RECOVERING RESOURCES FROM MUNICIPAL WASTEWATERS

How must our thinking change to reap the benefits?

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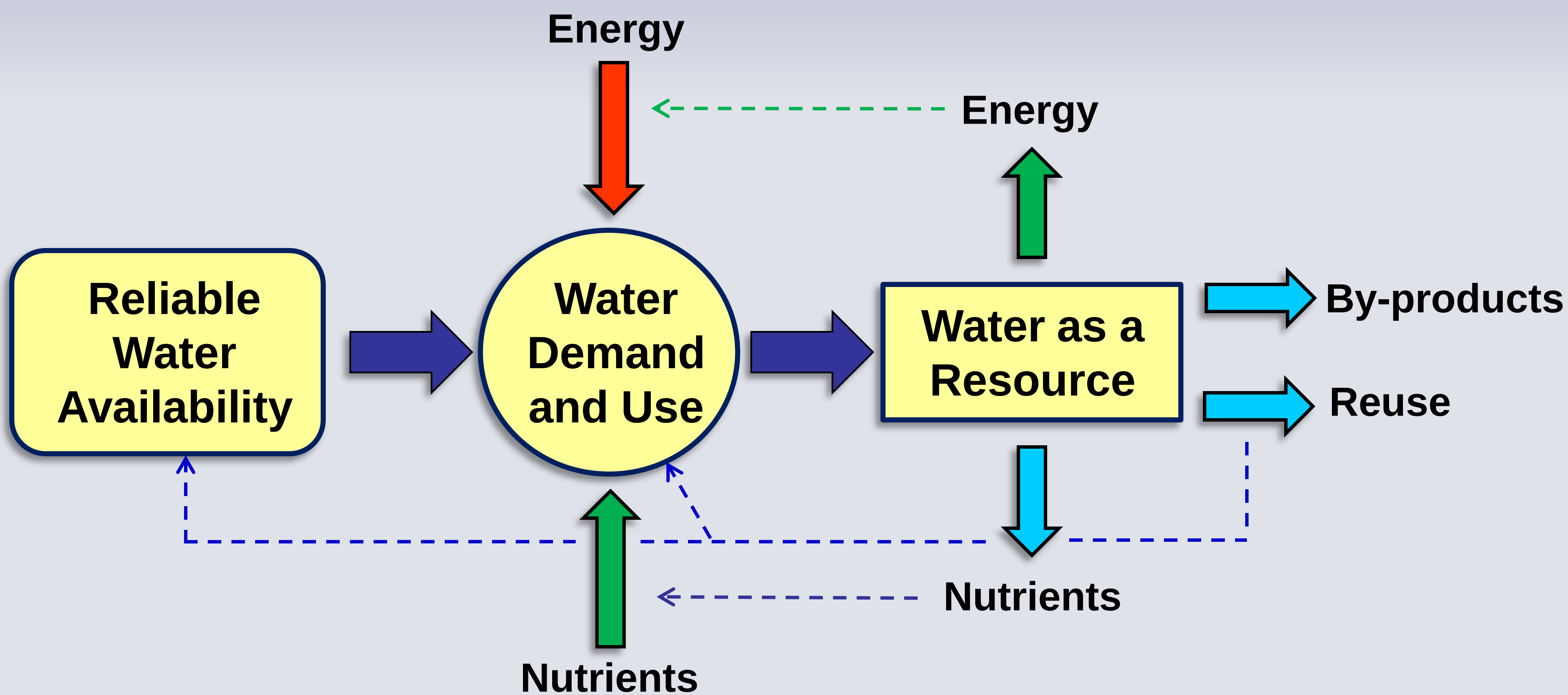
OUTLINE

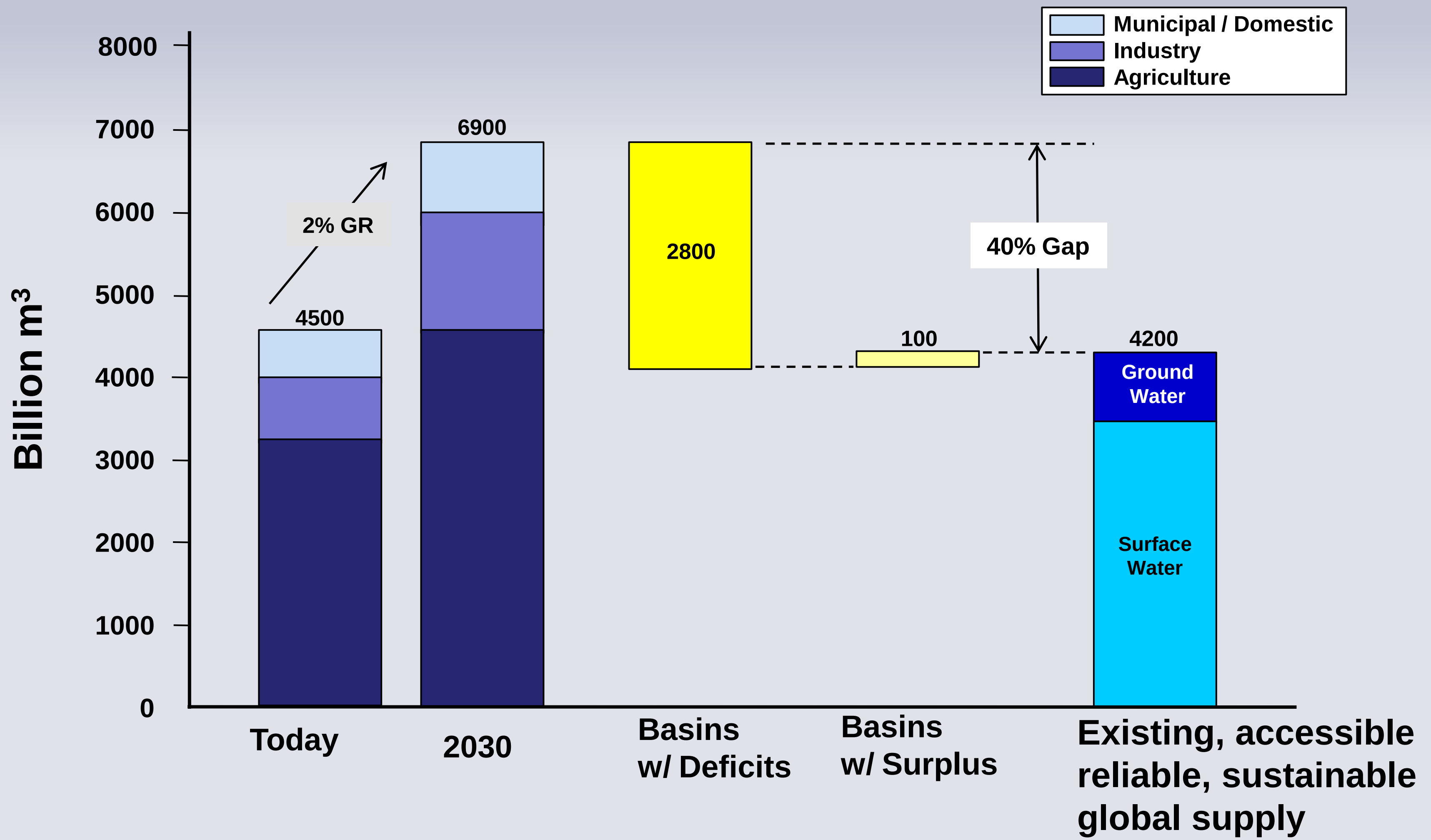
1. A Look at Our World's Water Future
2. Putting Energy Into Perspective
3. Recovering Energy from Wastewater
4. Recovering Useful By-products from Wastewater
5. Recovering Nutrients from Wastewater
6. Recovering Quality from Wastewater
7. Obstacles for Achieving the Future
8. Gaps in Our Knowledge for Achieving the Future
9. Conclusions

