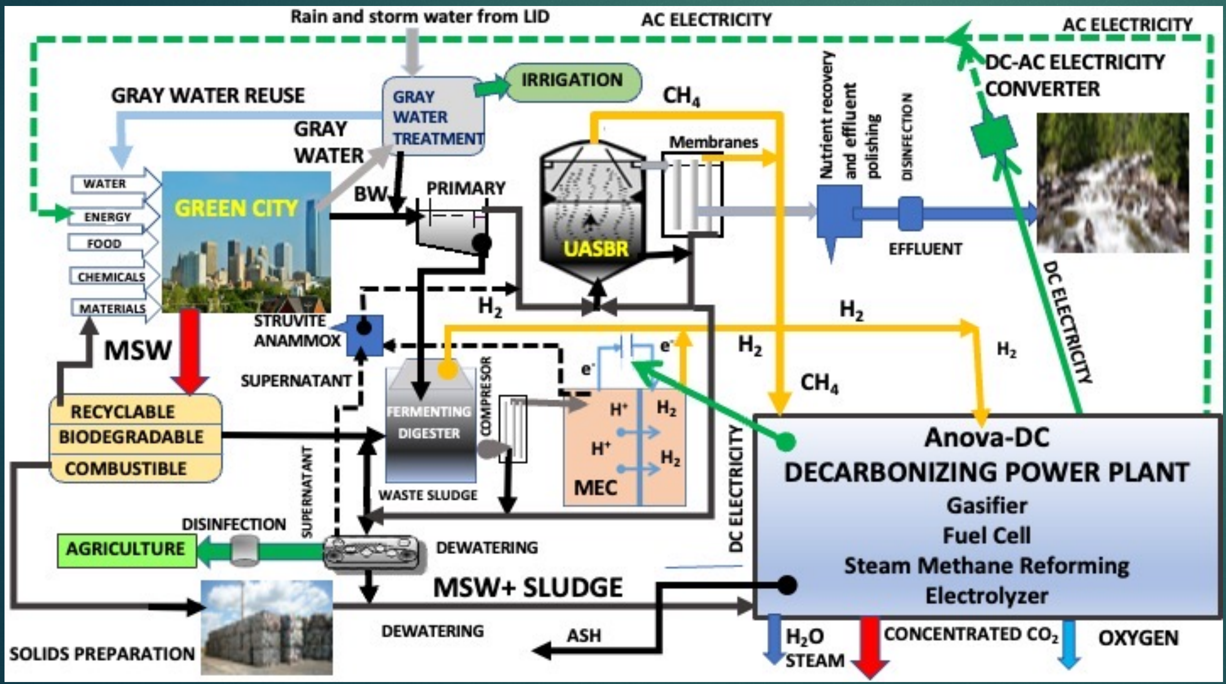
Decarbonization of Integrated Urban Water, Energy and Solids Management

AMERICAN ACADEMY OF ENVIRONMENTAL ENGINEERS AND SCIENTISTS

WEBINAR PRESENTATION OCTOBER 6, 2021



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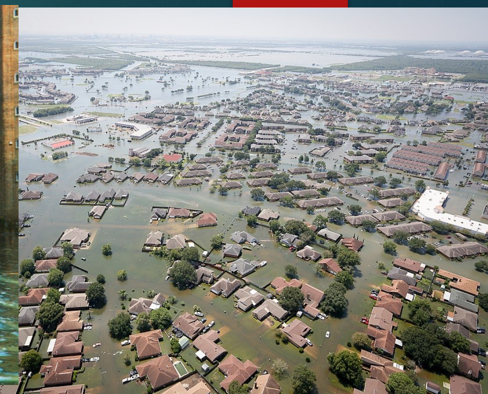
OUTLINE OF THE PRESENTATION

1. Global warming problem
2. Greenhouse Gas (GHG) Emissions and problems
3. Energy sources, fossil fuels , domestic energy , solids
    1. Water use and conservation
4. Current used water and solids management systems
    1. Aerobic treatment with landfill for solids, codigestion, energy recovery
    2. Incineration, waste to energy systems
5. Near future more sustainable biogas systems and technologies
    1. Anaerobic treatment
    2. Solids and sludge gasification
    3. Other advanced technologies
6. Introducing hydrogen-based system and technologies
    1. New hydrogen producing technologies, hydrogen potential of solids waste and sludge
    2. Switching from methane to hydrogen
    3. Hydrogen fuel cell and power plant
7. Comparison of alternatives, decarbonization
8. Negative emissions
9. Conclusions

Problems caused by Green House Gas (GHG) emissions

- Global warming
- Droughts
- Flooding
- Hurricanes
- Sea level rise
- Ice sheets and glaciers melting
- Methane emissions from tundra
- Plastic pollution
- Harmful algal blooms
- Forest fires
- Loss of coral reefs



First and second decade of 2000s

SOURCES OF EXCESSIVE GREENHOUSE GAS (GHG)EMISSIONS

- Burning fossil fuels (coal, petroleum, gasoline, and natural gas)
- Fossil energy use by industries (steel, plastic, aluminum, others)
- Production of industrial fertilizers, hydrogen from natural gas, and cement
- Emission of methane from natural gas extraction, and from agriculture
- Emissions of methane from anaerobic decomposition in landfill, sludge digestion, wetland treatment, open liquid and solid manure storage.
- Vehicular emissions of CO_2 and nitric oxides
- Forest and tundra fires caused by humans and lightning
- Methane emissions from melting tundra permafrost by global warming

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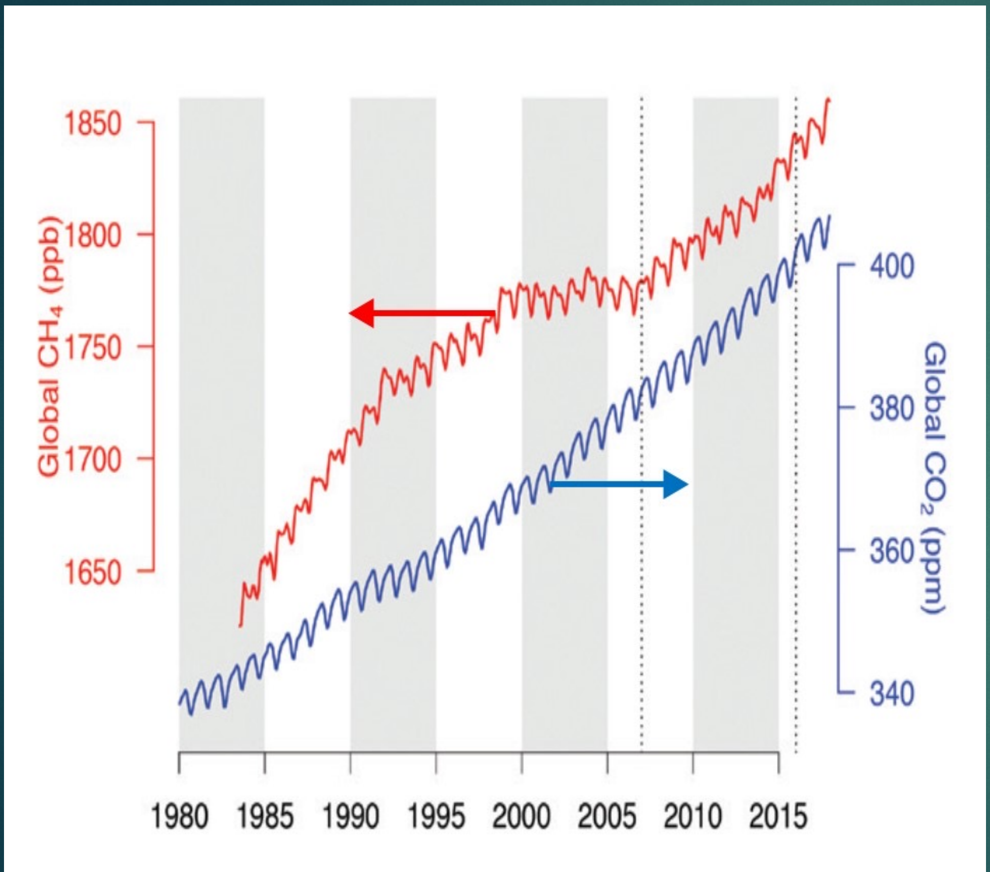
Global Climatic Change



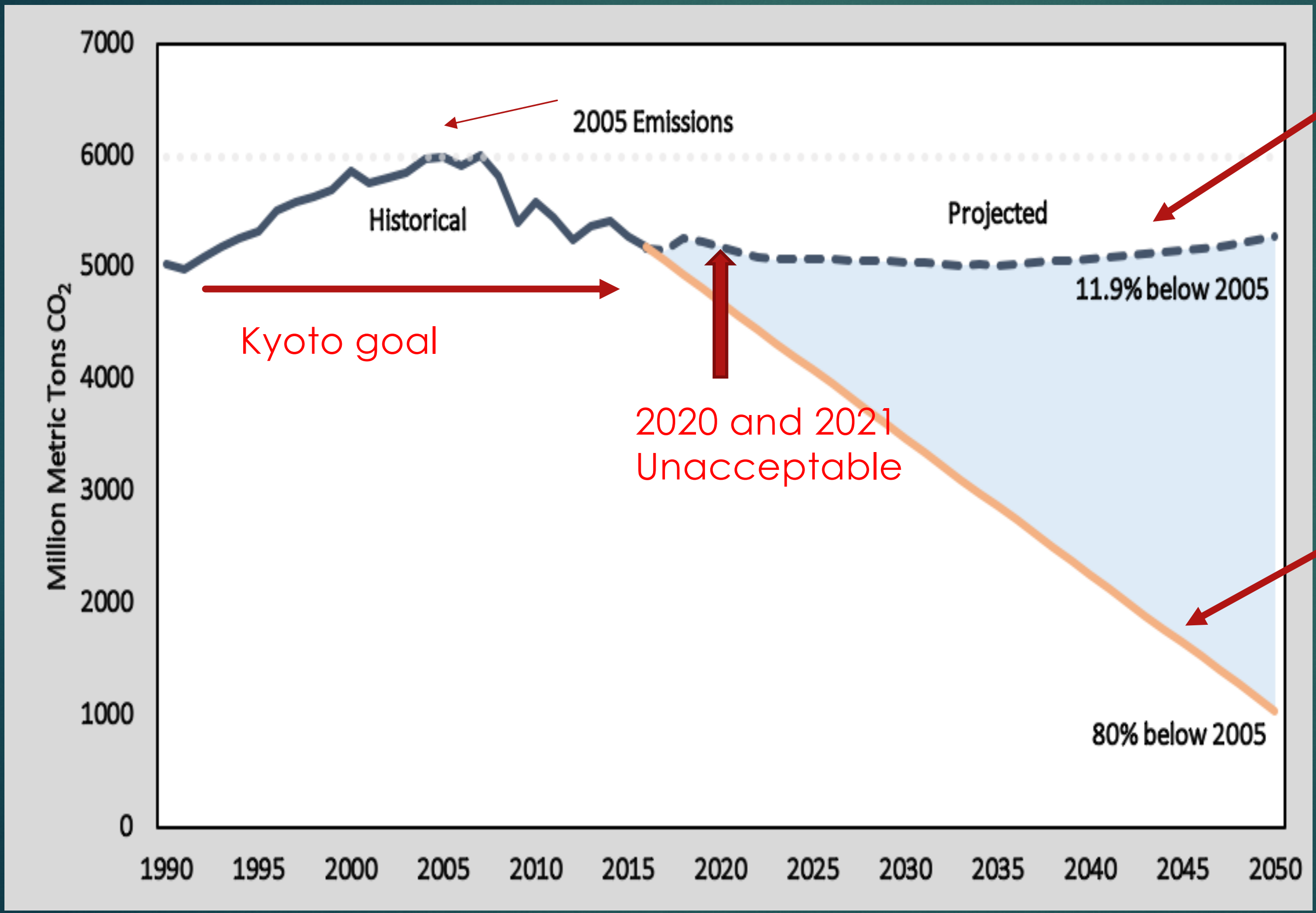
- CO_2 concentration at the onset of the industrial age was stable at 280 ppm
- Doubling of carbon dioxide in Earth's atmosphere from preindustrial levels would warm Earth's surface between 1.5°C and 4.5°C
- 2020 CO_2 concentration in the atmosphere was 420 ppm and growing. Temperature already increased by 1.2 °C
- Methane, because of the high Global Warming Potential (GWP -25 - over 20 years, more over 100 years) is as problematic as CO_2

