ENERGY RECOVERY FROM WASTE WATER

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March 1, 2010

ARPA-E Pre-Summit Workshop

Why Energy from Wastewater Technologies?

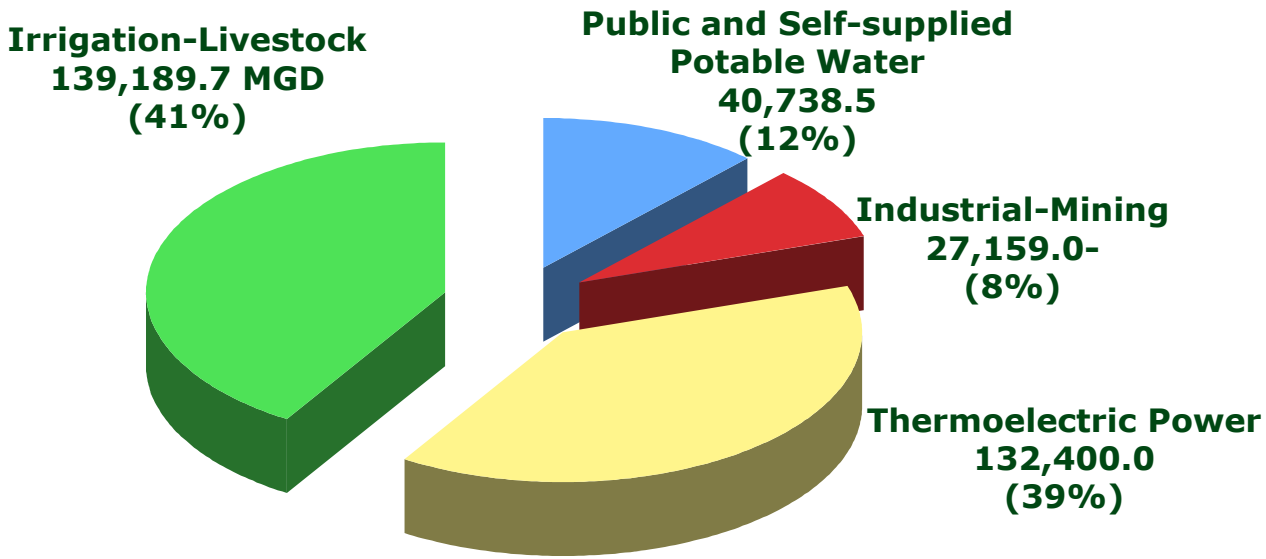
Workshop Structure and Approach

Workshop Keynote and Breakout Session Highlights

Workshop Takeaways

UNITED STATES WATER USAGE

Water Withdrawn in the US for All Uses

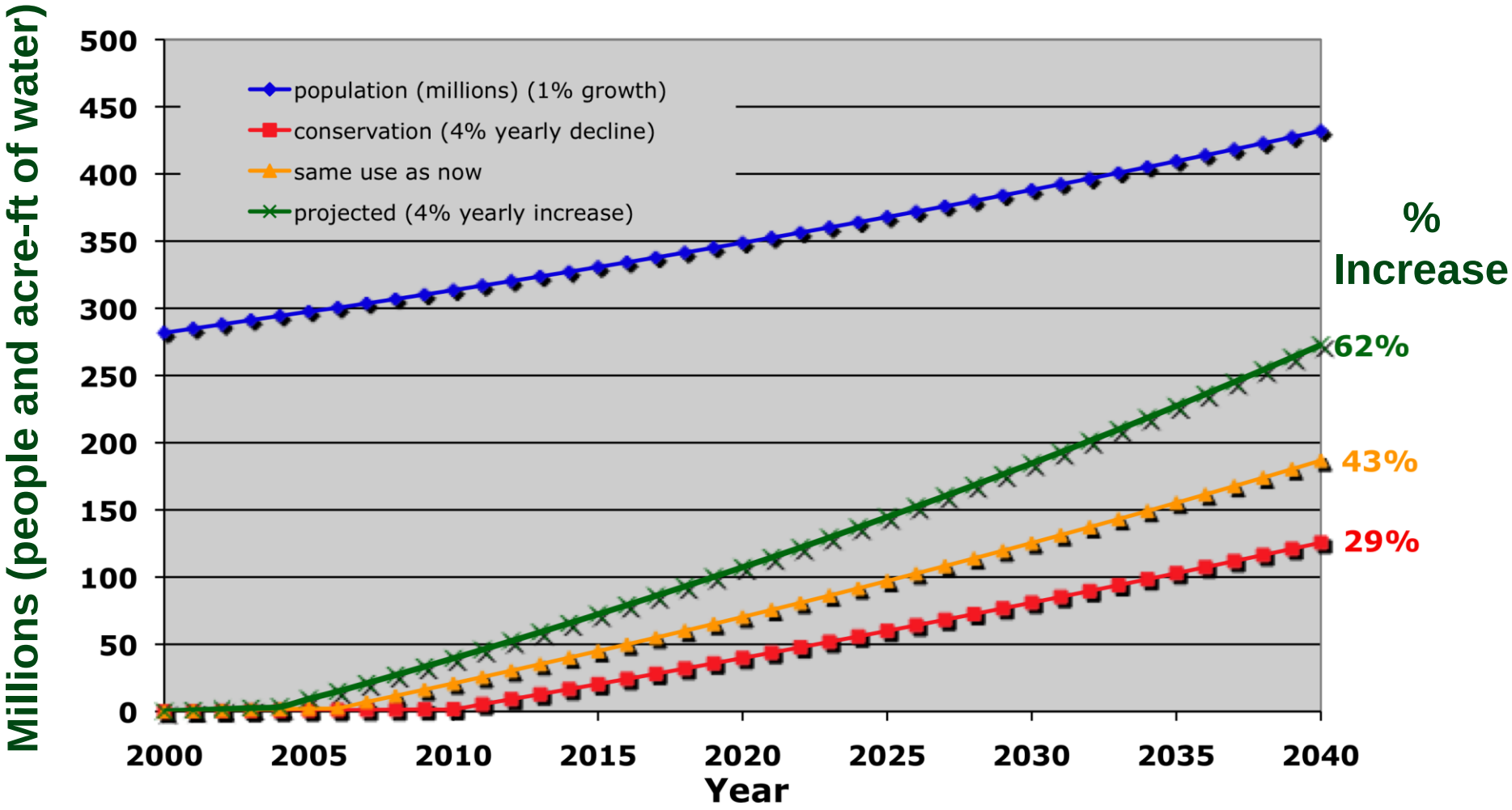


"Consumptive Water Use for U.S. Power Production,
P. Torcellini, et.al., National Renewable Energy Laboratory, 2003.

Costs directly related to withdrawals: Source matters

- **Total water withdrawn per year 123.9 trillion gallons, which is ~ yearly outflow of Mississippi river**

