Awards*. www.iwa-pia.org

Jäkel, K. 2007. "Der Schwefel muss raus (The sulphur ha to be eliminated), (in German language)." dlz agrarmagazin, 90-96. February.

Jansen, A.C., et al. 2004. "Digestion of sludge and organic waste in the sustainability concept for Malmö, Sweden." Water Science and Technology, Vol 49. No 10. 63–169.

Jenicek, P. 2012. "Wastewater treatment & energy production - Prague's experience." ICT Prague, Czech Republic.

Jiang, L., et al. 2013. "Operation analysis of sludge anaerobic digestion system at Bailonggang Wastewater Treatment Plant." China Water & Wastewater, 09.

Jilg, M. 2012. Komplettentleerung der Faulbehälter hielt manche Überraschung bereit (Complete digester emptying with several surprises), (in German language)." KA-Betriebs-Info 2012 (42), Nr.1.1912-1914.

Johnson, T., Shea, T., Gabel, D., and B. Forbes. 2011. "Introducing FOG to solids, a sticky proposition." WE&T.49-53. April.

KA-Betriebs-Info Editor. 2011. "Taucharbeiten erfordern höchste Qualifikation (Diving works require superior qualification), (in German language)." KA-Betriebs-Info 2011 (41), Nr.1.1807-1809.

Kang, S.J., Olmstead, K.P., and T.A. Almbaugh. 2010. "Four steps to energy self-sufficiency – A roadmap for U.S. Wastewater Treatment Plants." WE&T. 46-49. December. www.weforg/magazine

Kapp, H. 1984. "Schlammfaulung mit hohem Feststoffgehalt (Sludge digestion with high dry solids concentration), (in German language)." Stuttgarter Berichte zur Siedlungswasserwirtschaft, Nr. 86. 300. Oldenbourg Munich, Germany.

Keil, S. 2013. "Wunschtraum oder Wirklichkeit – Die energieautarke Kläranlage (Wishful thinking or reality – The energy independent WWTP), (in German language)." KA-Betriebs-Info 2013 (43), Nr.3. 2103-2107.

Kletke, T., et al. 2010. "Mikrobielle Brennstoffzellen in der Abwasserreinigung (Microbial Fuel Cells in Wastewater Treatment), (in German language)." Ruhr-University Bochum, Schriftenreihe Siedlungswasserwirtschaft Bochum, Nr. 61.153-171.

Kolisch, G., et al. 2010. "Increasing Energy Efficiency in Municipal Wastewater Treatment Plants Examination of the Results of Energy Analyses (in German language)." Korrespondenz Abwasser, Abfall (KA), (57) Nr.10. 1028-1032.

Kougias, P.G., et al. 2013. "Anaerobic digestion foaming in Danish full-scale biogas plants: a survey on causes and solutions.", Proceedings of 13th IWA World Congress on Anaerobic Digestion, Santiago de Compostela (Spain). 4. June 25-28.

Kusowski, J., et al. 2013. "Anaerobic co-digestion planning and research for new water (Green Bay, WI)." Proceedings of Weftec 2013. 20. Chicago, USA. October 5-9.

Libhaber, M. 2010. "Wastewater Management Training. Part 4: Generation of Energy from Wastewater." World Bank. Beijing, China. May 10.

Libhaber M., and A. Orozco-Jaramillo. 2012. "Sustainable Treatment and Reuse of Municipal Wastewater." IWA Publishing.

Lindtner, S. 2011. "Kläranlagenleistungsvergleich – Bereich Energie (Comparison of WWTPs – Sector Energy), (in German language)." Kläranlagen-Nachbarschaft Sprechertag. 19.

Lindtner, S., and J. Haslinger. 2012. "Stand und Zukunft des Benchmarkings auf österreichischen Kläranlagen (in German language)." Technical University Vienna, Wiener Mitteilungen. Band 226. 77.

Lobato, L.C.S. 2011. "Aproveitamento energético de biogás gerado em reatores UASB tratando esgoto doméstico (Utilization of biogas from UASB reactors treating domestic wastewater), (in Portuguese language)." *PhD thesis at Universidade Federal de Minas Gerais (UFMG)*. Belo Horizonte, Brazil.171.

Lobato, L.C.S., et al. 2012. "Estimates of methane loss and energy recovery potential in anaerobic reactors treating domestic wastewater." Water Science and Technology, 66.12. 2745-2753.