Most of CO_2 and CH_4 emitted today will still be in the atmosphere, land biosphere, or oceans thousands of years later, until geologic processes can form rocks and deposits that would incorporate this carbon (carbonate)

Intergovernmental Panel on Climate Change - IPCC

- In 1997 in Kyoto (Japan) 192 countries adopted a binding treaty on climate change calling for an average 5 % emission reduction compared to 1990 levels by 2012 and limit global atmospheric warming to 1.5 degrees Celsius (1.5°C) over pre-industrial levels by middle of the century
- If busines as usual (BAU) economics and emissions continue, the 1.5 °C limits will be exceeded in less than a decade from now
- The IPCC (2021) Climatic Warming report is a" Code Red" warning to the societies and individuals. There is no scientific doubt that humans are fueling climate change.
- Earth is progressing to a warming threshold that, if crossed, could push the Earth System toward an irreversible "Hothouse Earth". Decarbonization of economic sectors is needed to avoid the Hothouse Earth status (is it here already?)

Pre 2020 US CO_2 emission forecast



Business as Usual (BAU) scenario

CO_2 emissions reduction to meet Paris 15 Goals

Source: U.S. Energy Information Administration (2017). Reprinted from Levin and Davis (2020)

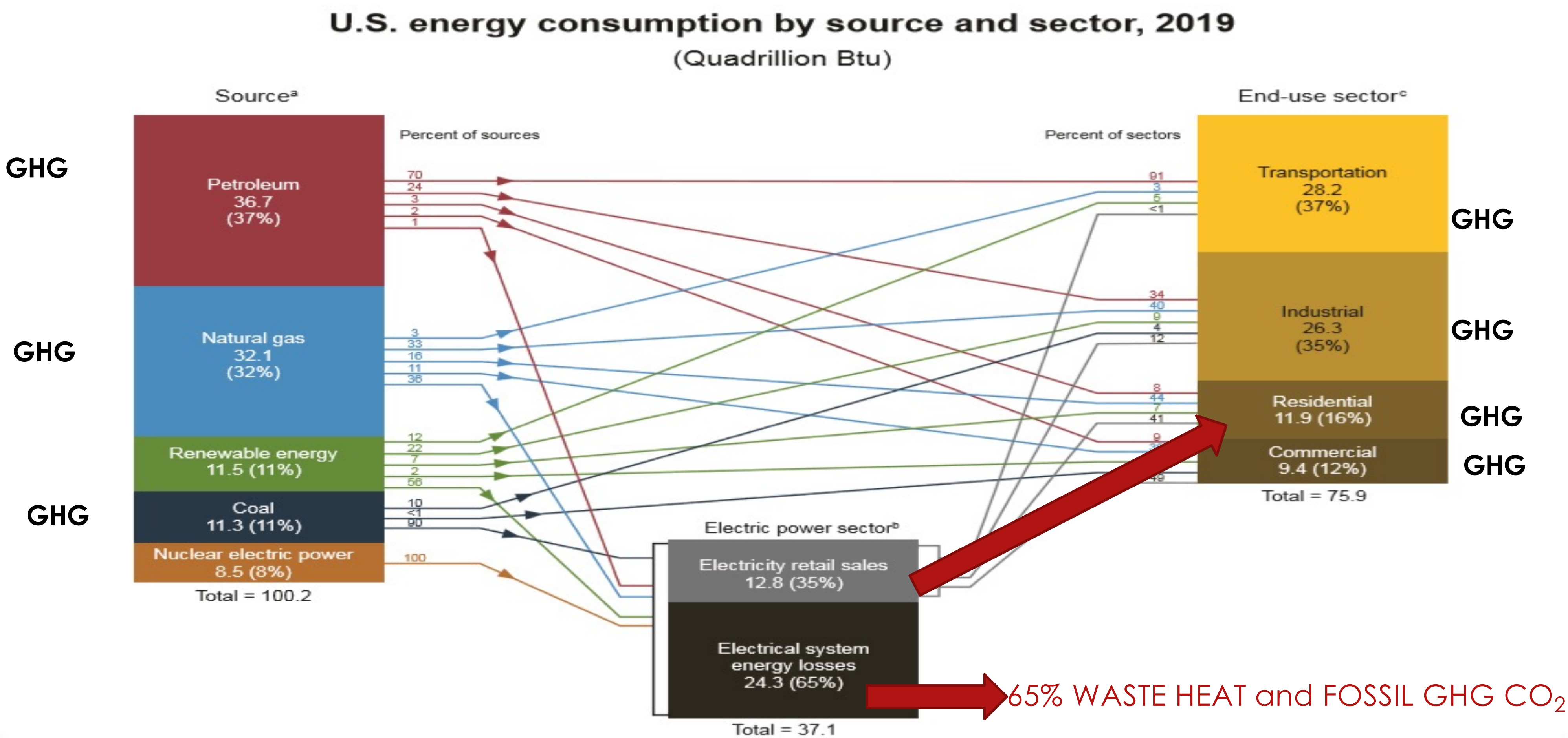
Net zero carbon emissions and Decarbonization

Net-zero emissions are achieved when any CO_2 or other GHG emitted by a utility or by a city is offset by an equivalent amount of CO_2 removal and sequestration.

Decarbonization means removal of CO_{2eq} emissions from sources of GHG

Full or deep decarbonization means no GHG emissions and should include implementing **negative emissions** which would remove CO_2 from the atmosphere and reduce catastrophic impacts of global warming

"Climate stabilization requires full decarbonization of our energy systems and net zero greenhouse-gas emissions. Decarbonization – the only safe haven from disastrous climate change – is the ultimate goal" . J.C. Sachs (2015)



1 Quadrillion BTU = 10^{15} (Btu) * 0.000293 (kW-h/Btu) = 0.293 * 10^{12} (kWatt-hours) = 0.293 (TeraWatt-hr)

Total Energy production = 29.3 TeraWatt-h

To produce electricity = 10.87 TeraWatt-hr

Residential energy use = 3.5 TeraWatt-hr

Commercial energy use = 2.75 TeraWatt–hr.

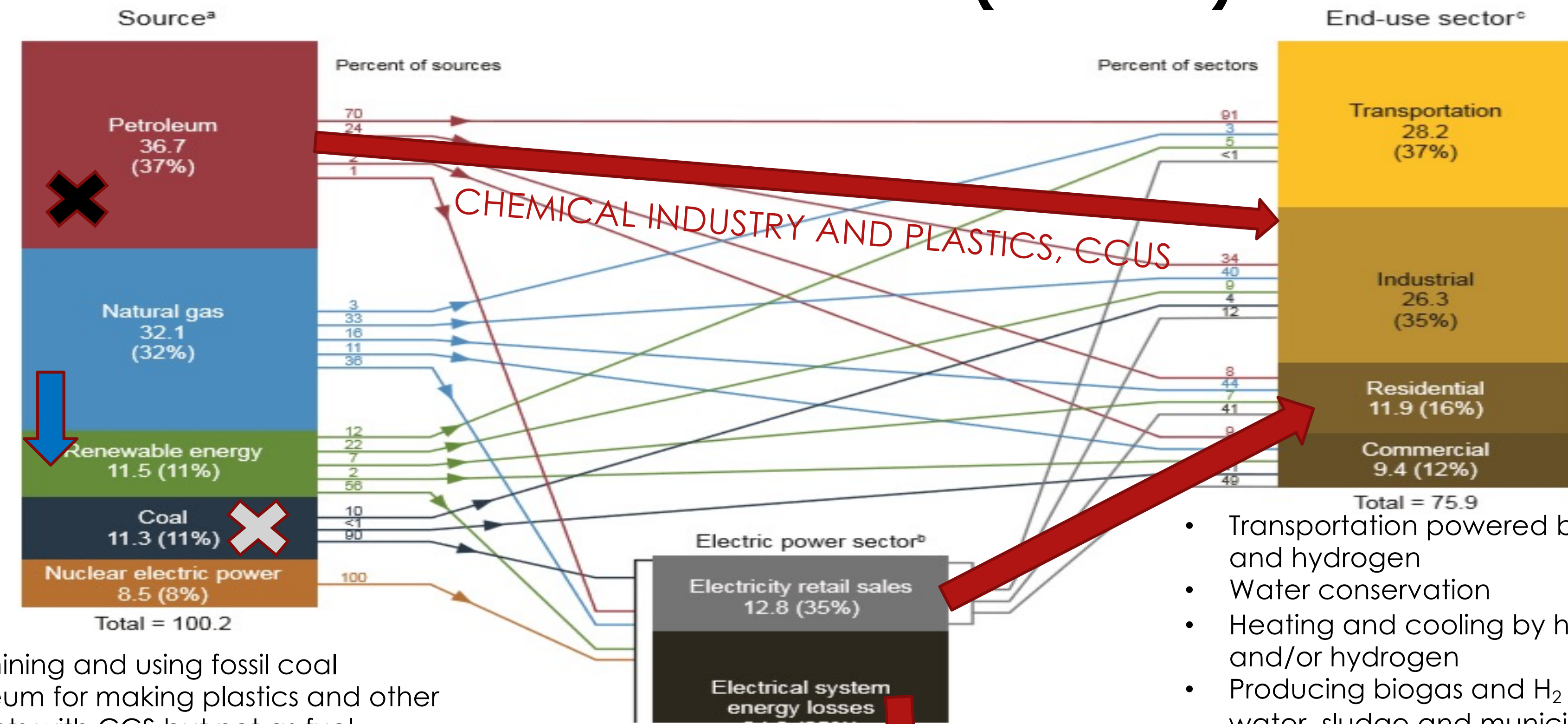
US Population in 2019 = 330 million

Per capita daily electric energy use = 29.9 kW-hr capita^{-1} day^{-1}

Source Energy Information Agency April 2020

PLAN FOR THE FUTURE (2030 +)