OVERVIEW



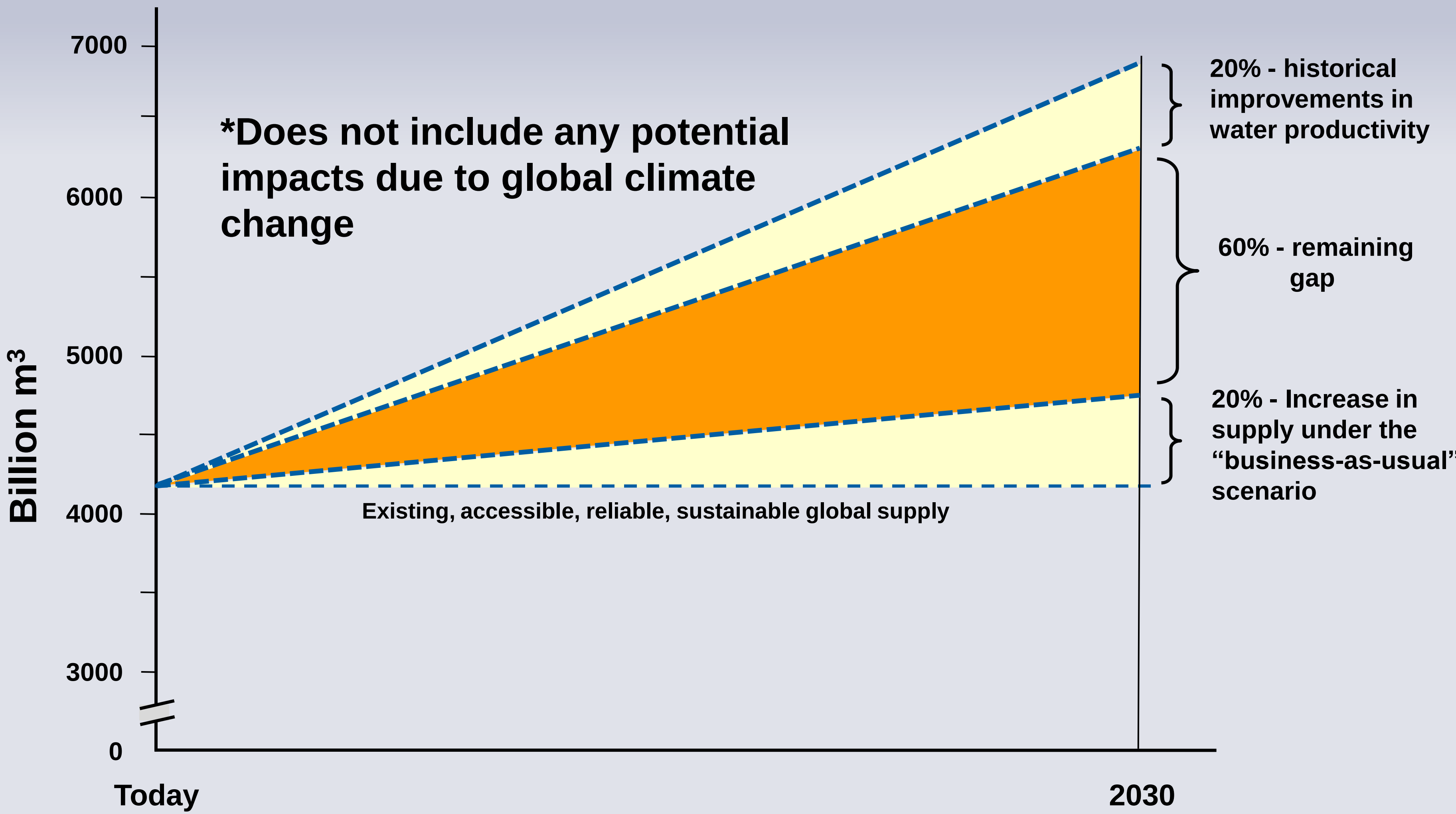
**"Unless we change our direction,
we are likely to end up where we're headed."**

Water: The Resource the Must Be Recovered First



Source: 2030 Water Resources Group (2009)

Water: The Resource the Must Be Recovered First



Source: 2030 Water Resources Group (2009)

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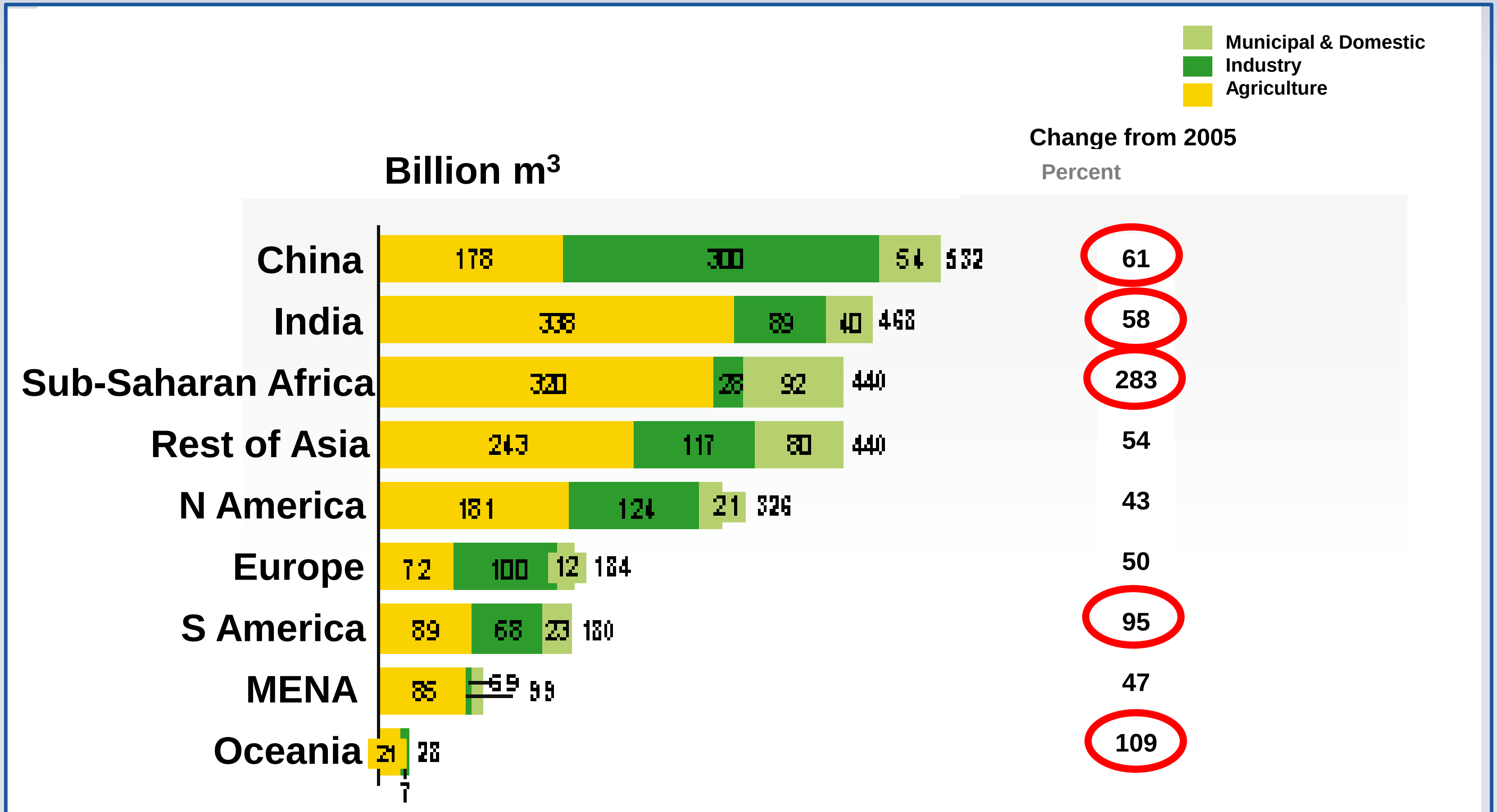
Water: The Resource that Must Be Recovered First

