# Energy-Water Nexus in Urban Water Systems

**Hongtao WANG**
**Tongji University**

**September 8, 2021**

# Contents

# Introduction to water-energy nexus

**Emerging solutions to the water challenges of an urbanizing world**

Tove A. Larsen, Sabine Hoffmann, Christoph Lüthi, Bernhard Truffer and Max Maurer (May 19, 2016)

*Science* **352** (6288), 928-933. [doi: 10.1126/science.aad8641]

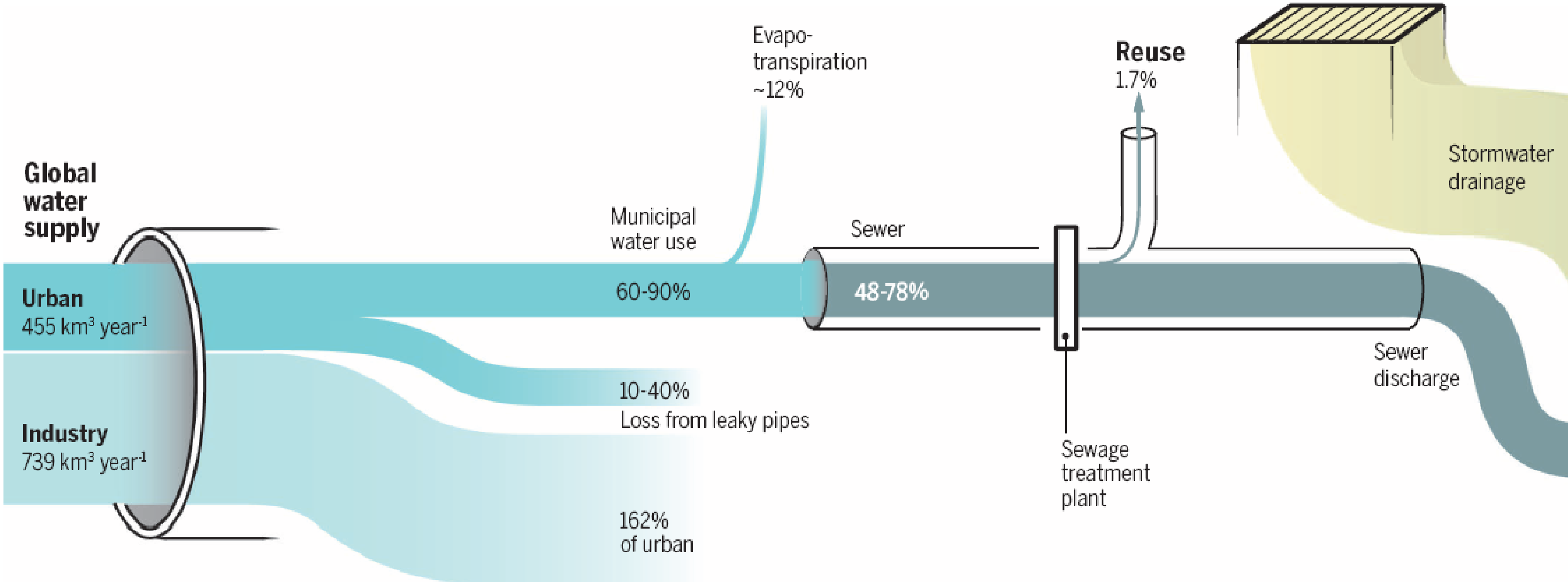



**Fig. 1. The global urban water cycle.**

- According to country-specific data from FAO, the global municipal water withdrawal is estimated to be 454.8 × $10^9 m^3$ $year^{-1}$ (**184 liters $person^{-1}$ $day^{-1}$**),
- and 738.8 × $10^9 m^3$ $year^{-1}$ (**300 liters $person^{-1}$ $day^{-1}$)** for industrial use.
- This corresponds to **12%and 19%,** respectively, of the total global water withdrawal.
- Shiklomanov estimates global urban **evapotranspiration to be around 12%.**
- Typical water “losses” due to leaky supply systems are between 10 and 40%.
- Globally, around **1.7%** [7.7 × $10^9 m^3$ $year^{-1}$] of the municipal water supply is **reused** in this way—**mostly for irrigation**.

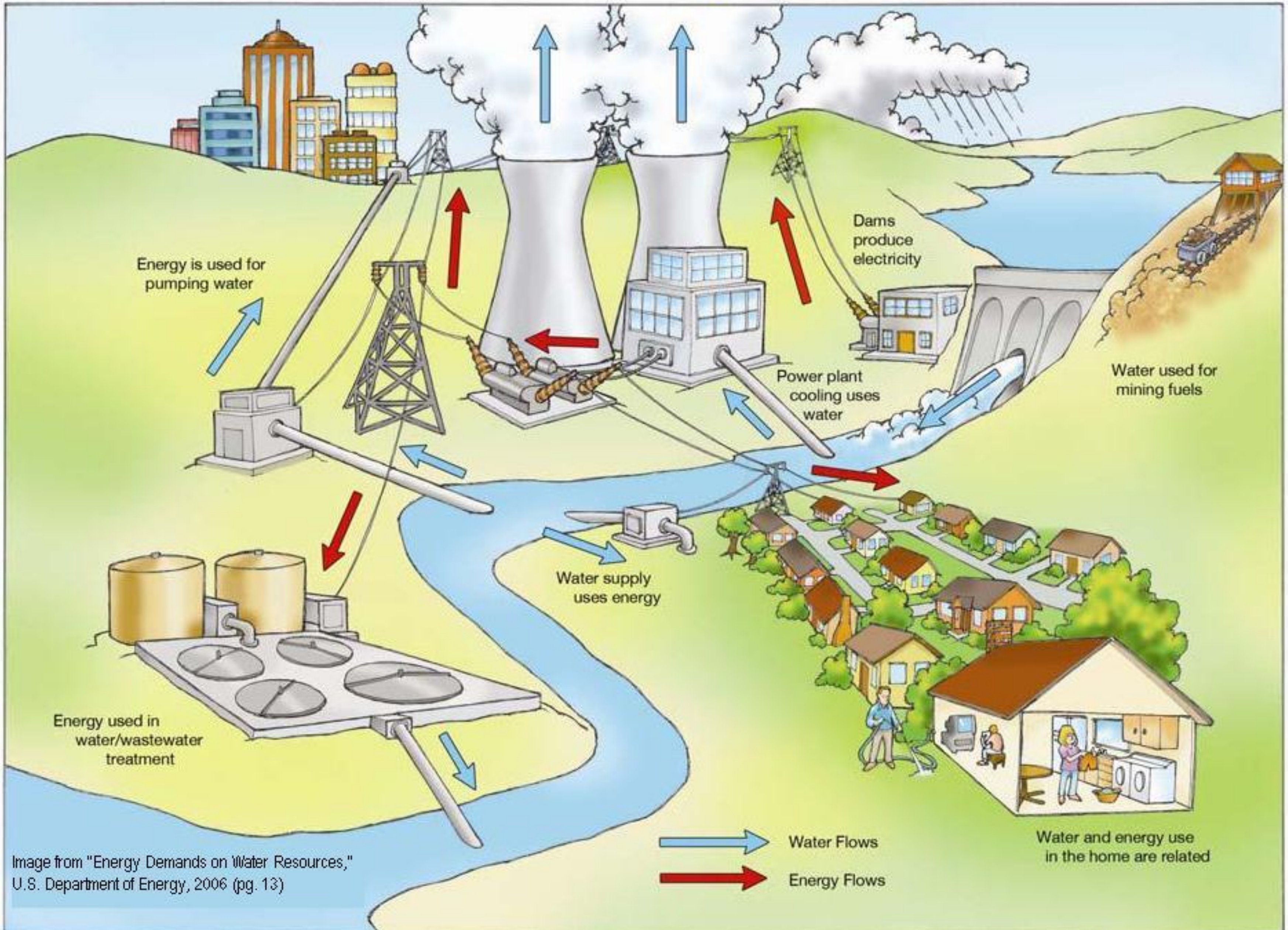
# Resources in wastewater

| | | |
|---|---|---|
| Water (liters person$^{-1}$ day$^{-1}$) | | |
| Domestic | 184 | Global average (69) |
| Industrial | 300 | Industrial global average (69) |
| Energy (MJ person$^{-1}$ year$^{-1}$) | | |
| Heat contained in warm water | 2800 | Typical European country (*11*) |
| Chemical energy contained in organic matter | 540 | Typical European country (*11*) |
| Chemical energy "embedded" in N and P | 180 | Global average, year 2000 (*11*, *17*) |
| Nutrients from human metabolism (g person$^{-1}$ day$^{-1}$) | | |
| Nitrogen (N) | 10 | Global average, year 2000 (*17*) |
| Phosphorus (P) | 2 | Global average (*17*) |

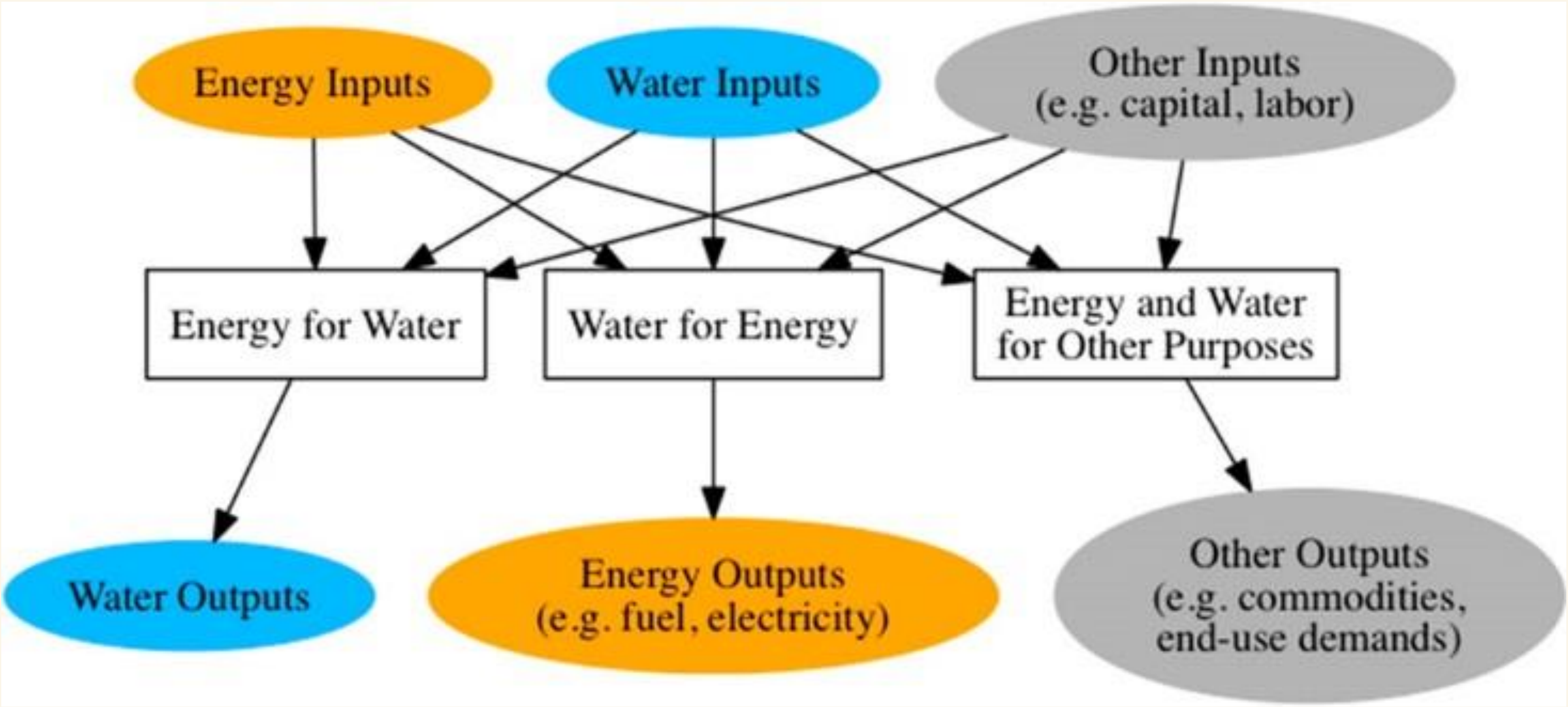
- For nutrients and water, global averages are given.
- No global information is available concerning warm water and organic matter in wastewater.
- Local loads depend inter alia on nutritional status, household devices, water availability, and habits