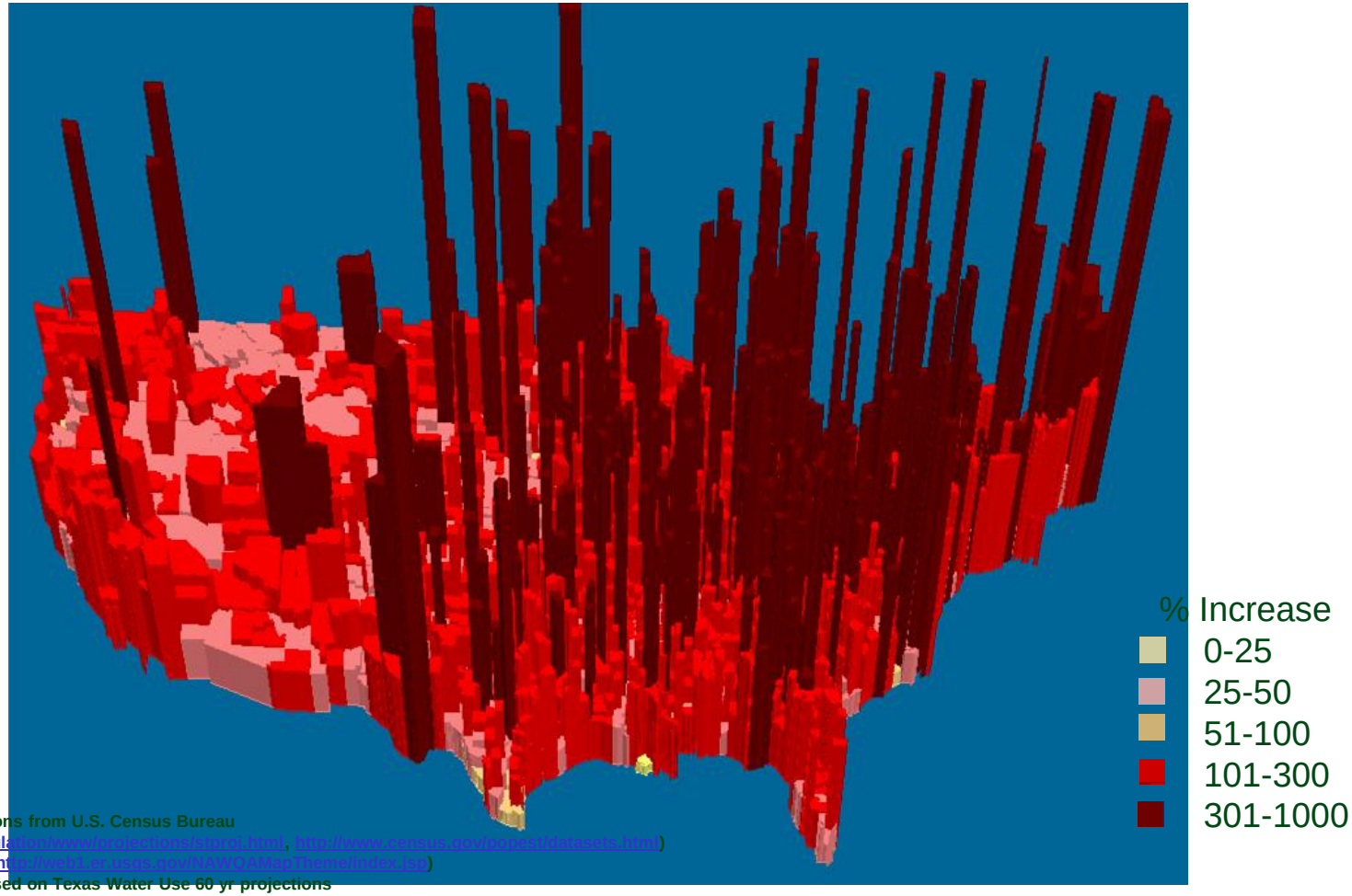
INCREASE IN WATER DEMAND WITH POPULATION GROWTH



Population Data form US Census Bureau

The Blueprint 2030 forecast share of the revised United States population growth forecast from 2000 to 2030 was 1.14%

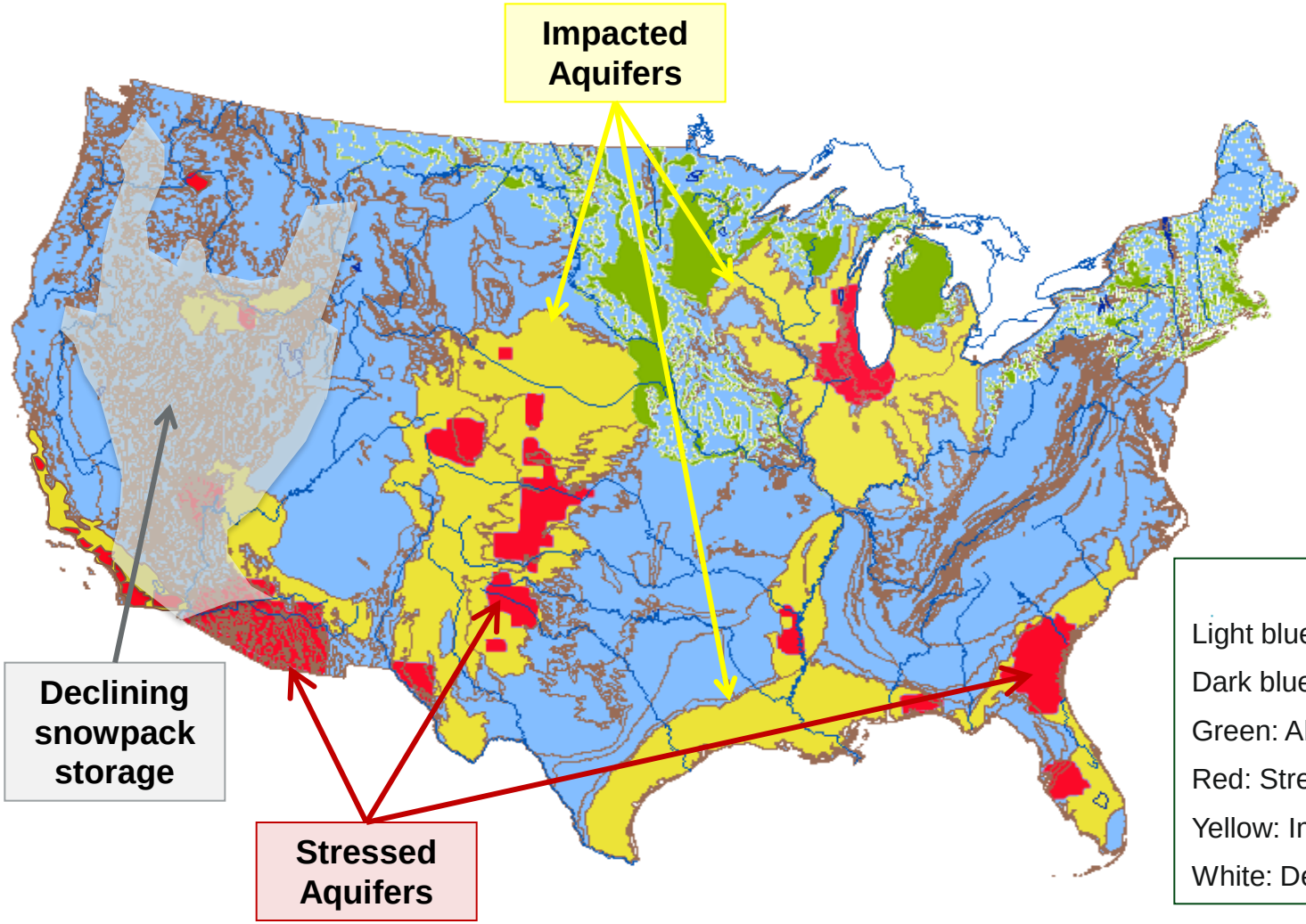
2030 PROJECTED % INCREASE (SINCE 2000)



Population data and projections from U.S. Census Bureau (http://www.census.gov/population/www/projections/stcrosi.html, http://www.census.gov/popest/datasets.html)
Water Use Data from USGS (http://water1.er.usgs.gov/NAWQAMapTheme/index.jsp)
Projections for water use based on Texas Water Use 60 yr projections (http://www.twdb.state.tx.us/publications/reports/State_Water_Plan/2007/2007StateWaterPlan/2007StateWaterPlan.htm)

Averages don't tell the real story: Growth & *supply* problems will be local.