Loll, U. 2001. "Biogaspotenziale im Klärschlamm und anderen biogenen Abfällen (Biogas potentials in sewage sludge and other biogenous waste), (in German language)." Korrespondenz Abwasser, Abfall (KA), (48) Nr.1.

Mara, D., and H. Pearson. 1998. "Design Manual for Waste Stabilization Ponds in Mediterranean Countries." Lagoon Technology International Ltd.

Meda, A., et al. 2006. "Treatment and quality of sewage sludge in Germany – Results of a survey." Conference Proceedings of IWA Specialized Conference: Sustainable sludge management: state of the art, challenges and perspectives.8. Moscow, Russia. May 29-31.

Melbourne Water. 2014. Personal Information.

Mercato-Romain, C.E., et al. 2013. "Evaluation of air and $FeCl_3$ for the removal of hydrogen sulphide in biogas: performance and bacterial diversity". Proceedings of 13th World Congress on Anaerobic Digestion. Santiago de Compostela, Spain. June 25-28.

Metcalf & Eddy. 2003. "Wastewater Engineering – Treatment and Reuse." McGraw Hill, 4th edition.1819.

Meyer-Scharenberg, U., and M. Pöppke. 2010. "Large-scale Solar Sludge Drying in Managua, Nicaragua." Water and Waste. 26-27.

Miot, A., et al. 2013. "Restaurant trap waste characterization and full scale FOG co-digestion at the San Francisco Oceanside Plant." Proceedings of Weftec 2013. 18. Chicago, USA. October 5-9.

Monteith, H., et al. 2006. "Assessing feasibility of direct drive technology for energy recovery from digester biogas." Weftec. 517-3540.

Moos, M. 2012. "Schaum im Faulbehälter war einmal … (Foam in the digester has disappeared…), (in German language)." KA-Betriebs-Info 2012 (42), Nr.1, 1921-1923.

Morais, J.C., et al. 2013. "Operational aspects of an anaerobic wastewater treatment plant treating domestic sewage." Proceedings of 13th IWA World Congress on Anaerobic Digestion. Santiago de Compostela, Spain. 4. June 25-28.

Müller, E., and B. Kobel. 2004. "Stocktaking at Wastewater Treatment Plants in North Rhine Westphalia with 30 million Population Equivalent – Energy Benchmarking and Savings Potentials (in German language)." Korrespondenz Abwasser, Abfall (KA), (51) Nr.6. 625-631.

Müller, E., Schmid, F., and B. Kobel. 2006. "Energy in Sewage Treatment Plants Action. Ten Years' Experience in Switzerland (in German)." Korrespondenz Abwasser, Abfall (KA), (53) Nr.8. 793-797.

Müller, J. 2010. "Energiebilanzierung bei der Klärschlammdesintegration (Energy balance of ultrasound sludge disintegration), (in German language)." Proceedings of OWAV conference on sewage sludge. 26

MUFV-RP. 2006. "Ministerium für Umwelt, Forsten und Verbraucherschutz des Landes Rheinland-Pfalz: Benchmarking Wasserwirtschaft Rheinland-Pfalz, Öffentlicher Bericht für das Projektjahr 2005."

MURL. 1999. "Ministerium für Umwelt, Raumordnung und Landwirtschaft des Landes Nordrhein-Westfalen, Deutschland: Energie in Kläranlagen – Handbuch (in German language)." 369.

Murray, A., Horvath, A., and K.L. Nelson K.L. 2008. "Hybrid life-cycle environmental and cost inventory of sewage sludge treatment and end-use scenarios: A case study from China." Environ. Sci. Technol., 42. 3163-3169.

NIWA (National Institute of Water and Atmospheric Research). 2008. "Covered anaerobic ponds for anaerobic digestion and biogas capture: piggeries." *NIWA Information Series, No.32.* 8. www.niwa.co.nz

Nolasco, D., et al. 2000. "How often should we clean our anaerobic digesters? Optimizing mixing and performance using tracer and sampling techniques." Proceedings of First Canadian Biosolids Conference, Biosolids. Toronto, Ontario. September 25.

Norgaard, K., Swanback, S., and D. Frost. 2013. "Proven results from a full scale FOG facility." Proceedings of Weftec. 13. Chicago, USA. October 5-9.

Nowak, O., and C. Ebner. 2013. "Co-Substrate – Rückbelastung, Gasproduktion, Gaszusammensetzung, Entwässerung (Co-substrates – return load, gas production, gas quality, dewatering), (in German language)." Österreichischer Wasser- und Abfallwirtschaftsverband (ÖWAV) Kanal- und Kläranlagennachbarschaften Folge 21. 18.