*Larsen, 2016*

# The Water-Energy Nexus



# Nexus: Water for Energy and Energy for Water



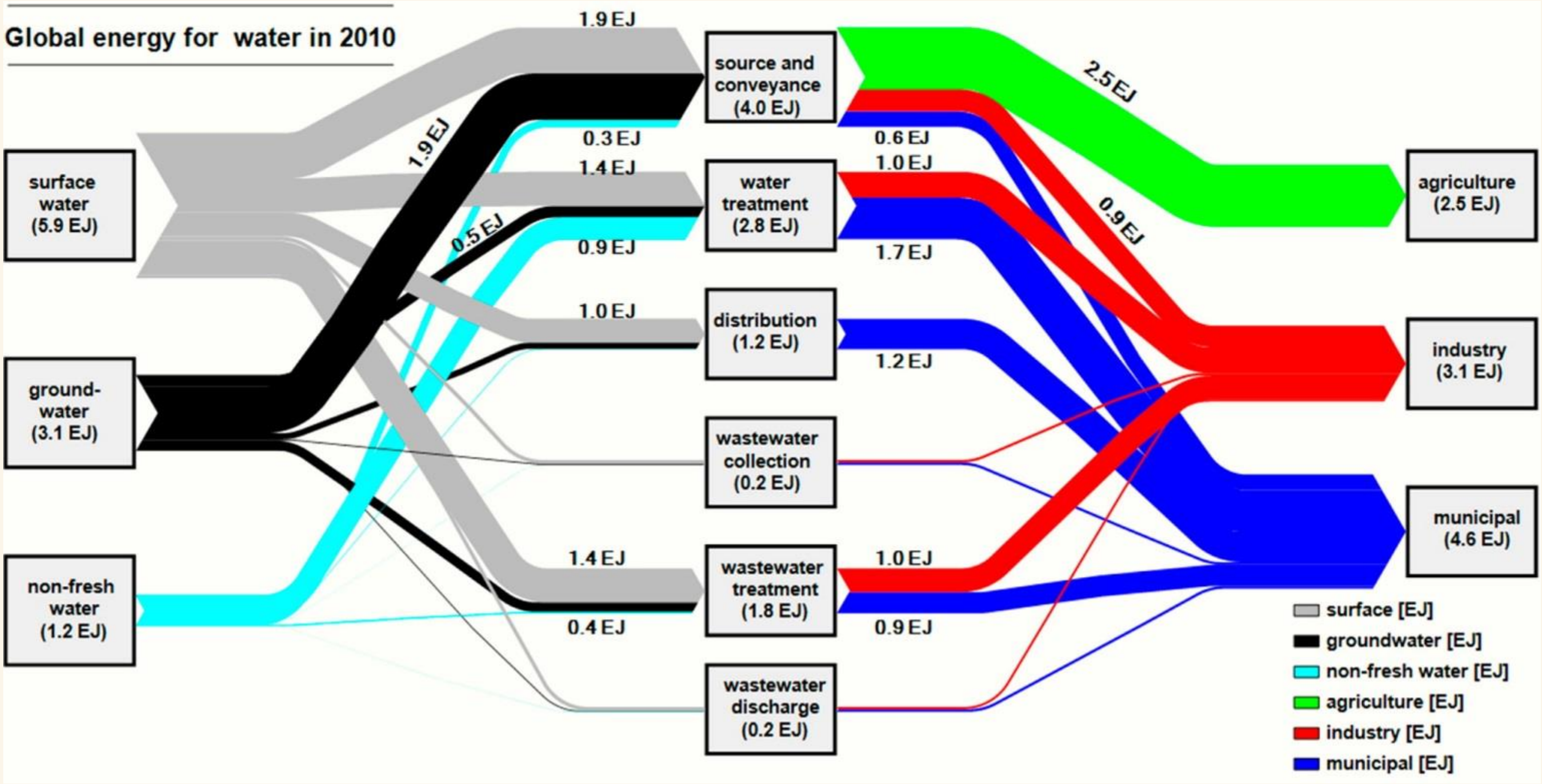

*Kyle, EST&, 2016*

# Introduction

- **"water-energy nexus":**
  - ✓ generally defined as the interdependency between water and energy in their supply, processing, distribution, and use.
- **Two components** of water-energy nexus:
  - ✓ "water for energy" and "energy for water."
- **"water for energy":**
  - ✓ water required for the extraction, processing, and transformation of energy as well as the irrigation of bioenergy
- There has been less agreement on the definition and system boundaries of **"energy for water."**

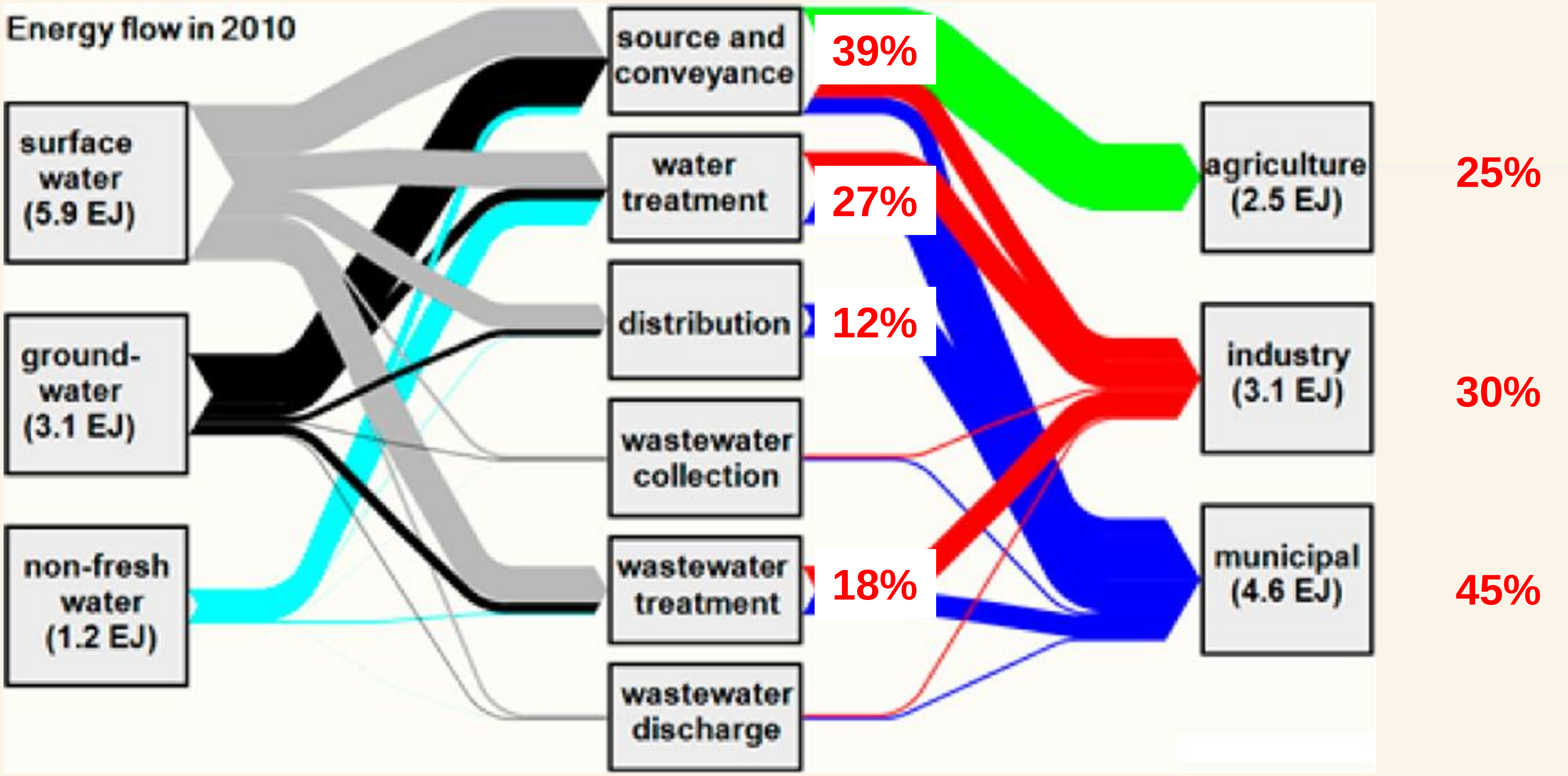
# Introduction

- **"Energy for water":**
  - ✓ the energy used for water **abstraction, treatment, distribution, and postuse** wastewater treatment.
  - ✓ Others have also included water-related energy consumption in the **residential, commercial, and industrial sectors** (e.g., for water heating and cooling).
  - ✓ When included, these "**end-use" processes typically account for more than two-thirds** of total "energy for water."
- Using **even broader system boundaries that consider all processes where energy is applied to water**, including all primary energy used at thermoelectric power plants, Sanders and Webber classified **47% of total primary energy in the United States as "energy for water."**




**Flow of energy for water (E4W, EJ) from water sources to water processes and to water end-use sectors in 2010.**

*Liu et al, ES&T.2016*




The sectoral E4W allocation includes municipal (45%), industrial (30%), and agricultural (25%), and main process-level contributions are from source/conveyance (39%), water purification (27%), water distribution (12%), and wastewater treatment (18%).

*Liu et al, ES&T.2016*

Applied Energy 205 (2017) 589–601

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Applied Energy

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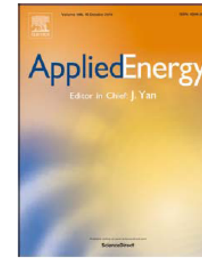
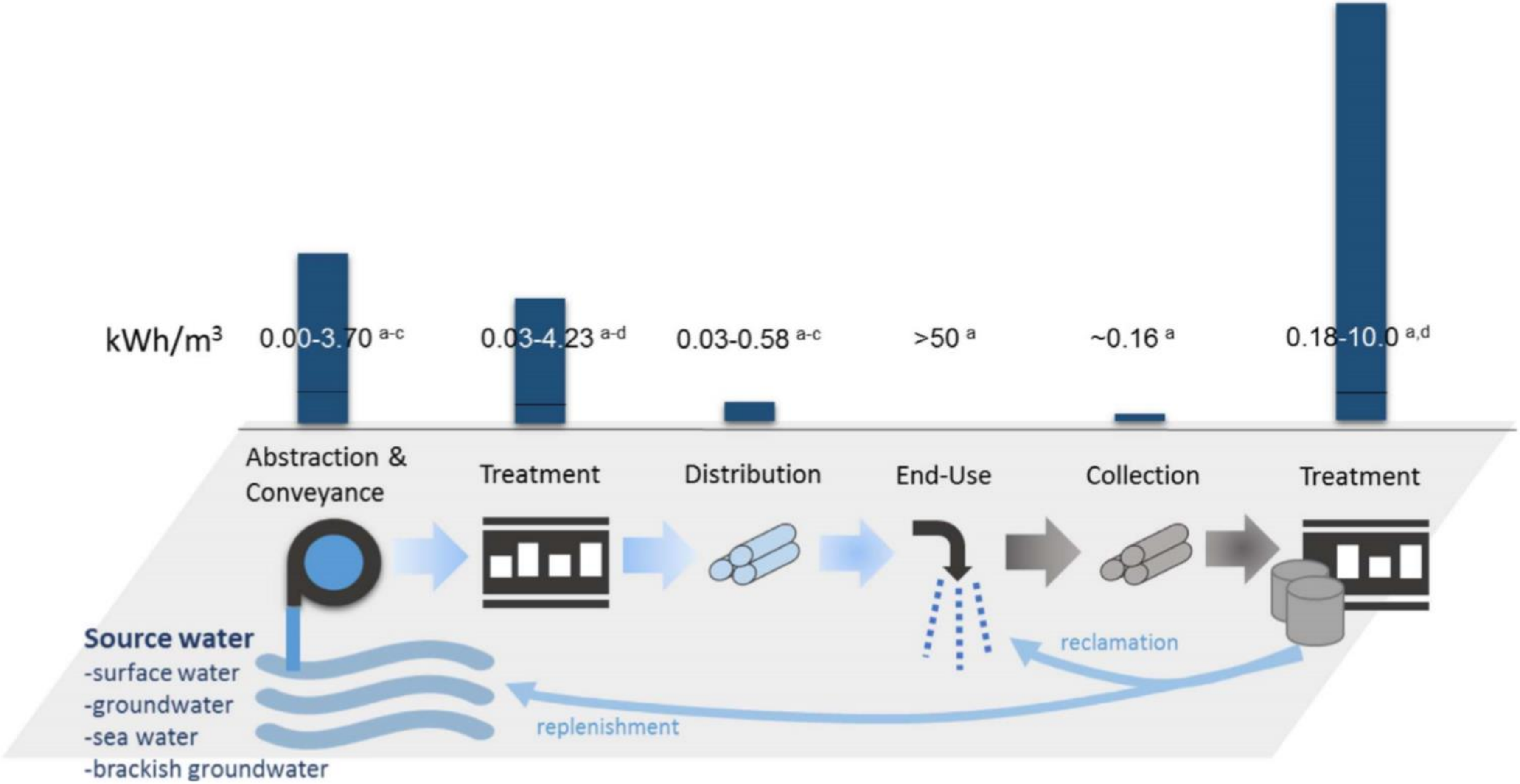



# Water-energy nexus for urban water systems: A comparative review on energy intensity and environmental impacts in relation to global water risks

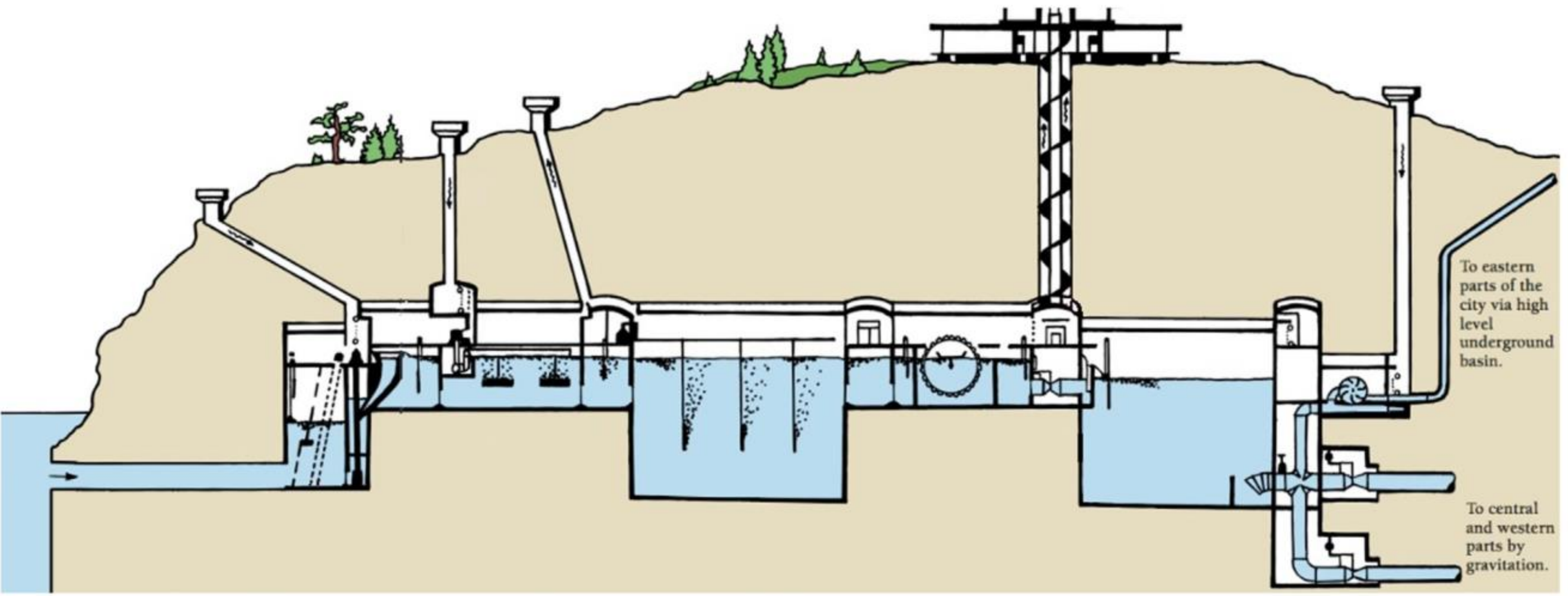
Mengshan Lee[a], Arturo A. Keller[b], Pen-Chi Chiang[a], Walter Den[c], Hongtao Wang[d,*], Chia-Hung Hou[a,*], Jiang Wu[e], Xin Wang[e], Jinyue Yan[e,f,g]