DEPLETION OF GROUNDWATER & LOSS OF ICE-SNOWPACK STORAGE



KEY:

Light blue: Standard aquifers

Dark blue: Rivers and lakes

Green: Aluvial and glacial aquifers

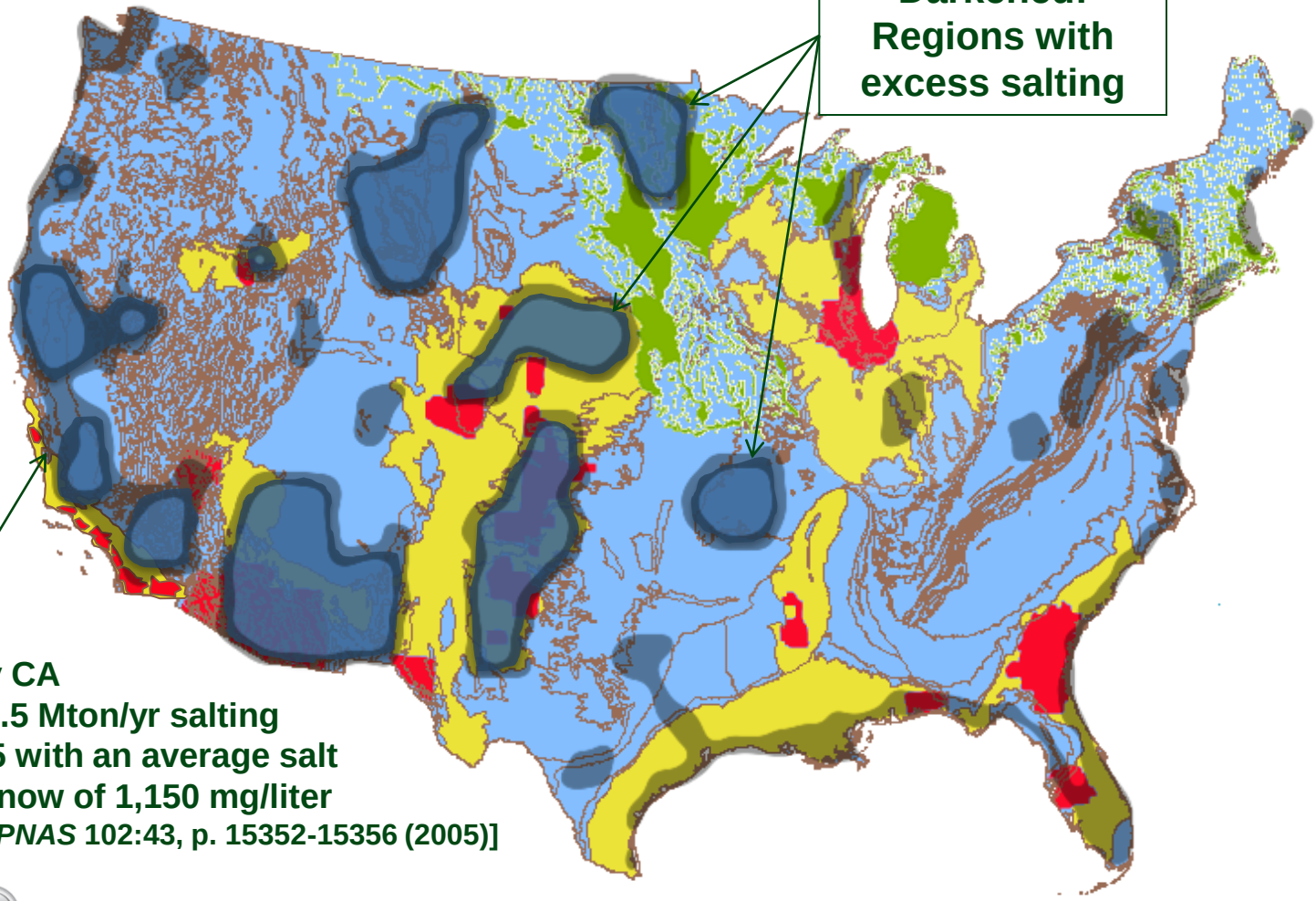
Red: Stressed aquifers

Yellow: Impacted aquifers

White: Declining snowpack storage

U.S. Department of the Interior: (http://www.nationalatlas.gov)
WaterCAMPWS: (http://www.watercampws.org)

SALTING FROM SEAWATER INTRUSION, AGRICULTURAL PRACTICES, INDUSTRY, & WATER TREATMENT



Fresno County CA experiencing 0.5 Mton/yr salting rate since 1945 with an average salt concentration now of 1,150 mg/liter

[Schoups *et al.*, *PNAS* 102:43, p. 15352-15356 (2005)]

WILL HAVE TO SUPPLY MAJOR NEW WATER SOURCES

- Conservation alone cannot meet demand…not even rationing by 50% or more (at most a 2x increase).
- Need something that can increase effective supplies by many factors (3x, 4x, up to 10x)
- But it will take a huge amount of energy to supply new waters – old water sources nearly free << $50/acre-ft – new sources well over $500.
- Energy is embedded throughtout water cycle

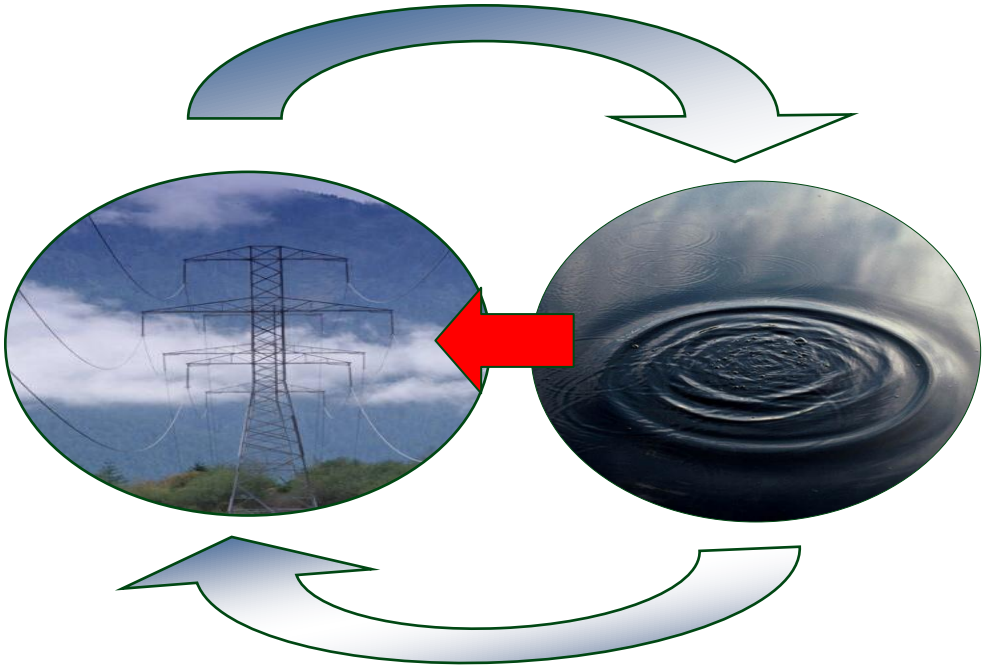
ENERGY AND WATER ARE INTERDEPENDENT

Energy and power production require water:

- Thermoelectric cooling
- Hydropower
- Energy minerals extraction/ mining
- Fuel Production (fossil fuels, H_2, biofuels)
- Emission control