Increase in Annual Water Demand 2005 - 2030



Source: 2030 Water Resources Group (2009)

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The Responsibility of Stakeholders

- **Governments, Public Agencies, NGOs**
  - Actively reduce withdrawals: change the underlying set of economic activities that rely on water
- **Agricultural Producers**
  - Food production technology and technique efficiency, and the water these require, must be enhanced
- **Financial Institutions**
  - Water has suffered from chronic under-investment… institutions must make up the shortfall
- **Large Industrial Users**
  - Water/energy nexus…must focus on efficiency in recycling and reuse
- **Technology Providers**
  - Dramatically increase production of goods and services for scale-up
- **Construction Sectors**
  - Must deliver more large-scale infrastructure

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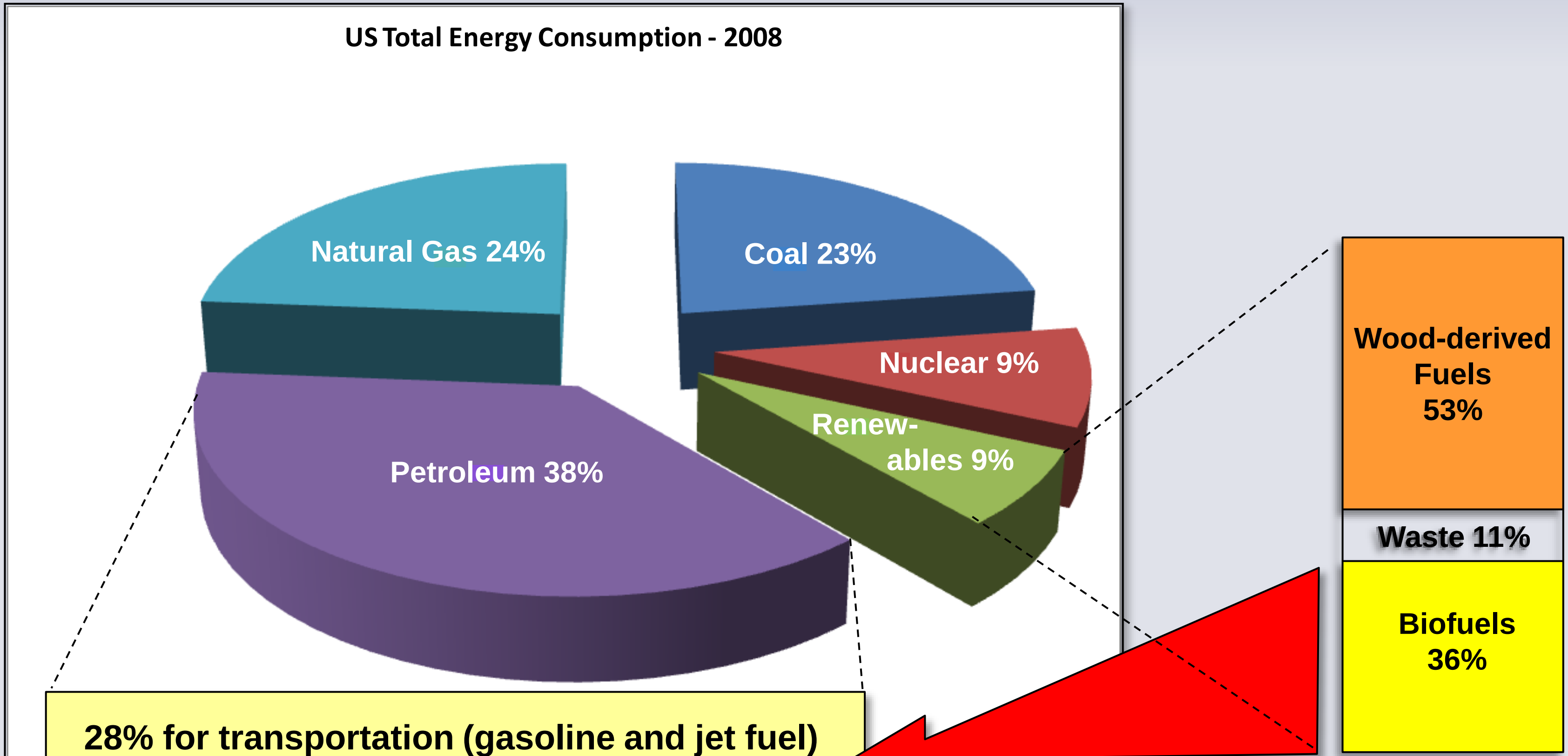
Source: 2030 Water Resources Group (2009)

Grasping Realities Associated with Energy

"Energy is the single greatest challenge facing humanity."

- Richard E. Smalley, Nobel Laureate for Chemistry - 1996



28% for transportation (gasoline and jet fuel)
40% for electricity generation
20% for direct heating (natural gas and coal)
32% for industrial

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Source: Energy Information Administration - US DOE, (2009); Muller, R., UC Berkeley, (2009)

Some Key Facts About Energy

- Gasoline delivers 15x more energy than an equal weight of TNT
- Gasoline has 1000x as much energy as an equal weight of flashlight batteries; 100x as computer batteries
- Gasoline has 4.5x more energy per gallon than $H_{2(L)}$
- Natural Gas is 1.3x better than gasoline per pound
- H_2 is 2.6x better than gasoline per pound*
- To separate hydrogen from water requires energy
- Only 30% to 40% of the energy put into releasing hydrogen is usable…the rest is lost to heat
- The only way to get net positive energy from H_2 is to obtain it from natural gas.

Source: Muller, R., UC Berkeley, (2009)

Some Key Facts About Energy

Power is the *RATE* at which energy is used.

Therefore, a kW is the *rate* of energy delivered;

US electric power usage is about 450 GW (1 GW = 1×10^6 kW)
A typical US Household uses about 1 kW

A kW-hr is the *TOTAL* amount of energy delivered in 1 hour

What are the baseline energy costs today?

Coal:	$0.04 – $0.08 / kW-hr
Natural gas:	$0.03 / kW-hr
Gasoline:	$0.11 / kW-hr
Car Battery:	$0.21 / kW-hr
Computer Battery:	$4.00 / kW-hr
AAA Battery:	$1,000 / kW-hr

Source: Muller, R., UC Berkeley, 2009

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Some Key Facts About Energy

FACT: The US has enormous coal reserves.

- 2 trillion tons of known reserves
- About 4 trillion tons may actually be available
- We consume about 1 billion tons per year
- At current consumption rate, supply is >1,000 years!!
- If used to replace expensive oil, supply is ≈300 years

FACT: The alternatives to fossil fuels are numerous. Their emergence depends primarily on cost.

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Source: Muller, R., UC Berkeley, 2009

ENERGY RECOVERY:
Should we focus on it?

- Our average annual efficiency in the way we use energy is equivalent to about 1% per year.
- If we continue at the current 1% rate, by 2100 we will be using 40% more energy than today, unable to sustain population demands
- Minor governmental intervention could push this to 2%
- At 2%, after 55 years, our efficiency would have tripled (or 1/3 the energy we use today) and at same productivity
- By 2100, world population is projected at 10 billion
- At the 2% efficiency rate, all could live at a western standard but consume only 1/2 of what we consume today

"THE SOLUTION TO POLLUTION IS CONSERVATION."