[a] *Graduate Institute of Environmental Engineering, National Taiwan University, Taipei 10617, Taiwan, ROC*
[b] *Bren School of Environmental Science and Management, University of California, Santa Barbara, CA 93106, United States*
[c] *Department of Environmental Science and Engineering, Tunghai University, Taichung 40704, Taiwan, ROC*
[d] *State Key Laboratory of Pollution Control and Resource Reuse, Key Laboratory of Yangtze River Water Environment, Ministry of Education, College of Environmental Science and Engineering, Tongji University, Shanghai 200092, PR China*
[e] *College of Architecture and Urban Planning, Tongji University, Shanghai 200092, PR China*
[f] *Department of Chemical Engineering, Royal Institute of Technology (KTH), Sweden*
[g] *Department of Energy, Building and Environment, Mälardalen University (MDH), Sweden*




# Ranges of energy intensity within an urban water cycle using average values of benchmarking studies.

*In Spain, the specific level of energy consumption per unit of delivered water is reported as* ***0.21, 0.34 and 0.56 kWh/m³*** *for* ***urban users, agriculture and wastewater treatment for recycling****, respectively*




**Treatment process at the Oset water treatment facility**

# Water-energy nexus in wastewater treatment plants

Applied Energy 184 (2016) 873–881

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

# Comparative analysis of energy intensity and carbon emissions in wastewater treatment in USA, Germany, China and South Africa

Hongtao Wang [a,*], Yi Yang [b], Arturo A. Keller [c,*], Xiang Li [a], Shijin Feng [d], Ya-nan Dong [a], Fengting Li [a]

Applied Energy 204 (2017) 1463–1475

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

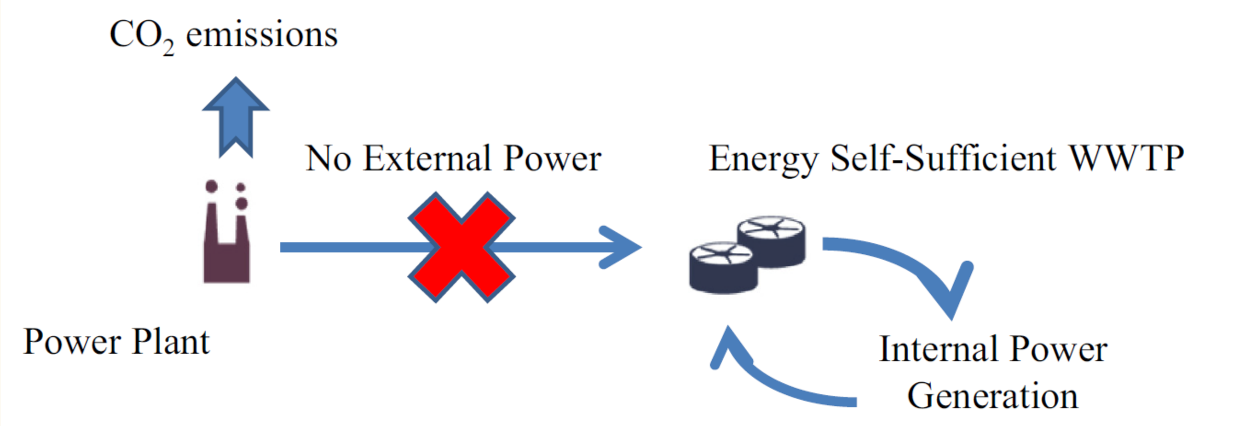
# The feasibility and challenges of energy self-sufficient wastewater treatment plants

Yifan Gu [a], Yue Li [a], Xuyao Li [a], Pengzhou Luo [a], Hongtao Wang [a,*], Zoe P. Robinson [b], Xin Wang [c], Jiang Wu [c,*], Fengting Li [a]

# Energy self-sufficient wastewater treatment plants (WWTPs): feasibilities and challenges

# Energy self-sufficient WWTPs

**Usually, energy selfsufficient WWTPs refers to the WWTP generating 100% or more of the energy it needs for its operation solely from the energy embedded in the water and wastes it treats with zero external energy supply.**




# Question:

**Do you think energy self-sufficient wastewater treatment plants (WWTPs) are feasible?**

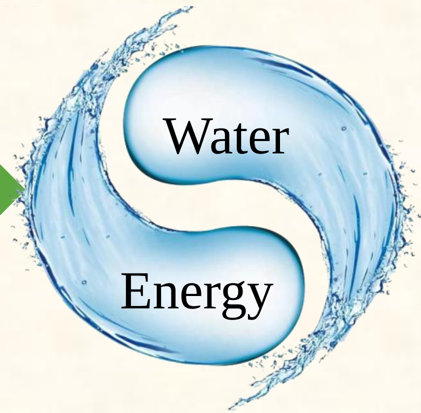
**Why?**

**What is the major challenge?**

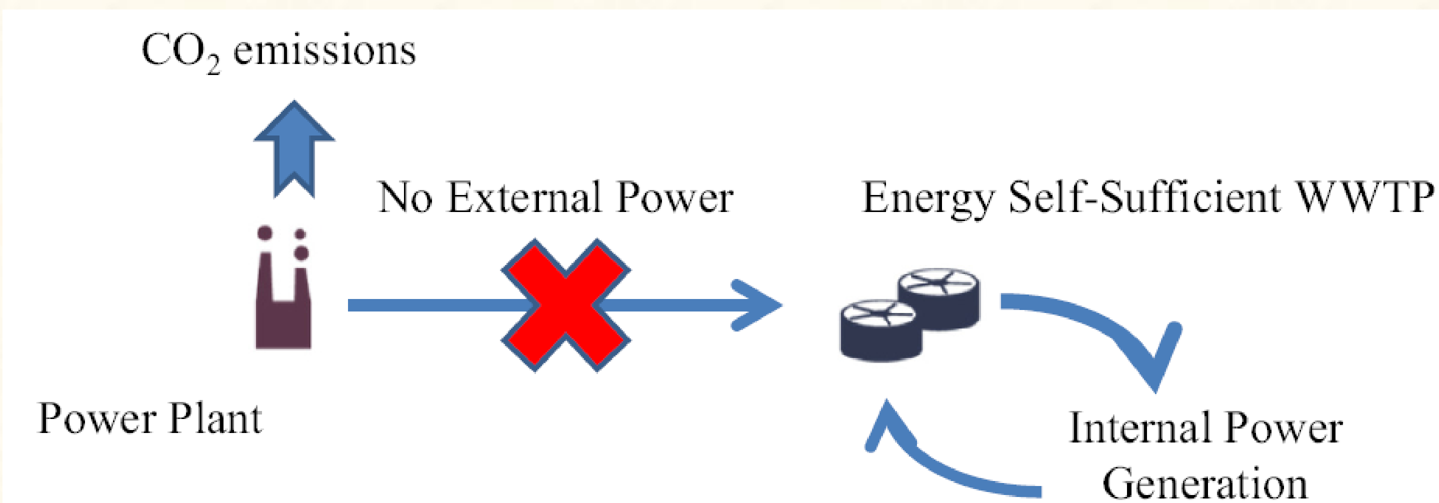
# Contents

# Objective

**Energy self-efficient wastewater treatment plant (WWTP)**




Balance the **resources efficiency** with **environmental benefits**

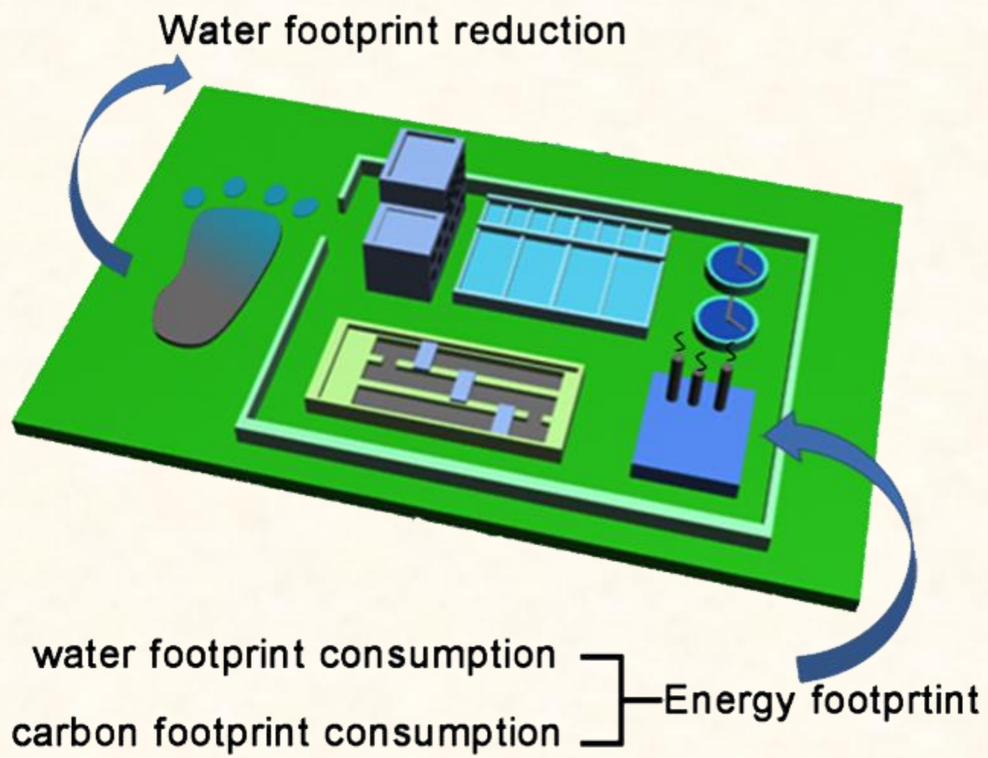


# Objective


- It should be noted the **energy self-sufficient WWTPs** and **carbon neutral WWTPs** are different.
- **Energy self-sufficient WWTPs:** the WWTPs generating 100% or more of the energy it needs for its operation solely from the energy embedded in the water and wastes it treats with **zero external energy supply.**
- **Carbon neutral WWTPs:** WWTPs achieving net zero GHG emissions over their life time.

# Purpose

- ◆Reduce costs
- ◆Save energy
- ◆Achieve carbon neutrality




**WWTP Footprint**



*Gu et.al, Ecological Indicators, 2016, 60:402-409*

# Energy consumption

01 Technology

Energy consumption of WWTPs with different technologies

02 Size/capacity

Energy consumption of WWTPs with different sizes/capacities

03 Location

Energy consumption of WWTPs in different locations

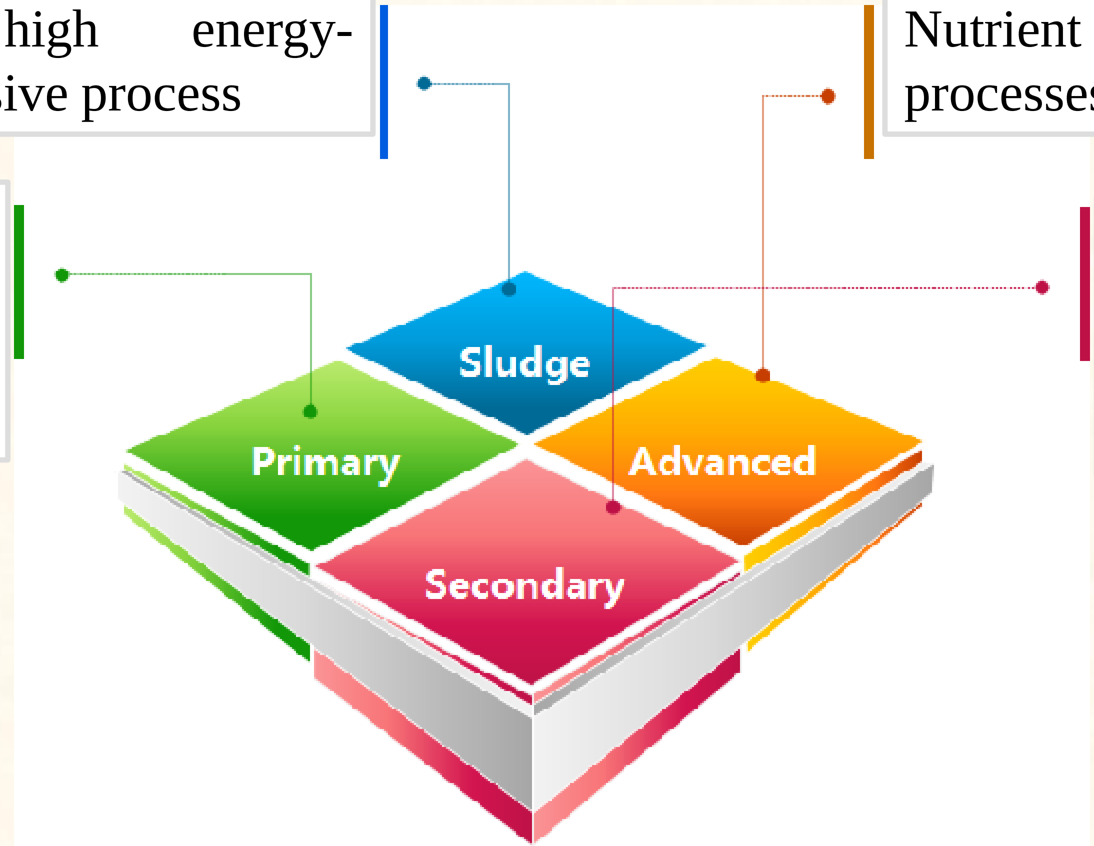
# Energy consumption in four stages of WWTPs