Water production, processing, distribution, & end-use require energy

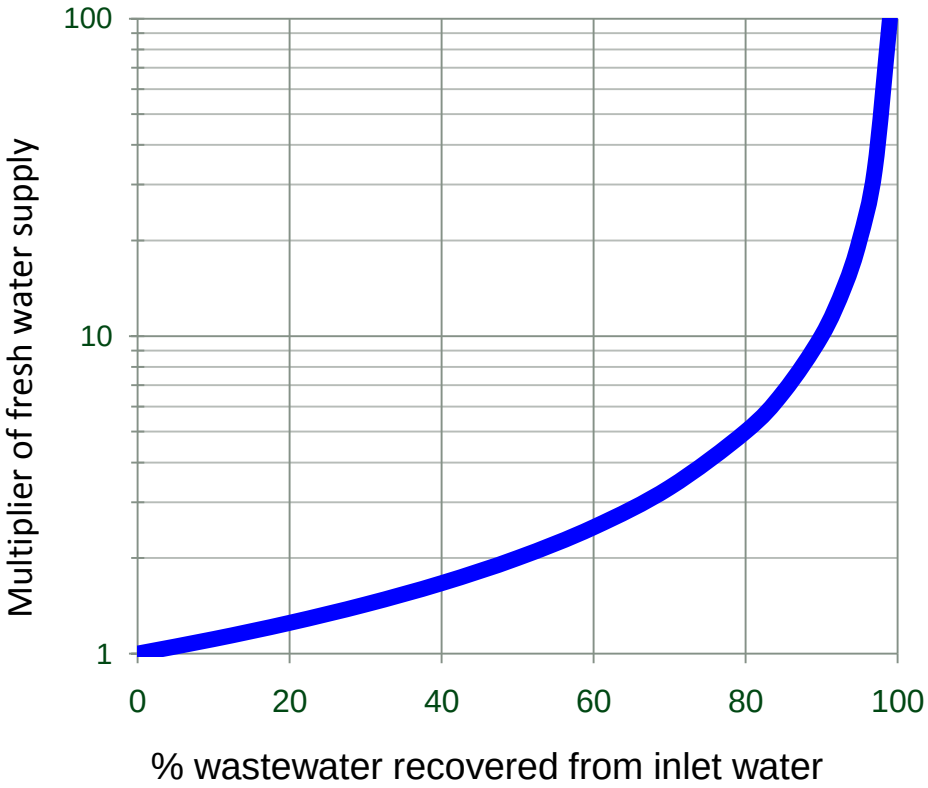
- Pumping
- Conveyance and Transport
- Treatment
- Use conditioning
- Surface and Ground water



Dr. Michael Hightower, Sandia National Labs, 2010

A MAJOR SOLUTION FOR WATER: REUSE

- ~80 to 90% of industrial & domestic use can be reclaimed.
- Reuse can effectively increase supplies by an order of magnitude.
- Reclaimed water currently costs near desalinated water.



- Can recharge ground water (as in Orange county & coming to San Diego).
- Challenge: How can reuse be made cost effective?

HOW TO MAKE IT AFFORDABLE: EXTRACT ENERGY

- U.S. municiple wastewater contains 7.2×10^9 kg of "dry solids" annually.
  - ~ 25 MJ/kg (7 kW.hr/kg) of energy content
  - Total energy available ~2×10^{17} J (51 billion kW.hr).
- Currently, most municipalities do not generate energy from biosolids:
  - 49% treated & applied to land, 45% incinerated or landfilled, 6% to other
- U.S. 2008/2009 electrically generated: 14×10^{18} J

Energy content in wastewater is ~2% of US electrical demand

New energy demands to supply new water: Up to 20% of electrical usage of total U.S. if western states model followed.

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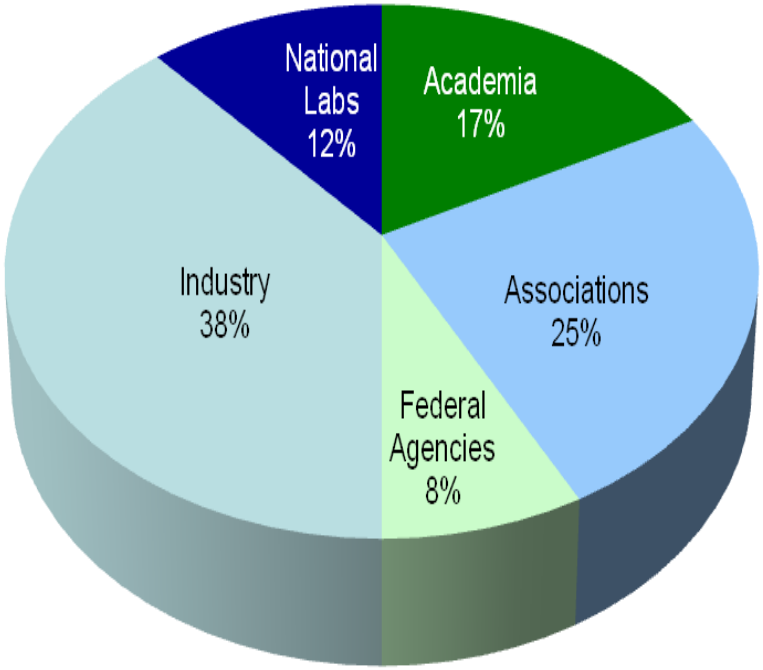
ARPA-E GATHERED INPUT FROM LEADING TECHNICAL EXPERTS AND CUSTOMERS IN WASTEWATER ENERGY TECHNOLOGIES

- **Purpose: Allow DOE to gather input about the most promising R&D pathways to radically improve simultaneous net energy extraction and clean water from wastewater.**
- **Topical areas discussed:**
  - Emerging methods of *generating clean water* and associated science and technology challenges.
  - Emerging methods of *extracting energy from wastewater* and associated science and technology challenges.
  - Quality and costs needed for clean usuable water
  - Barriers (Infrastructure, codes, permits, etc) and incentives needed
  - Metrics and outcomes needed for pilot demonstrations
  - Barriers to adoption and technology transition strategies

ARPA-E SOLICITED EXPERT PERSPECTIVES FROM ACADEMIA, FEDERAL AGENCIES, NATIONAL LABS AND INDUSTRY

Breakdown of 52 Attendees by Affiliation



Representative Attendees

	Dr. James E. Smith US EPA National Risk Management Research Laboratory	Senior Environmental Engineer for the EPA and pathogen expert
	Dr. Mohamed Dahab University of Nebraska-Lincoln	Professor and Chair, Environmental Engineering
	William Horak Brookhaven National Laboratory	Chair of Energy Sciences & Technology (ES&T) Department
	Joe Zuback Global Water Advisors	President and Founder. Water treatment expert (municipal, industrial, commercial, residential)
	Dr. Cat Shrier Watercat Consulting	Water Resources Planning & Policy Services

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BECAUSE OF ENERGY AND WATER INTERDEPENDENCY AND GROWING WATER DEMAND, ADVANCED WATER TECHNOLOGIES WILL BE CRITICAL

Dr. Michael Hightower,
Sandia National Laboratories

Embedded Energy for Water Supply Alternatives

- Emerging consideration of wastewater for energy production
  - Many municipal and industrial processes have large waste water streams
  - Embedded nutrients, embedded energy, and available utilization of byproducts such as biomass, heat, CO_2
- Substantial growth in the use of non-traditional water resources
- Water reuse analysis shows energy savings over other water options (desalination or fresh water import)

ENERGY FROM WASTEWATER CAN MEET A SIGNIFICANT PART OF THE NATIONAL DEMAND FOR ELECTRICITY

Lauren Fillmore
Water Environment Research Foundation

State of the Science Energy Conservation and Recovery from Wastewater

- 3% of electricity is water and wastewater conveyance and treatment and growing
- Energy in wastewater is 10X the energy needed for treatment
- The best wastewater treatment facilities already produce more energy than needed for treatment, but are outside of the US and water quality is not fully reusable
- Achieved through highly educated workforce, high level of automation, and maximizing energy recovery AND efficiency/conservation

EFFICIENCY IMPROVEMENTS & TREATMENT MECHANISMS REQUIRED FOR CLEAN WATER TECHNOLOGY DEVELOPMENT

Clean Water from Wastewater– Groups 1 and 2

Chairpersons: Jim Smith, US EPA NRML; Benito Marinas, Univ of Illinois

Key Barriers	**Energy intensity high** – Aeration, heating, transport **Output water quality low** – Pathogens, toxic compounds, disinfection byproducts **Scalability** – Microbial systems (including fuel cells), centralized vs. decentralized
Breakthrough Technologies	**Advanced membranes, catalysts, adsorbents** – Need anti-fouling, high flux **Microbes** – Fuel cells, superspecies evolution **Novel Hybrid Systems** – Combined anaerobic and aerobic systems **Disinfection** – Wave energy, photocatalysts