- Richard Muller, UC Berkeley

First priority is conservation; second is new technology.

Source: Rosenfeld, A., *Lawrence Berkeley National Laboratory*, UC Berkeley

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What About Biofuels?

- US law: 7.5 billion gallons of ethanol per year by 2012
- Today, 1/5 of corn acreage has been diverted to ethanol production
- Ethanol delivers only 2/3 the energy of gasoline
- Though cheaper than gasoline per gallon, ethanol is more expensive per mile
- Corn ethanol use nets about 13% in CO_2 emissions

Does it make economic sense to put all the costs into ethanol production just to replace 13% of the total CO_2 emissions from the transportation industry when it is more expensive per mile to utilize?

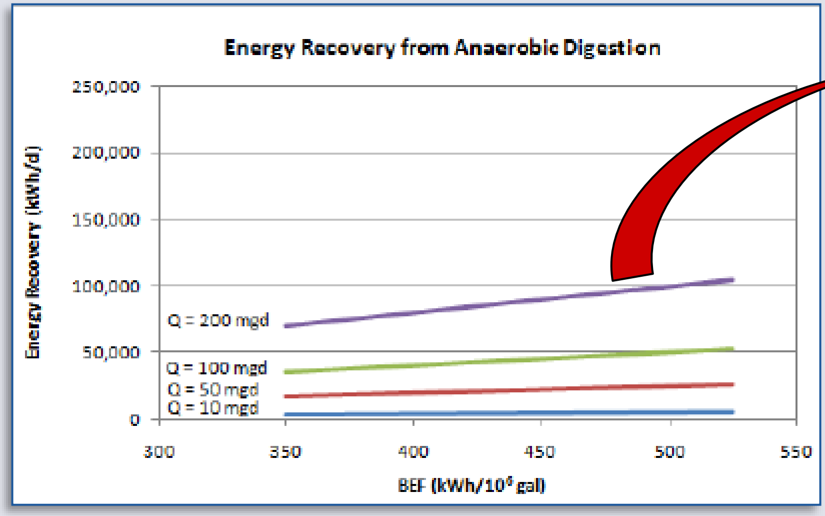
Crop & Fuel	Fuel Yield gallon/ac
Soy biodiesel	45 – 60
Canola biodiesel	100 – 130
Algal biodiesel	
(15% oil, 10 g/m^2/d)	600 –
(50% oil, 50 g/m^2/d)	10,000
Corn ethanol	300 – 600
Miscanthus ethanol	800 – 1200

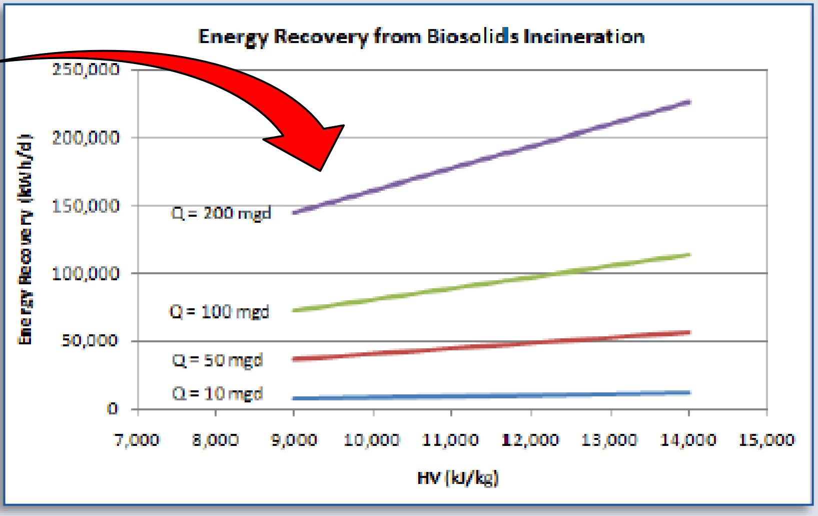
Source: Muller, R., UC Berkeley, 2009
Schideman, L.; Agriculture & Biological Engineering, U. of Illinois; Bioenergy Seminar (2010)

ENERGY RECOVERY:
How much can you count on?

- For plants with anaerobic digestion with biogas utilization, the energy recovery potential can be estimated by:

Energy Recovery = Q x (Biogas Energy Factor)





- For plants with biosolids incineration with power generation, the energy recovery potential can be estimated by:

Energy Recovery = Q x (C_S) x (biosolids Heat Value) / (Steam Heat Value)

Cs = the wastewater dry solids content (kg/MG)

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Source: Stillwell, A., et al., *Sustainability* (2010)

ENERGY RECOVERY:
What about raw WW Anaerobics?

- Few technical obstacles limit the use of anaerobic processes for waste treatment; obstacles are mostly in public's perception of its implementation
- If wider acceptability of anaerobic processes for the treatment of raw wastewater is to be gained, then odor control and biogas utilization must be properly addressed
- Process produces CH_4 (70%-80%), CO_2 (5%-10%), and N_2 (10%-25%)
- Actual CH_4 yields are well below theoretical: 0.08 to 0.18 m3/kg COD removed vs. 0.35 m3/kg
- There must be a standard set for upgrading biogas to natural gas; European standards should suffice
- CH_4 can be utilized as supplemental carbon for denitrification in nutrient removal bioreactors

Source: Noyola, A., et al., *Reviews in Environ. Sci. and Biotech*. (2006)
Classen, P., et al., Applied Microbiology & Biotechnology (1999)

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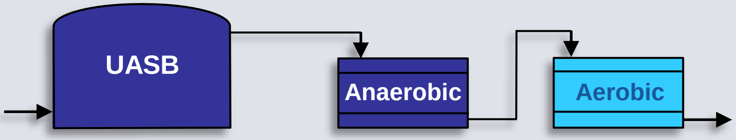
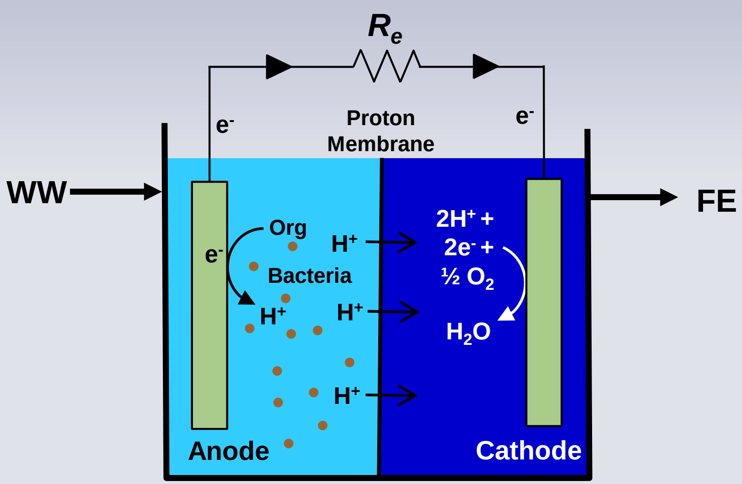
ENERGY RECOVERY:
What about UASBs?

- UASBs seem to be getting the most attention
  - High SRT (<40 days) in relation to HRT
  - COD reduction efficiency between 60%-80% for loadings in the range of 0.4 to 3.0 kg COD/m^3/d
  - BOD reduction efficiency generally about 5% - 8% higher than COD
  - If used alone, may not meet the effluent standards for surface water discharge; some type of post-treatment is typically required
  - Most effective configuration seems to be the UASB followed in series with anaerobic downflow filter and an aerobic downflow filter (COD removal > 90%)



Source: Ghangrekar, M. Kahalekar, U., *IE(I) Journal* – EN (2003)

ENERGY RECOVERY:
What about MFCs?