A high energy-intensive process

Nutrient removal processes

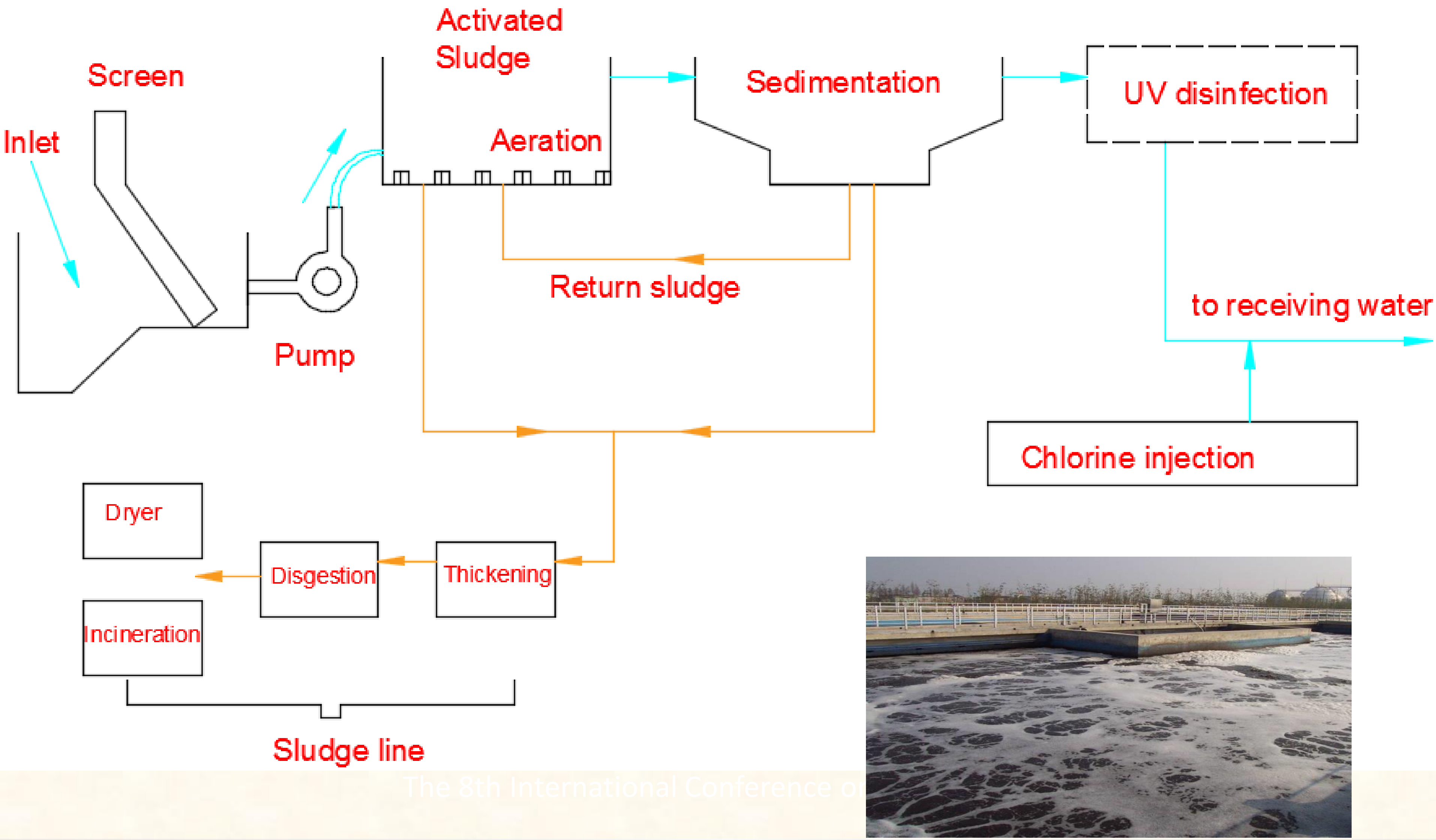
Raw wastewater collection & pumping

The aeration processes (vary from technologies)



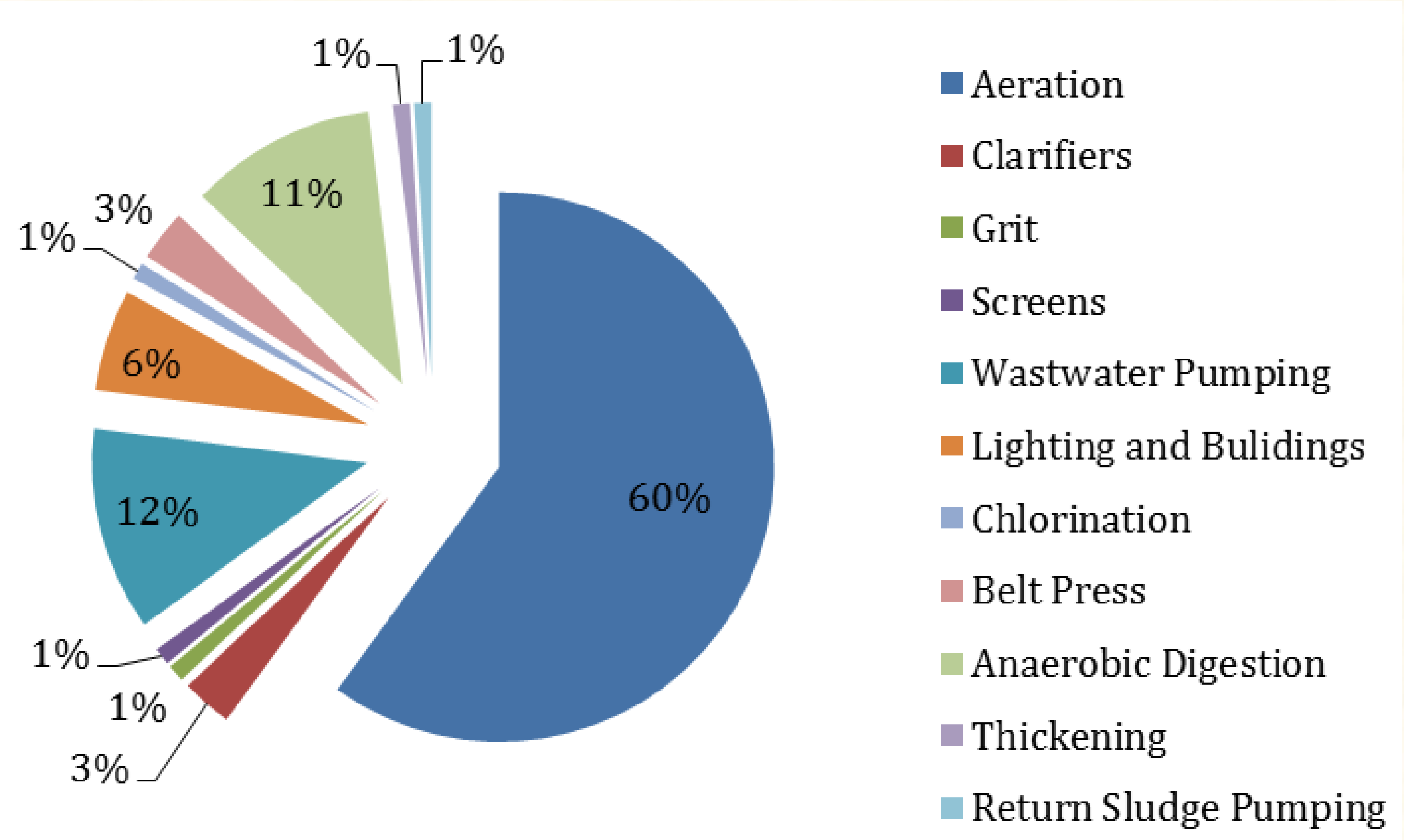

Electrical energy consumption for an activated sludge ranges from **1,400 - 1,900 kWh per million gallons** (kWh/MG) for **a 5-mgd facility**, to approximately **1,000 - 1,600 kWh/MG** for **a 100-mgd facility** (WERF,2010).

# Conventional Activated Sludge(CAS)



# Energy consumption of different treatment stages

## Energy distribution in conventional activated sludge system[1]




*[1] Energy Solutions. Energy Efficiency and GHG Reduction in Wastewater Facilities. 2009*

# Energy consumption with different technologies

## Energy consumption in secondary treatment plants in China [1]

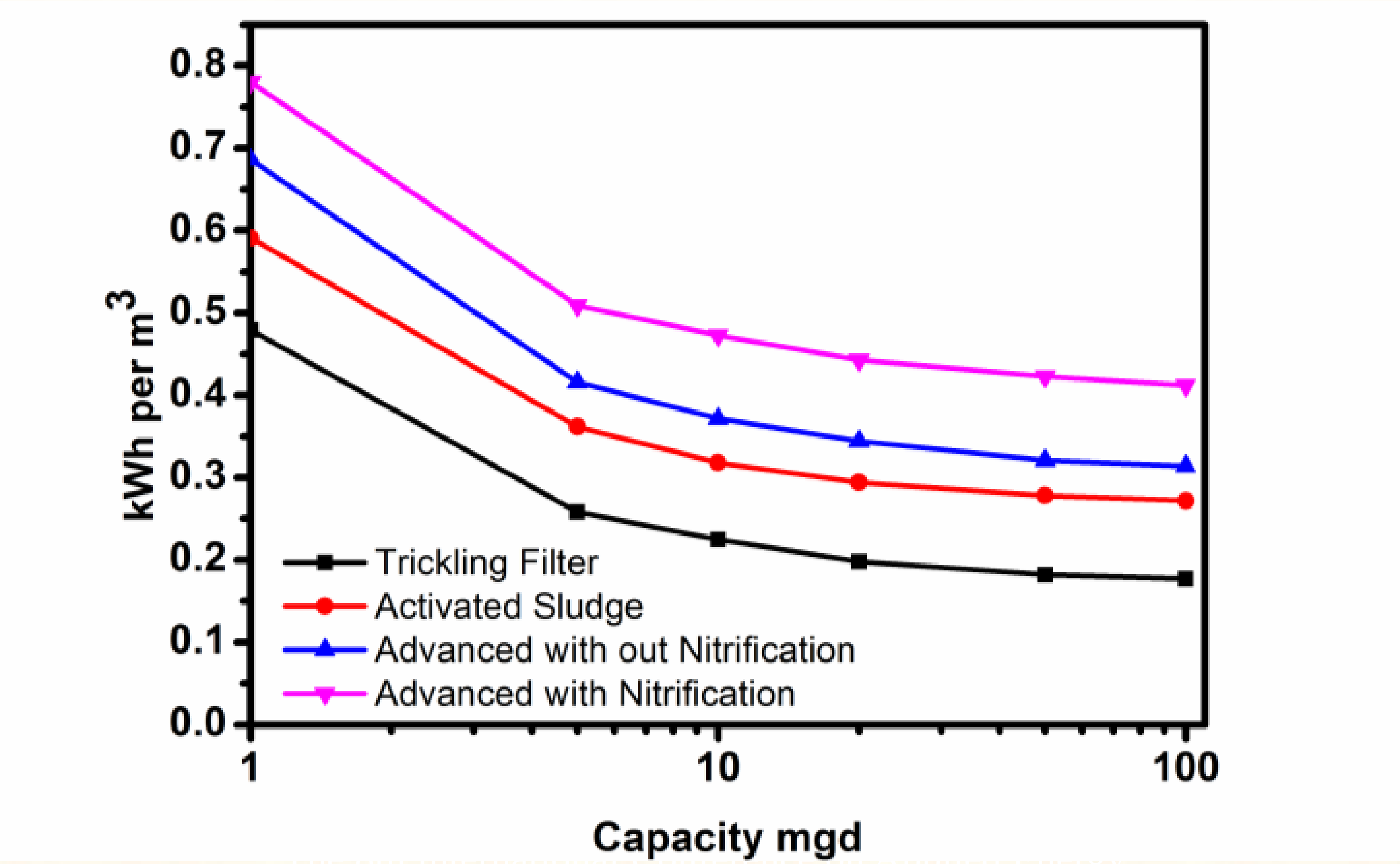
| Technologies | Energy ($kWh/m^3$) | Number of WWTPs |
|---|---|---|
| Extended aeration | 0.340 | 13 |
| SBR | 0.336 | 103 |
| Biomembrane | 0.330 | 36 |
| OD(oxidation ditch) | 0.302 | 170 |
| A/O | 0.283 | 48 |
| CAS | 0.269 | 36 |
| A/A/O | 0.267 | 87 |
| Land treatment | 0.253 | 10 |
| Adsorption-biology | 0.219 | 17 |

**SBR**: sequencing batch reactor **A/O**: Anoxic/Oxic **A/A/O**: Anaerobic-Anoxic-Oxic

*[1] Yang et.al. Water Science and Technology. 2010*

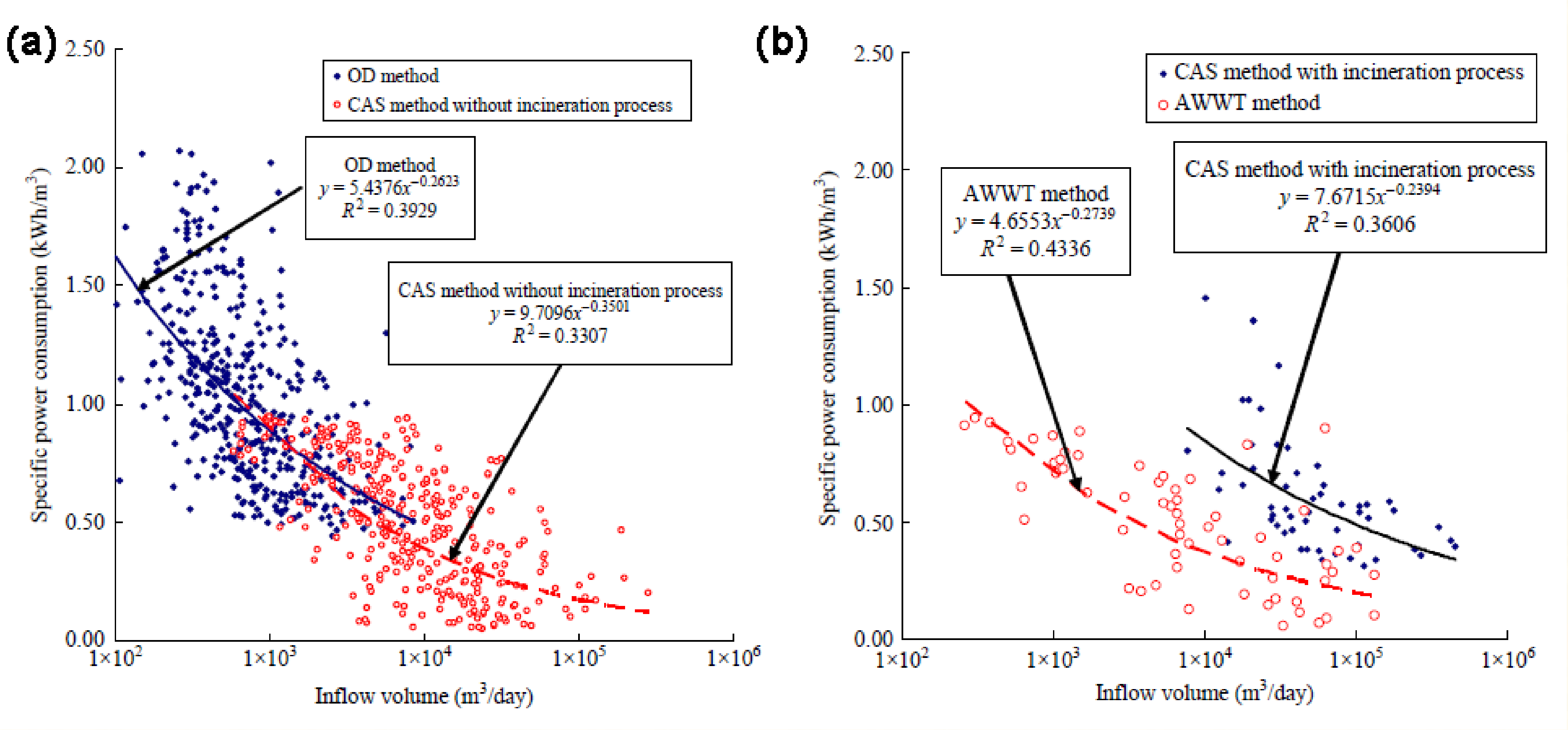
# Energy consumption with different sizes