Noyola, A., Morgan-Sagastume, J.M., and J. E López-Hernández. 2006. "Treatment of biogas produced in anaerobic reactors for domestic wastewater: odor control and energy/resource recovery." *Reviews in Environmental Science and Bio/Technology, 5.* 93–114. Springer.

Noyola, A., et al. 2012. "Typology of Municipal Wastewater Treatment Technologies in Latin America." Clean – Soli, Air, Water, 40 (9). 926-932.

OEWA. 2006. "Zusammenstellung von Schadensfällen in Zusammenhang mit Gas und Explosionen (Compilation of accidents related to biogas and explosions), (in German language)."34.

OEWAV. 2012. "Benchmarking für Kläranlagen im Geschäftsjahr 2011 (Benchmarking for WWTPs in 2011), (in German language)." 46.

Parravicini, V. 2012. "Entwicklungen der Anaerobtechnik in der Industrieabwasserreinigung (Developments in industrial anaerobic wastewater treatment), (in German language)." Technical University Vienna, Wiener Mitteilungen, Nr. 226. 251-296.

Petrik, G. 2006. "Optimierung der Schlammfaulung mit Hilfe der Ultraschalldesintegration, Ergebnisse der KA Wasserfeld in Südtirol (Optimization of sludge digestion with ultrasound disintegration at Wasserfeld WWTP, South Tyrol), (in German language)." KA-Betriebs-Info (36) Nr.3. 1397-1399.

Pressinotti, F.C., Krampe, J., and H. Steinmetz. 2011. "Das Tropfkörperverfahren für heiße Klimazonen (Trickling filter for hot climate zones), (in German language)." Korrespondenz Abwasser, Abfall (KA), (58) Nr.4. 339-347.

Procházka, J., Stindl, P., and P. Dolejs. 2013. "Comparison of biogas desulphurization methods on full-scale biogas plants." Proceedings of 13th World Congress on Anaerobic Digestion. Santiago de Compostela, Spain. June 25-28.

PWC (Pricewaterhouse Coopers). 2011. "Electricity in Indonesia – Investment and Taxation Guide.".98.

Rausch, W. 2007. "Erfahrungen mit der VTA-GSD Ultraschalldesintegration auf der Kläranlage Halle-Nord (Experiences with ultrasound disintegration at Halle-Nord WWTP), (in German language)." Proceedings of Kitzbüheler Wassersymposium. Kitzbühel, Austria. November 13-14.

Ren, N. 2013. "AD in China: From technical innovation to full-scale implementation." Proceedings of 13th World Congress on Anaerobic Digestion. Santiago de Compostela, Spain. June 25-28.

Resch, H. 2011."Kläranlage Roth - Auswertung eines Pilotversuches zur Ultraschalldesintegration (Roth WWTP - Piloting ultrasound disintegration), (in German language)." 26. May.

Ries, T., Orth, H., and H.H. Niehoff. 1992. "Bemessungsansatz für die Reduzierung von Schwefelwasserstoff im Faulgas durch Sulfidfällung mit Eisenchlorid (Design of H_2S removal from biogas by chemical precipitation with $FeCl_3$), (in German language)." Korrespondenz Abwasser, Abfall (KA), (39) Nr.8. 1156-1163.

Rodríguez-Roda, I., et al. 2013. "Anaerobic Digester Foaming: occurence and control in Spain." Proceedings of 13th IWA World Congress on Anaerobic Digestion. Santiago de Compostela, Spain. 4. June 25-28.

Roediger, H., Roediger, M., and H. Kapp. 1990. "Anaerobe alkalische Schlammfaulung (in German language)." 4th edition, Oldenbourg Verlag. 194.

Rulkens, W. 2007. "Sewage Sludge as a Biomass Resource for the Production of Energy: Overview and Assessment of the Various Options." American Chemical Society, Published on Web 09/25/2007.

RWI (Renewable Waste Intelligence). 2013. "Business analysis of anaerobic digestion in the USA." 8. March.

Saguapac. 2008. "Proyecto de mejoramiento y reducción de emisiones atmosféricas (Project for rehabilitation and emission reduction), (in Spanish language)." Presentation made to the World Bank.15.

Saguapac, 2010. "Informe Técnico – Operación de estaciones de quema de biogás (Technical Report – Operation of biogás flaring stations), (in Spanish language)." 8. July.