BLUE H_2



Electricity +H_2

- Transportation powered by electricity and hydrogen
- Water conservation
- Heating and cooling by heat pumps and/or hydrogen
- Producing biogas and H_2 from used water, sludge and municipal solid waste
- Carbon sequestering
- Renewable energy production by sun and wind with battery storage

- Stop mining and using fossil coal
- Petroleum for making plastics and other products with CCS but not as fuel
- Natural gas to make blue H_2 with CCS
- Greatly increase renewable energy production, including energy from used water and waste solids
- Greatly increase geothermal and wind power

CCS – Carbon capture and storage

Recoup Heat and Implement Carbon Capture Utilization and Storage (CCUS)
Electricity by hydrogen fuel cells
Convert natural gas power to Blue H_2

ELECTRICITY PRODUCTION ESTIMATES IN THE USA[1] after 2010 in TeraWatts – hrs			Decarbonization			ELECTRICITY estimate in 2020 (EIA, 2021)	
YEAR	2010	2020	2030	2040	2050	2020	2050
US Population in millions	309	332	355	373	389	332	389
Coal and oil	1 884	791	300	0	0	791	540
Natural gas	999	1630	1 500	900	200[2]	1 630	1 900
Nuclear[3]	807	790	730	670	600	790	600
Hydro, air, geothermal[3]	275	310	350	450	500	310	310
Wind[4]	95	338	1 100	1 850	2 500	338	700
Solar[5]	1	133	600	1 100	1 800[6]	133	1 000
Wood, manure, food waste biogas, and H_2 [6]	54	Blue H_2 56	200 200	900 300	1 700 400	56	150
TOTAL EIA) predicted (with excess for electric transportation)	4 118	4 048	4 200 (4 980)	4 350 (6 170)	4 500 (7 700)	4 048	5 200
Average fossil kg CO_2/kWatt-h	0.60	0.43	0.22	0.12[2]	0.05[2]	0.43	Positive 0.32

[1] First two columns (2010 and 2010) contain EIA (2021) estimates. (1 TeraWatt-h = 10^9 kiloWatt-h).
[2] It is expected that after 2025 natural gas will become a source of blue hydrogen by steam reforming . Also, methane could be replaced by renewable energies that do not emit CO_2, similarly to IEA (2019) and Sachs' (2015) forecasts. However, extracting methane has losses into atmosphere and by flaring that could account for around 3-4% GHG emissions. (Howard and Jacobson, 2021)
[3] The increase of renewable energy production is primarily from geothermal energy and geo to air and air to air heat pumps and exchangers.
[4] Based on IEA (2021) forecast and EERN (2021) reporting of wind power installations in 2021
[5] Biden's administration goal for solar energy production by 2050 is 40% of the total
[6] Based on the estimated conversion of water/energy/ solids management from the current to hydrogen presented in this report. Also it will include green hydrogen made from natural gas with sequestering CO_2

0.98 kg of CO_2 / kW-hour produced by coal fired power plants

0.60 kg of CO_2 / kW-hour produced by natural gas power plants

0 kg of CO_2 / kW-hour by nuclear, solar, wind, geothermal and hydro power

France 0.1 kg of CO_2 / kW-hour because of a high reliance on nuclear and hydro power (90% in 2014)

Similarly, Austria, Brazil, Italy, Norway, Paraguay, Switzerland, where hydropower dominates

In the table total electric energy produced in 2020 represents 13% of the total energy sources.

In 2021 **16 836** Megawatts land wind power was added in the US. Second to China. Assuming 50% efficiency this represents about 75 Terawatt-hr annual increase of wind renewable energy after 2020 . Coastal wind production is also significant.

Solid waste problems

Landfill in Arizona

- In 2015 the US generated 238 Mt MSW. 35 % was recycled or composted, 13 % combusted with small energy recovery, and 52 % discarded, into landfills (US EPA)
- About 18% of MSW is plastic and rubber made from fossil petroleum using a lot of fossil energy. Plastic incineration emits GHG.
- Landfill emits methane that is a GHG pollutant (25 times more potent than CO_2).
- Until 2017 most of recycled solid waste in the US and other developed countries was exported to China. In 2018 China restricted the import of "garbage" and the recyclables go to landfills in the US.
- In EU countries, landfilling will be banned after 2030.

Much of nicely packaged and preprocessed recyclable waste is after 2018 going to landfills.

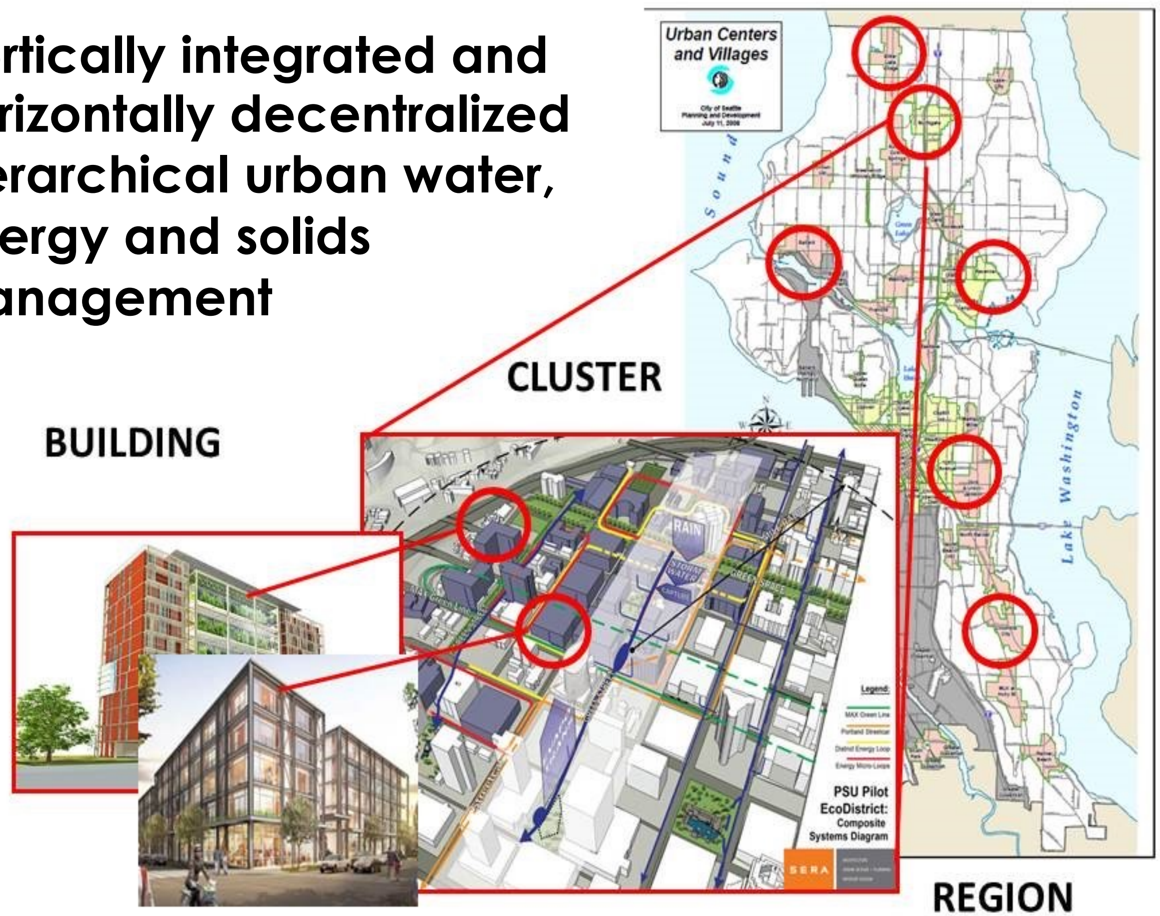
Figures credit Top Adam Lavine Flicks. Bottom China dialogue Ocean

REGION
Integrated resource recovery
Energy recovery (power plant)
Recharging groundwater
Solid waste recycle facility

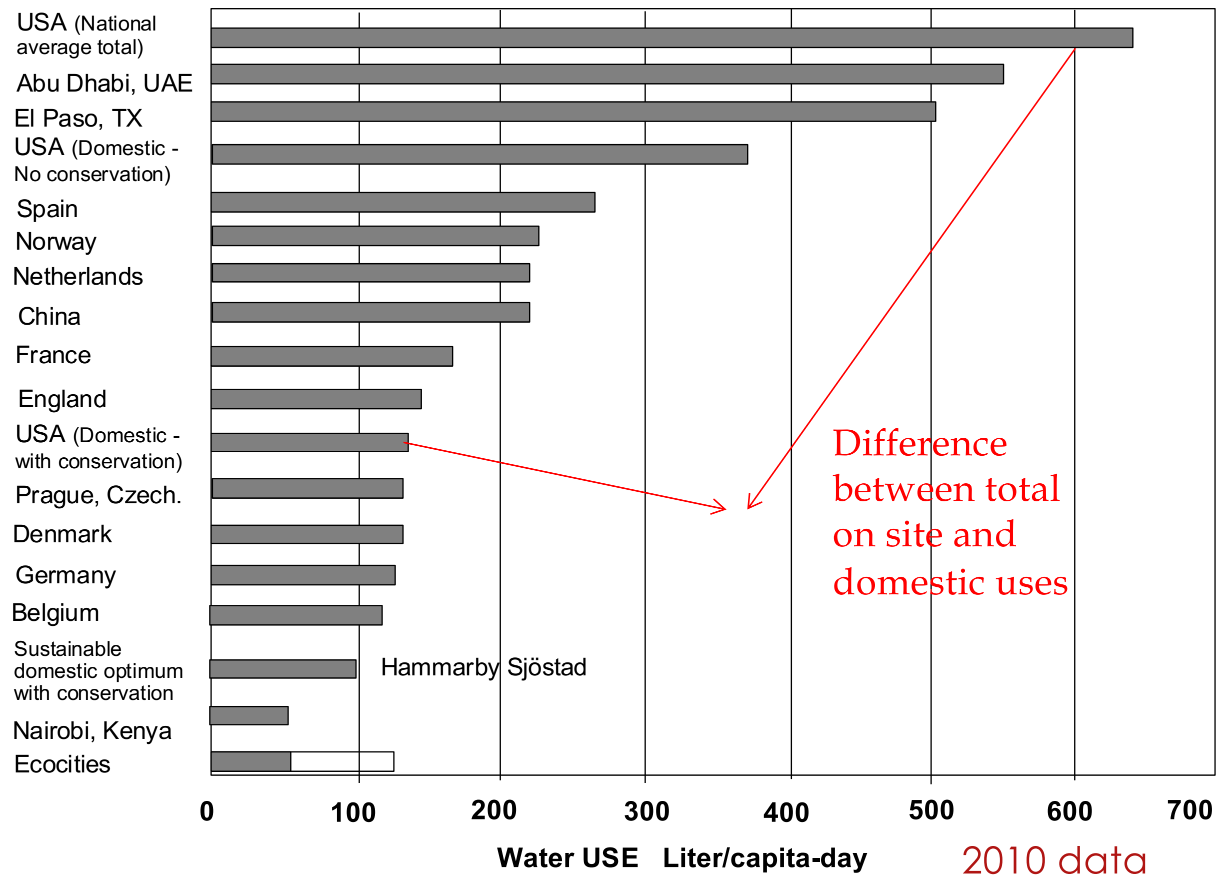
DISTRICT
Grey water recovery and fit for reuse treatment, district reuse
Stormwater capture, drainage and storage
Providing ecological flow