WATER AND ENERGY QUALITY AND AVAILABILITY SHOULD SHAPE TECHNOLOGY DEVELOPMENT STRATEGY

Energy and Clean Water from Wastewater – Groups 1 and 2

Chairpersons: Eugene Giraldo, American Water; Sudhir Murthy, DC WASA

Key Barriers	**Risk mitigation** – Respiratory pathogens, algae and algae related toxins **Conveyance** – Non-water methods to convey waste, true life cycle cost **Utility Management** – Integrate planning & operations, interconnection **Energy Loss** – Pipes, treatment processes, extraction techniques
Breakthrough Steps	**Breakthrough approaches** – Systems level implementation with full cycle sustainability **Demonstration and Pilot Programs** – Integrated approach of entire system

THE GOAL SHOULD BE FOR A NET POSITIVE ENERGY SYSTEM, BUT MANY DEVELOPMENTS WILL BE REQUIRED

Net Energy from Wastewater, S&T Needed and Metrics – Groups 1 and 2

Chairpersons: Mohamed Dahab, Univ of Nebraska; William Horak, BNL

Key Barriers	**Concentration –** Low concentration of COD in wastewater **"Clean Water" –** Definition is a moving target **Quality of Wastewater** - infiltration and inflow, leakage
Breakthrough Technologies	**Cogeneration** – Use wastewater and other organics delivered to site **Algae Farms** – Phosphorus and Nitrogen extraction **Granular Bioflocs** – Easier to separate

CENTRALIZED AND DECENTRALIZED STRATEGIES WILL BOTH BE NECESSARY, AND ADEQUATE TESTS FACILITIES ARE NEEDED

Translation into Practice – Groups 1 and 2

Chairpersons: Cat Shrier, Watercat Consulting; Joe Zuback, Global Water Advisors

Key Barriers	**Strategy** – No established goals for cost and performance metrics **Scalability** – Lab concepts to full systems **Implementation -** novel techs into established, older infrastructure
Breakthrough Steps	**Decentralization –** Connect to electrical grid, & transport of energy **Test Sites** – Use lessons from other federal approaches and create places for independent assessments

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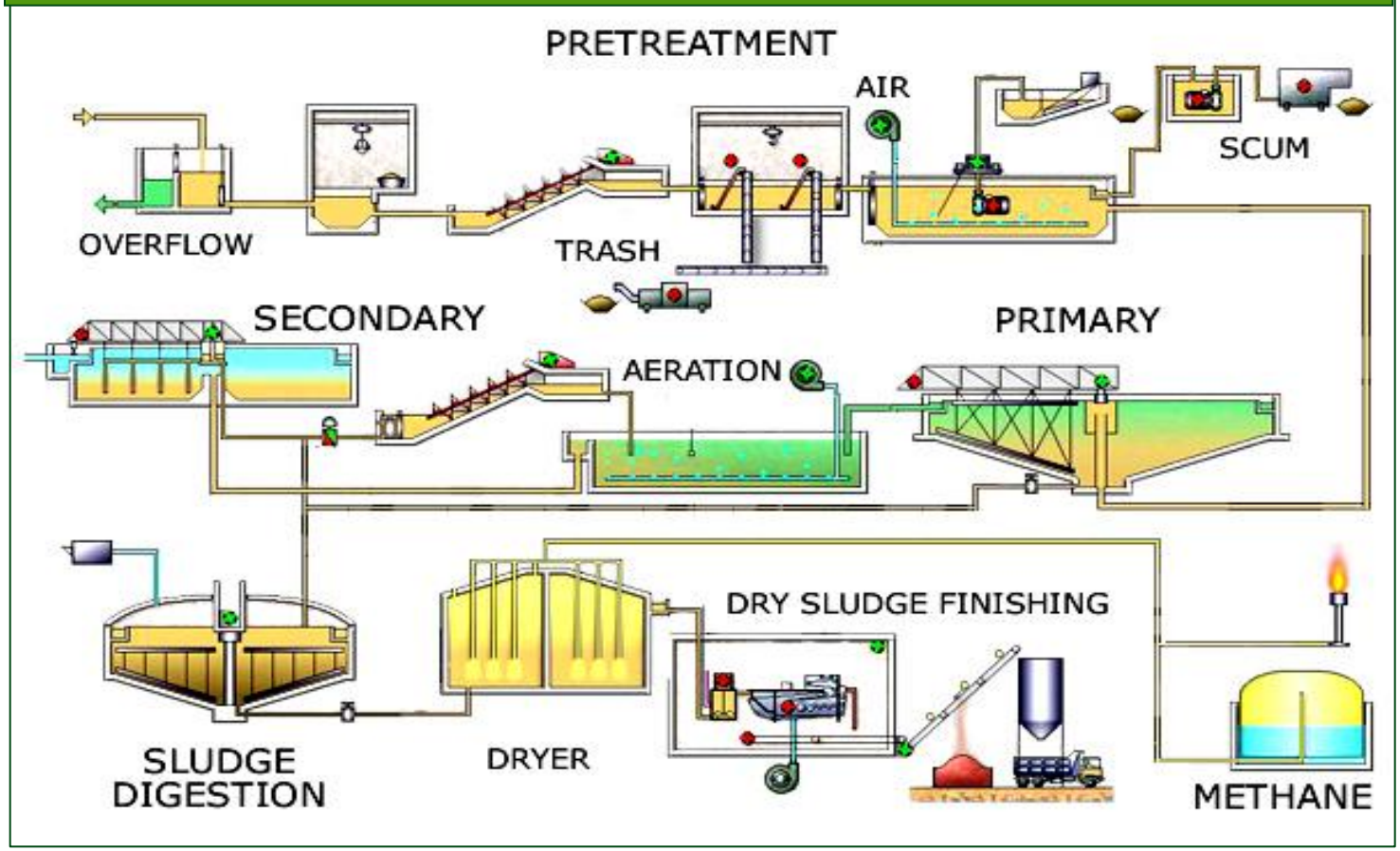
CURRENT TREATMENT METHOD

