CLOSINIG THE WATER CYCLE AND RECOVERING WATER, ENERGY, NUTRIENTS AND OTHER RESOURCES IN THE CITIES OF THE FUTURE

Vladimir Novotny

Partner AquaNova LLC, Newton, MA

Professor Emeritus Marquette University, Milwaukee, WI

Northeastern University, Boston, MA

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Cities of the Future – Utopia or Unavoidable Reality

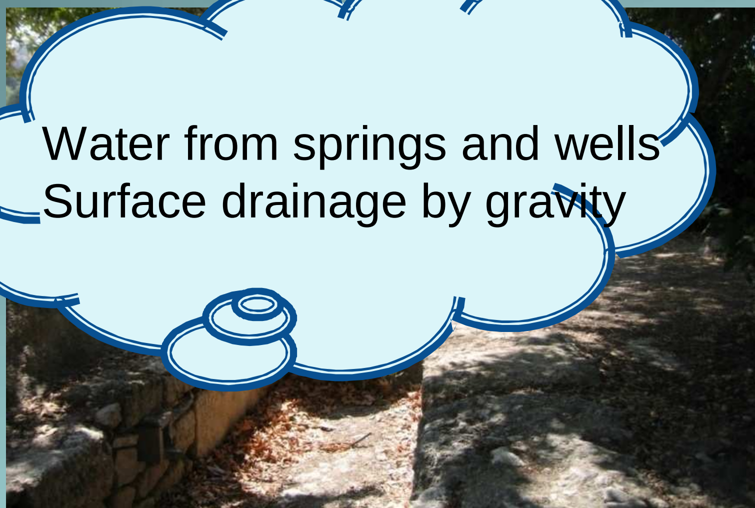
Model of Tianjin Ecocity, China

COF – an international movement towards urban water, energy and resources sustainability

- "Urbanites now outnumber their rural cousins – and that's surprisingly **good news for the environment"**
- "The average New Yorker uses far less water and produces just 30 per cent of the greenhouse emissions of the average US citizen"

Barley 2010, *New Scientist* 2785, 32-37

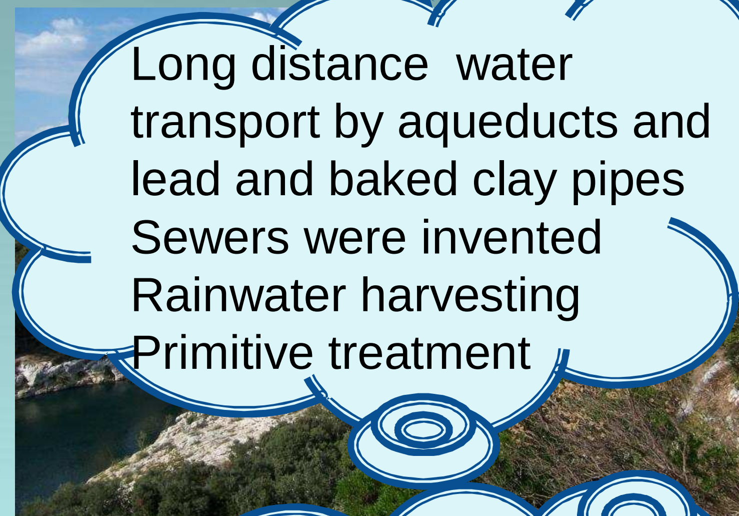
Historic Paradigms



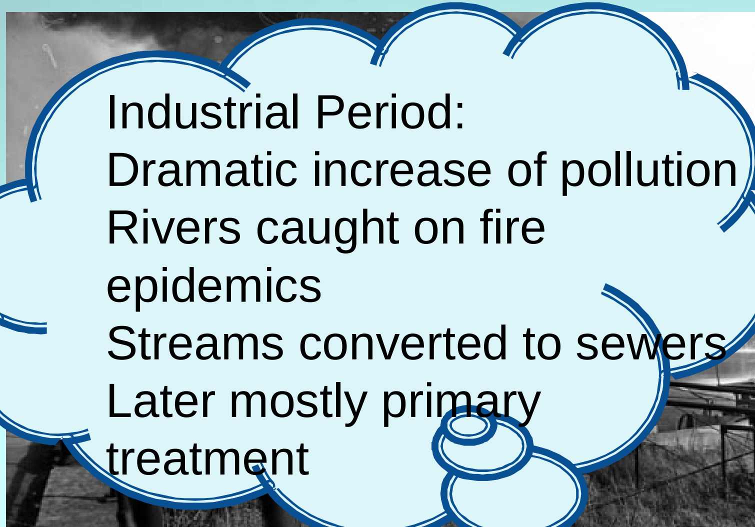
Water from springs and wells
Surface drainage by gravity

I

II

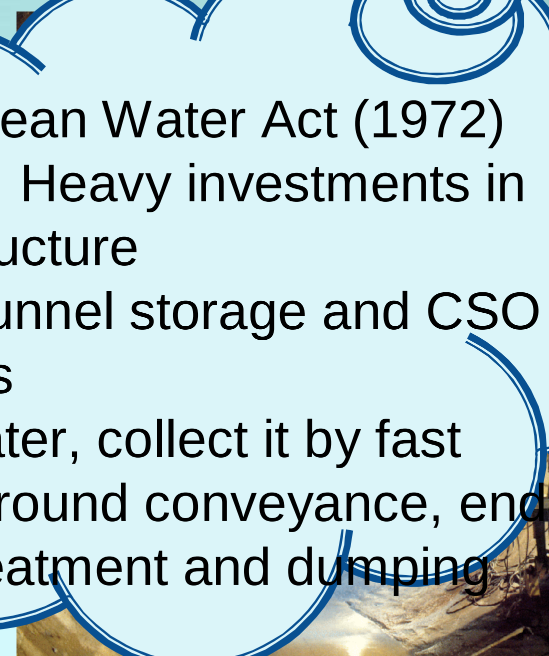


Long distance water transport by aqueducts and lead and baked clay pipes
Sewers were invented
Rainwater harvesting
Primitive treatment



Industrial Period:
Dramatic increase of pollution
Rivers caught on fire
epidemics
Streams converted to sewers
Later mostly primary treatment

III



Post Clean Water Act (1972) period: Heavy investments in infrastructure
Deep tunnel storage and CSO controls
Use water, collect it by fast underground conveyance, end of pipe treatment and dumping

Drivers for Change towards Sustainability

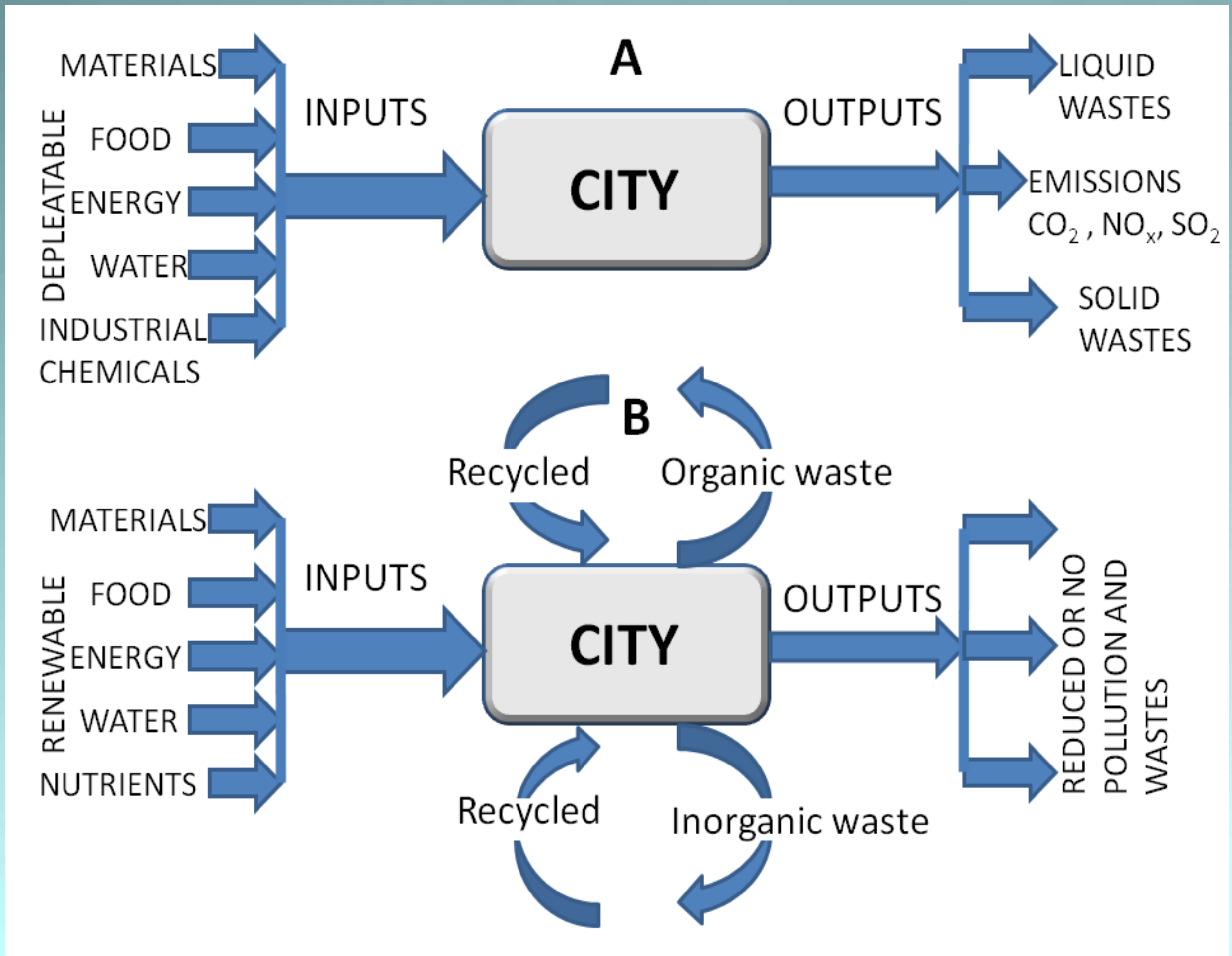
- Population increase and resulting migration of population into cities, emergence of megacities