Saguapac. 2014a. "Captura y Quema de Biogás en Lagunas Anaerobias en el Oriente Boliviano (Collection and flaring of biogas from anaerobic ponds in the East of Bolivia), (in Spanish language)." 7. Personal communication.

Saguapac. 2014b. "Información PTARs de Saguapac (Information regarding Saguapac's WWTPs), (in Spanish language)." Personal communication.

Sandino, J., et al. 2013. "Achieving energy self-sufficiency in a nutrient removal facility through operational optimization." Proceedings of Weftec 2013. Chicago, USA. 11. October 5-9.

SCE. 2013. "Ho Chi Minh City Environmental Sanitation Project – Phase II, Nhieu Loc Thi Nghe Wastewater Treatment Plant, Complementary services for Feasibility Study completion." 30. May.

Schafer, P., Muller, C., and J. Willis. 2013. "Improving the performance and economics of co-digestion and energy production." Proceedings of Weftec 2013. Chicago, USA11. October 5-9.

Schmelz, K.G. 2000. "Co-Vergärung von Klärschlamm und Bioabfällen (Co-digestion of sewahe sludge and biowaste), (in German language)." Manuskripte zur Abfallwirtschaft, Bauhaus-Universität Weimar. Rhombos Verlag, Berlin. 220.

Schmelz, K.G. 2003. "Erfahrungen bei der Co-Vergärung von Klärschlamm und Bioabfällen (Experiences with co-fermentation of sewage sludge and biological waste), (in German language)." Korrespondenz Abwasser, Abfall (KA), (50) Nr.6.

Schmelz, K.G., and J. Müller. 2004. "Klärschlammdesintegration zur Verbesserung der Faulung – Ergebnisse großtechnischer Parallelversuche (Sewage sludge disintegration to improve digestion – Results of parallel large-scale tests), (in German language)." Korrespondenz Abwasser, Abfall (KA), (51) Nr.6. 632-642.

Schwarzenbeck, N., Bomball, E., and W. Pfeiffer. 2008. "Can a wastewater treatment plant be a powerplant? A case study." Wat.Sci & Technol. 57.10, 1555-1561.

Shimp, G.F., et al. 2010. "Get a grip on digester foaming - Recent research identifies facility, process and operations changes that can keep bubbles in check." Water Environment & Technology (WE&T). 54-59. December.

Singh, K.S., and T. Viraraghavan. 2003. "Impact of temperature on performance, microbiological, and hydrodynamic aspects of UASB reactors treating municipal wastewater." Water Science and Technology, Vol 48, No.6. 211-217.

Sperling, M., and C. A. Chernicharo. 2005. "Biological Wastewater Treatment in Warm Climate Regions. IWA publishing, UK. 1460.

Stabnikova, O., and J. Y. Wang. 2006. "Bioconversion of sewage sludge and food waste into fertilizer." IWA Conference on Sustainable Sludge Management. Moscow, Russia. 6. May 29-31.

Strässle. R. 2012. "Kläranlage mutiert zum Energiepark – Ein Leuchtturmprojekt in der Ostschweiz (in German language)." Umwelt Perspektiven.18-19.

Svardal, K., and S. Haider. 2010. "Co-Fermentation, (in German language)." Proceedings of OWAV Conference on Sewage Sludge. 29.

Tectraa, University of Luxembourg, Ingenieurgesellschaft Siekmann + Partner. 2010. "Neubewertung von Abwasserreinigungsanlagen mit anaerober Schlammbehandlung vor dem Hintergrund der energetischen Rahmenbedingungen und der abwassertechnischen Situation in Rheinland-Pfalz, Modul 1: Grundlegende Untersuchungen (Assessment update of WWTPs with anaerobic digestion under the specific conditions in Rhineland-Palatine, Module 1: Basic investigations), (in German language)." Final Report. 82. August.

Tectraa, University of Luxembourg, Ingenieurgesellschaft Siekmann + Partner. 2011. "Neubewertung von Abwasserreinigungsanlagen mit anaerober Schlammbehandlung vor dem Hintergrund der energetischen Rahmenbedingungen und der abwassertechnischen Situation in Rheinland-Pfalz, Modul 2: Weitergehende Untersuchungen (Assessment update of WWTPs with anaerobic digestion under the specific conditions in Rhineland-Palatine, Module 2: In-depth investigations), (in German language)." Final Report. 85. December.

Traversi, D., et al. 2013. "Environmental advances due to the integration of food industries and anaerobic digestion for biogas production: Perspectives of the Italian milk and dairy product sector." Bioenerg. Res., 6. 851–863.