Energy and water recovery in an secondary treatment plant



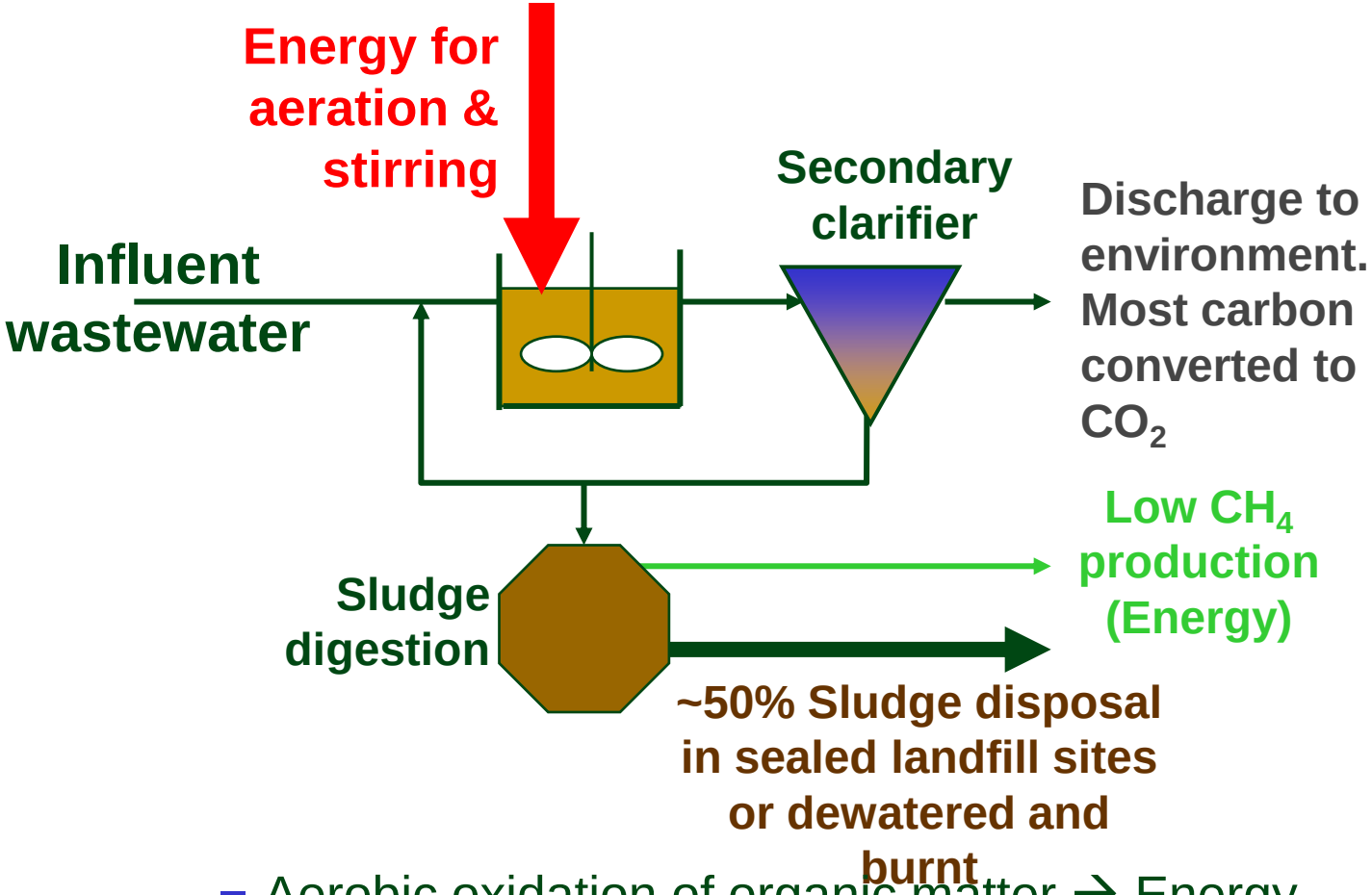
Many points of energy inputs and losses.

CURRENT METHODS TO EXTRACT ENERGY

- Anaerobic digestion: Out of 16,000 municipal wastewater treatment plants in the U.S, 3500 large plants employ anaerobic digestion to produce ~60% methane biogas.
- Biogass heat used to complete the digestion process.
- Only 2% produce electricity using scrubbed gas of hydrogen sulfide, CO_2 and H_2O.
- Methane concentration can reach 95%, but not without additional strengthening (energy input).

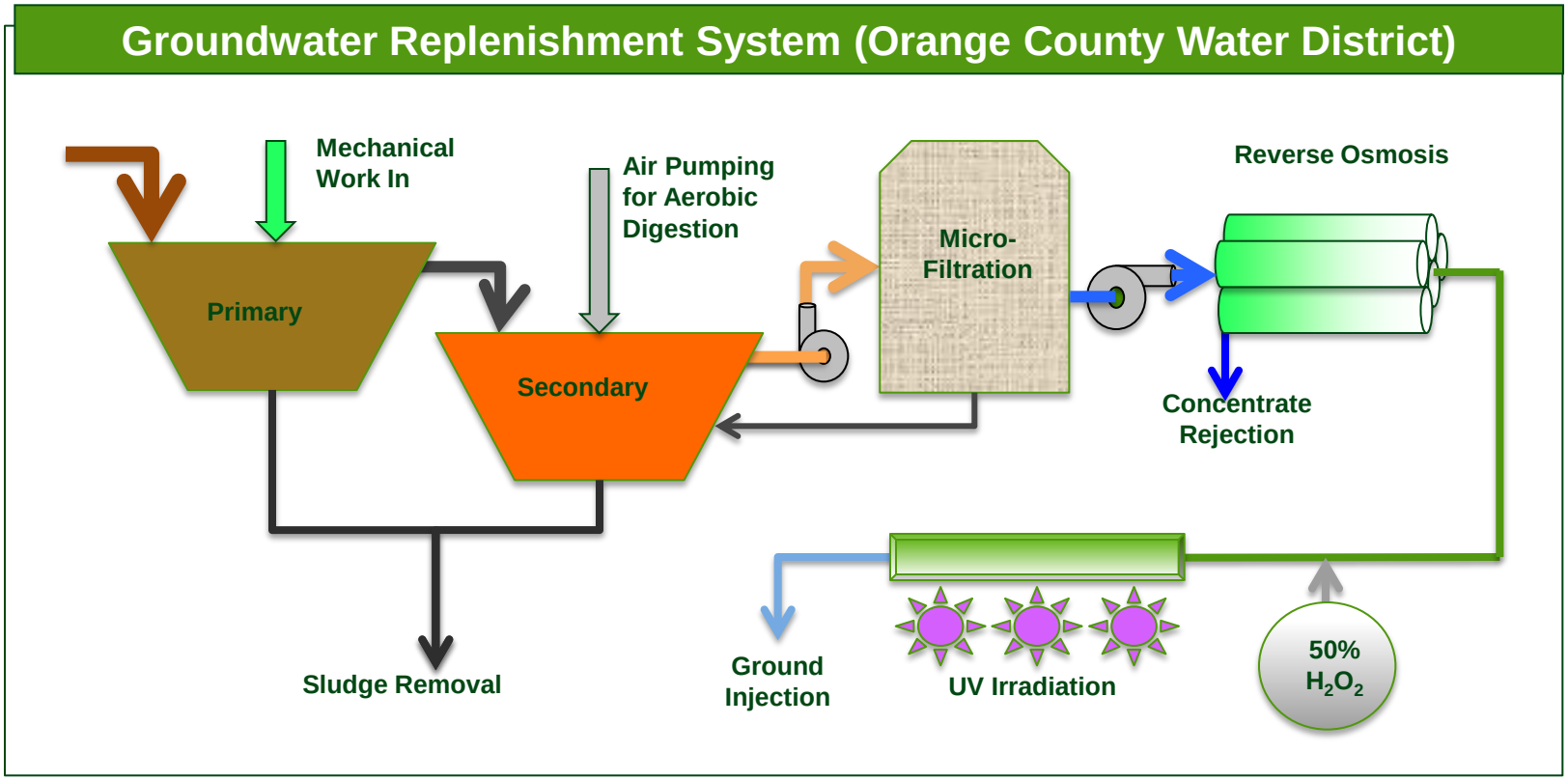
Reciprocating engine fueled with digester gas at work in Washington State (Federal Energy Management Program)

Aerobic Digestion



- Aerobic oxidation of organic matter → Energy demand higher than can be recovered
- Sludge reduced by ~40 to 50% → Rest disposed