Microbial Fuel Cell
"microbially mediated combustion"

- **Today, 4% of all electricity consumed in the US is for the operation of water & wastewater treatment**
- **Conventional aerobic treatment requires about 0.5 kW-hr/m3 of wastewater treated; equivalent to 30 kW-hr/person/yr**
- **Theoretical delivery (100% efficiency) of 3 kW-hr/kg of COD removed (dry weight) in one single step**
- **Minimal inefficiencies due to heat losses**

Challenges to Overcome for Use in Wastewater:

- **Limitations: kinetics, intracellular substrate transport rates, internal system resistance**
- **Required surface areas for electrodes remains excessive**
- **Large surface areas are required for bacterial biofilms**
- **Scale-up costs associated with materials for wastewater treatment remain high**
- **identifying and selecting for microbial consortia that support high current densities**
- **successful continuous flow system designs remain elusive**

Source: Logan, B., Regan, J., ES&T (2006); Aelterman, P., et al. , WS&T (2006); He, Z., et al., WS&T (2005)

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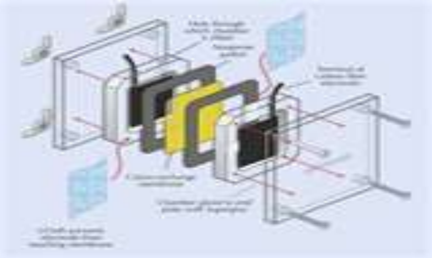
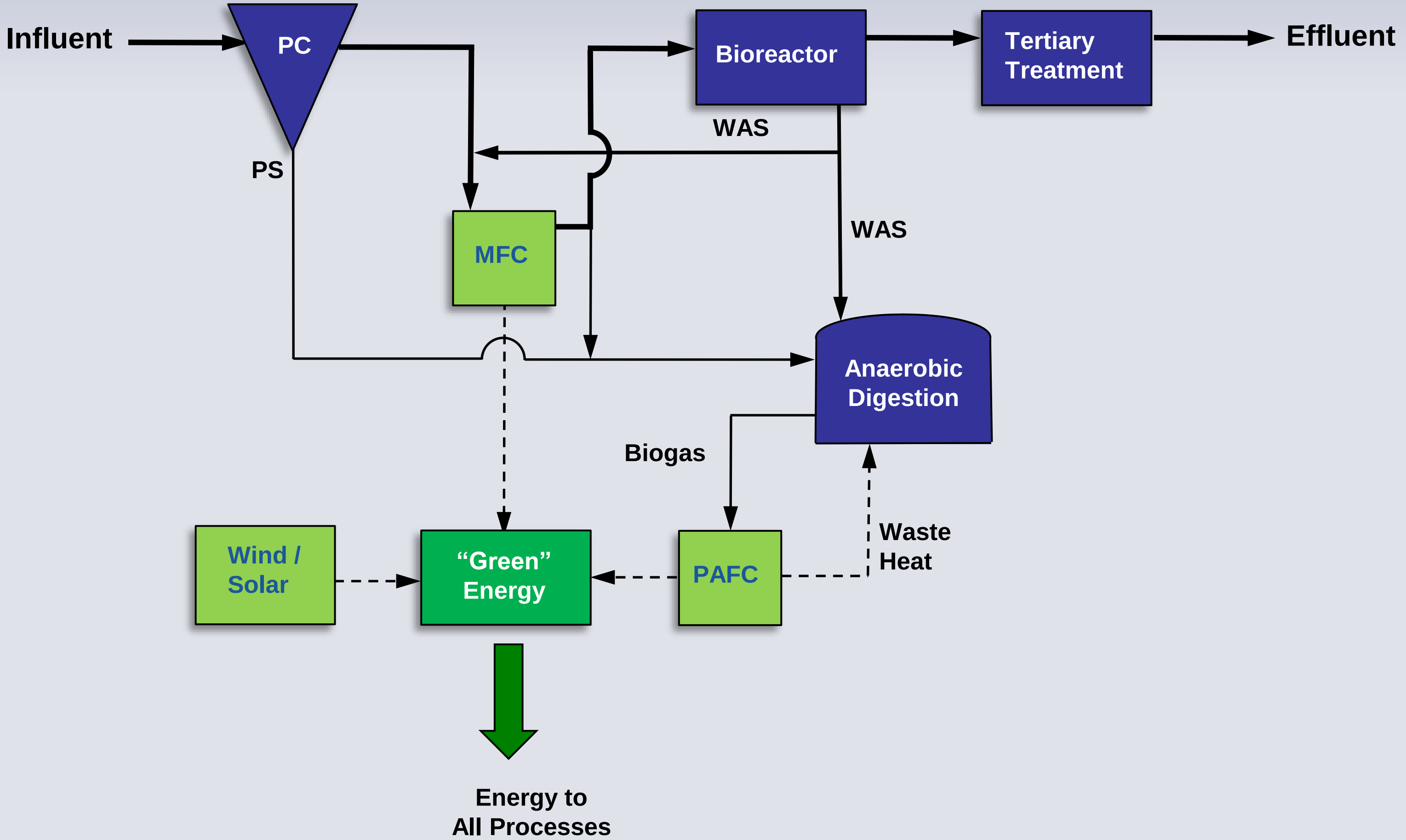
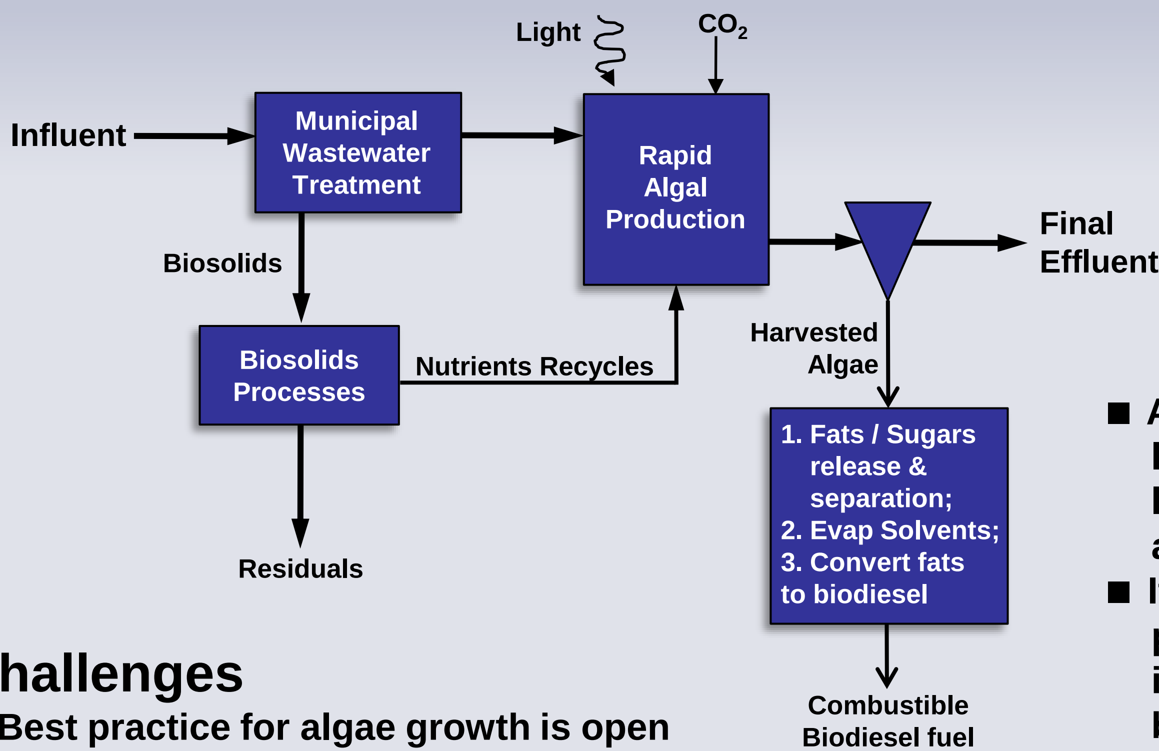
ENERGY RECOVERY:
What about MFCs?