## Variations in Unit Electricity Consumption with Size for Representative Wastewater Treatment Processes[1]




*[1] GOLDSTEIN et.al. Electric Power Research Institute, 2002*

# Energy consumption with different sizes




**(a) The energy consumption distribution of OD method and CAS method without incineration process, Japan**

**(b) The energy consumption distribution of CAS method with incineration process and advanced wastewater treatment method, Japan**

*MIZUTA et.al. Water Science and Technology. 2010*

# Energy consumption with different countries

## The energy intensity proportion and energy consumption in WWTPs at national level in different countries

| Regions/ Countries | Energy intensity ($kWh/m^3$) | Proportion of energy consumption national level (%) | Reference |
|---|---|---|---|
| **USA** | 0.52 | 0.6 | [1] |
| **China** | 0.31 | 0.25 | [1] |
| **Germany** | 0.40-0.43 | 0.7 | [1] |
| **South Africa** | 0.079-0.41 | - | [1] |
| **Japan** | 0.304[a] | - | [2] |
| **Korea** | 0.243 | 0.5 | [3] |
| **Sweden** | 0.42 | 1 | [4] |
| **Israel** | - | 10 | [4] |

*Note: a including effluent disinfection and sludge digestions*


*[1] Wang H, et al. Applied Energy. 2016*
*[2] Yang et al. Water Science and Technology. 2010*
*[3] Chae et al. Energy Conversion and Management. 2013*
*[4] Olsson. Springer New York; 2012*

# Produced energy

Wastewater is usually considered as a potential energy source. Chemical oxygen demand (COD) can be used to estimate the latent energy of raw wastewater .

1kg COD → $0.35 m^3$ of methane → 35.8 $MJ/m^3$ heating value

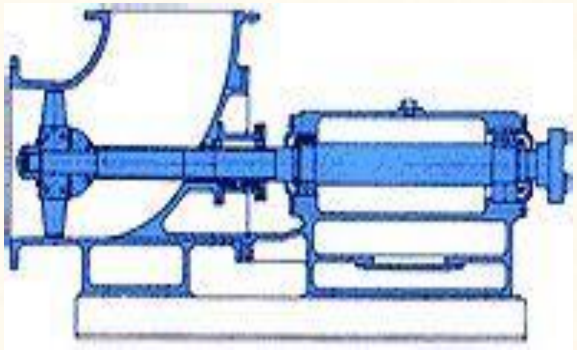
The calculated latent energy of a "typical" North American raw wastewater

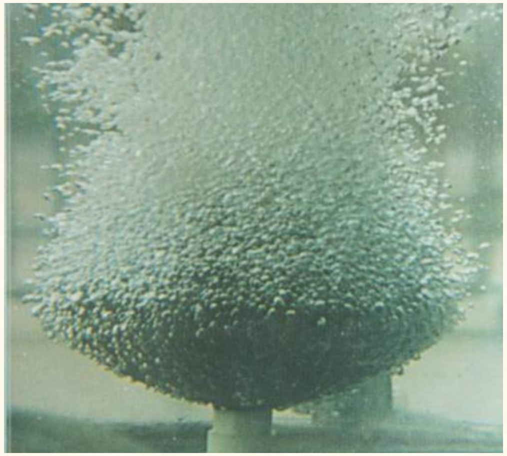
500 mg/L COD, 245 mg/L **cBOD,** **195** mg/L **VSS** → 23,700 MJ/MG → 6,600 kWh/MG

***cBOD*** *(carbonaceous Biochemical Oxygen Demand),*
***VSS*** *(Volatile suspended solids)* *MG(million gallon)*

*[1] Rittmann et.al. Environment Biotechnology. 2001.*

# Energy-saving





## Pumping

- 5~30% possibility
- use high efficiency pump

## Aeration

- 15~35% possibility
- control DO on-line
- update the air Blower

## Sludge line

- Use side stream technology to remove nitrogen
- recycle the biogas production of sludge digestion

*[1] Stefanoet.al. Applied Energy, 2016*

Environmental Science & Technology

FEATURE

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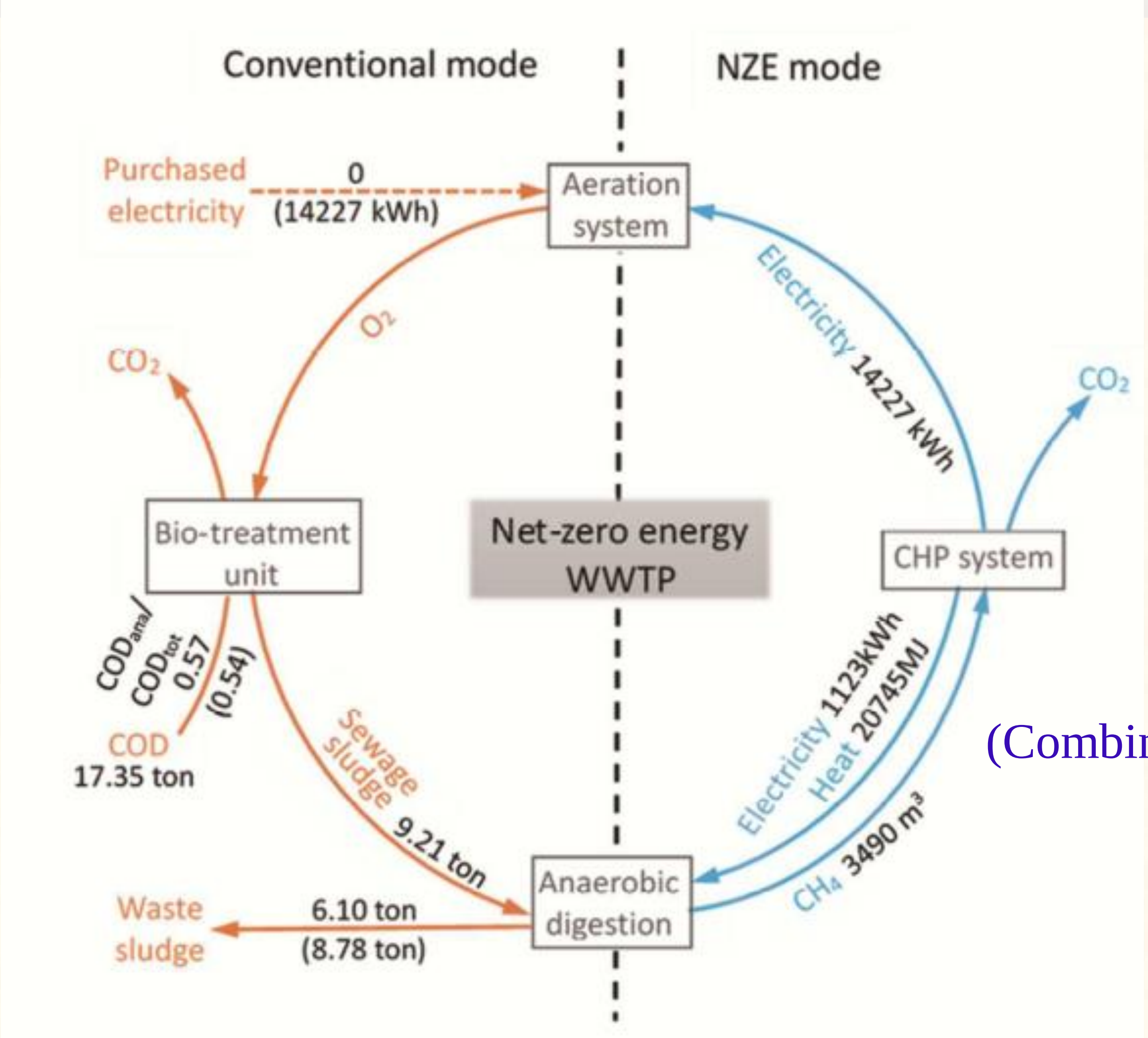
# Domestic Wastewater Treatment as a Net Energy Producer—Can This be Achieved?

Perry L. McCarty,*[,†,‡] Jaeho Bae,[‡] and Jeonghwan Kim[‡]

[†]Department of Civil and Environmental Engineering, Stanford University, 473 Via Ortega MC 4020, Stanford, California 94305, United States
[‡]Department of Environmental Engineering, INHA University, Namgu, Yonghyun dong 253, Incheon, Republic of Korea