BUILDING
Water conservation
Heat and cooling energy recovery (heat pumps)
Xeriscape landscape
Roof solar panels
Passive energy conservation
Green roofs

Vertically integrated and horizontally decentralized hierarchical urban water, energy and solids management

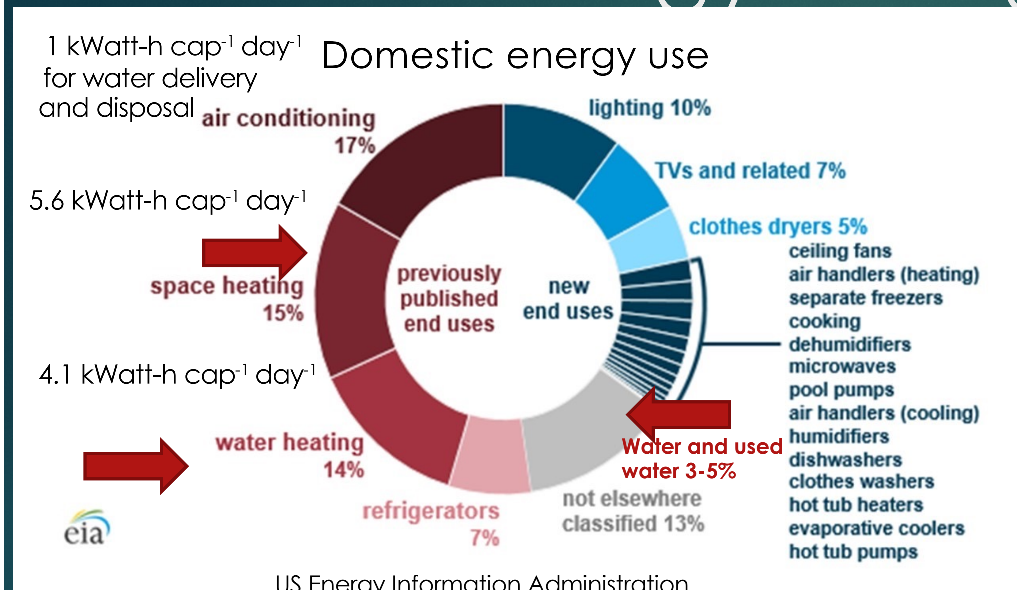


Water use is high in US

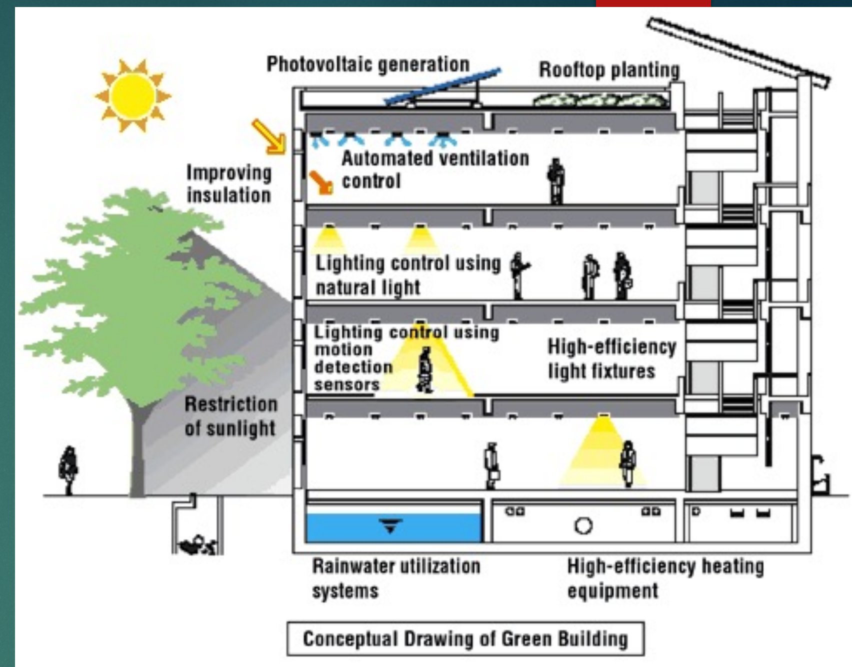


- In the US and some other countries water use is very high and unsustainable.
- The largest unsustainable use is outdoor for irrigation of lawns in regions that originally were arid and desert and where water must be delivered from large distances (Colorado River to California and Arizona, South China to North China)
- With global warming the availability of water is diminishing.
- Water use in Europe is much smaller . US Goal shall be bringing US water use to that of Europe

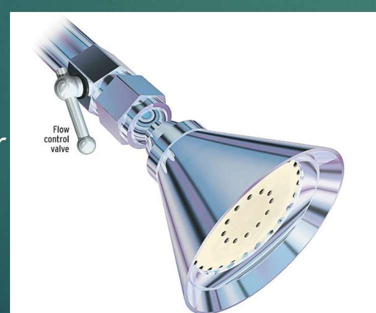
Domestic energy savings



Passive energy savings



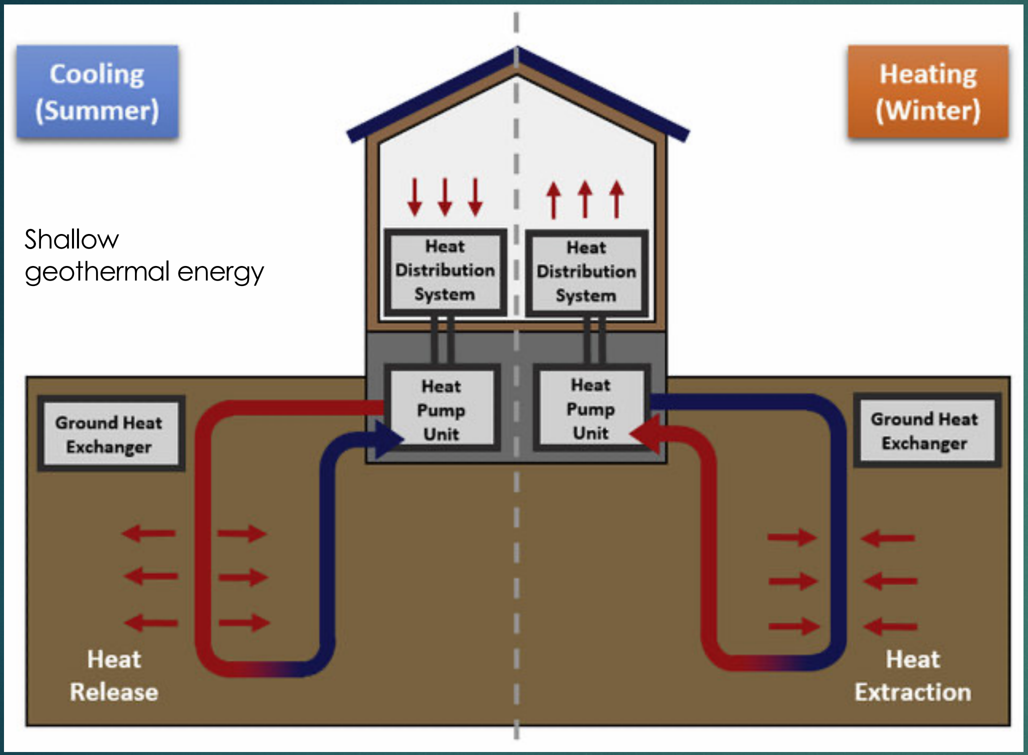
Tankless water heaters



Water saving showerhead

Dual flush toilet 3 and 6 liters/flush will save up to 75% of water for flushing when compared to standard pre 2000 toilet

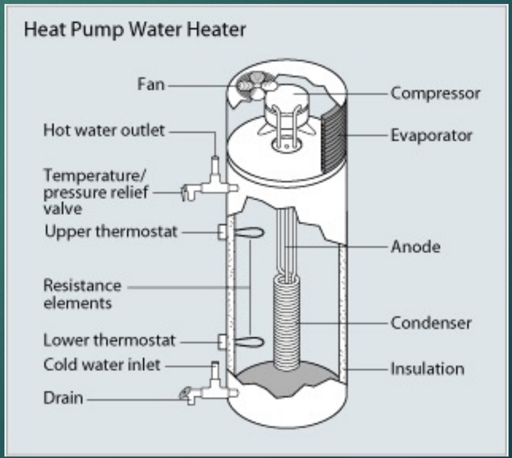
HEAT PUMPS – ON-SITE SOURCE OF ENERGY



Heat pumps can be used to extract heat and cooling from sewers, lakes, ground, air, etc., with 80% energy conversion efficiency

- Air to air
- Water to Air
- Water to Water
- Ground to Air and water

Goodman standard heat pump and air conditioner



TRANE Ground to Air Pump

Picture credit Jeon J.S. et al. (2018), Energy, 152, DOI:10.1016/j.energy.2018.04.007, Copyright Elsevier

Bullitt Center in Seattle

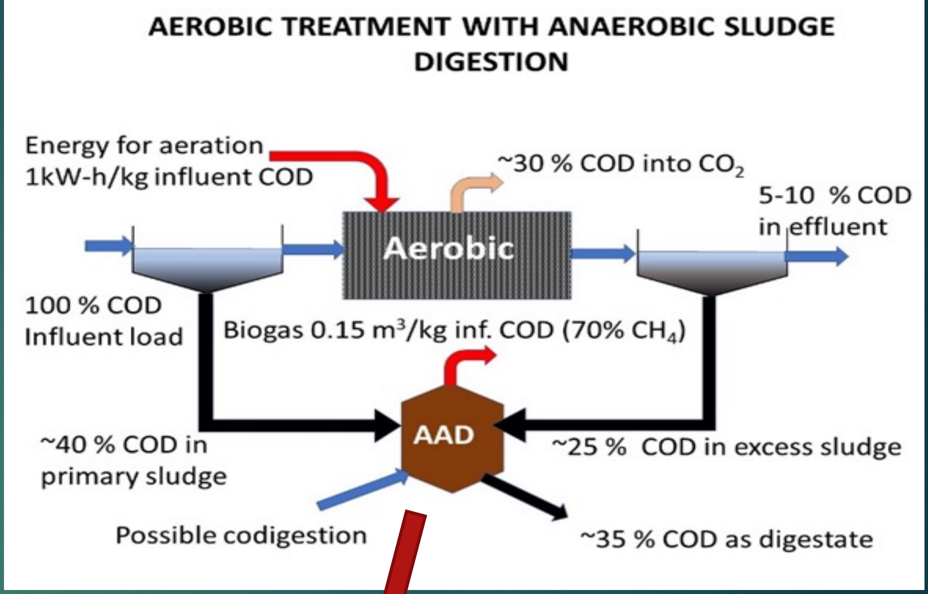
Negative (better than net zero) carbon emissions and no water waste building in Seattle

The practices incorporated in the building include energy conservation and geothermal energy, roof solar panels, rainwater harvesting, water-less toilets, black water and solids aerobically composted, gray water treated by wetland and reused. (Pictures credit Nick Lehoux) .