UBA by B.Haberkern, W.Maier, U.Schneider. 2008. "Steigerung der Energieeffizienz auf kommunalen Kläranlagen (in German language)." Research Report 205 26 307, UBA-FB 001075.

Ullrich, A., and B. Eder. 2006. "Abschlussbericht über den Einsatz der VTA-GSD Ultraschalldesintegration auf der KA Großostheim (Assessment report of the application of ultrasound sludge disintegration at Großostheim WWTP), (in German language)." 14. September.

Urban I., and H. Scheer. 2011. "Co-Vergärung in kommunalen Faulbehältern – Ein CSB-basierter Ansatz zur Bestimmung von Freivolumen (Co-digestion in municipal digester tanks - A COD-based approach to determine free volume), (in German language)." Korrespondenz Abwasser, Abfall (KA), (58) Nr.1. 56-62.

US-EPA (United States Environmental Protection Agency). 2006. "Auxiliary and Supplemental Power Fact Sheet: Fuel Cells." 3. March.

U.S.EPA CHP Partnership. 2011: "Opportunities for Combined Heat and Power at Wastewater Treatment Facilities: Market Analysis and Lessons from the Field." 50. October.

VA Tech Wabag. 2006. "Sludge Reduction Study, Pilot tests at Bailongang WWTP, Shanghai." Final Report. 138. March.

Viet Anh, N., Thu Hang, D., and T. Minh Thanh. 2014. "Co-treatment of municipal organic waste flows for more efficient utilization of engineering infrastructure facilities and resource recovery (in Vietnamese language)." Hội thảo Quản lý bùn thải từ hệ thống thoát nước. Cục Hạ tầng kỹ thuật, Bộ Xây dựng. February.

VSA (Verband Schweizer Abwasser- und Gewässerschutzfachleute) by E.A.Müller, et al. 2010. "Energie in ARA – Leitfaden zur Energieoptimierung auf Abwasserreinigungsanlagen (Energy at WWTPs – A guide towards energy optimization in wastewater treatment), (in German language)." November 2008 & September 2010.

VSA (Verband Schweizer Abwasser- und Gewässerschutzfachleute) by J.Kopp. 2012a. "Weiterbildungskurs W17: Klärschlamm; Anfall, Behandlung, Entsorgung (Training W17: Sludge, Production, Treatment, Disposal), Modul: Schlammfaulung, Betriebsprobleme, Optimierung (Module: Digestion, Operation Problems, Optimization), (in German language)." 40.

VSA (Verband Schweizer Abwasser- und Gewässerschutzfachleute) by W.Müller. 2012b. "Weiterbildungskurs W17: Klärschlamm; Anfall, Behandlung, Entsorgung (Training W17: Sludge, Production, Treatment, Disposal), Modul: Energie und Abwasser (Module: Energy and Wastewater), (in German language)." 60.

VTA. 2010. "Desintegration tipp-topp (Optimum disintegration), (in German language)." Der Laubfrosch, Nr.51. 18-19, December.

VTA. 2012. "VTA-GSD Reverse flow disintegration for the treatment of sewage sludge with ultrasound, Technical description." 6. www.vta.cc

VTA. 2014. Private Communication.

Wacker, J. 2007. "Einsatz einer Mikrogasturbine im Klärwerk Darmstadt-Eberstadt (Use of a microturbine at Darmstadt-Eberstadt WWTP), (in German language)." Proceedings of Kitzbüheler Wassersymposium. Kitzbühel, Austria. November 13-14.

Wagner, W. 2010. "Recomendaciones para la elección de plantas de tratamiento de agua residual aptas para Bolivia (Recommendations for the selection of WWTPs suited for Bolivia), (in Spanish language)." ANESAPA, CIM, GTZ. 125.

WEF (Water Environment Federation). 2011. "WEF Position Statement – Renewable Energy Generation from Wastewater." Adopted by WEF Board of Trustees. October 14.

WEF (Water Environment Federation). 2012. "Energy Roadmap Version 1.0. Driving Water and Wastewater Utilities to More Sustainable Energy Management."

WEF (Water Environment Federation). 2013a. "The Energy Roadmap: A Water and Wastewater Utility Guide to More Sustainable Energy Management."

WEF (Water Environment Federation), WERF (Water Environment Research Foundation), National Biosolids Partnership. 2013b. "Enabling the future: Advancing resource recovery from biosolids," 65.