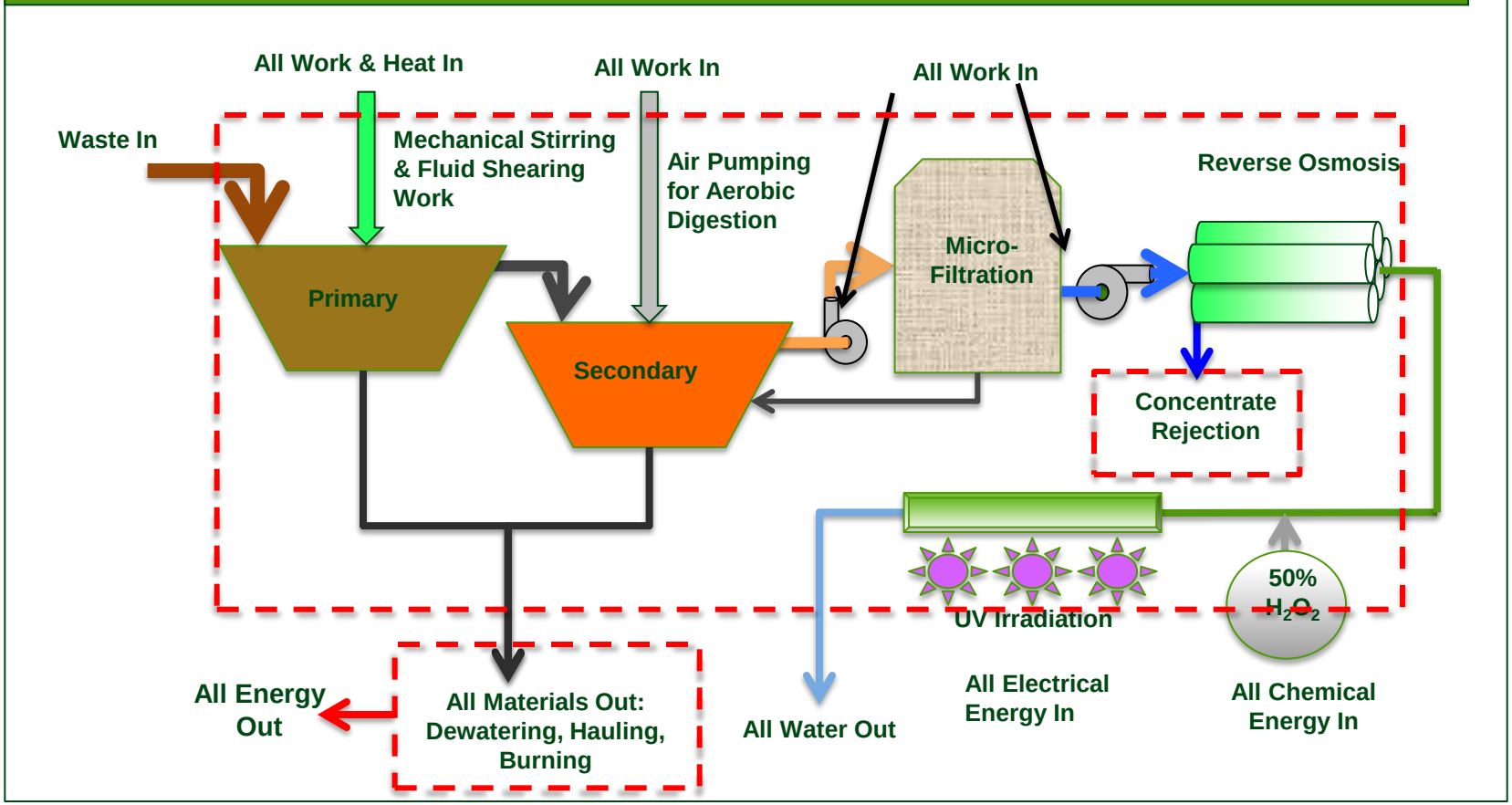
STATE-OF-ART WATER REUSE METHOD



- Influent water subject to primary and secondary treatment
- Effluent from treatment then purified using energy intense, state-of-the-art treatment processes before injection into the ground.

ACHIEVING NET ENERGY & CLEAN WATER OUTPUT

Control Volume for Energy Balance Considerations



Balancing all inputs & outputs from source water to output is challenging!

NEED TOTAL LIFE CYCLE ANALYSIS TO DETERMINE SUSTAINABILITY

- **Account for all energy inputs and outputs:**
  - Chemical, thermal, mechanical, electrical
  - Input and output streams, discharge stream, sludge out
  - Must even include chemicals, nutrients, etc. (ozone, chlorine, ammonia, HCl, NaOH, nutrients).
- **Account for all change in greenhouse gases:**
  - Organics remaining in sludge discharged
  - Savings from converting to usable net energy
  - Chemicals used or saved, and nutrients recovered
  - Embedded energy avoided
  - Electrical to primary energy multiplier
  - Quality of discharged water

PROBLEM WITH RECOVERING ENERGY: WATER!

- **Water content does not add to energy**
  - Need to extract energy from multiphase waste at cost per kW-hr that is competitive with other sources of energy.
- **Dewatering waste takes lots of energy**
  - Taking it all the way to dry mass takes a lot of energy (latent heat of evaporation ~2,260 kJ/kg of water content)
- **Separating out solids and volatiles energy intensive**
  - Settling: cheap, but slow and limited in performance
  - Flocculation: leaves chemical residual
  - Spinning: capital intensive
  - Vacuum stripping: energy-capital intensive
  - Evaporation: very energy intensive

MORE PROBLEMS TO OVERCOME

- Low strength (< 500 mg/liter) very hard to extract net energy
- Wastewater highly variable
- Contain clays, hard salts, sulfur compounds, etc.
- Pathogens in abundance
- Small toxic compounds pass through many processes
- Long retention times (many hours to days) typically needed

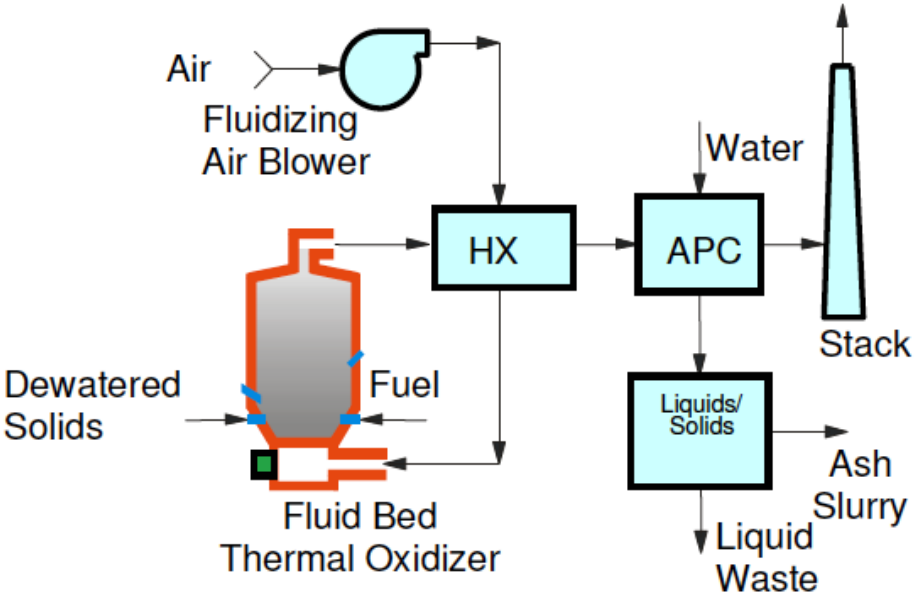
METHODS FOR ENERGY FROM WASTEWATER: THERMAL

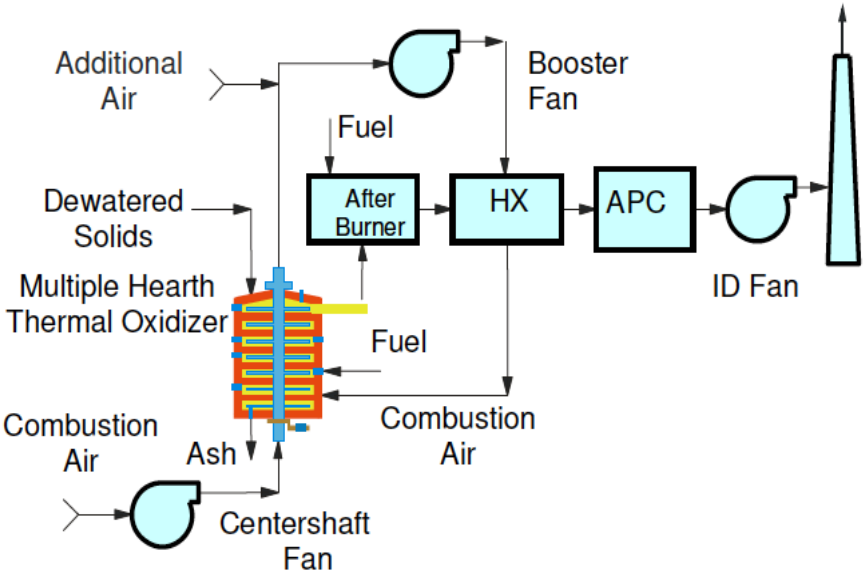
- **Direct incineration**
  - Net heat generated depends on water content, and pollution controls needed. Breakeven for dewatering >> 3 MGD
- **Pyrolysis gasification of solids**
  - Conversion of biomass solids to char (600°C) then to syngas.
  - Unclear if or where there is breakeven point.
- **Plasma processing**
  - Dewatered solids and volatiles passed through plasma arc.
  - Unproven claims of net energy generation, but everything burns, unlike other methods.