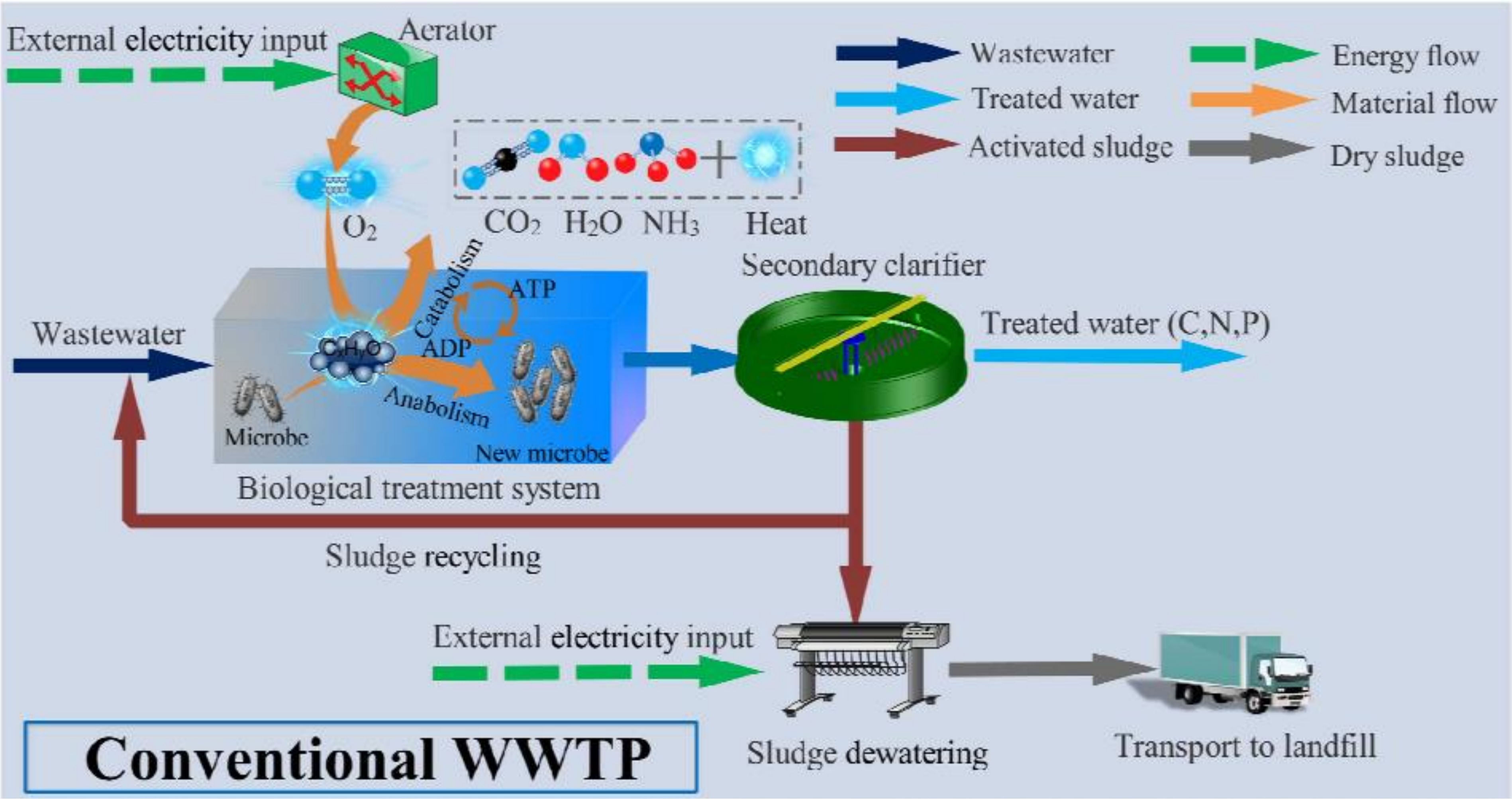



**CHP**

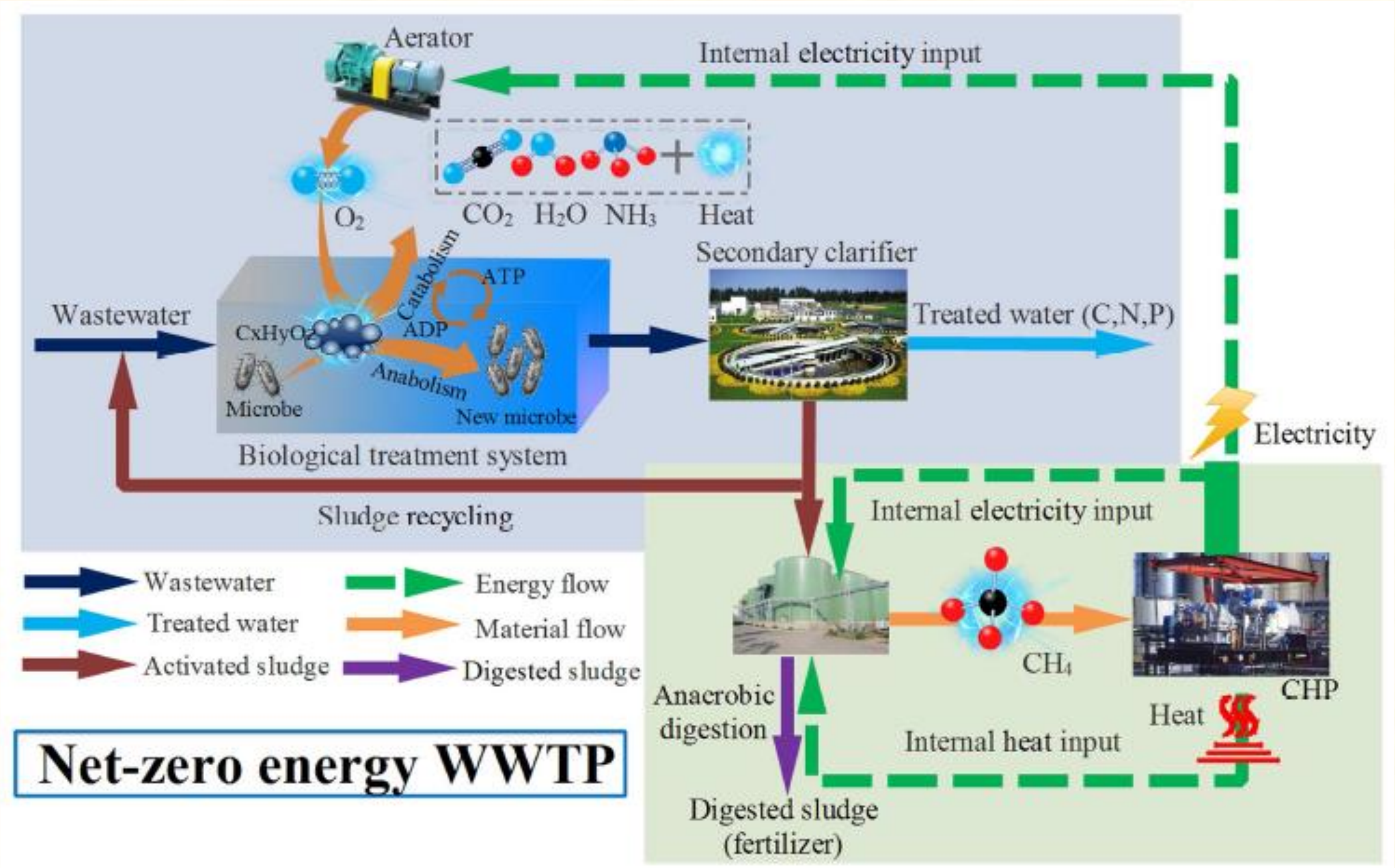
(Combined-Heat-Power)

An outline of energy balance at the Beibei WWTP under NZE mode

*Yan, P., et al. (2016). "A net-zero energy model for sustainable wastewater treatment." Environ Sci Technol.*




*Yan, P., et al. (2016). "A net-zero energy model for sustainable wastewater treatment." Environ Sci Technol.*




*Yan, P., et al. (2016). "A net-zero energy model for sustainable wastewater treatment." Environ Sci Technol.*

# Challenges

## Investment/cost

Some technologies such as CHP (Combined-Heat-Power) and photovoltaics require a big investment in the early stage.

## CHP cost in wastewater treatment plants

**Invest**

approximate
$7,500/kW for fuel cell
$2,000/kW for internal combustion engine
$4,500/kW for microturbine

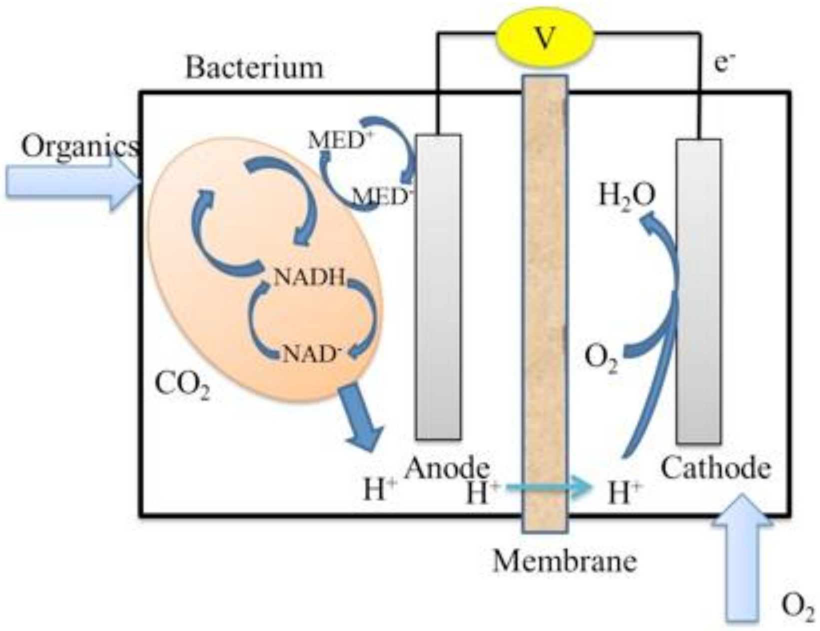
**Operate**

above 5 million gallons per day

# Challenges

## Applicable technologies

- MFC (microbial fuel cell) and its derivative technologies
- still in development and have a long way to engineering application.




**MFC schematic diagram**

# Challenges

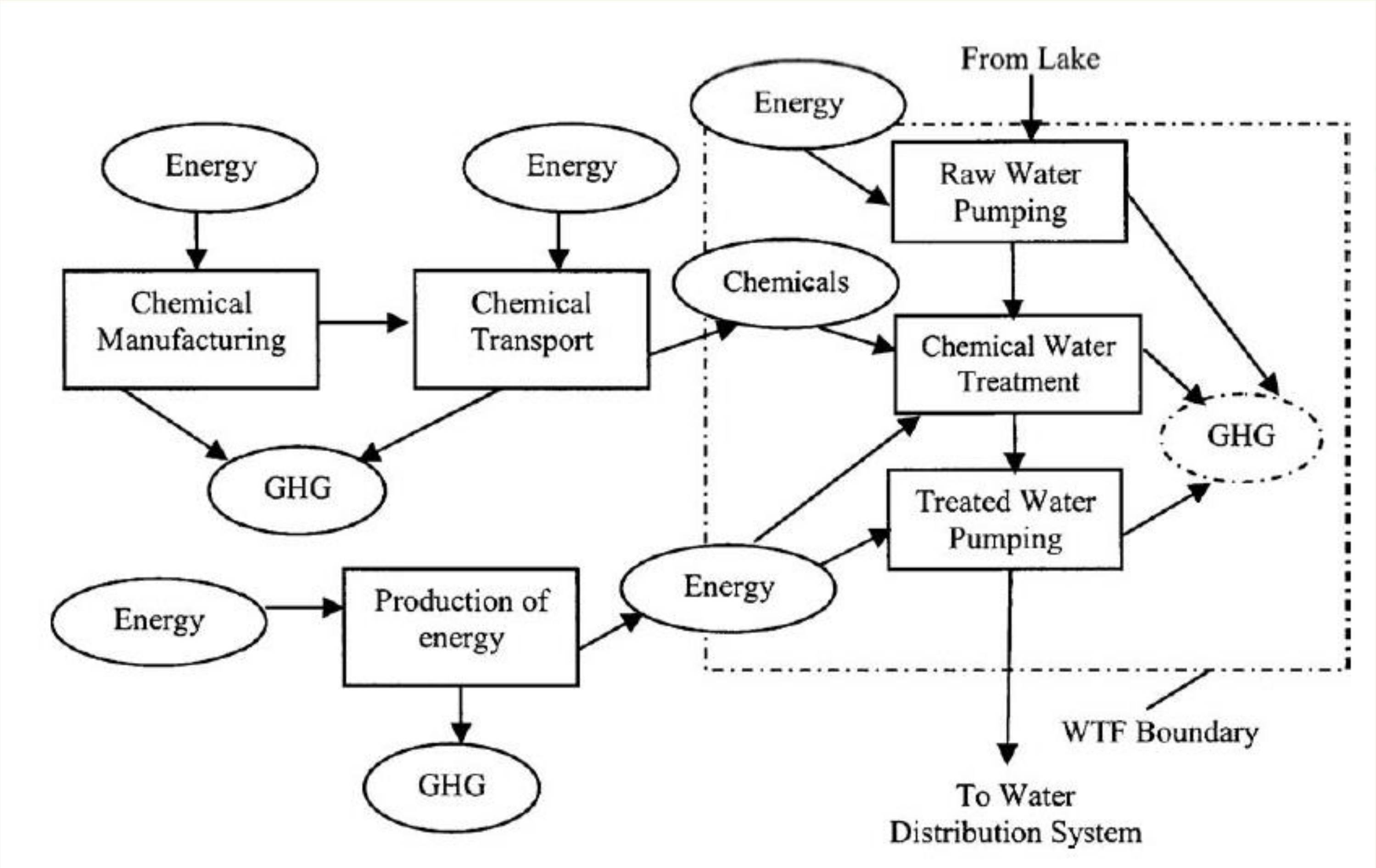
## Capacities

WWTPs with low capacity and organic load are difficult to realize completely energy self-sufficiency.

## Environmental problems

- Inadequate anaerobic treatment may influence adjacent environment .
- The leakage of $CH_4$ and $N_2O$ is more likely to cause global warming and air pollution.

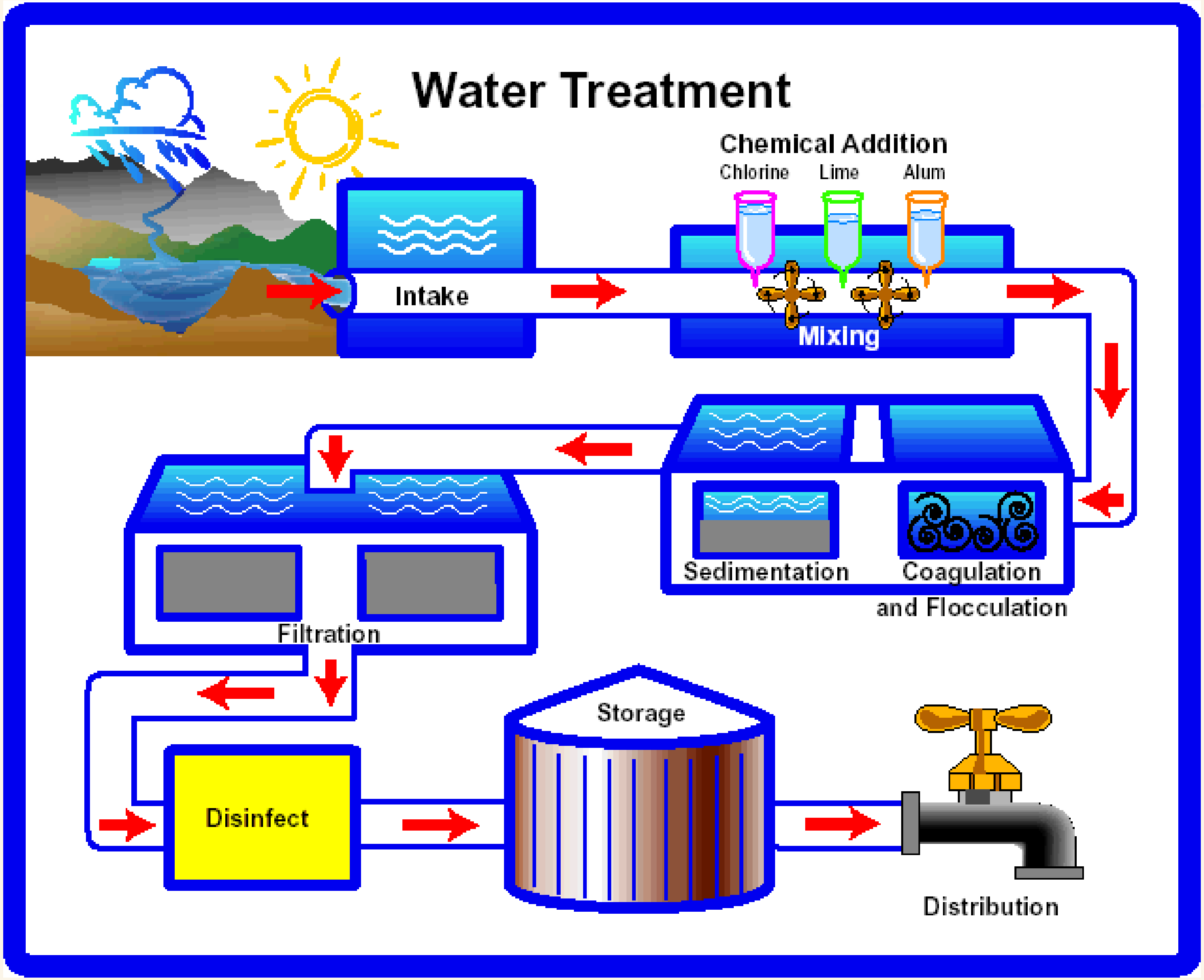
# Water-energy nexus in drinking water treatment plant




**Life-cycle energy and GHG flow diagram. Dashed boundaries represent processes/products not included in this analysis.**

*Alina I. Racoviceanu, et al. Life-Cycle Energy Use and Greenhouse Gas Emissions Inventory for Water Treatment Systems. J. Infrastruct. Syst., 2007, 13(4): 261-270*