		POPULATION IN MILLIONS (% URBAN)					
YEAR	World	US		UK		China	
		Total	Urban	Total	Urban	Total	Urban
1960	3 041	180.6		52.3		650.6	
1980	4 452	227.7		56.3		984.7	
2000	6 084	282.3	227 (80)	59.5	46.3 (78)	1 268.8	453 (35)
2010	6 895	310.3	261 (84)	62 .0	49.2 (79)	1 341.3	635 (47)
2030	8 321	361.6	321(89)	69.3	56.9 (82)	1 393.0	786 (56)
2050	9 306	403.1	345 (86)	72.8	60.3(83)	1 295.6	987 (76)

Source: UN World Population Prospect. 2010

- Megalopoli and Megaregions (Guanzhu-Hong Kong-Shenzen megaregion will have 120 million people in 2050)

Urban Metabolism



A Linear

needs to be changed to

B Cyclic or Hybrid

- Current urban systems are mostly linear
  - Excessive water volumes are withdrawn from mostly distant surface and groundwater sources
    - Inside the community water is used only once and wastefully, e.g., treated drinking water is used in landscape irrigation for growing grass
    - Only about 5 % of treated potable water is used for drinking and cooking
    - Great losses of water by leaks and evapotranspiration
  - Water is transferred underground to distant large wastewater treatment plants
    - The WWTPs use energy excessively, emit carbon dioxide and often methane which are green house gases
    - The WWTPs remove but rarely recover nutrients for reuse
    - The receiving water bodies become effluent dominated after discharge

Macroscale (Giant) Footprints of Sustainability

- A "footprint" is a quantitative measure showing the appropriation of natural resources by human beings
  - Ecological - a measure of the use of bio-productive space (e.g., hectares (acres) of productive land needed to support life in the cities)
  - Water - measures the total water use on site and also virtual water (usually expressed per capita)
  - Carbon - is a measure of the impact that human activities have on the environment in terms of the amount of GHG emissions measured in units of carbon dioxide

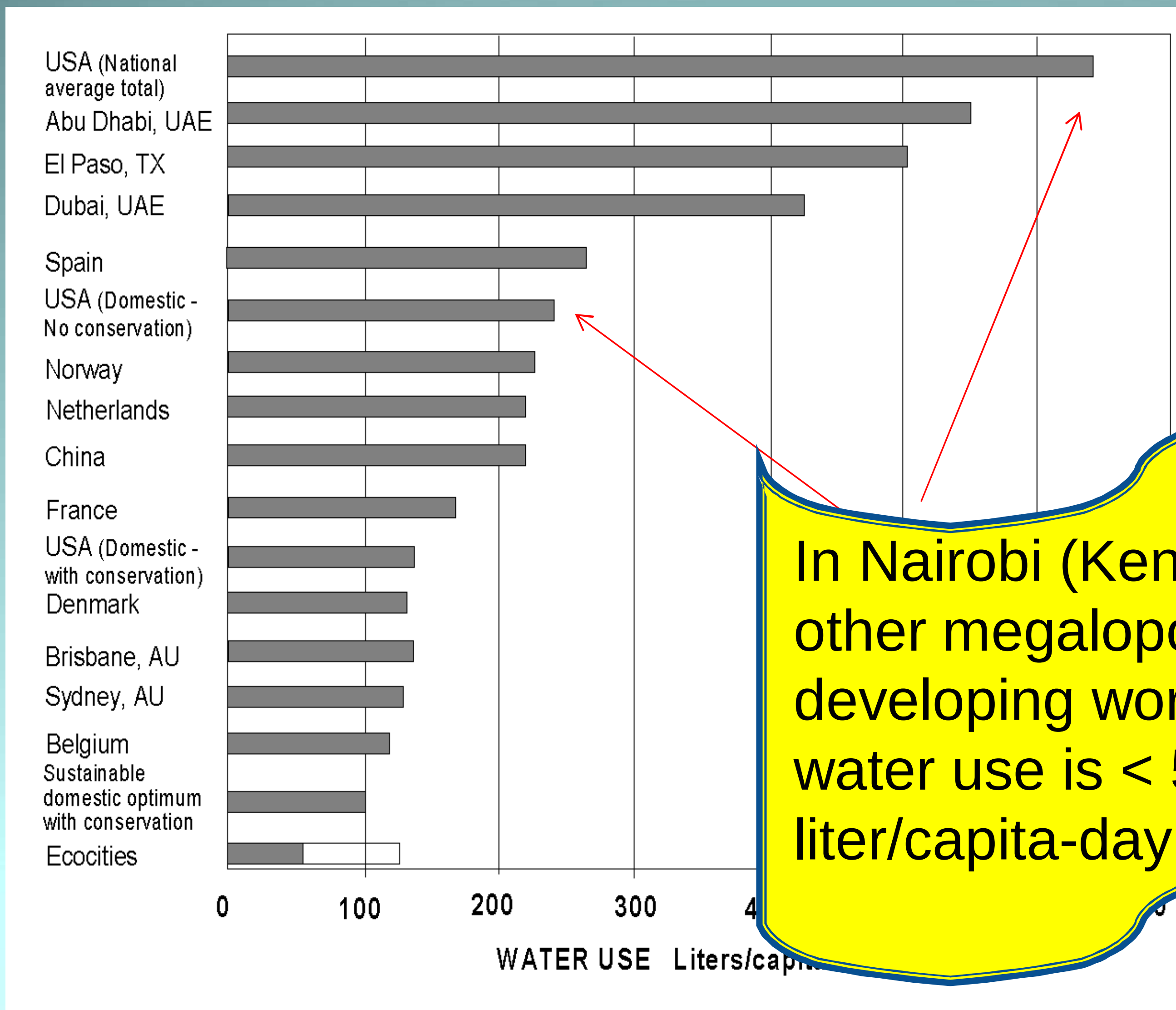
Ecological footprint

Year	World Population	Available productive land	
		Ha/person	Ac/person
1995	< 6 billion	1.5	3.6
2040	10 billion	<<1	2
Current ecological footprint			
Countries with 1 ha/person or less	Most cities in undeveloped countries		
Countries with 2-3 ha/person	Japan and Republic of Korea (democratic)		
Countries with 3-4 ha/person	Austria, Belgium, United Kingdom, Denmark, France, Germany, Netherlands, Switzerland		
Countries with 4-5 ha/person	Australia, Canada and USA		

Imbalance

If the cities in the currently rapidly developing countries (China, India, Brazil) try to reach the same resource use as that in developed countries, conflicts may ensue

countries



VIRTUAL WATER

l/cap-day

Food 1928

Electricity 53-73

liter/kg

In Nairobi (Kenya) and other megalopoli of the developing world urban water use is < 50 liter/capita-day

ters

GHG (carbon) Emission by Cities

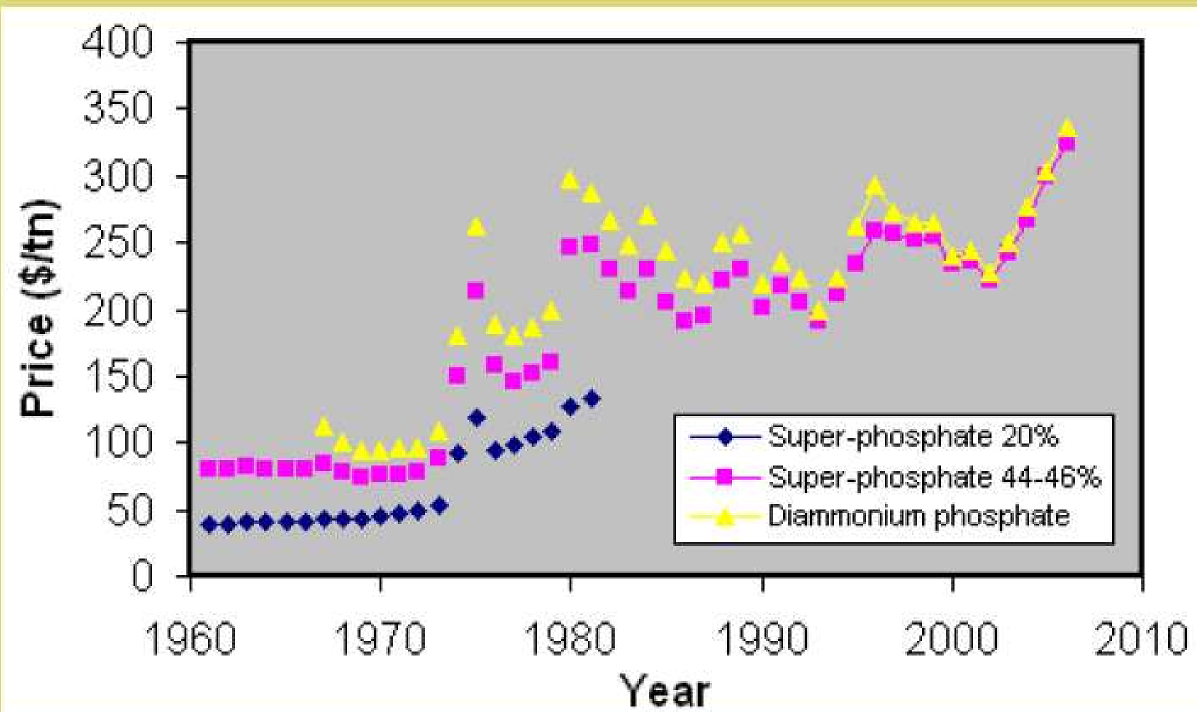
Top ten countries in the CO_2 emissions in tons/person-year in 2006[1]									
Qatar	UAE	Kuwait	Bahrain	Aruba	Luxembourg	USA	Australia	Canada	Saudi Arabia
56.2	32.8	31.8	28.8	23.3	22.4	19.1	18.8	17.4	15.8
Selected world cities total emissions of CO_2 equivalent in tons/person-year[2]									
Washington DC	Glasgow UK	Toronto CA	Shanghai, China	New York City	Beijing China	London UK	Tokyo Japan	Seoul Korea	Barcelona Spain
19.7	8.4	8.2	8.1	7.1	6.9	6.2	4.8	3.8	3.4
Selected US cities domestic emissions of CO_2 equivalent in tons/person-year[3]									
San Diego CA	San Francisco	Boston MA	Portland OR	Chicago IL	Tampa FL	Atlanta GA	Tulsa OK	Austin TX	Memphis TN
7.2	4.5	8.7	8.9	9.3	9.3	10.4	9.9	12.6	11.06
[1]Wikipedia (2009); [2] Dodman (2009) ; [3]Gleaser and Kahn (2008) [2,3] Values include transportation (private and public), heating, and electricity									