Source: Karrat, V., et al (2009)

ENERGY RECOVERY:
What about Algal Biofuels?



Fuel	Energy Density, MJ/L
Ethanol	19.6
Butanol	29.2
Gasoline	32.0
Diesel	38.6
Biodiesel	33-36

- Algal biofuel feedstocks require less land and can be grown on marginal land and water bodies not suitable for agriculture
- If 100% of the US diesel demand were provided by algae-produced biodiesel, it would consume between 0.3 and 40 billion gallons/day…total municipal wastewater in US exceeds 40 billion gallons/day
- Does not contribute to carbon debt
- Removes nutrients
- 30 times more energy per acre than land crops

Challenges

- Best practice for algae growth is open ponds about 0.5 m deep…massive land req't
- Rotifer grazing reduces production potential
- Culturing *Chlorella* is not cost effective ($10M/ha)
- Oil extraction processes remain expensive
- High rate wastewater systems are often carbon-limited

Algae: C:N:P = 50:8:1
WW: C:N:P = 20:8:1

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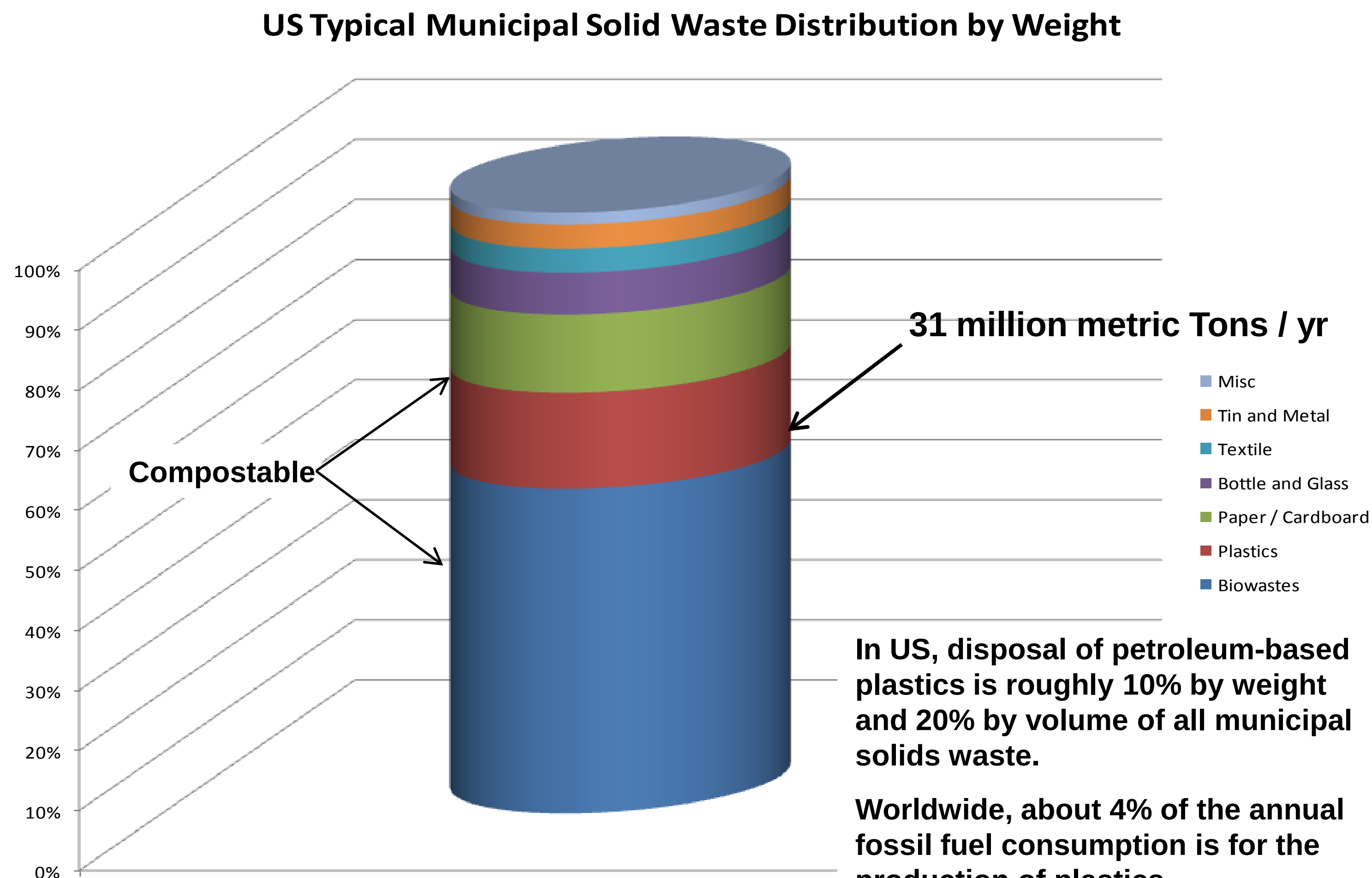
Source: Schideman, L.; Agriculture & Biological Engineering, U. of Illinois; Bioenergy Seminar (2010)
Lundquist, T.; CalPoly State U.

END PRODUCTS:
What about “Bioplastics”?



In US, disposal of petroleum-based plastics is roughly 10% by weight and 20% by volume of all municipal solids waste.

Worldwide, about 4% of the annual fossil fuel consumption is for the production of plastics.

Source: Narayan, R. (2006)
Morgan, F., et al. (2008)
Liu, H.Y. (2008)

END PRODUCTS:
What about "Bioplastics"?

- Bioplastics can be produced from many microorganisms from renewable raw materials
- Bioplastics have similar properties as fossil fuel plastics
- Bioplastics are formed from PHAs, which are natural polyesters synthesized as discrete intracellular granules which can reach 90% of the dry cell weight
- Currently, about 300 species have been identified to be capable of PHA production
- Primary substrate is VFA (fermentation products)
- PHA yield varies from 0.1 - 0.2 g PHA / g COD influent
- Raw PHA bioplastics markets for about $7 per pound

Source: Morgan, F., et al. (2008)
Liu, H.Y. (2008)
USEPA Grant – National Center for Environmental Research, (2008)