# DRINKING WATER TREATMENT



# Conventional treatment process of drinking water

Coagulant

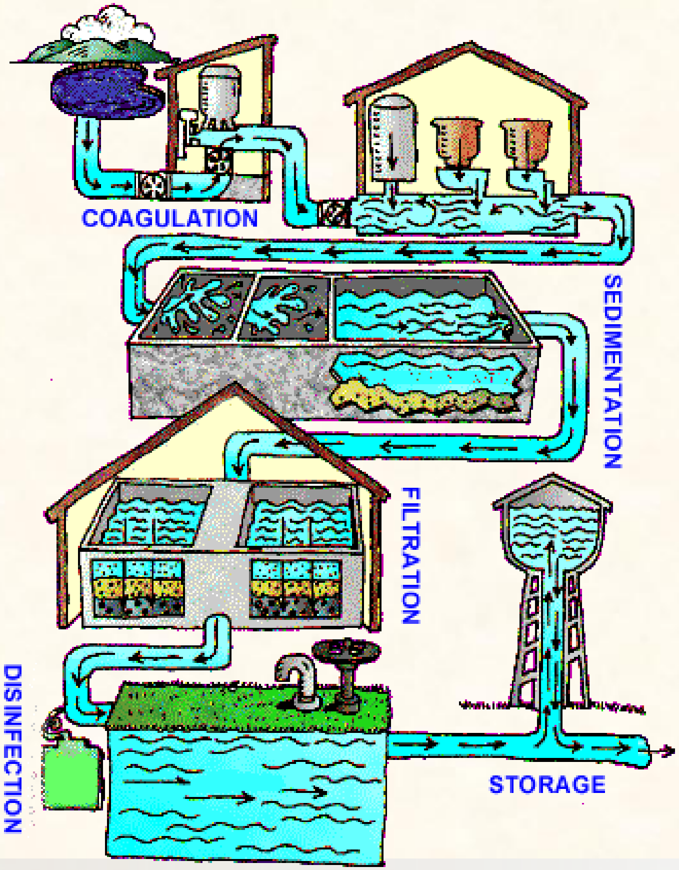
$Cl_2$

Disinfection

Source Water → Coagulation → Sedimentation → Filtration → Clean water

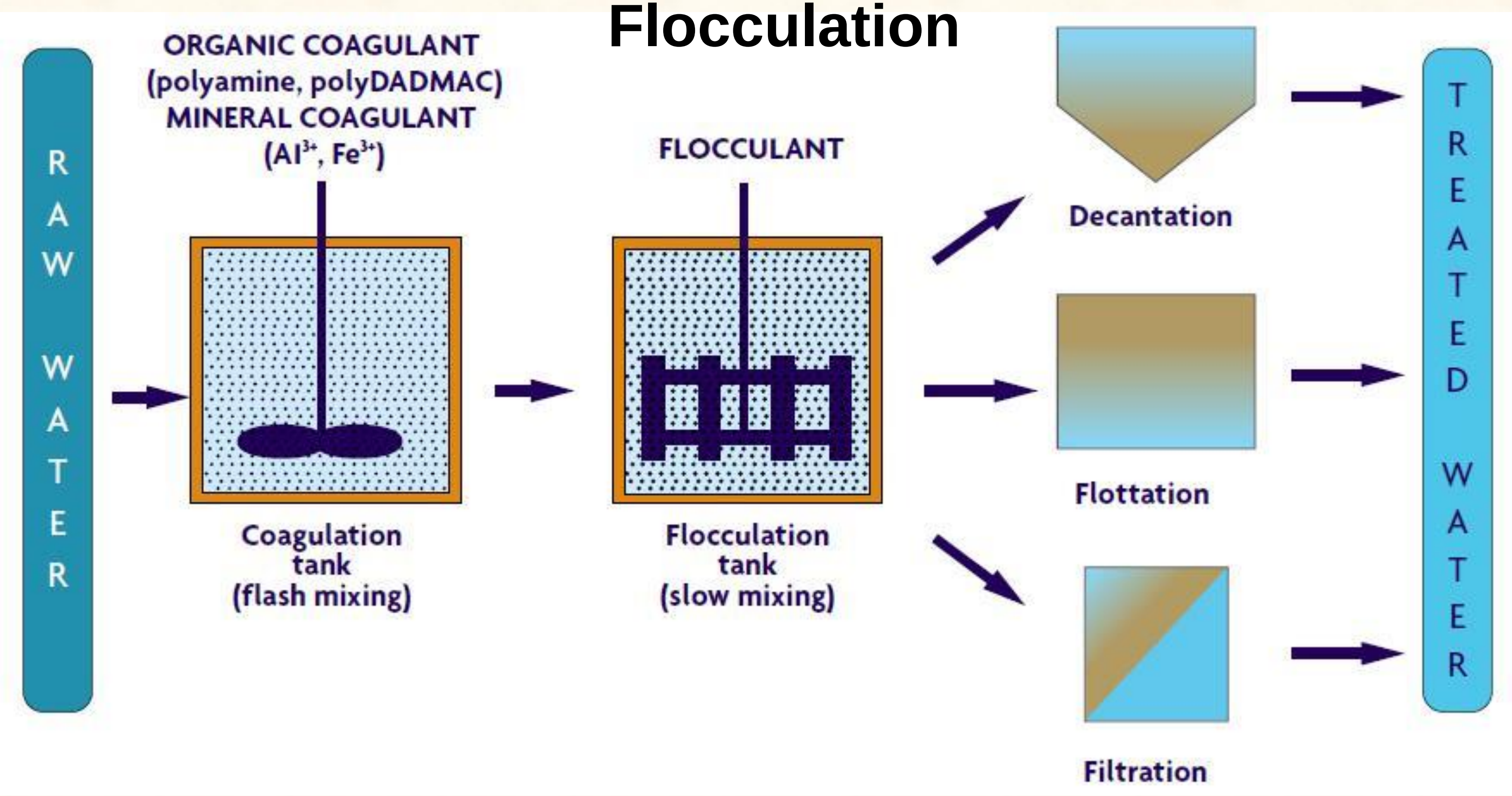
Distribution

Customer ← Pump




**Source: US EPA**

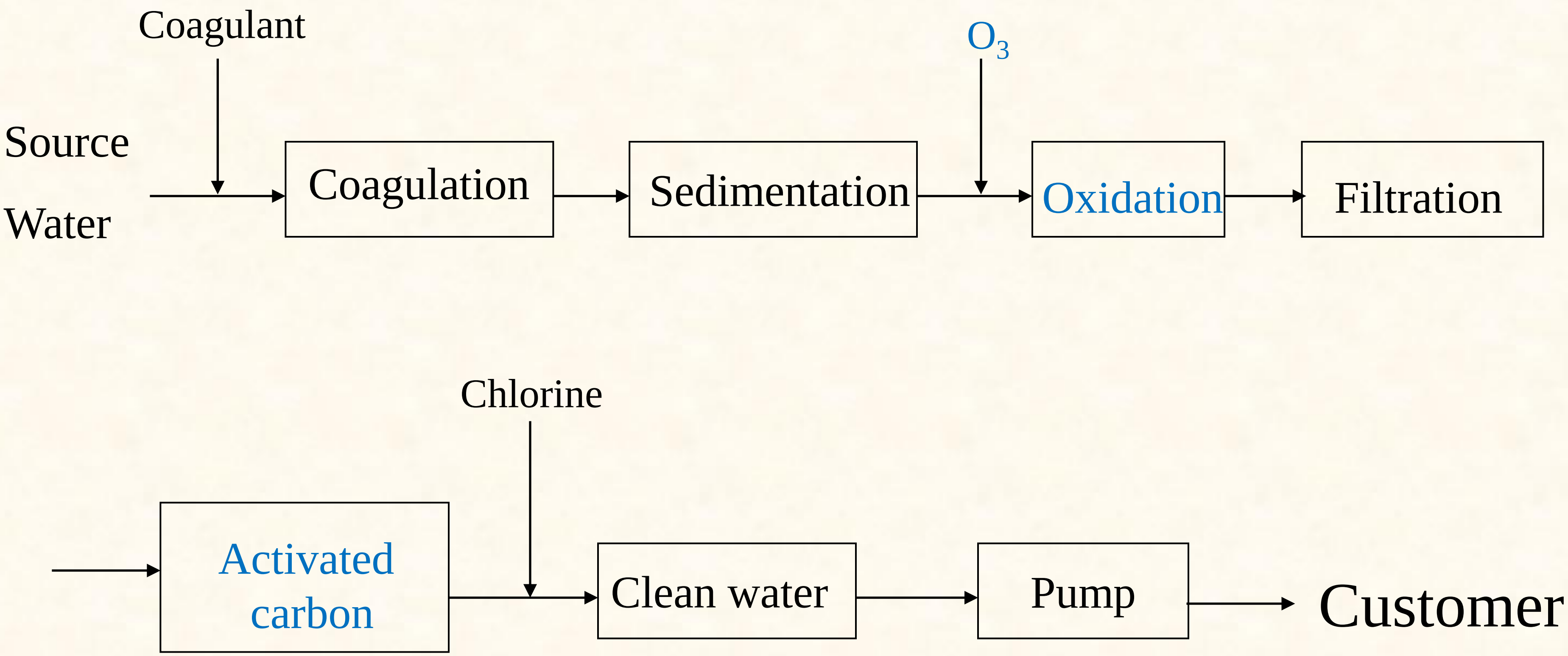
# Physical-chemical process involved in Coagulation-Flocculation




*Coagulation-flocculation*: The use of chemical reagents to destabilise and increase the size of the particles; mixing; increasing of flocs size.