ENERGY AND OTHER RESOUCES FROM USED (WASTE) WATER AND WASTE SOLIDS

Current Aerobic Used Water Treatment and Anaerobic Codigestion of Sludge with biodegradable MSW Solids

- Aerobic treatment uses energy and emits CO_2
- Codigestion of sludge with biodegradable waste solids and liquids produces more biogas and residual solids.
- Typical biodegradable solid (food and yard) waste production in the US is about 0.5 kg/cap-day that can be co-digested with the sludge and produce biogas Manure, airport deicing deicing fluids and other biodegradable waste solids can be also codigested
- Electric energy can be recovered from biogas by combustion and turbines



Beginning of 20th Century Aerobic Used Water Treatment

Advanced biological treatment processes for used water treatment and reuse treating mixed sewage or separated black water

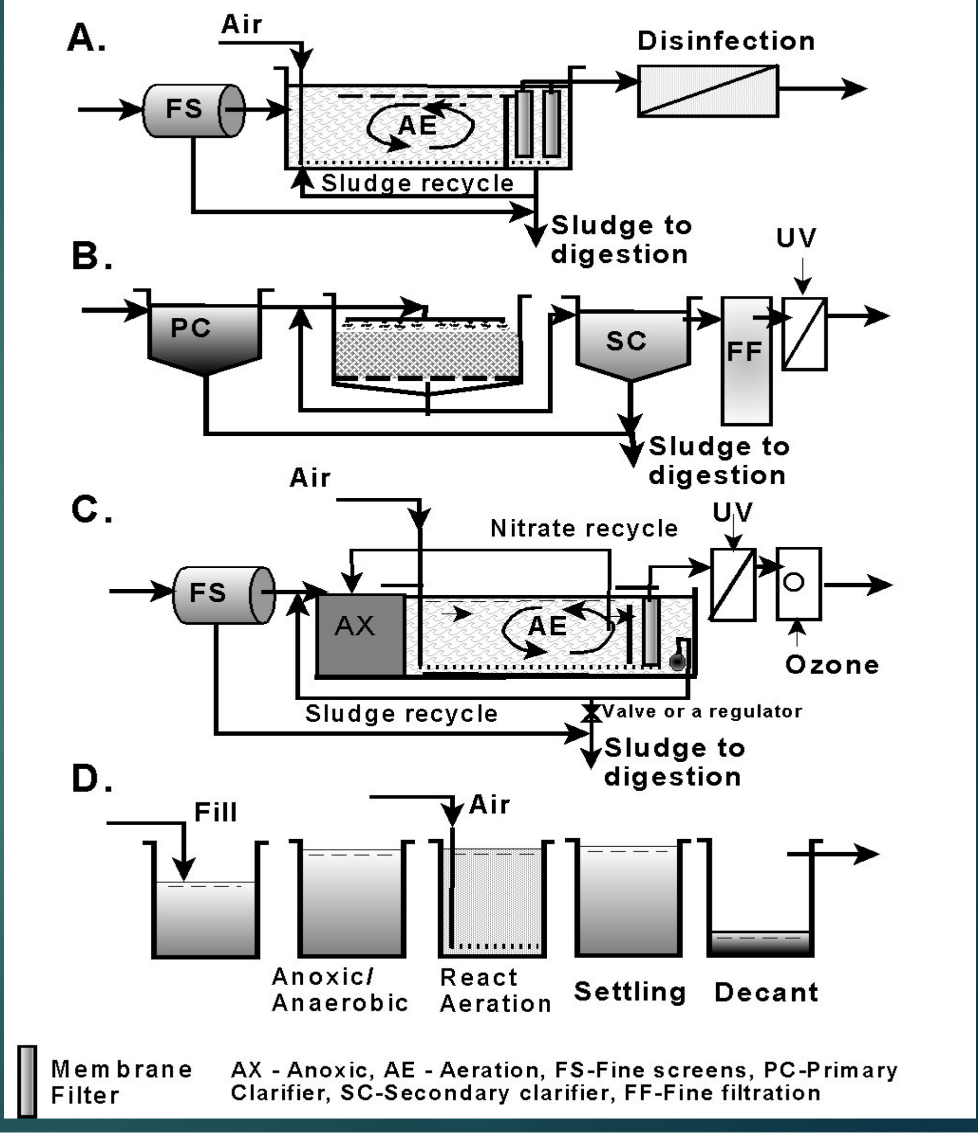
A. Aerobic membrane bioreactor, a modification of the conventional activated sludge process;

B. Trickling filter;

C. Bardenpho process for BOD, TSS, nitrogen and phosphorus removal with anoxic and oxic units; and

D. Sequencing Batch Reactor.

Between 50 % to 70% of incoming COD is converted to CO_2 and bicarbonate. Systems A, C, and D use fossil energy for aeration and pumping.



There is not enough energy in used water

ENERGY POTENTIAL - Daily production per capita

COD per capita unit load (including in-sink grinders) 130 g
COD removed (minus COD in the effluent (95%) 123 g
Methane produced 0.45 L/g of COD removed 55 L of CH_4
Methane energy 9.2 W-hr/L of CH_4 0.51 kW-hr

TOTAL ENERGY POTENTIAL 182 kW-hr/year
35% efficiency when converted to electricity 64 kW-hr/year

TOTAL AVEGAGE ENERGY USE RELATED TO MUNICIPAL WATER USE (WITHOUT HEATING)[1] 365 kW-hr/capita-year

Type of used water	Combined	Graywater with grinded food waste in	Graywater without food waste[1]	Black water
	(Waste) Water Loads in Grams capita^{-1} day^{-1}			
COD	130	55	32	75
BOD_5	60	35	20	25
Nitrogen	13	2	1.5	11
Phosphorus	2.5	0.5	1.5	2

1 Food waste collected and reused with the municipal solid waste (MSW
2 The difference between the phosphorus content of Graywater and combined used water reflects the ban on the use of phosphate detergents
3 Source Henze and Comeau (2008) – open access

Include other sources and convert WTRP to Integrated Resource Recovery Facility (IRRF)

[1] per US EPA

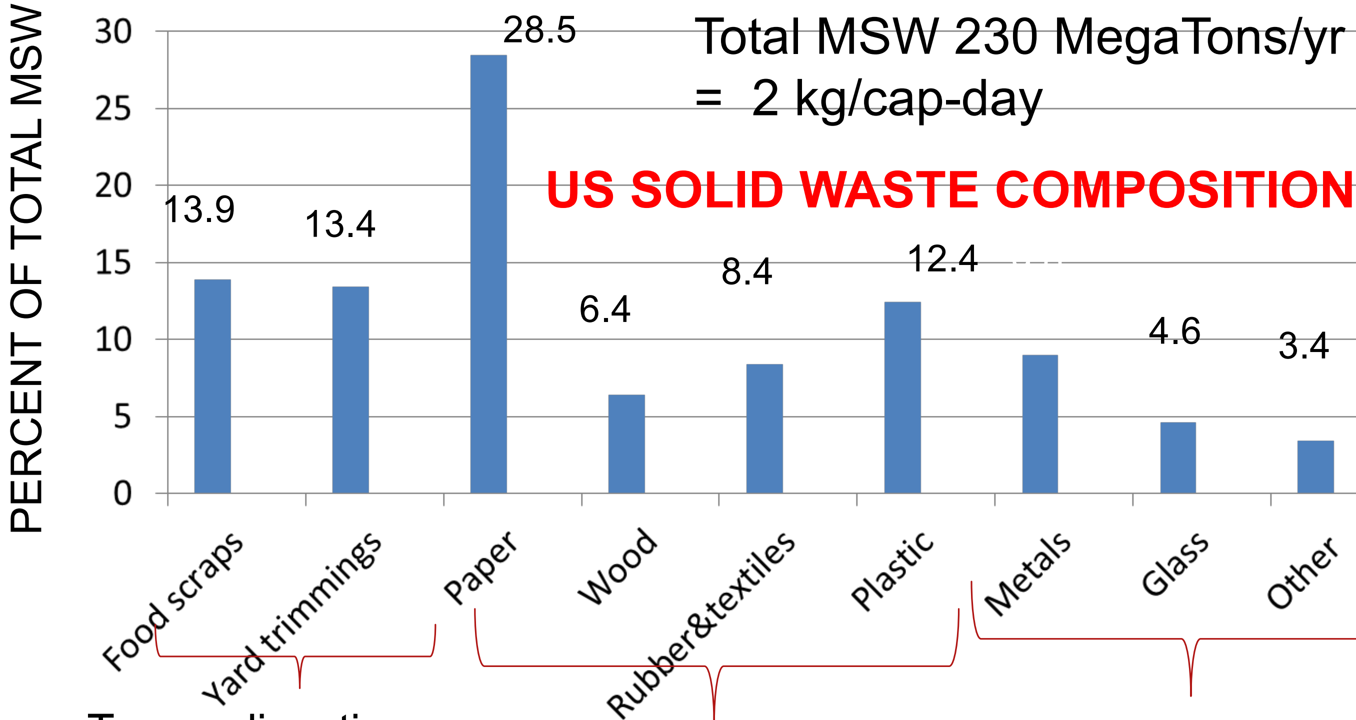
Integrate Municipal Solid Waste

- Majority of MSW is deposited to landfills where slow anaerobic decomposition emits landfill gas – LFG (CH_4 and CO_2). Not all MSW is decomposed to LFG
- LFG capture needs capping the landfill to reduce the LFG emissions
- About 60 to 80 % of the LFG can be captured; rest (mostly methane and CO_2) is emitted.
- High COD landfill leachate can be anaerobically treated , which produces more CH_4
- Municipal biodegradable and combustible solids have relatively high energy content up to 7 kWatt –h per kg of volatile solids . 5.2 kWatt-h/kg solids was measured for NY city combustible garbage