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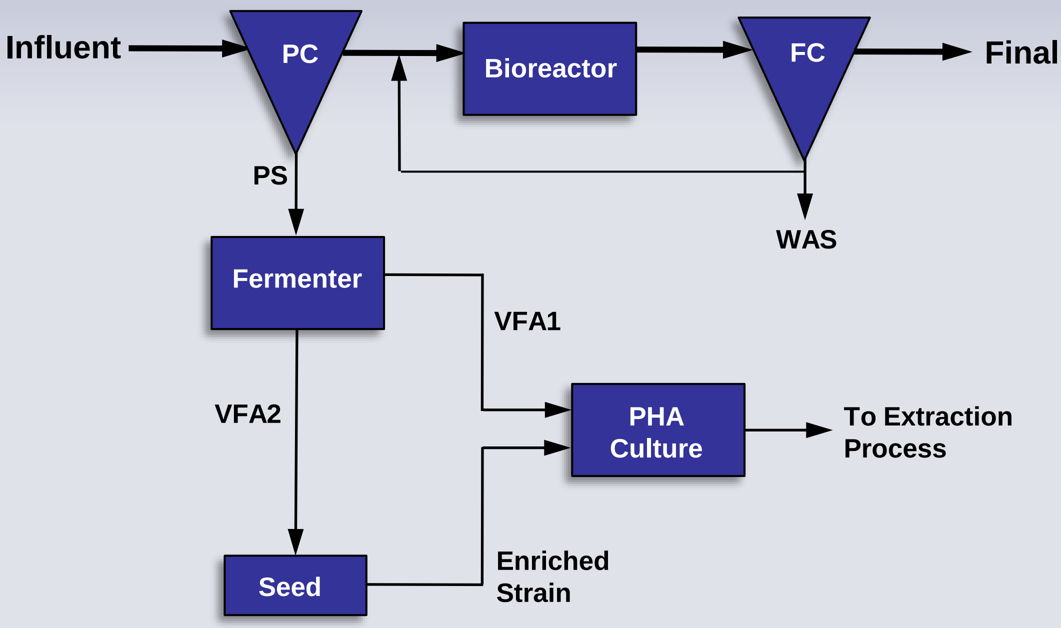
What about "Bioplastics"?



- Biodegradable and used for packaging and waste bags
- Europe seeing bioplastics accounting for about 60% of biodegradable materials market
- Starch-based bioplastics currently account for 50% of the bioplastics market

Barriers to production:

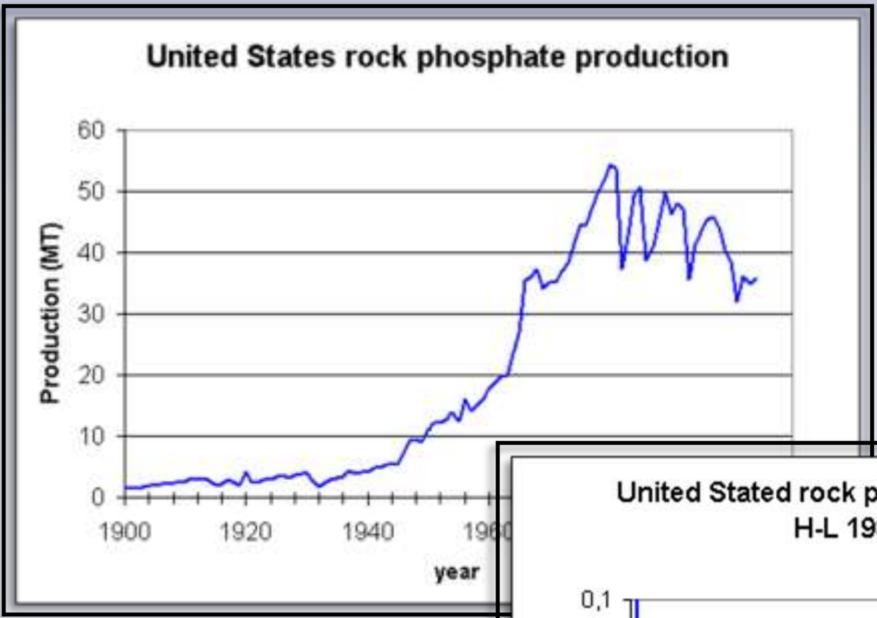
- commercial production remains very expensive
  - substrate is synthesized from corn or soy oil
  - ½ of cost associated with substrate synthesis
  - pure cultures still used
  - 30%-40% of cost associated maintaining reactor environment
  - PHA extraction technology still needs to mature

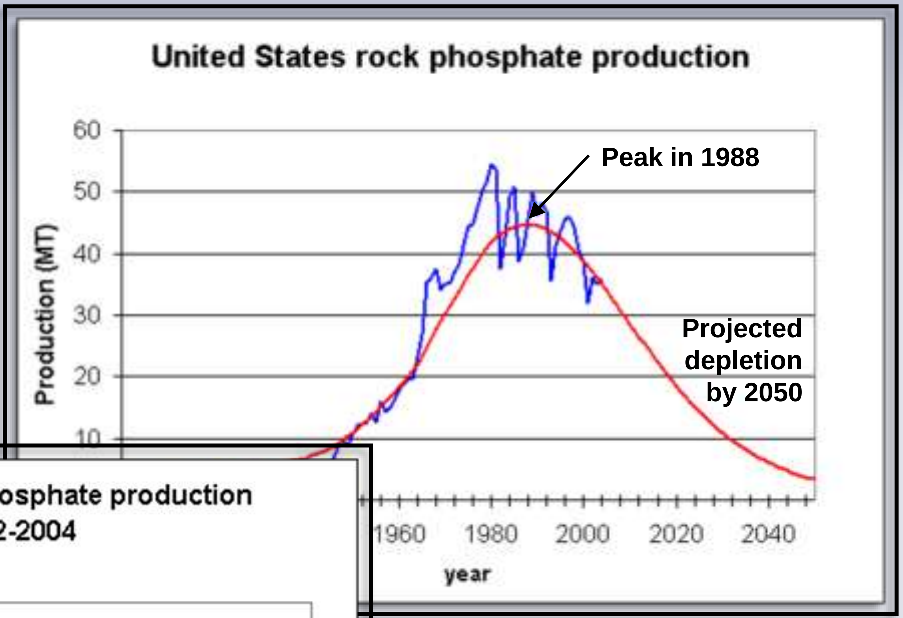
Barriers to Overcome for Use in Wastewater:

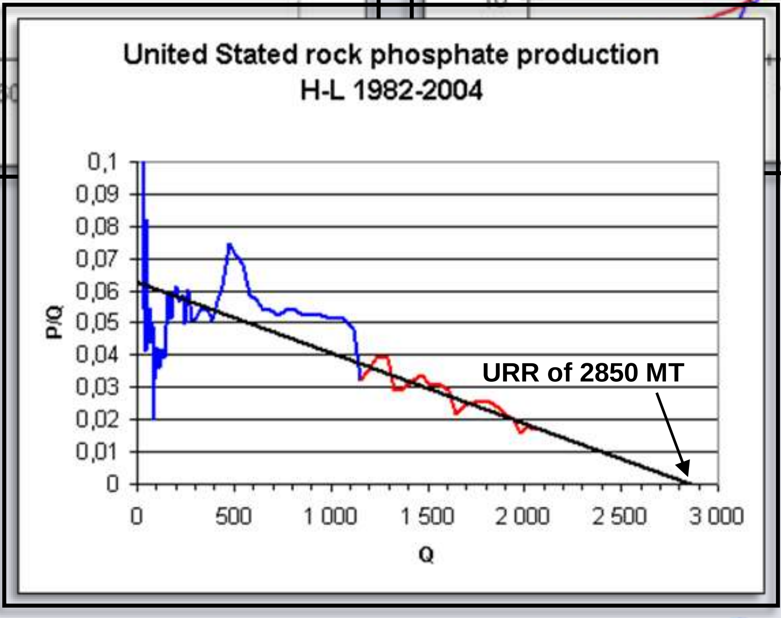
- expand spectrum of substrates
- production capacity of the microbe consortia
- broaden the range of operational conditions
- bioplastic-specific PHA is mixed with other protein in cell

Source: USEPA Grant – National Center for Environmental Research, (2008)
Liu, H.Y. (2008)

NUTRIENT RECOVERY:
What about phosphate?







Trouble begins not when a resource is depleted, but when the production peaks. Beyond that, the resource is more difficult to extract and more expensive.

Feeding the world's increasing population accelerates the rate phosphate reserve depletion.

Phosphate limits the ultimate size of the world's population.