Weimer, H.P., Dollinger, R., and B. Eder. 2005. "Abschlussbericht über den Einsatz der Klärschlammdesintegration mit Ultraschall auf der KA Miltenberg (Assessment report of the application of ultrasound sludge disintegration at Miltenberg WWTP), (in German language)." 15. November.

WERF (Water Environment Research Foundation) by G.V. Crawford, CH2M Hill Canada Limited 2010a. "Best Practices for Sustainable Wastewater Treatment: Initial Case Study Incorporating European Experience and Evaluation Tool Concept." Report:OWSO4R07a. January.

WERF (Water Environment Research Foundation) by G.V. Crawford, J. Sandino, CH2M Hill Canada Limited. 2010b. "Energy Efficiency in Wastewater Treatment in North America: A Compendium of Best Practices and Case Studies of Novel Approaches." Report: OWSO4R07e. May.

WERF (Water Environment Research Foundation) M.J .Brandt, R.A. Middleton, S. Wang, Black & Veatch. 2010c. "Energy Efficiency in the Water Industry: A Compendium of Best Practices and Case Studies." Global Report. Report: OWSO9C09.

WERF (Water Environment Research Foundation). 2011a. "Fact Sheet: Energy Production and Efficiency Research – The Roadmap to Net-Zero Energy."

WERF (Water Environment Research Foundation) by B.Li, K. Scheible, and M. Curtis. 2011b. "Electricity Generation from Anaerobic Wastewater Treatment in Microbial Fuel Cells." Report. OWSO8C09.

WERF (Water Environment Research Foundation) by J. Willies, et al. 2012a. "Barriers to Biogas Use for Renewable Energy." Report: OWSO11C10.

WERF (Water Environment Research Foundation) by K.Chandran et al. 2012b. "Greenhouse Nitrogen Emissions from Wastewater Treatment Operation: Phase I – Molecular Level through Whole Reactor Level Characterization." Report: U4R07.

Wernitznig, A., and B. Eder. 2006. "Abschlussbericht über den Einsatz der VTA-GSD Ultraschalldesintegration auf der KA Villach (Assessment report of the application of USD at Villach WWTP), (in German language)." 16. September.

Wernitznig, A. 2010. "Kläranlage Villach - Erfahrungen mit der Ultraschalldesintegration von Überschussschlamm (Villach WWTP - Practical results from WAS disintegration with ultrasound), (in German language). " OWAV conference on Sewage Sludge.

Wett, B., Buchauer, K., and C. Fimml. 2007. "Energy self-sufficiency as a feasible concept for wastewater treatment systems." Asian Water. 22-25. September.

Willis, J., and L. Stone L. 2012. "Barriers to Biogas Utilization for Renewable Energy: What's keeping WWTPs from using biogas?" *VWEA Educational Seminar 2012: Operational and Process Control / Energy Management*. 28. March 27.

Witzgall, R., Parker, D., Waterman, N., Sen, S., and M. Hetherington. 2013. "How a trickling filter/ solids contact plant was designed and optimized for handling greater flow variability while requiring much lower energy than OCSD's activated sludge plants." Proceedings of Weftec 2013. Chicago, USA. 19. October 5-9.

World Bank prepared by Buchauer, K., and N. Khambati. 2010. "Independent review of design, operation and maintenance of sewage treatment plants adjacent to Ganges River." Report rev.1. December.

World Bank. 2013a. "The Little Green Data Book."

World Bank. 2013b. "East Asia Urban Sanitation Review: A call for Action." Presentation. May.

World Bank. 2013c. "East Asia and the Pacific Region, Urban Sanitation Review: A Call for Action." Report. November.

World Bank. 2013d. "East Asia and the Pacific Region, Urban Sanitation Review: Indonesia – Country Study." Report. 52. September.

World Bank. 2013e. "East Asia and the Pacific Region, Urban Sanitation Review: Philippines – Country Study." Report. 54. December.

World Bank. 2013f. "East Asia Pacific Region, Urban Sanitation Review: Vietnam Urban Wastewater Review." Main Report. 151. December.

World Bank. 2013g. "Green Investment Climate, Country Profile – Indonesia". 53.

World Bank 2014. "East Asia's Changing Urban Landscape: Measuring a Decade of Spatial Growth" World Bank. June.

WSP (Water & Sanitation Program) by E. Perez, et al. 2012. "What Does it Take to Scale Up Rural Sanitation?" July.

Zupancic, G.D., Uranjek-Zevart ,N., and M. Ros. 2008. "Full-scale anaerobic co-digestion of organic waste and municipal sludge." Biomass and Bioenergy 32. 162-167.

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