GHG = Green House Gases (CO_2, methane, nitrogen oxides and other gases)

New Threats to Water Supplies and Ecology

- Large increases of losses of fertilizers from agricultural lands, urban lawns and continuing nutrient discharges from point sources
  - Hyper-trophic water – Harmful algal blooms by cyanobacteria
    - Toxins
    - Loss of oxygen and biota
    - Loss of recreation
- New chemicals accumulate in the environment
  - Endocrine disruptors
  - Pharmaceutical
    - Antibiotics
  - Nanoparticles

We are running out of phosphorus



Phosphate rock (2010):	119.6 $/mt
Diammonium phosphate (2010):	482.6 $/mt
Currently (2010):	**1.1 – 1.6 $/kg-P**

Sources: US Geological Survey Minerals Yearbook 2006 and the World Bank Commodity Data 2010, graph from Verstraete 2010

Virtual energy for producing fertilizer

$$\frac{19.4 \text{ KW-h}}{\text{Kg N}}$$

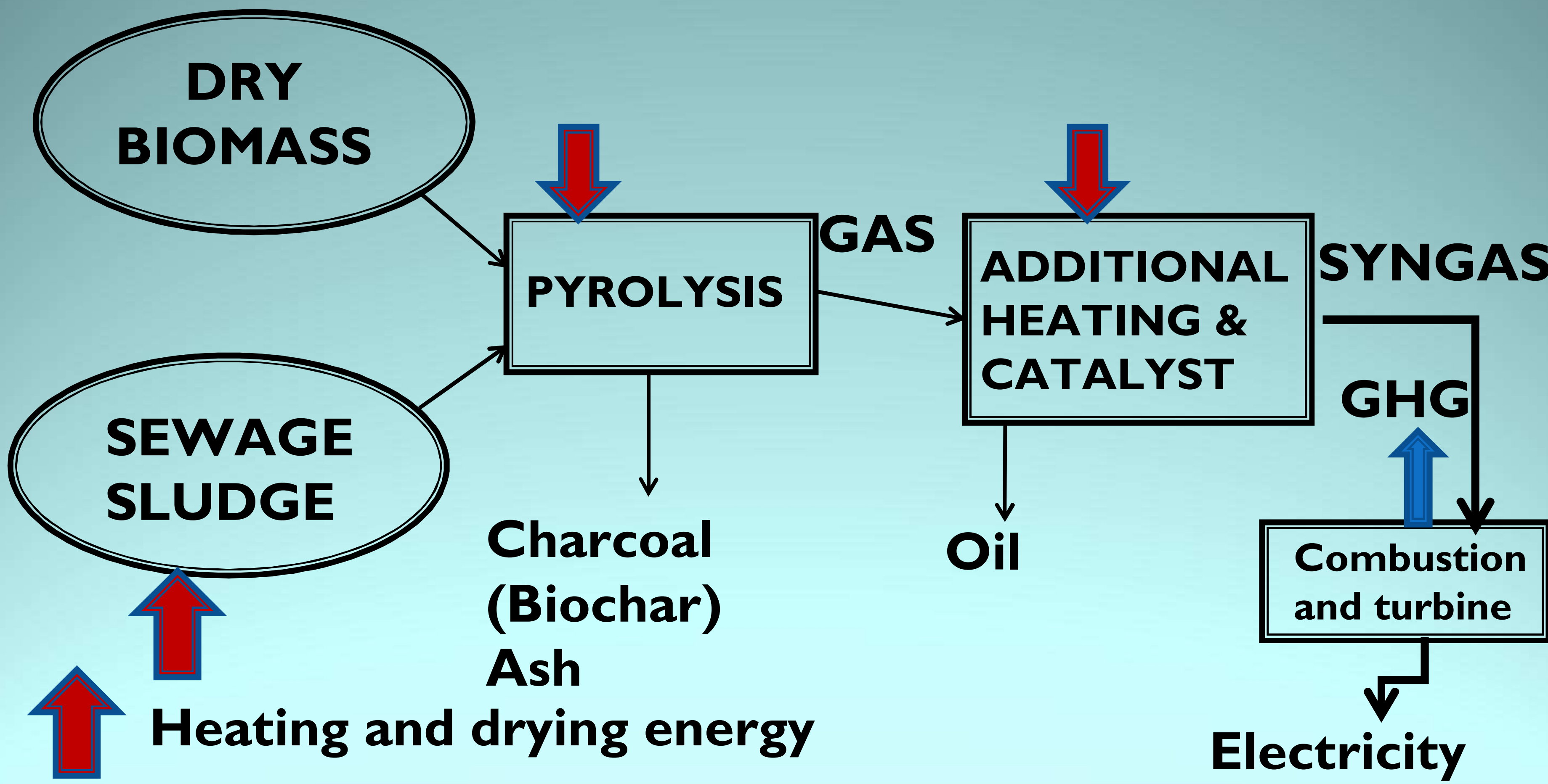
For N produced by Haber/Bosch

$$\frac{2.11 \text{ KW-h}}{\text{Kg P}}$$

GHG emissions in US
0.61 kg CO_2/KW-h

Source P. McCarty et al. 2011

Energy from Used Water and Solids via Syngas (H_2 + CO) and Oil Production



This traditional energy recovery will provide less than ½ of energy needs of an aerobic/anoxic WWTP

The Fifth Paradigm

GOAL:

WATER CENTRIC SUSTAINABLE COMMUNITIES

Vision of the Cities of the Future
The 5th (Sustainable) Paradigm

Definition/Vision of an Ecocity:

An ecocity is a city or a part thereof that balances social, economic and environmental factors (triple bottom line) to achieve sustainable development. A sustainable city or ecocity is a city designed with consideration of environmental impact, inhabited by people dedicated to minimization of required inputs of energy, water and food, and waste output of heat, air pollution - CO2, methane, and water pollution. Ideally, a sustainable city powers itself with renewable sources of energy, creates the smallest possible ecological footprint, and produces the lowest quantity of pollution possible. It also uses land efficiently; composts used materials, recycles or converts waste-to-energy. If such practices are adapted, overall contribution of the city to climate change will be none or minimal below the resiliency threshold. Urban (green) infrastructure, resilient and hydrologically and ecologically functioning landscape, and water resources will constitute one system.

Adapted from R. Register UC-Berkeley

One Planet Living (WWF) Goals

- WATER – Reduce water demand by 50% from the national (state) average
  - Water conservation (more efficient water fixtures), xeriscape)
  - Using additional sources (stormwater, desalination)
  - Reclamation and reuse
- SOLID WASTE - Zero solid waste to landfills, recycling
- ENERGY – Carbon neutrality
  - Minimization or elimination use of fossil fuels
  - Renewable energy sources
  - Passive energy savings (Energy STAR)
  - Water conservation (reduction of pumping energy, CO_2 emissions
  - Energy and resource recovery from water, used water and solids