Pictures by V. Novotny

Landfill in Wisconsin in 2000

LFG energy plant with gas storage and cleaning tanks



To: co-digestion, Include also manure, glycols & other biodegradable wastes

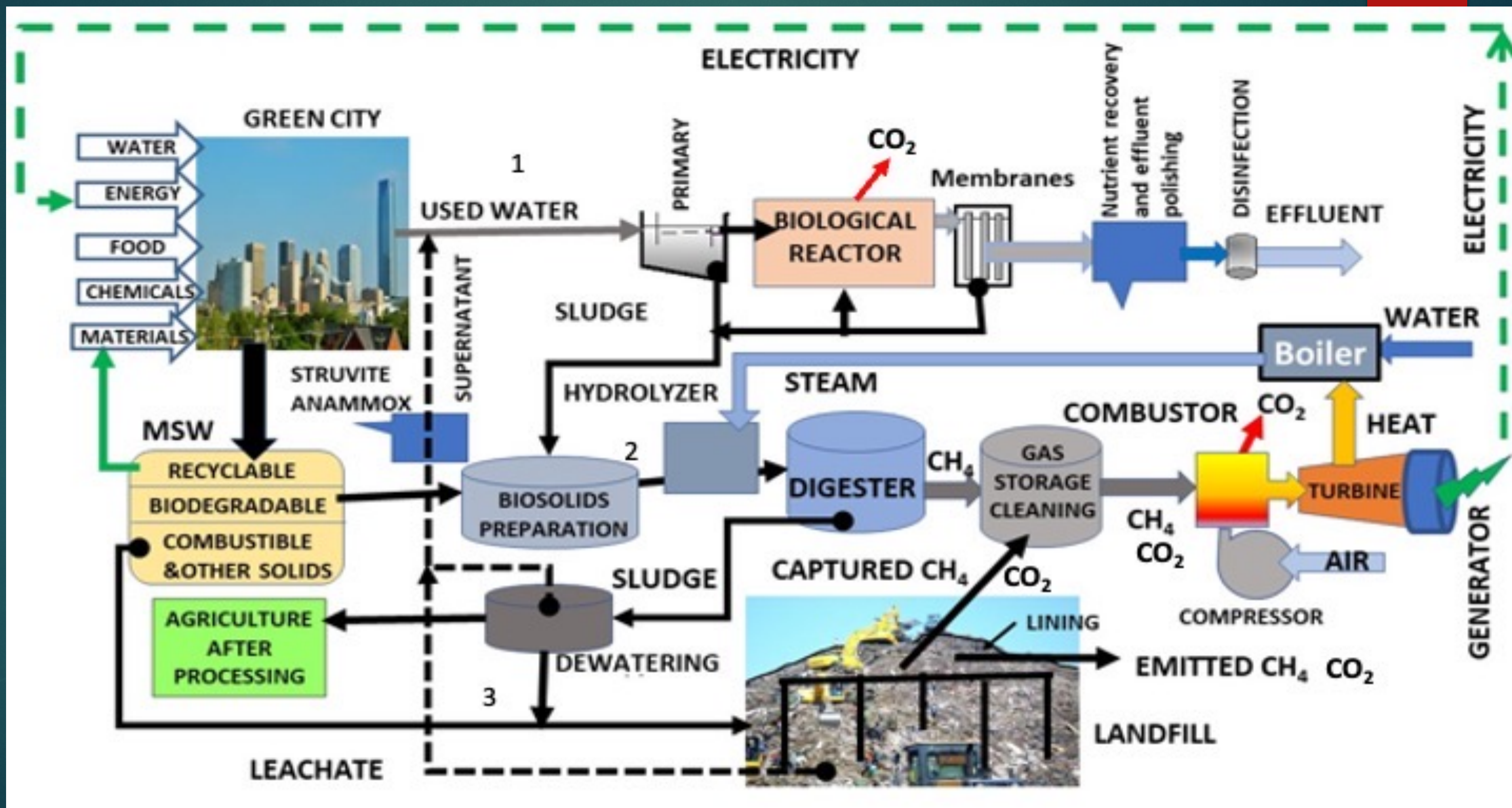
To: Incineration or gasification and/or recycle

To: recycle

Residual sludge from treatment of used water represents about 10% of the biodegradable MSW

Rubber and plastics are made from fossil petroleum and emit GHG when incinerated or gasified. Fossil energy use for making plastic is high (7-32 kWatt-h/kg of plastic)and cannot be fully recovered

Alt. 1. Current advanced Three lines Integrated Resource Recovery System with traditional process units linked to Urban Metabolism



Source Novotny (2020)

2015

SUMMARY

Alternative 1

CO_2 EMISSIONS AND CREDITS

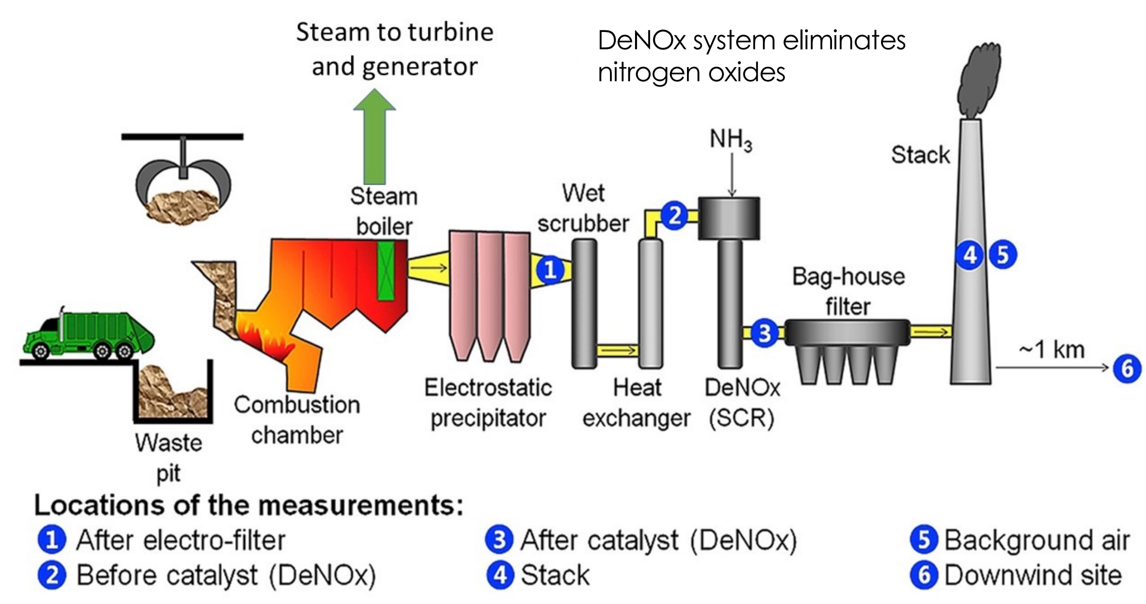
In kg CO_2 $cap^{-1}day^{-1}$ and ($kWatt\text{-}h$ $cap^{-1}day^{-1}$)

for a traditional system with aerobic used water treatment, codigestion and landfill gas capture

0.52 kg Fossil CO_2/kWatt-h

Line	GHG CO_2 emissions	Non GHG CO_2 emissions	GHG CO_2 credit	Comment
1	Positive emissions		Negative emissions	
Water delivery and treatment	0.46 (0.88)			Fossil energy of water delivery and aeration. Large CO_2/kWatt-h
		0.1		Aeration CO_2 emission from COD oxidation
2 Digester				No CO_2 emissions. CO_2 from digestion is sent to power plant
3 Landfill	0.54			LFG escaping from landfill
Power plant			-0.44 (-0.61)	CO_2 emission credit for green electricity
		0.41		Turbine flue gas CO_2 emission
Totals	1.0 (0.88)	0.51	-0.44(-0.61)	Totals without water heating
Water heating	2.13 (4.1)			Domestic water heating for dishwasher, shower, and laundry
Total without hydrolyzer	3.13 (4.98)	0.51	-0.44(-0.61)	The system is a highly positive CO_2 emitter
Hydrolyzer heat		0.6 -1 (1.2-2)		Dewatering biomass, increasing temperature to 160°C, and pressurizing

INCINERATION OF SOLID WASTE AND SLUDGE



Swiss incinerator. Source and credit Setyan et al. (2017), *Atmospheric Environment* **66:**99-109, Copyright and permission Elsevier (2017)

Air Pollutant	Removal Process	Reduction %
Fly ash	Electrostatic precipitators + fabric filter	95 – 99
SO_x and HCl	Wet scrubbers or multicyclones	50 – 90
$DeNO_x$	Selective catalytic reduction	10 – 60
Heavy metals	Dry scrubbers + electrostatic precipitation	70 – 95
Dioxin and furans	Activated carbon + fabric hose filters	50 – 99.9

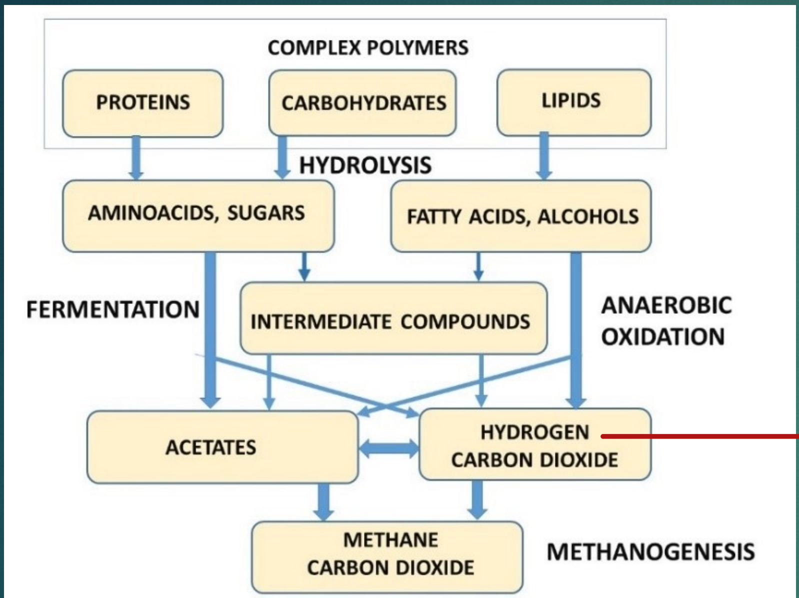
- Burning of MSW is known as Waste-To-Energy (WTE). It involves complete combustion of MSW and sludge mix
- *Residues generated by incinerators* include bottom ash (25%of feed), fly ash (1-5% of feed), scrubber water, and several miscellaneous waste streams.
- Flue gas contains about 33% fossil carbon (GHG) from burning plastics and rubber and 67% of non fossil carbon.
- Energy yield from incineration is less than 1 kWatt-hr from 1 kg of combustible MSW
- If moisture of feed solids is high, auxiliary heating by natural gas is needed