Each needs high concentration of biosolids that have been pre-separated from water…energy of separation not considered, nor water quality of effulent from separation, or volatiles

HIGH TEMPERATURE THERMAL OXIDATION

- High temperature thermal oxidation of volatiles
  - Volatiles and water needs separation, breakeven about 10,000 ppm.





Fluidized bed now dominates new installations over multiple hearth, primarily due to air pollution. Higher rate, but lower efficiency, and both leave residuals.

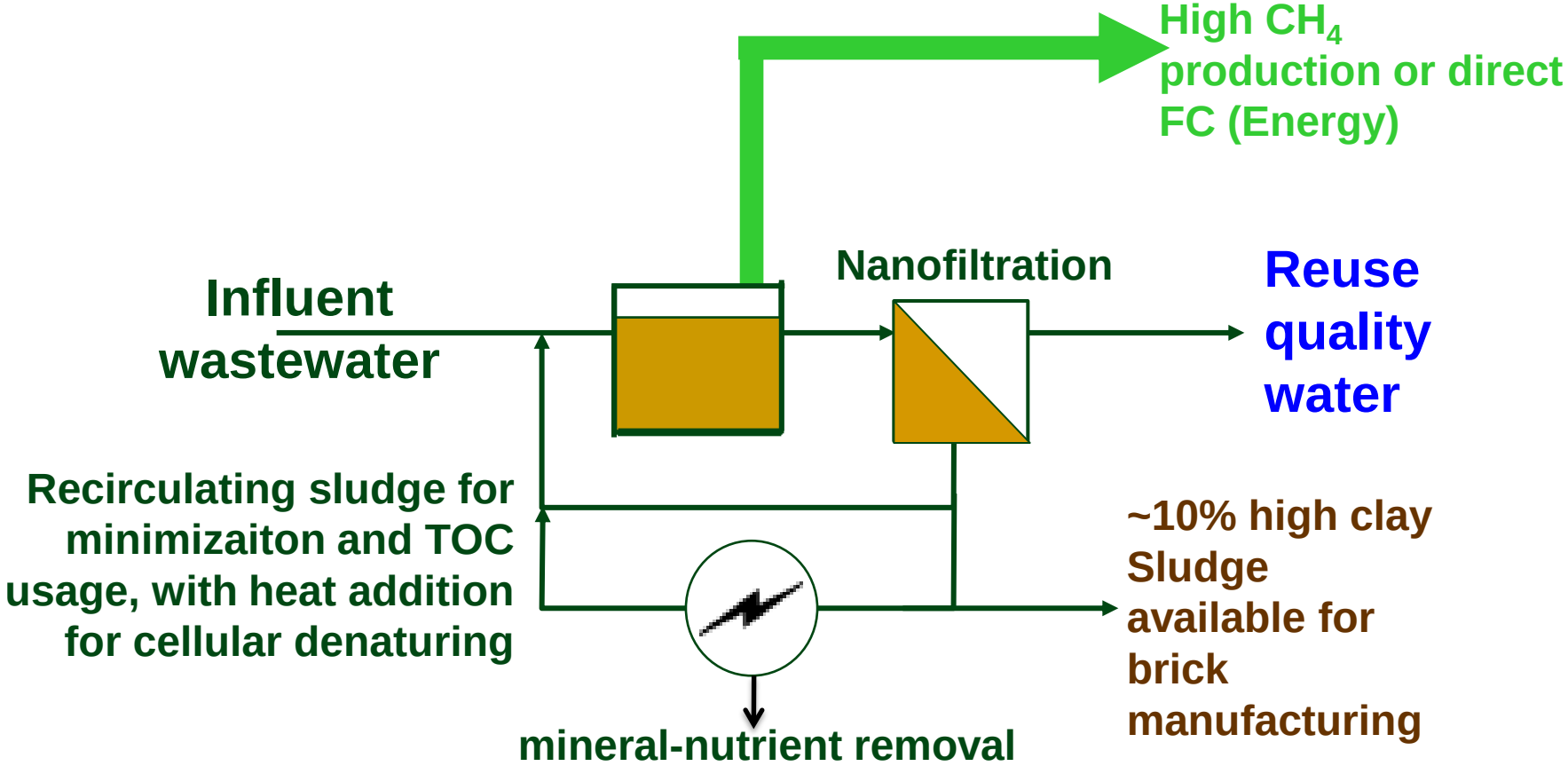
COMBINED EZEMATIC HYDROLYSIS + DIGESTION

- UK advanced high rate digestion technology.
- Maximum sludge throughput of 350m^3/d at 8% DS or 10,220 TDS per annum with an average of 285 m^3/d at 7% DS. Goddards Green operates 2 digesters nominally 1900 m^3 each, average 13 days (!) retention for peak organic loading of 4.8 kgVS/m^3.day.
- Plug flow reactor with hydrolysis reactions prior to anaerobic digestion.
- But starts with sludge and secondary treated water not clean enough.

METHODS TO EXTRACT ENERGY: COMBINED CHEMICAL/BIOLOGICAL & THERMAL METHODS

- **Chemical hydrolysis + heat**
  - Net energy output not goal of method.
- **Algae**
  - Proposed, but no known operating systems.
  - May be a great connection to co-generation and CO_2 capture and processing to liquid fuels.
- **Anaerobic digestion + heat**
  - Most common method to produce methane
  - Can be used with membrane separation in Membrane Bioreactors (MBRs), but must solve fouling
- **Enzymatic hydrolysis + heat**
  - Enzymes are expensive, need low cost synthesis technology

Anaerobic Digestion – NF MBR



- Direct anaerobic degradation of biomass → Energy production
- Nanofiltration removes pathogens/micropollutants → Water reuse

METHODS TO EXTRACT ENERGY: OTHER

- **Microbial Fuel Cells**
  - Efficiency potential: directly produce electrical energy.
  - Conversion efficiency, kinetics, and robustness are major issues.

- **Takeaway: Likely will take a combination of methods to achieve net energy generation at common wastewater TOC**
  - With currently known methods will need combination like enzymatic hydrolysis + anaerobic digestion with thermal heating to exploiting high CH_4 production of extremophiles
  - Need to develop new materails, biological compounds, and systems than used the to leapfrog to orders of magnitude gain in permformance.

EXCITING NEW ADVANCEMENTS POSSIBLE

- **New Materials Development**
  - Non-fouling membranes to obviate extreme fouling
  - Functionalized dendritic materials for binding nutrients.
  - Blue light active photocatalysis to degrade complex hydrocarbons to volatiles, destroy pathogens, and degrade toxic organic compounds.
- **New biological microbes**
  - Increase production of methane and butanol
  - Low cost enzymes for hydrolysis
- **Hybrid system development**
  - Ab initio system development of total process from intake to output, with zero-discharge of wastes.