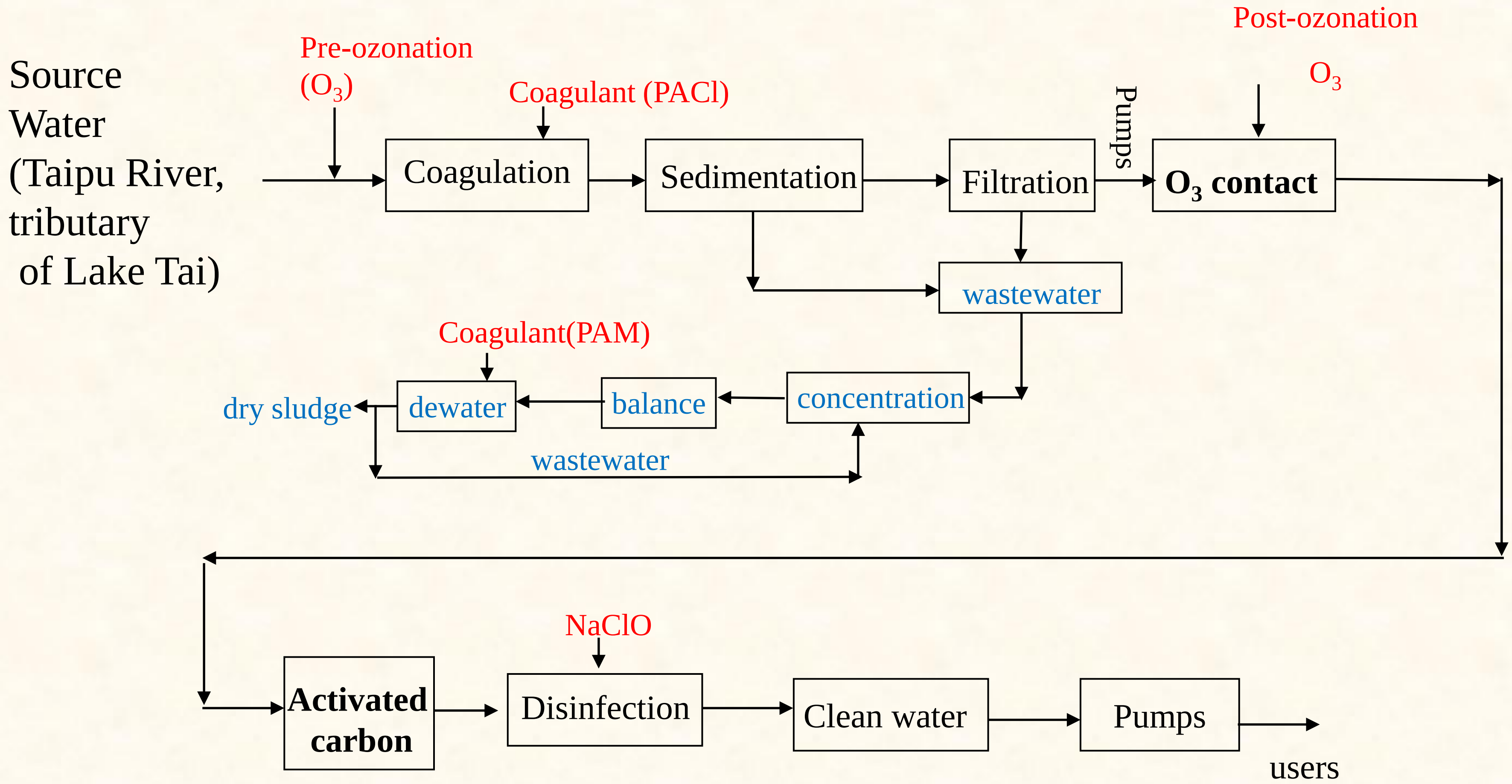
Source: SNF FLOERGER (20

# Advanced treatment process of drinking water

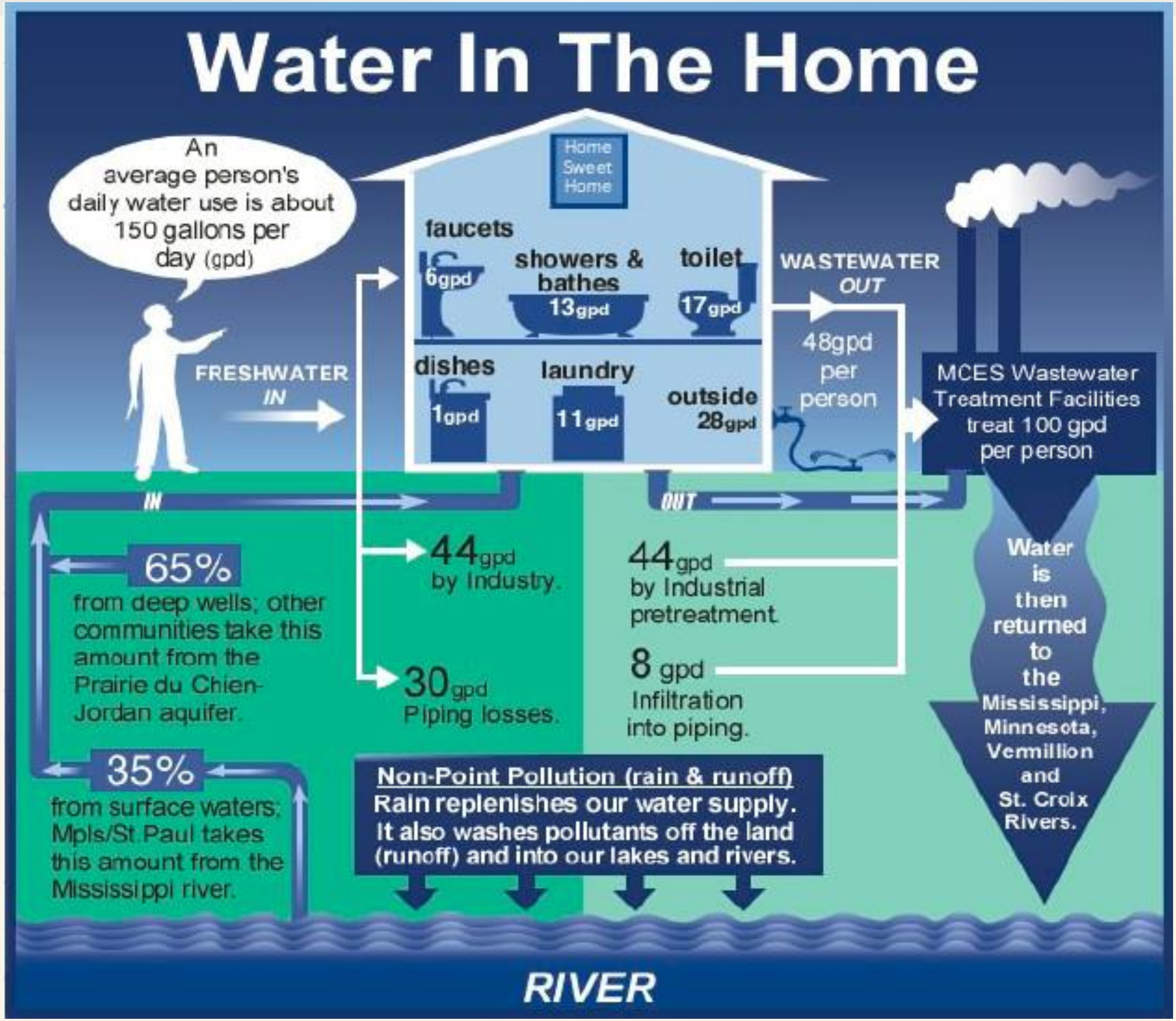



**Ozone biological activated carbon technology**

# Process of the 2nd Waterworks in Qingpu District, Shanghai

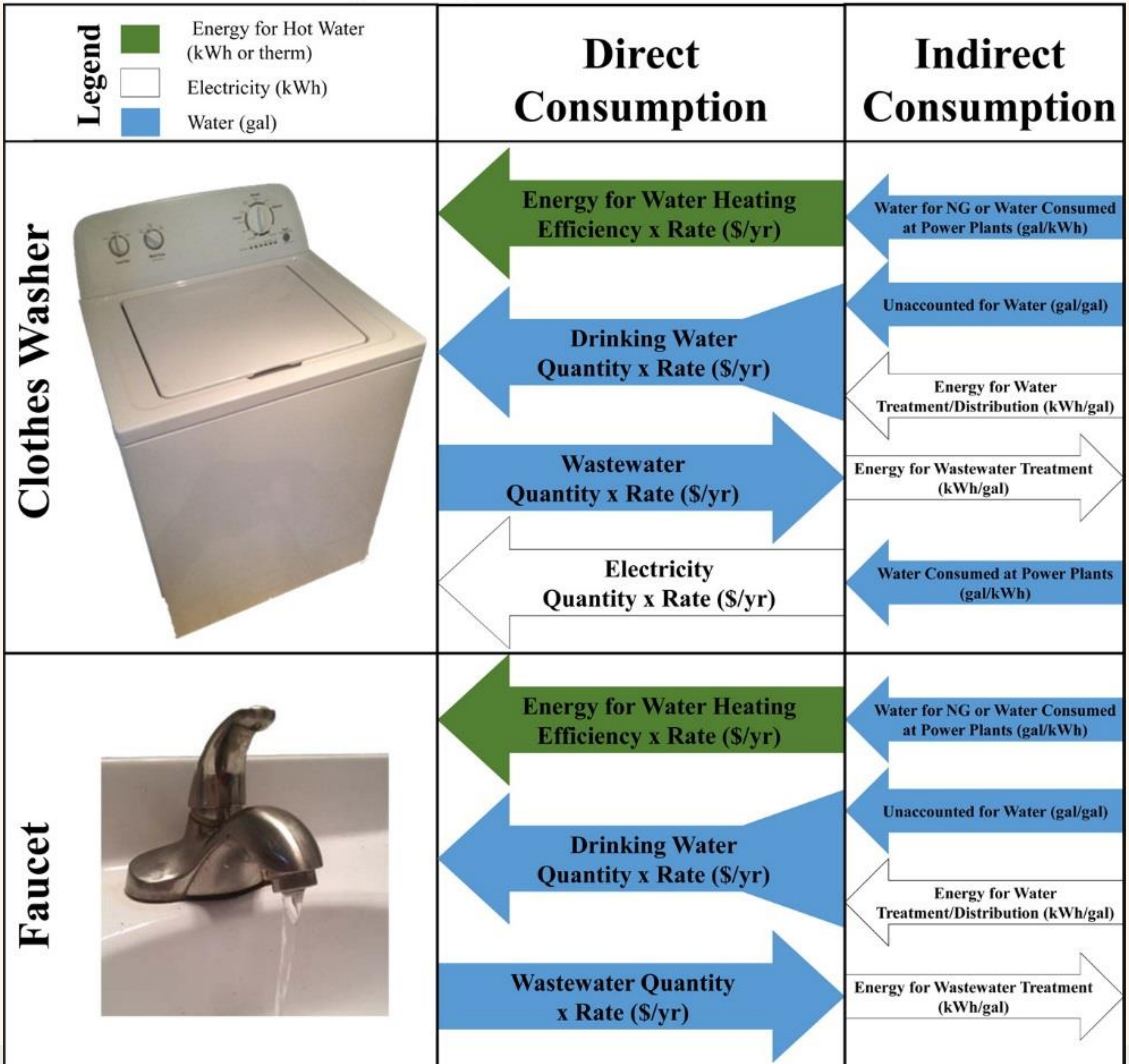


# Water-energy nexus in the Residential Sector


Water In The Home
An average person's daily water use is about 150 gallons per day (gpd)
Home Sweet Home
faucets
6gpd
showers & bathes
13gpd
toilet
17gpd
dishes
1gpd
laundry
11gpd
outside
28gpd
FRESHWATER IN
WASTEWATER OUT
48gpd per person
MCES Wastewater Treatment Facilities treat 100 gpd per person
IN
OUT
65%
from deep wells; other communities take this amount from the Prairie du Chien-Jordan aquifer.
35%
from surface waters; Mpls/St.Paul takes this amount from the Mississippi river.
44gpd by Industry.
30gpd Piping losses.
44gpd by Industrial pretreatment.
8 gpd Infiltration into piping.
Water is then returned to the Mississippi, Minnesota, Vermillion and St. Croix Rivers.
Non-Point Pollution (rain & runoff)
Rain replenishes our water supply. It also washes pollutants off the land (runoff) and into our lakes and rivers.
RIVER

# Quantifying Energy and Water Savings in the Residential Sector

# Direct and Indirect Resource Consumption for Sample Appliances and Fixtures



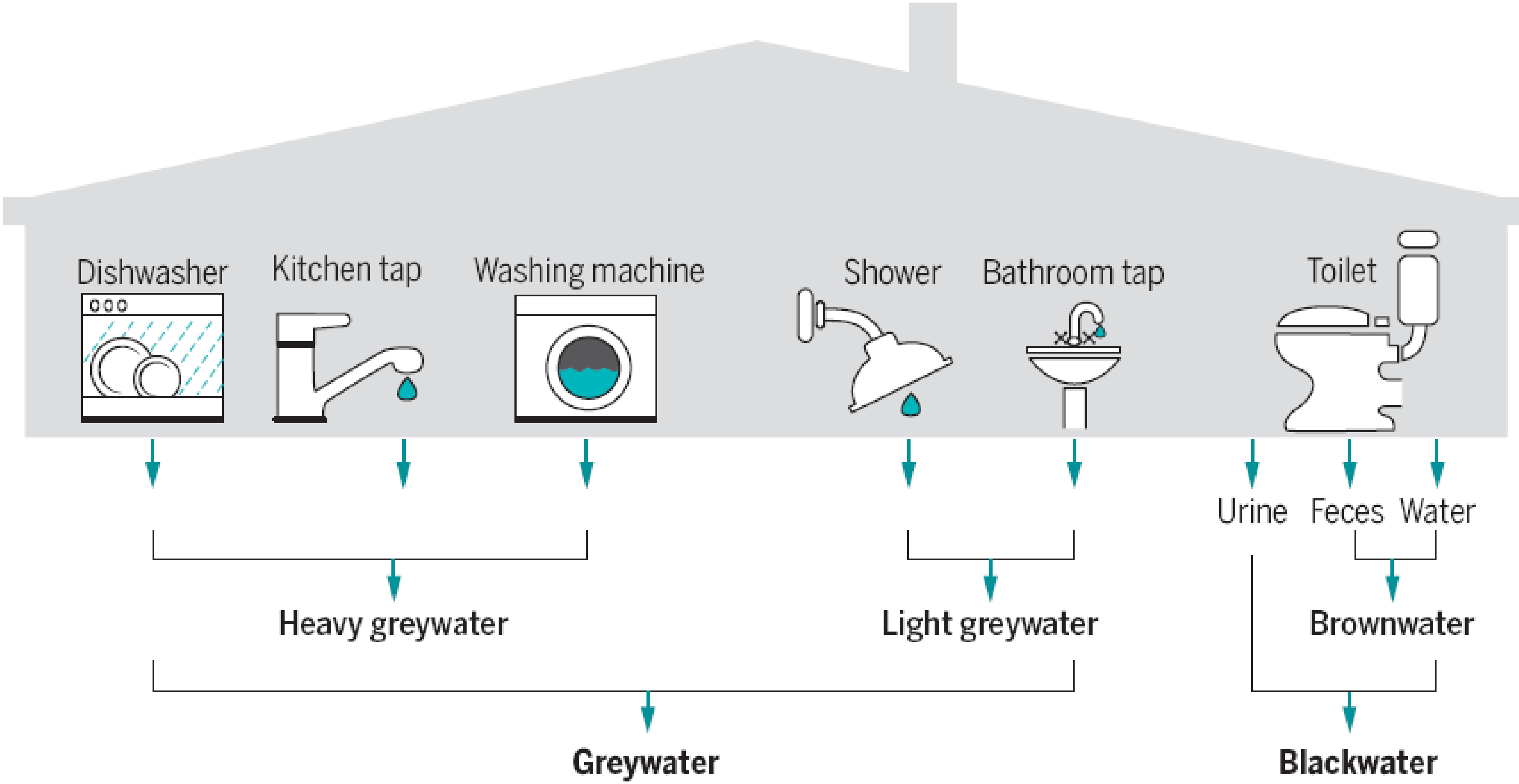
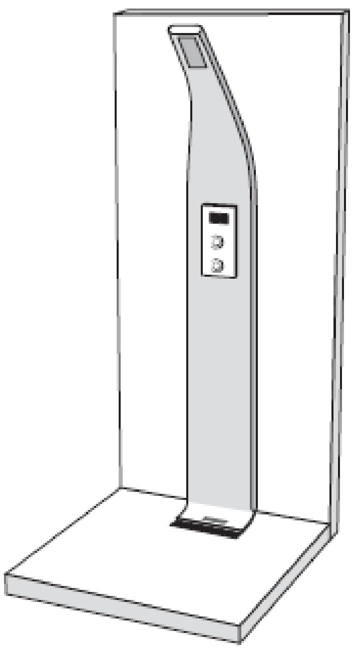


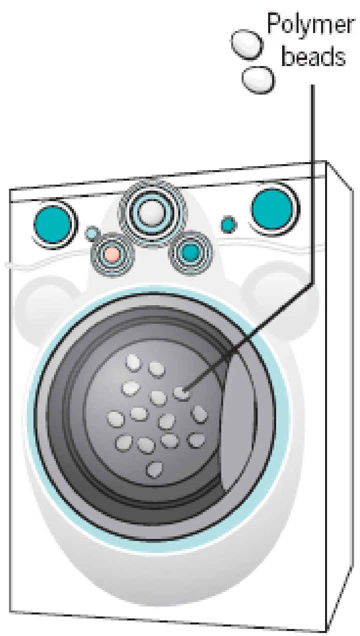

**Fig. 3. With source separation of wastewater in the household, new types of wastewater can be constructed for optimal treatment.** It is even possible to include treatment and recycling processes in a single device. This offers totally new perspectives for mass-produced, consumer-friendly wastewater treatment technology (for examples, see Table 2).

**Table 2. Examples of emerging solutions to UWM challenges.**

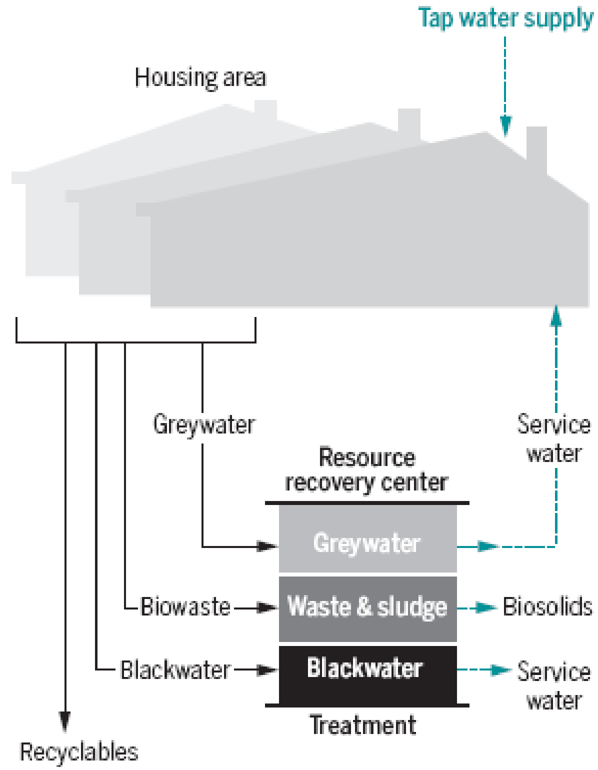
| Increasing water productivity | | Distributed treatment | Source separation of waste |
|---|---|---|---|
| Reuse | Substitution | | |



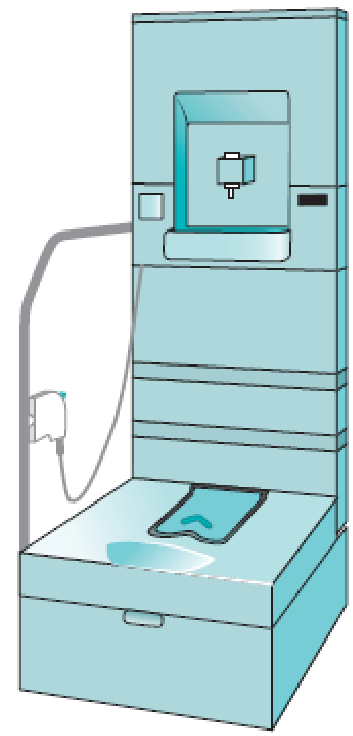
Recycling shower (*70*)




Waterless washing machine (*71*)




Distributed treatment of waste at district level (*72*)



Blue Diversion Toilet (*73*)

# Take-away message

1. Water and energy are interdependent!
2. Water for energy
3. Energy for water