The EU is in the process of cutting off funding for new incinerators,

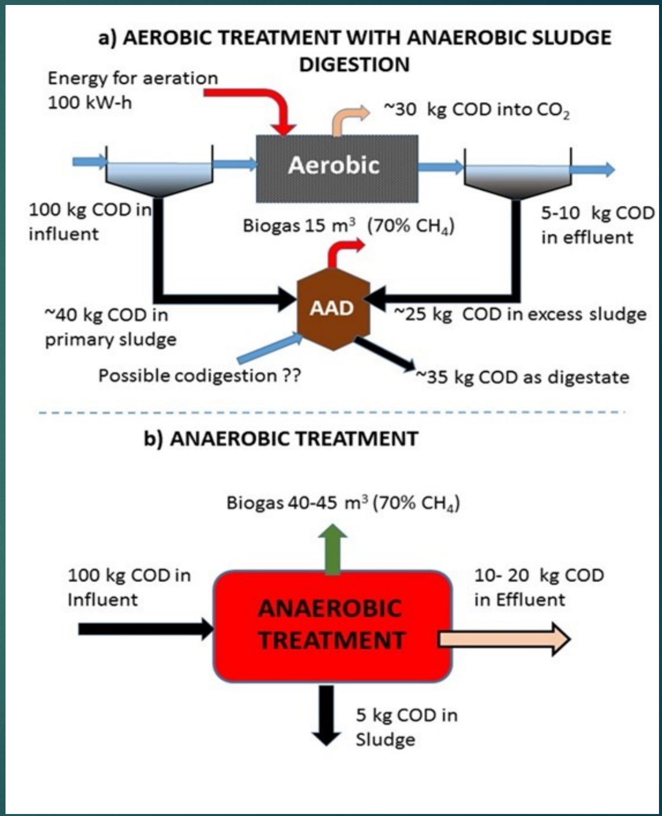
SUSTAINABILITY OUTLOOK AND PROBLEMS WITH CURRENT WATER & MSW SYSTEMS

- The traditional aerobic water reclamation systems use more energy than contained in organics in used water and sludge.
- The energy needed to treat, transfer and deliver water to the city users is significant, from 1 kWatt-h/m^3 to 5 kWatt-h/m^3.
- Household water heating requires far more energy (~ 10 kWatt-hr/m^3) than that contained in used water organics (~ 1 kWatt-hr/m^3). Part of the heat energy could be recovered by heat pumps.
- Combusting digester gas for producing electric energy emits CO_2.
- Without expensive and energy demanding air pollution control Incineration of MSW emits toxins and fossil CO_2 from plastics.

ANAEROBIC TREATMENT AND DIGESTION PRODUCE BIOGAS (CO_2 AND CH_4) AND ALSO SOME HYDROGEN



If H_2 is desired digestion product, methanogenesis is suppressed by keeping pH at 5.5

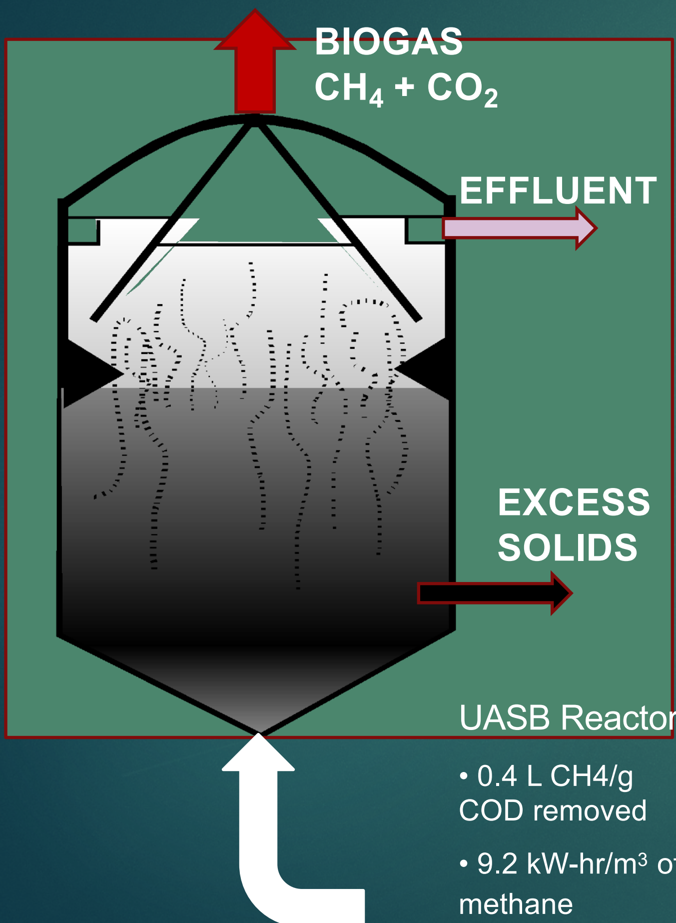


Fermentation and Methanogenesis. Products of low pH fermentation and oxidation are acetates and hydrogen that are used by methanogens to make methane in the methanogenesis step

Comparison of aerobic and anaerobic treatment
3 times more biogas produced by anaerobic treatment

Sources Van Lier et al. (200) and Bartáček and Novotny (2015)

Upflow Anaerobic Sludge Blanket (Fluidized bed) Reactor - UASBR



UASB Reactor

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

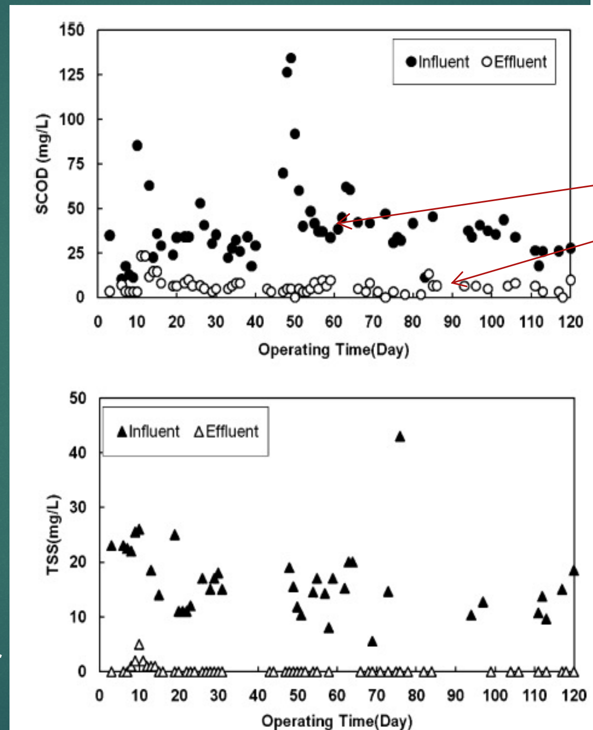
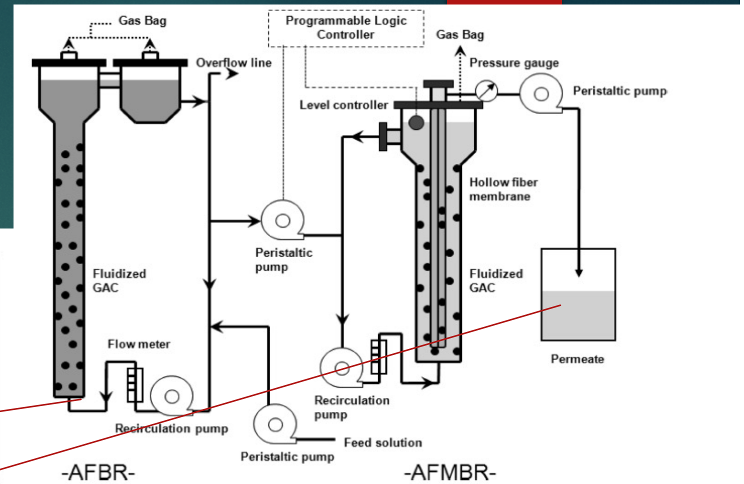


FIGURE 6. Removal behavior of SCOD and TSS in the AFMBR component of the two-stage AFBR/AFMBR system at a permeate flux of 10 L/m^2/h.



TWO STEP ANAEROBIC FLUIDIZED BED REACTOR WITH MEMBRANE REACTOR

Contains granular activated carbon (GAC)

Kim et al. (2011) EST 45:576-581 with permission of American Chemical Society

Membrane microfiltration

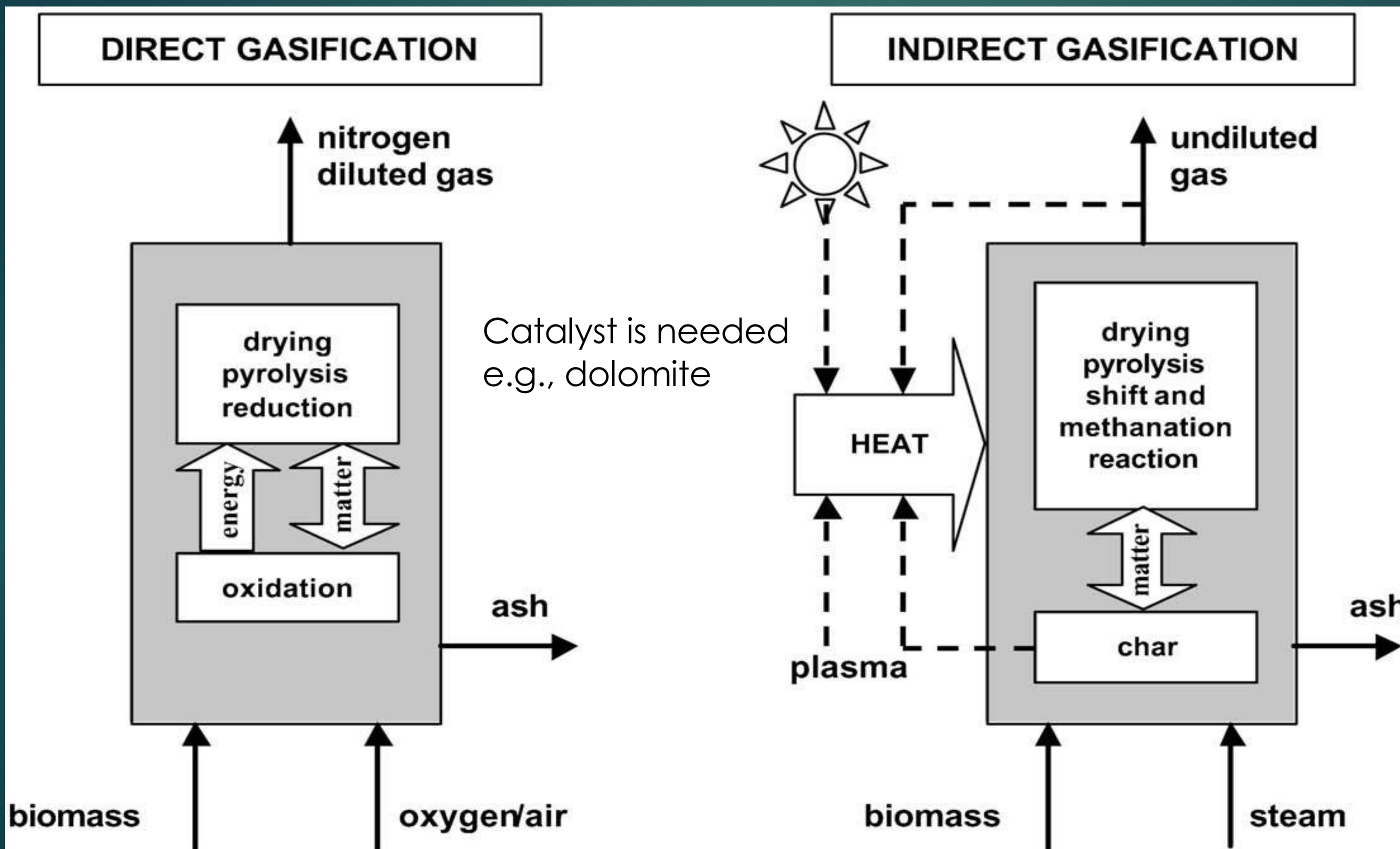
Replacing secondary settling and filtration. It could be energy demanding.