Source: Energy Bulletin (August 2007)

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NUTRIENT RECOVERY:
What about phosphate?

- Historical population growth was possible because phosphorus deposits have been cheap along with cheap energy to extract, transform and transport it.
- Even with full substitution for fossil fuels, population growth will be impossible to maintain as phosphorus deposits decline.
- Agriculture will be impossible to maintain without recycling of nutrients.
- Unlike fossil fuels, phosphorus can be recycled.

What about source separation for nutrient recycling?

Urine contributes about 50% of the phosphorus and 80% of the nitrogen in domestic wastewater.

Source: Energy Bulletin (August 2007)
Larsen, T., et al., WS&T (2009)

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NUTRIENT RECOVERY:
What about source separation?

- Wastewater without urine is more biologically balanced in its C:N:P ratio for more efficient COD removal treatment
- Urine contains 60%-70% of the micro-pollutants in municipal wastewater
- Removing nitrogen from the urine at the source is much more energy efficient than at the WWTP, but recovering nitrogen from urine at the source is difficult
- Source separation still more cost-competitive when urine is treated on-site; collection and transport requires a pipe system to treatment facility
- For urine separation, breakeven comparison against conventional technology occurs at an investment of $260 - $440 / household
- A family of 4 saves at least 80 L/day in flush water

Question: Is urine collection and conversion to fertilizers an appropriate long term goal?

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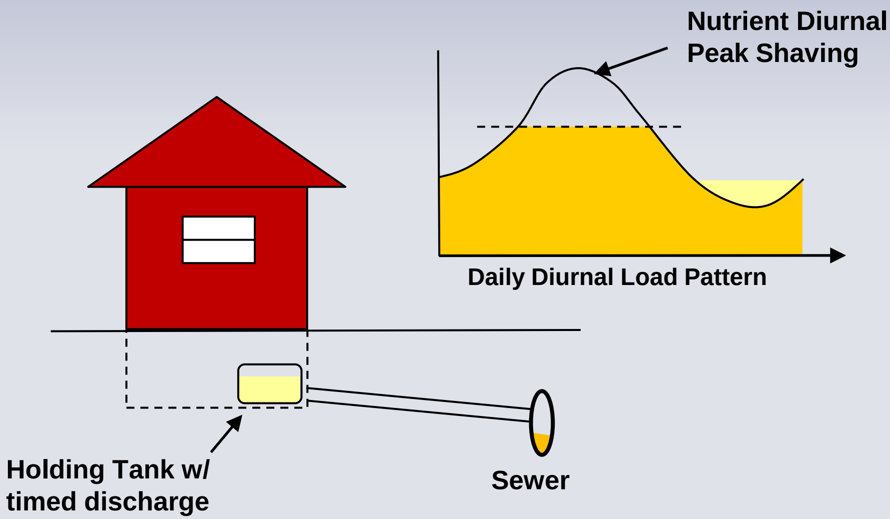
Source: Larsen, T., et al., WS&T (2009)
Leinert, J., Larsen, T., WS&T (2006)

NUTRIENT RECOVERY:
What about source separation?



NoMix Toilet

Some Challenges:

- Populous endorses concepts, but see convenience as more important
- Farmers endorse use of urine-based fertilizers if cost are not more than conventional fertilizers, and there are no risks to human health
- Technologies still seen as immature and risky by most wastewater professionals
- Technology still considered as "low tech"; limited resources are allocated to its development; thus no market
- To be widely accepted, bathroom comfort must be as it is today
- For developed countries, the transport of separated urine does not align with current, established infrastructure
- On-site Phosphate recovery technology remains difficult and expensive

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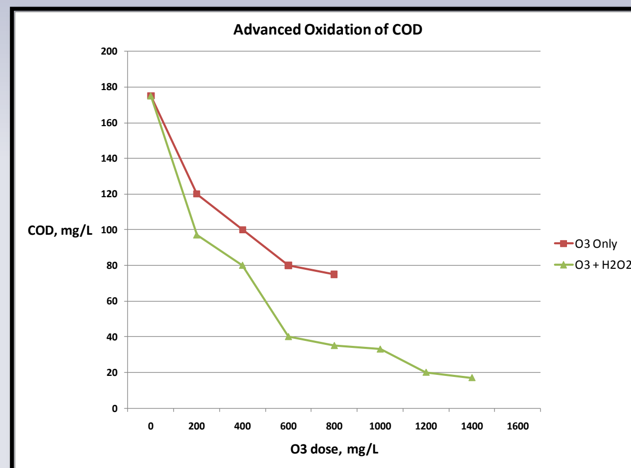
Source: Borsuk, M.E., et al., ES&T (2008)
Larsen, T., et al., WS&T (2009)

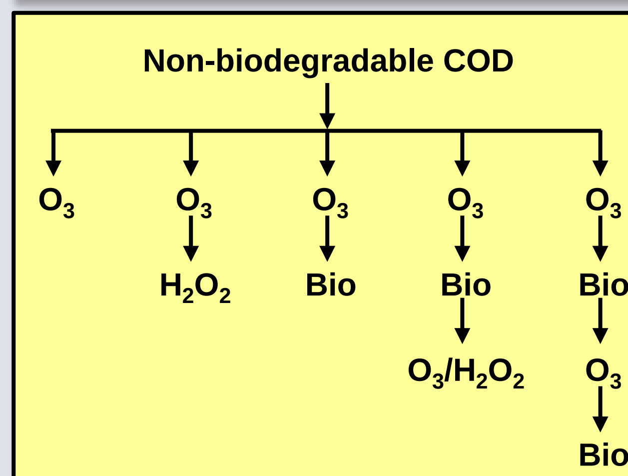
WATER REUSE:
What about Effluent Quality?

- As a general rule, oxidizing COD close to drinking water standards is possible, but economics (amount of oxidant required) limits the practical use of advanced oxidation techniques
- Implementation of a second biological step after the advanced oxidation step shows promise
- The most common practices today are
- O_3/H_2O_2, UV/H_2O_2, O_3/UV and TiO_2/UV
- For wastewater treatment, UV/H_2O_2 and Fenton's Reactions are gaining favor
- AOP O&M costs about $2000/MG treated



Challenges:

- High Energy and chemical costs
- Multiple pathways for Hydroxyl radical scavenging in wastewater
- H_2O_2 has poor absorbance of UV light
- Certain categories of toxic compounds resist attack from hydroxyl radicals



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Source: Reid, A., Kampmann. N., Wasser Berlin (2006)
Stasinakis, A.S., Global NEST Journal (2008)

RESOURCE RECOVERY:

What are some obstacles?

- Public understanding and resulting perceptions
- Technical community's lack of understanding
- Public and Private financing capacity
- Inertia for conservative design across industry
- Lack of regulatory vision at all levels
- Focused on efficiencies rather than innovation
- Barriers between the objectives of the water and wastewater professionals
- Lack of promotional incentives for change

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RESOURCE RECOVERY:

What are the knowledge gaps?

- Quality and value of the energy components present in wastewater
- Proper sequencing of technologies
- Scaling up of emerging technologies
- Data collection and establishing neuro-networks
- Broader innovations for reuse of wastes
- Centralized versus decentralized treatment
- Process models for anaerobic processes
- Genetically engineered metabolics for anaerobes
- Societal and environmental criteria for technology

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CONCLUSIONS

- Resource recovery must be viewed within the context of the entire "water environment" system
- We must see energy facts and issues pragmatically
- Resource recovery is first about conservation; second about innovative technology
- Resource recovery has numerous promising elements but economics still holds the bottom line
- Technical obstacles are few; it's the public's understanding and perceptions that hold the keys
- We must defeat our own inertias for conservatism and aversion to risk

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