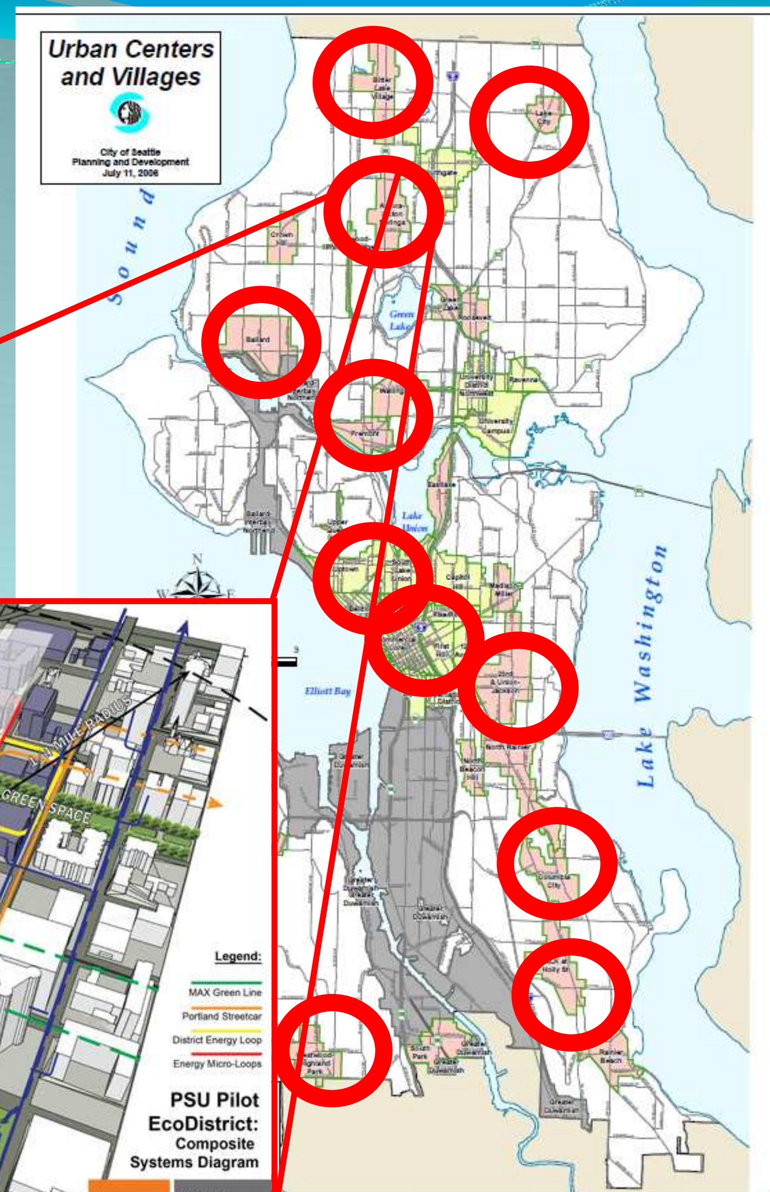
Closing the Cycle

- Reduce, Reclaim, Reuse and Restore - 4 Rs
  1. Reduce - Water and energy conservation
  2. Reclaim
     1. Treat for safe discharge into environment – TMDL
     2. Reclaim energy (heat), nutrients, solids
  3. Reuse after additional treatment
  4. 4th R – Restore water bodies as a resource
- Separate, Sequester and Store- 3 Ss
  1. Separate Blue, White, Gray, Yellow, and Black Water
  2. Sequester GHGs and remove/detoxify toxics
  3. Store reclaimed water on the surface and/or underground
- Toilet to Tap – 2Ts (is it needed?)
  - Reclamation with or without 3S for potable reuse

4 Rs, 3 Ss and 2 Ts

RESILIENT CITY

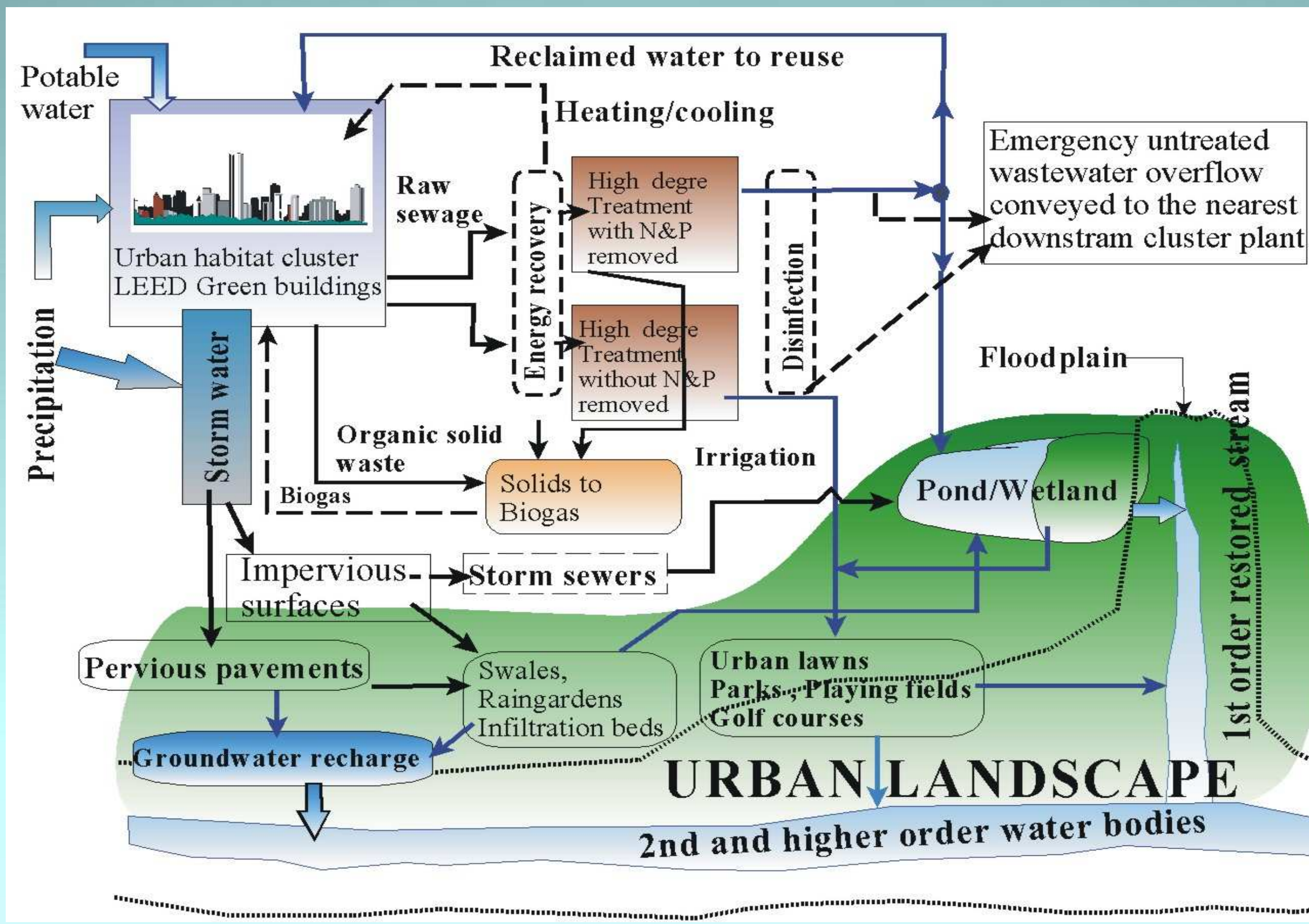
- Nested semi-autonomous
  - Buildings
  - Neighborhoods
  - Cities



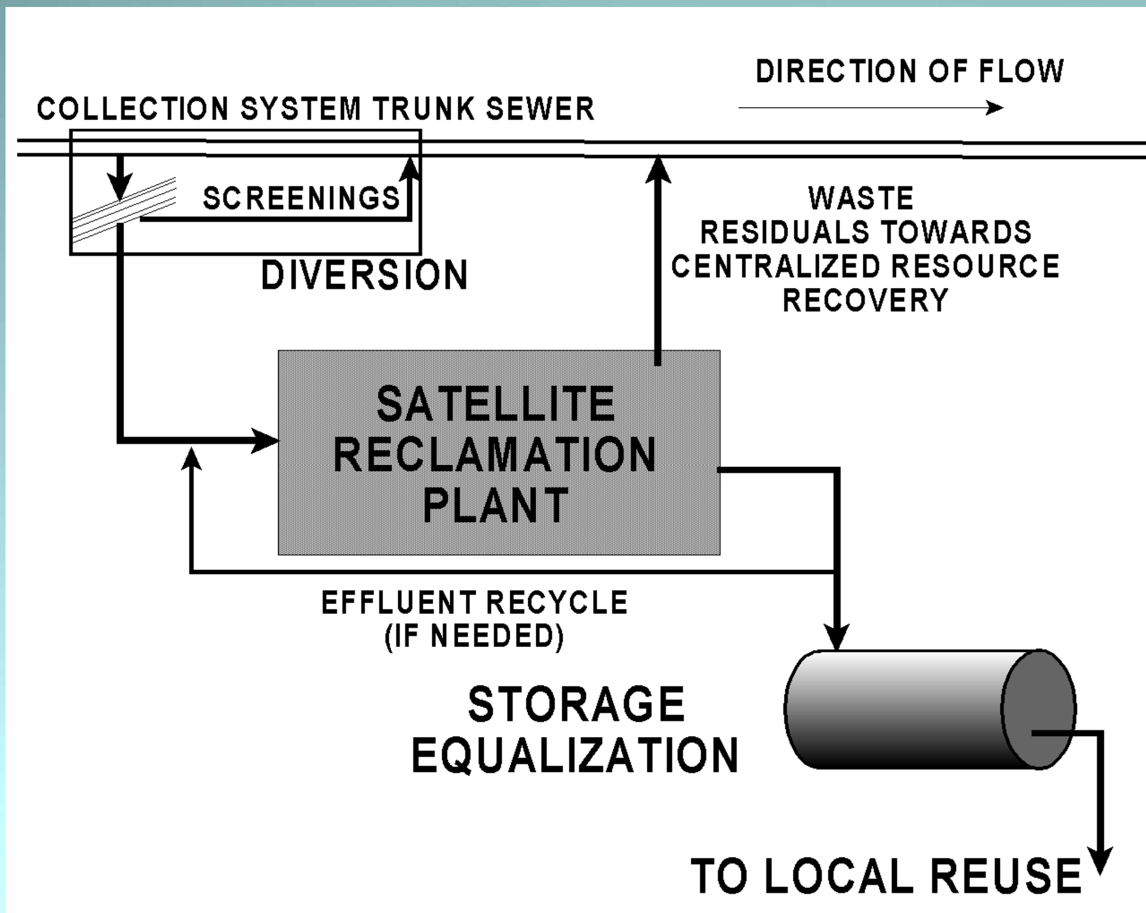
Source Steve Moddemeyer

Concept of Integrated Water Management in a Cluster/Ecoblock

Synergy of Landscape and Infrastructure



If water is needed for local reuse, sewers can be the source



Adapted from Asano et al. (2007)

Package and small high efficiency treatment units can be installed to provide locally water for:

•Ecological flow of restored streams

•Toilet flushing

•Landscape irrigation

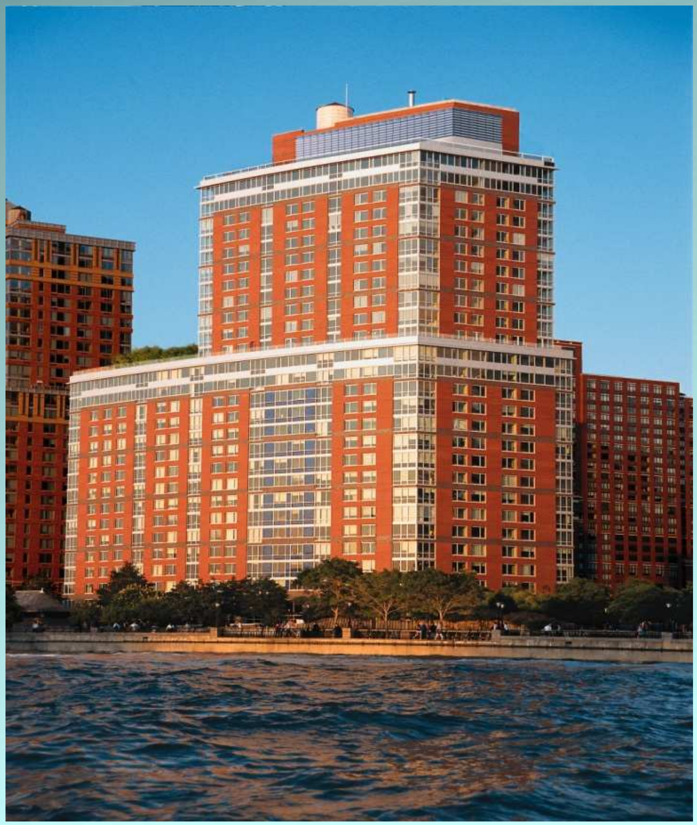
•Street flushing

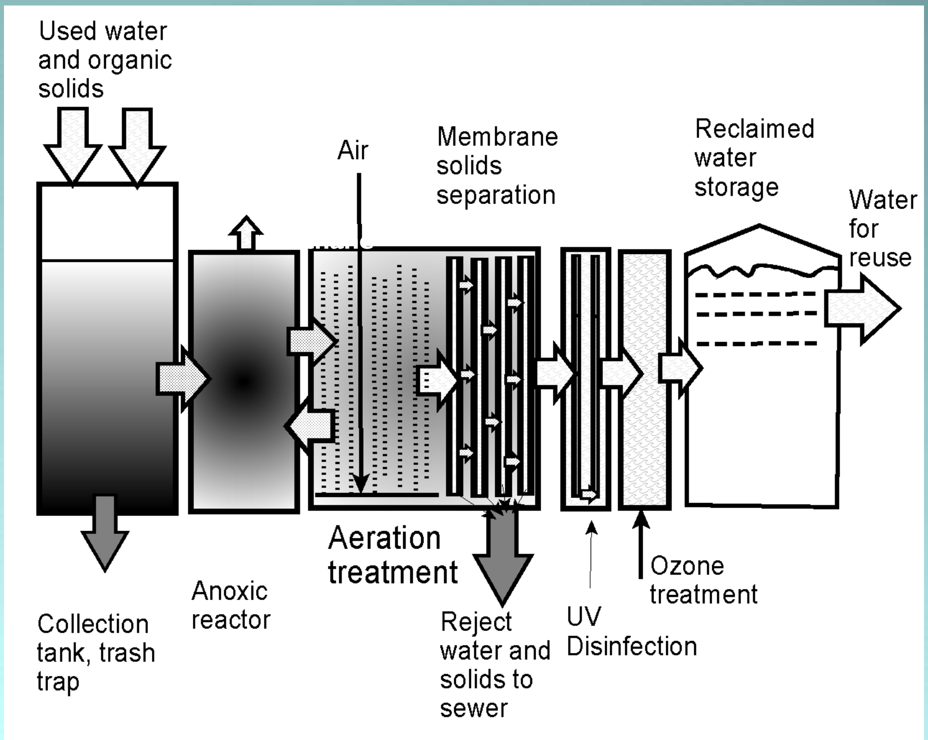
Idea:
Concentrate used water for centralized resource recovery

Treatment in the cluster is "fit for reuse"

- **IRRIGATION**
  - Secondary treatment - Nutrients stay in the effluent
- **FLOW SEPARATION**
  - Black, Gray, White and Yellow
- **ECOLOGIC FLOW** – Secondary treatment with membranes, phosphorus removal, disinfection with UV
- **TOILET FLUSHING**
  - Filtration with disinfection and "adding color"
- **INDIRECT POTABLE REUSE**
  - Secondary + tertiary (microfiltration + reverse osmosis) + long storage in aquifer or surface + more treatment

Water reclamation and reuse for toilet flushing and possibly irrigation





Rainwater harvesting and reuse for irrigation is also practiced

Battery Park Solaire development in New York - a semiautonomous water/used water management cluster

Designer Alliance Environmental

Need for reuse

It could be energy demanding

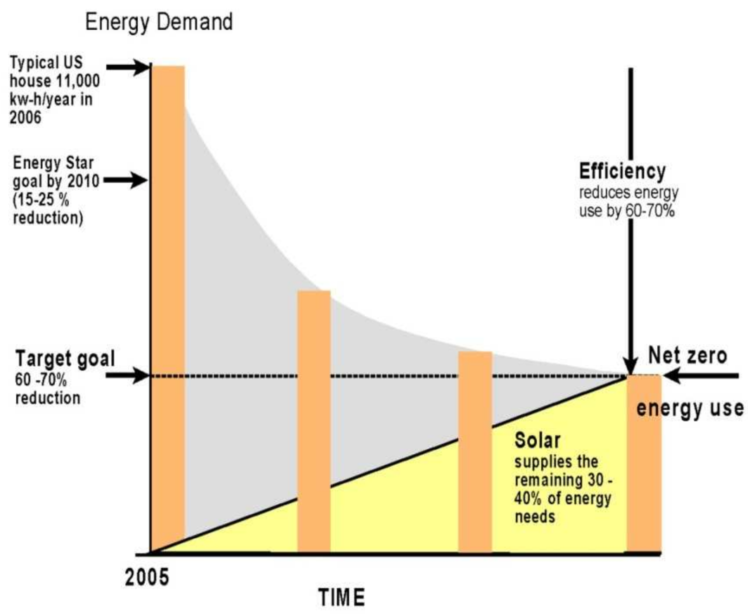
Reverse osmosis

Microfiltration

UV radiation

Water Energy Nexus

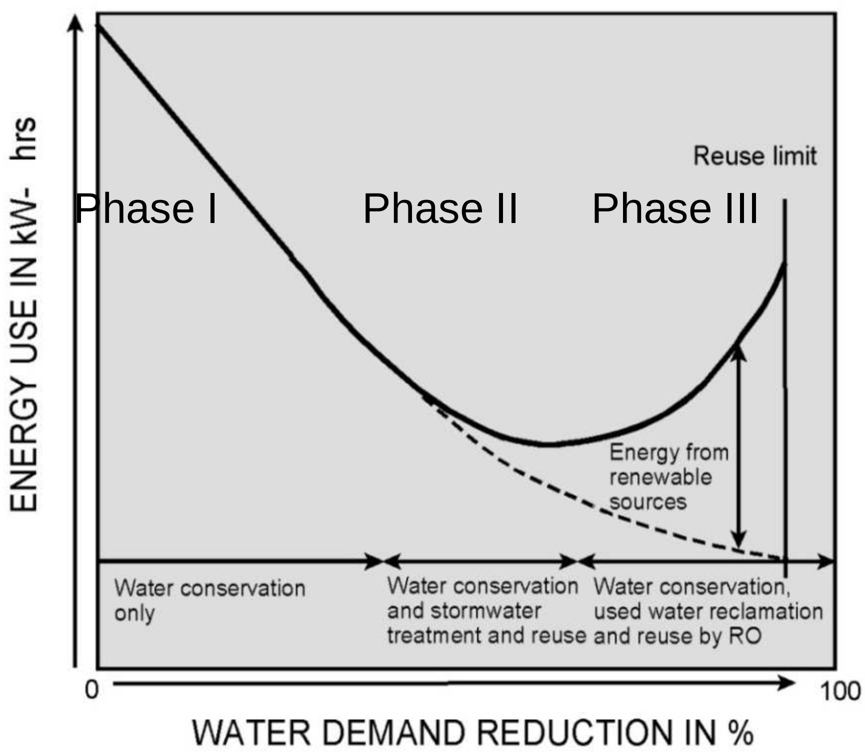
Implement water conservation first; it also concentrates used water for better energy recovery



Energy delivered from the grid

In the US 1 kW-hr = 0.6 kg CO_2 emissions

In France 1 kW-hr = 0.22 kg CO_2



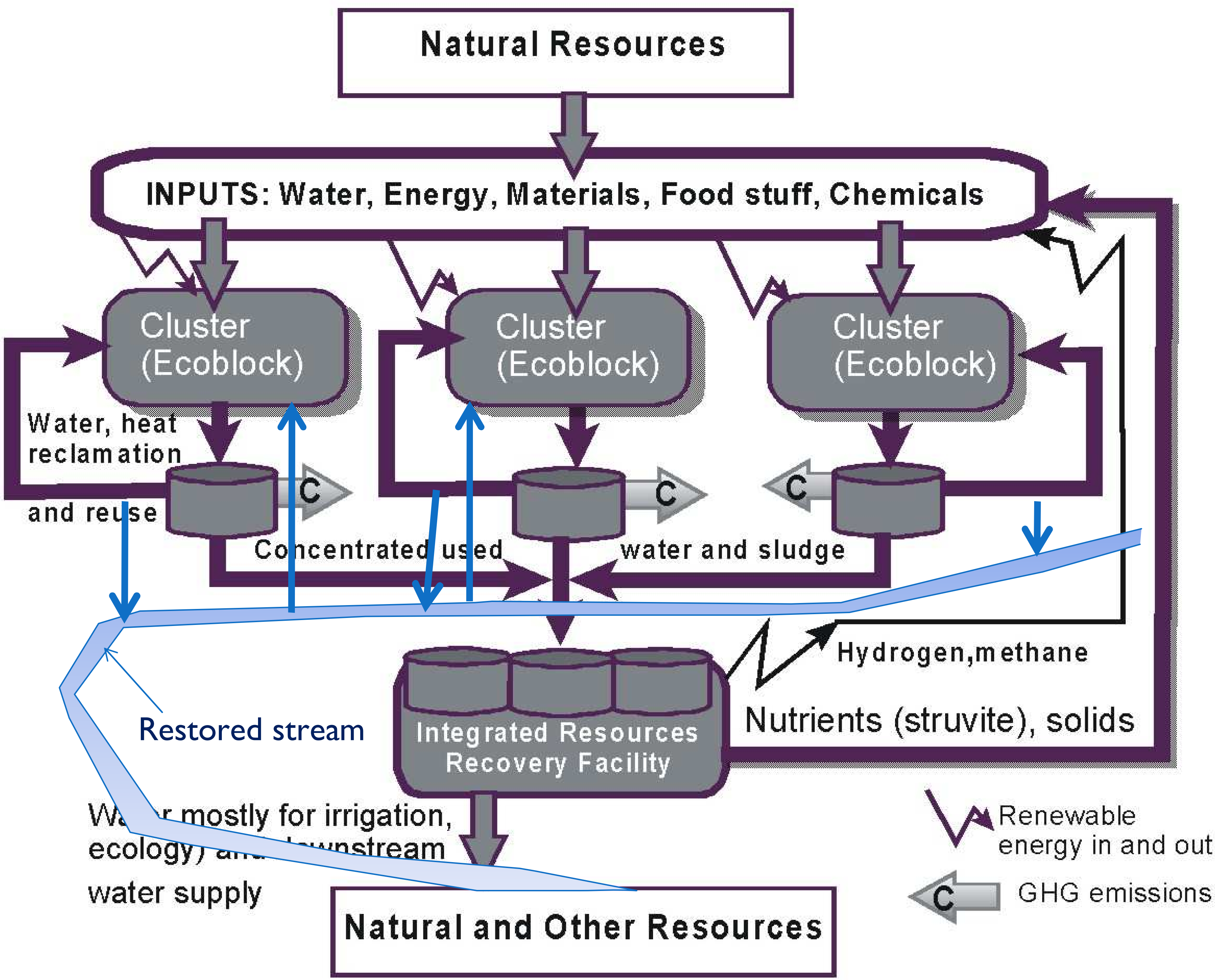
Energy use of treated volume of municipal used (waste) water and corresponding CO_2 emissions. Raw data from Asano et al. (2007) and from Novotny et al. (2010)

Treatment process	Daily flow volume of treated used water m³/day)		
	10,000	**25,000**	**>50,000**
	Energy use kw-hr/m³ (CO_2 emissions kg/m³)		
Activated sludge without nitrification and filtration	0.55 (0.33)	0.38(0.23)	0.28 (0.17)
Membrane bioreactor with nitrification	0.83 (0.51)	0.72 (0.44)	0.64 (0.37)
Reverse osmosis desalination			
Brackish water (TDS 1 – 2.5 g/L)		1.5 (0.91) – 2.5 (1.52)	
Sea water		5 (3.05) - 15 (9.15)	
Ozonization (ozone produced from air)			
Filtered nitrified effluent		0.24 (0.15) - 0.4 (0.24)	
Desalination by evaporation (using waste heat)		~ 25 (15.25)	
Typical water domestic water heating (recoverable)		8.00	

Switch from aerobic treatment in linear systems to water, energy and other resource recovery

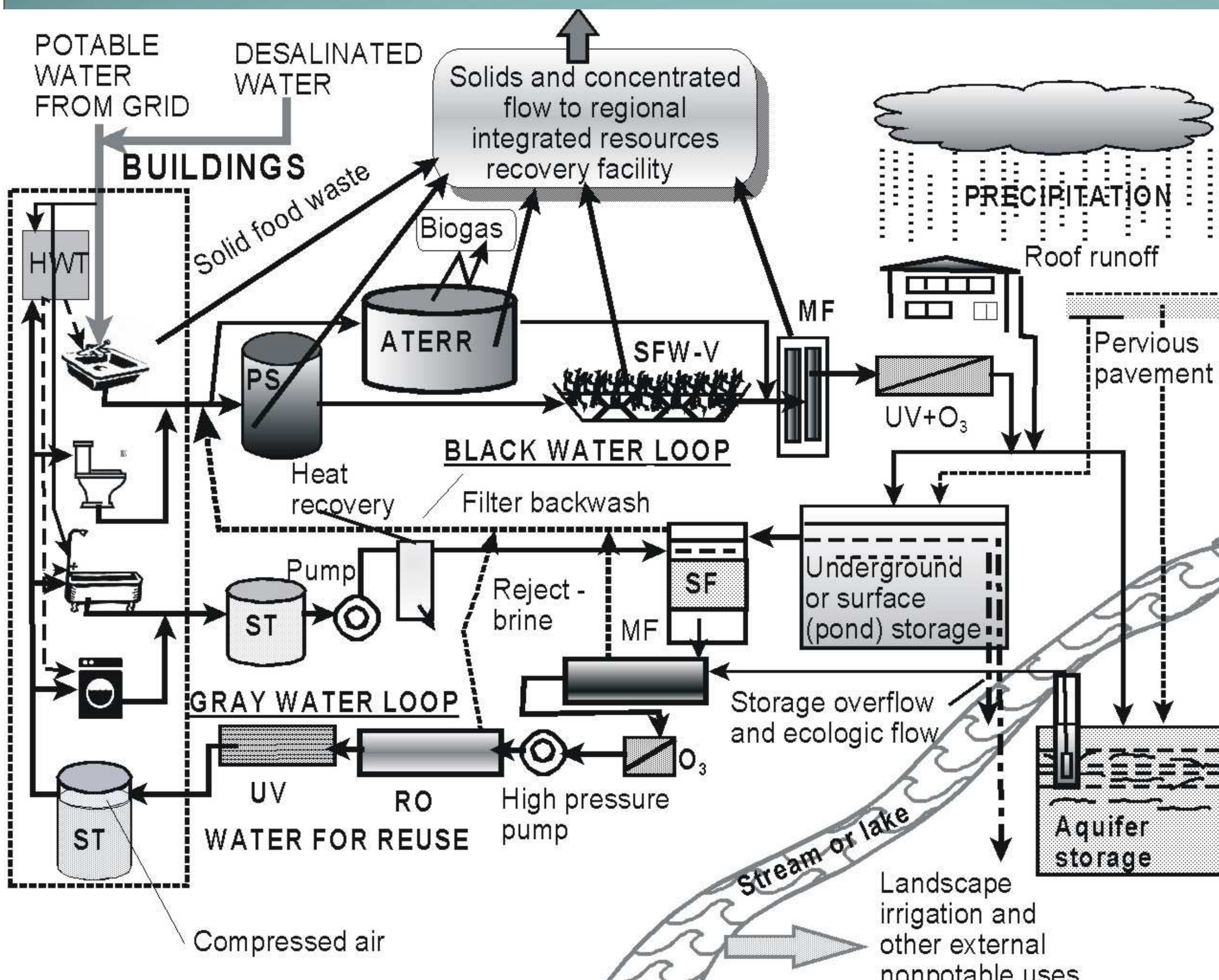
- 3 Ss- Separate, Store and Sequester (Gray and Black water, CO_2)
- 3 R-s, Reclaim, Reuse, Recycle (Blue and White water,)
- No 2 Ts
- Distributed water and energy reclamation/recovery (Gray, Blue, White and Black water, heat, methane)
- Concentrate Black water and with sludge send it to the regional Integrated Resource Recovery Facility

Anaerobic Processes are Key


Natural Resources
INPUTS: Water, Energy, Materials, Food stuff, Chemicals
Cluster (Ecoblock)
Cluster (Ecoblock)
Cluster (Ecoblock)
Water, heat reclamation and reuse
C
C
C
Concentrated used water and sludge
Hydrogen,methane
Nutrients (struvite), solids
Integrated Resources Recovery Facility
Restored stream
mostly for irrigation,
water supply
Renewable energy in and out
GHG emissions
Natural and Other Resources

Distributed recycle needs urban runoff

Losses by evapotranspiration, ecological flow and reject water – Qingdao Ecoblock (Prof. H. Fraker – University of California-Berkeley)



The number of cycles without make up water is very limited.

Make up water comes mainly from treated (and stored) storm water

PS – primary settler

MF - microfiltration (membrane filter)

O_3 - Ozonation

UV ultraviolet disinfection

ST storage

RO reverse osmosis

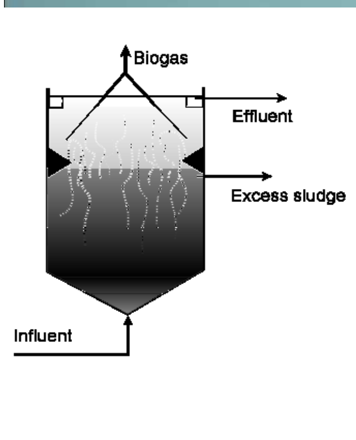
SFW – subsurface flow wetland
SF – sand filter
ATERR –anaerobic treatment and energy recovery reactor - concentrator

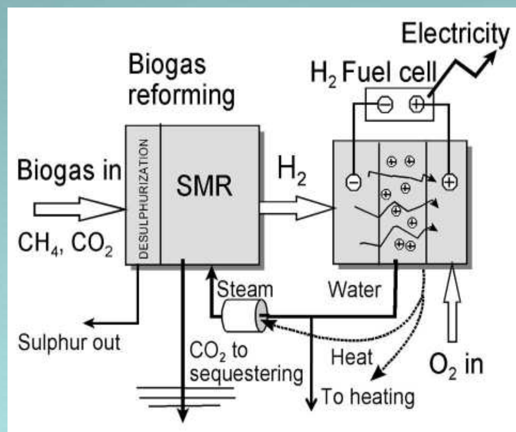
More centralized resource recovery

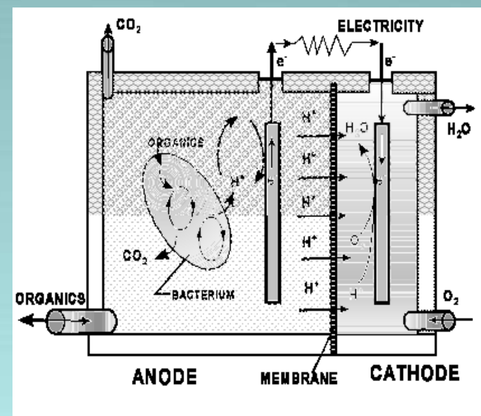
- Characteristics of integrated resource recovery facility
  - More concentrated influent (COD > 3000 mg/L desirable)
  - Urine may be separated (contains 50% of P and >75% N) in1% of flow
  - Inflow and input contains sludge and other solids (shredded food and other organic solids). Other organic biodegradable solid waste may be trucked in (co-digestion)
- Because of high COD, a conventional (energy demanding) activated sludge treatment is not feasible and should be replaced by an anaerobic processes
  - Conventional sludge digester requires large detention and high concentrations of solids and COD
  - Use Upflow Anaerobic Sludge Blanket (UASB) reactor

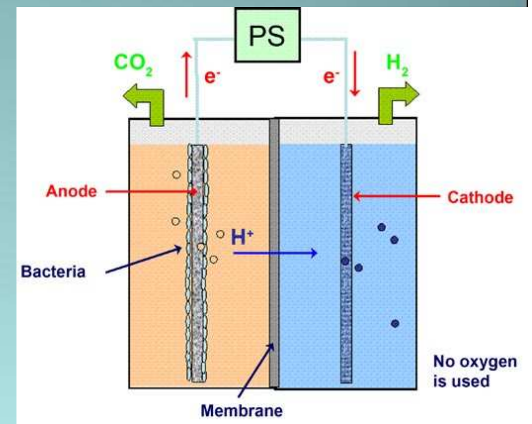
We can do better in the future

Examples of new technologies









UASB Reactor

- 0.4 L CH4/g COD removed
- 9.2 kW-hr/m^3 of methane

Hydrogen fuel cell with biogas reforming

- Converts methane into hydrogen, electricity and water
- Greater efficiency than methane combustion

SMR = Steam methane reforming

Microbial fuel cell

Converts organic biomass directly into electricity (from Rabaey and Verstraete, 2005)

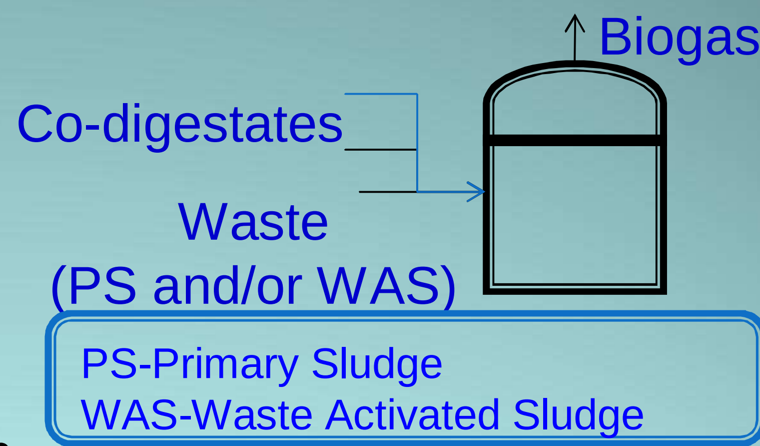
Bioelectrochemically Assisted Microbial Reactor (BEAMR)

Converts organic biomass directly into hydrogen by adding small electricity to the reactor (from Liu, Grot and Logan, 2005)

95 % energy recovery from produced acetate

CODIGESTION

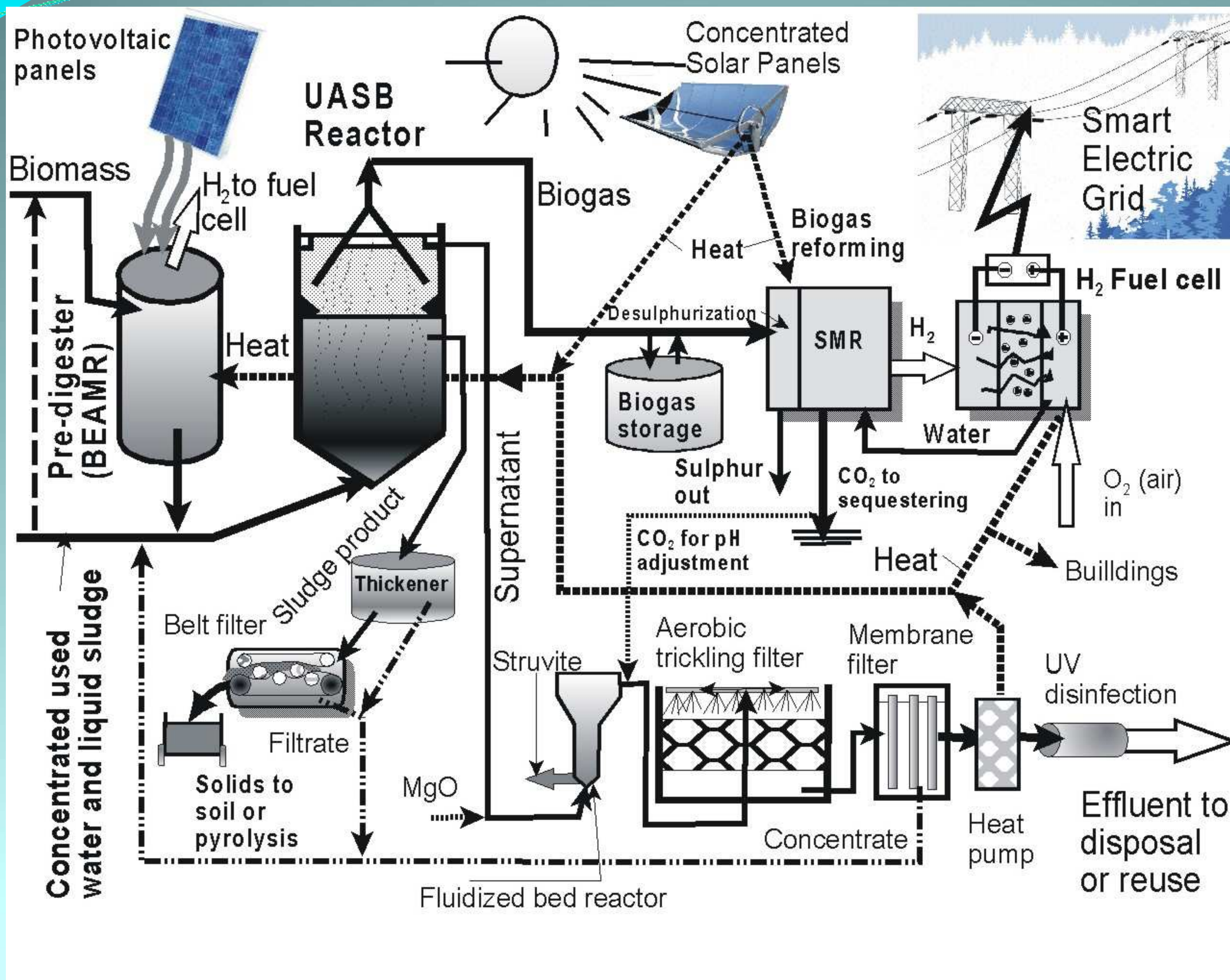
- There is not enough energy in used water to compensate for energy use for delivery, treatment, and (above all) heating
- Typical biodegradable solid (food and yard) recoverable waste production in the US is about 0.5 kg/cap-day that can be codigested with the sludge
- Nutrients in the effluent and CO_2 from IRRF can be used for growing algae for more energy
- Codigestates: Food waste, deicing fluids, yard waste, oil and hydraulic fluids, meat production waste, yeast, and many others



Credit Dan Zitomer

- Solar and wind energy can be implemented in IRRF and in clusters to provide more energy for heating the reactors and buildings and (in the future) to enhance fermentation

Integrated Resource Recovery Facility – IRRF (Future)



IRRF produces

- •Reclaimed water for reuse
- •Heat for heating reactors and buildings
- •Struvite (ammonium-magnesium phosphate) fertilizer
- •Biogas and hydrogen
- •Electricity
- •Organic solids
- •Carbon sequestration

BEAMR = Bioelectrochemically assisted microbial reactor - Logan (2008)

Comparison of Three Alternatives

- ALTERNATIVE 1
  - US household on irrigated lot – water use 550L/cap-day
  - Linear system with no reuse
  - Traditional activated sludge treatment
- Alternative 2
  - Hybrid system with cluster recovery of heat and water for toilet flushing and irrigation; household practicing water conservation – water use 166 L/cap-day
  - Conventional regional Bardenpho system removing nutrients
- Alternative 3
  - Hybrid system with double loop ecoblock recovery of heat and water – water use from grid 50 L/cap-day
  - Black water and solids sent to the IRRF for recovery of energy (methane electricity), fertilizer, biosolids, and water

Parameter		Alternative I Traditional Linear System with no Conservation	Alternative II Mostly Linear System with Water Conservation and Small Reuse	Alternative III Hybrid System with Energy Recovery and conversion to hydrogen
Water flow from the grid	L/cap-day	551	166	50
Energy to deliver and use water	kW-h/cap-d	1.245	0.375	0.113
Water used for irrigation from grid	L/cap-d	313	30[1]	0
Energy use for irrigation[2]	kW-h/cap-d	0.169	0.016	0
Total heating water flow	L/cap-d	106	71	71
Energy use for heating	kW-h/cap-d	**3.876**	**2.60**	**2.60**
Total wastewater (WW) flow[3]	L/cap-d	297	116	NA
Pumping WW in the sewers [4]	kW-h/cap-d	0.030	0.012	<0.01
COD content of used water	g/cap-day	95	95	95
Energy used to treat WW[5]	kW-h/cap-d	0.125	0.072	0
Methane recovery from sludge	kW-h/cap-d	0	-0.05	0
Gray water (GW) recycle	L/cap-d	0	20[6]	76
Energy to treat recycle	kW-h/cap-d	0	0.015[7]	0.160[8]
Heat recovery from GW	kW-h/cap-d	NA	NA	-1.00
Concentrated BW flow to IRRF	L/cap-d	NA	NA	69
Pumping BW to IRRF	kW-h/cap-d	NA	NA	0.007
Methane recovery from UASB	kg/cap-d	NA	NA	-0.02
H_2 from UASB methane conversion	kg/cap-d	NA	NA	-0.035
H_2 from BEAMR fermenting solids[9]	kg/cap-d	NA	NA	-0.02
Total energy from hydrogen	kW-h/cap-d	NA	NA	-1.50
Heat recovery from effluent	kW-h/cap-d	0	1.78[10)]	-1.20[10)]
Total energy expenditure (production) kW-h/cap-d		**5.45**	**1.26**	**(-0.83)**
Carbon GHG emissions (credit)	kg CO_2/cap-year	**1263**	**281**	**(-185)**

Centralized Nutrient Recovery

- Struvite production
  - Struvite is ammonium magnesium phosphate ($MgNH_4 PO_4$)
    - Magnesium is added in a form of $MgOH_2$ or $MgCl_2$ and pH is adjusted (if needed) to pH>9.
    - Struvite is a precipitate separated from flow, for example, in upflow fluidized be reactors
    - pH can be adjusted back to normal by waste CO_2 from the treatment process which sequesters carbon
    - Struvite has a commercial value as a slow release fertilizer
    - While struvite precipitation can recover over 90% of phosphorus, less than 10% of ammonium N in typical municipal used water is incorporated into struvite. About 50% of N or more can be removed by ammonia stripping at pH >9
- Ammonium recovery beyond struvite to be developed
    - Inonexchangers, possibly in a combination with struvite production

Based on Maurer, Prong and Larsen, *Water Research* (2006)

Local Nutrient Recovery

Typical nutrient load in used water and urine *				
	Nitrogen g/cap-day	Phosphate g/cap-day	COD g/cap-day	Volume l/cap-day
Used water	15	2.4	161	300
Urine (%)	12 (80)	1.0 (42)	12 (7.5)	3.6 (1.2)

* From Wilsenach and Van Loosdrecht, Env. Sci. Technol. (2004) **38:**1208-1215

- Use of fit-for-irrigation reuse reclaimed water
- Urine separation and collection for centralized treatment
  - Dual or triple pipes and collection tank
    - Realistic even today for public and commercial buildings and schools
    - Sterilization 6 months storage @ 20° C; otherwise energy demanding heat, pressure, UV, etc
    - Volume reduction by evaporation or freezing – energy demanding
    - Nutrient extraction – struvite (N and P – no pH adjustment is needed)
    - ionexchange (N)

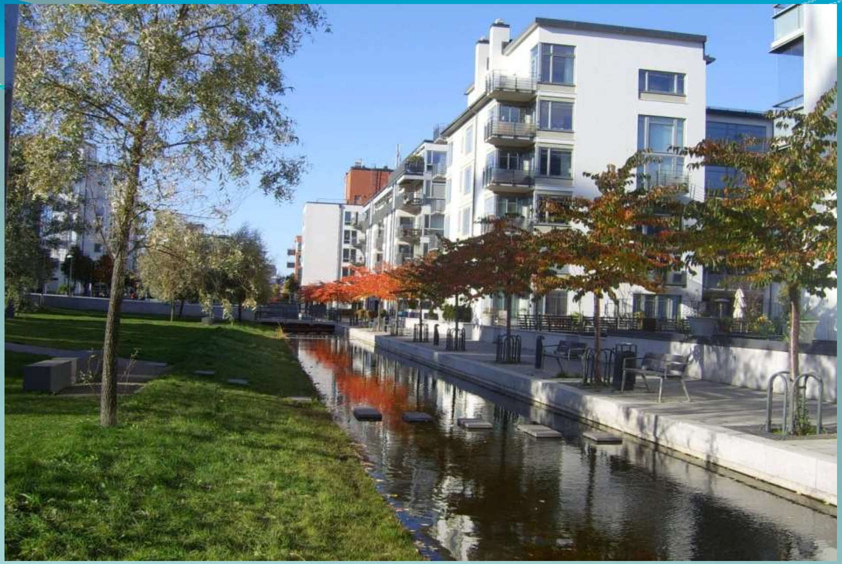
Summary and Conclusions

- Water conservation is the best alternative solution to a water availability problem. There is a direct relationship between water use and energy reductions.
- Reuse with high efficiency solids and pollutant removals (e.g., microfiltration and reverse osmosis) in a closed cycle requires more energy because of the energy requirement in the treatment. This energy should and could be provided by renewable sources
- Reuse/recycle needs make-up water to offset losses by reject water and liquid content in sludge and possibly by evaporation
- A new paradigm of urban drainage and used water reuse with resource recovery needs to be developed and implemented.
- Net zero GHG emissions, or better systems recovering and producing energy, fertilizer, solids, and water are technically feasible and achievable.

Summary and Conclusions – cont.

- Under current paradigm, nutrients are removed but rarely recovered.
- Switching from removal to recovery is needed
  - Using industrial fertilizer has a significant virtual carbon footprint that should not be overlooked
  - The world mineral phosphate ore (apatite) reserves are diminishing and may be exhausted in this century
  - The production of industrial nitrogen fertilizer in Haber – Bosch process and phosphate mining and processing require a lot of energy
  - Struvite recovery and production of needed magnesium hydroxide do not require much energy

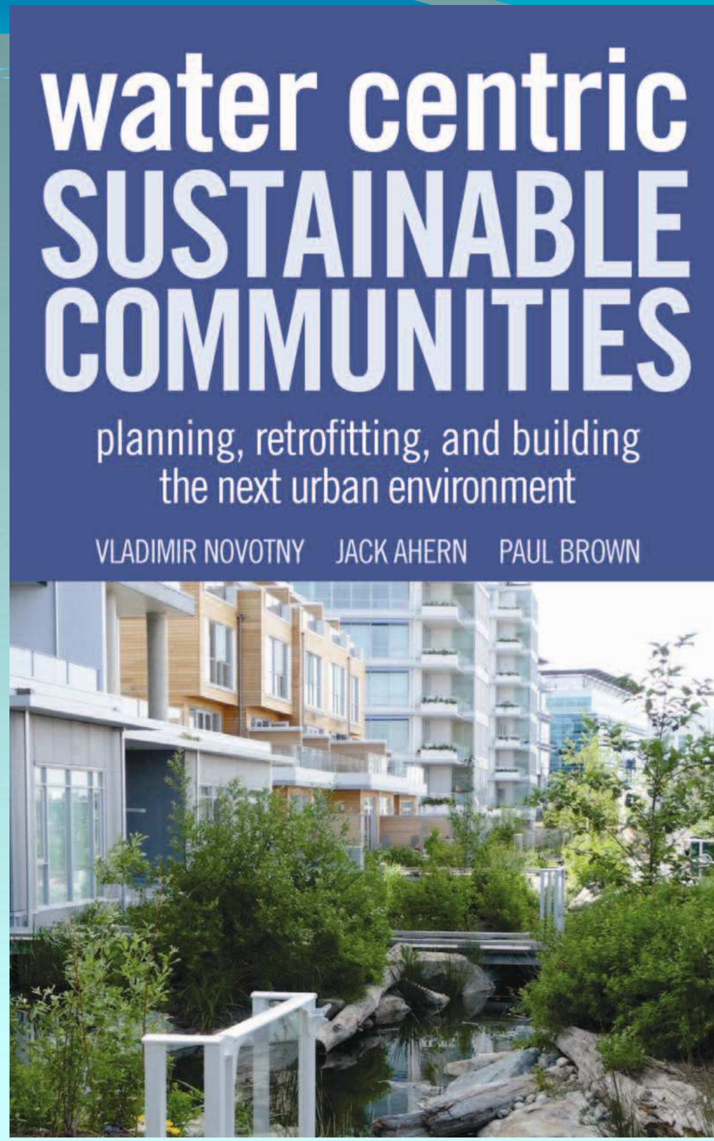
Dockside Greens, BC (courtesy P. Lucey)



Hammarby Sjöstad (courtesy Malena Karlsson)

Masdar (UAE). Courtesy Foster and Associates

Qingdao Ecoblock, courtesy Prof. H. Fraker UC-B



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