Reverse osmosis for grey water recovery

Microfiltration, courtesy Siemens

UV radiation or ozone disinfection

Replacing Digestion, Incineration and Landfill with Direct and Indirect Gasification.



Catalyst is needed e.g., dolomite

A chemical high temperature decomposition of organic matter into synthetic biogas (syngas), char and tar, and biofuel.

It can convert one ton of MSW to more than 2 MWatt-h energy/ton of combustible MSW

Modern future hydrogen - based systems with indirect gasification can reach energy yield greater than 5 MWatt-h/ton of combustible sorted MSW

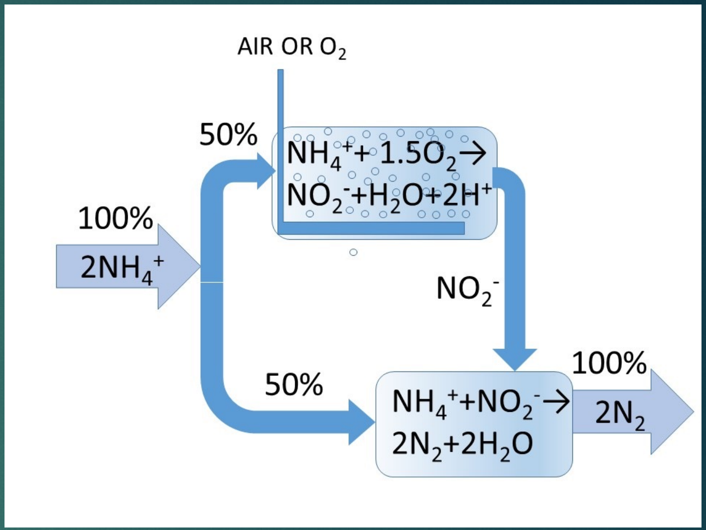
Picture replotted with permission from Belgiorno et al, 2003,. *Waste Management* **23:**1-15, Copyright Elsevier (2003)

ENERGY YIELD REACTIONS FOR GAIN IN CO & H_2

Energy from	Reactions	Temperature °C	Reaction energy kJ/mole	Comment
Combustion-Incineration	Org C + $O_2 \rightarrow CO_2$ $C_mH_nO_p$ + (m+0.5*(n-p)) O_2 $\rightarrow$ mCO_2+0.5 n H_2O		Exothermic 394	Flame is present, CO_2 is emitted
Direct gasification	Org C + 0.5 (O_2+3.7 N_2) $\rightarrow$ CO + 1.85 N_2 $C_mH_nO_p$ + 0.5 (m-p) (O_2+3.7N_2) $\rightarrow$ mCO+0.5n H_2+1.85 (m-p) N_2	>900	Exothermic 111	Air is the feed oxidizer and N_2 diluted syngas is the terminal product
Indirect gasification	Org C +$H_2O \rightarrow CO_2$ + 2H_2 $C_mH_nO_p$ + (m-p) H_2O $\rightarrow$ m CO + (m + 0.5n -p) H_2	>850	Endothermic -131	Steam is a feed to the gasifier and H_2 enriched and undiluted syngas is produced.
Low temperature steam reforming of CO to CO_2 and H_2	CO + $H_2O \rightarrow CO_2$ + H_2	400	Exothermic 41	Could occur in indirect gasification to produce more H_2 and adds heat to the gasifier, or internally in hydrogen fuel cell.

Other current more advanced technologies

- Heat/cooling energy recovery from water by heat pumps
- Production of struvite (ammonium magnesium phosphate) and calcium phosphate fertilizers from used water effluents and digester supernatants
- In ANAMMOX (anaerobic ammonium oxidation) microbiological process bacteria transform ammonium (NH_4^+) by oxidation with nitrite (NO_2) into nitrogen gas (N_2) and water (H_2O)
- New and more efficient and affordable capture of renewable solar energy by solar panels wind turbines



Concept of ANAMMOX
This process saves aeration energy when compared to a current nitrification- denitrification process

Three –Lines of Integrated Resource Recovery Facility (IRRF)

Line 1- District grey water separation, treatment and reuse followed by regional anaerobic treatment producing biogas from high COD liquid used water.

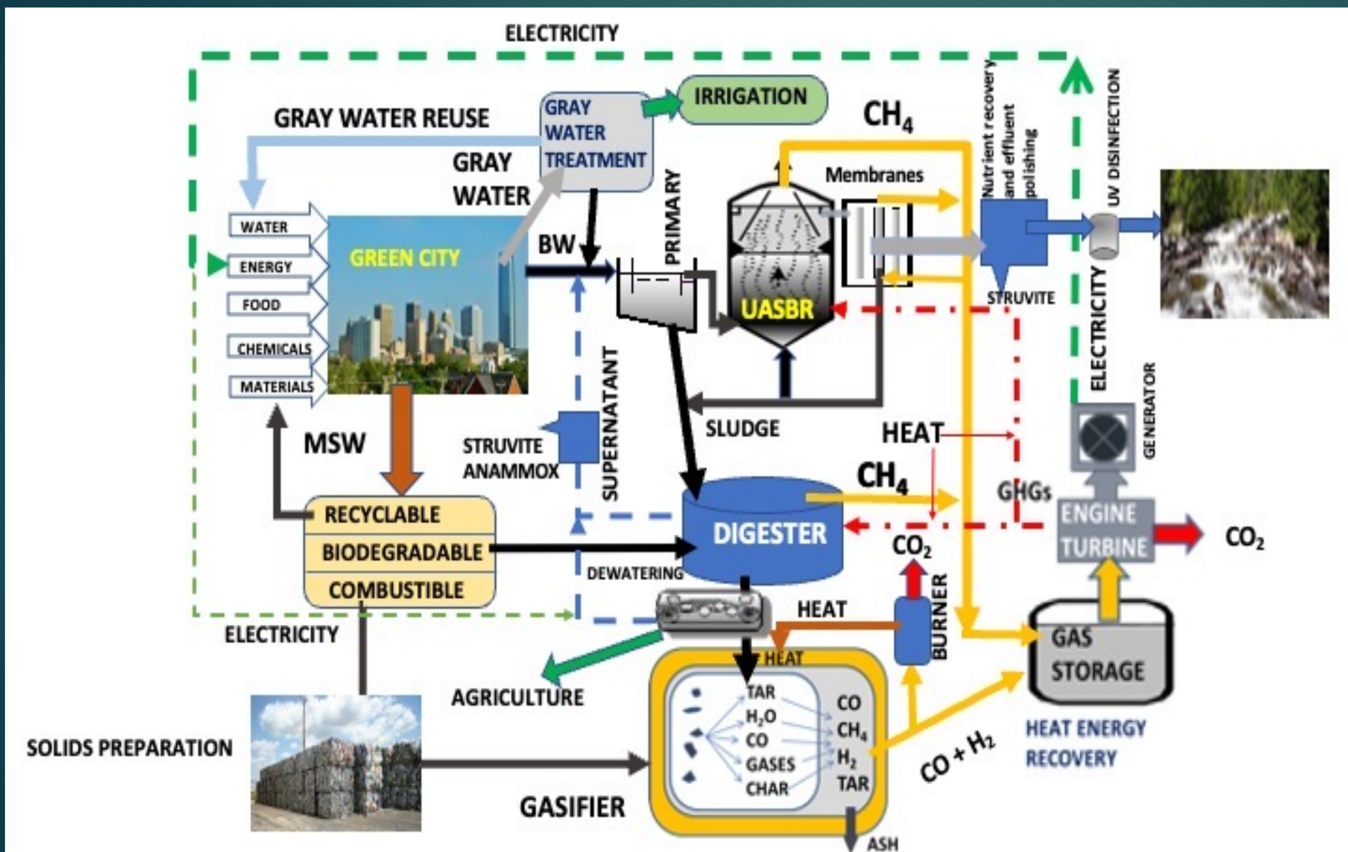
Line 2 – Codigestion of high COD semi-liquid sludge and solids (food waste, waste deicing glycols from airports, manure, biodegradable vegetation residues) producing biogas

Line 3 – Gasification of combustible difficult to biodegrade waste solids, wood, carboard, plastics, rubber and synthetic textile, and residual sludge from Line 2

Power plant – turbine with a generator

Transitional three lines of energy and resources recovery by 2020 technologies with gasification of solids

After 2025



Source Novotny (2020 (Picture Copyright © Vladimir Novotny and John Wiley Publishers)

Implementing water conservation and grey water recovery increases COD concentration in used water that requires biogas producing anaerobic treatment.

Codigestion of biodegradable MSW and replacing landfilling by syngas producing direct gasification of combustible MSW eliminates new landfills.

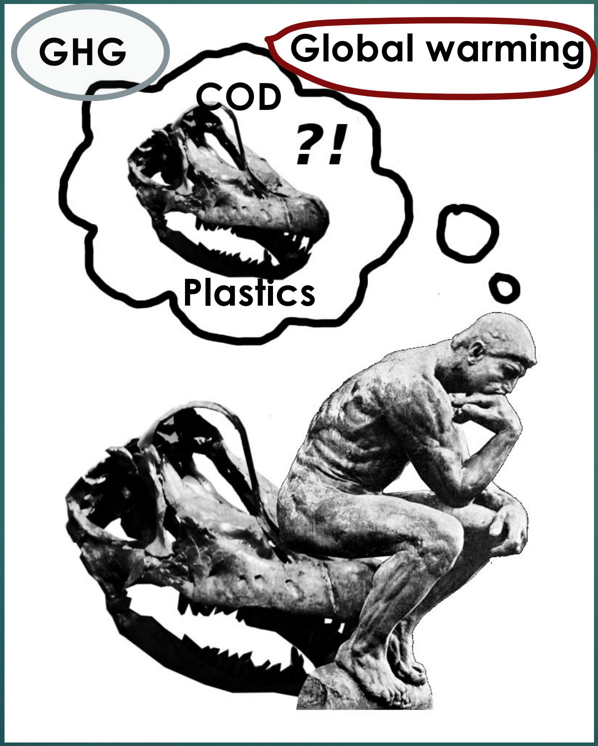
Old landfills will be capped and captured LFG can be added to the fuel

This IRRF can meet utility net zero CO_2 goal

WITH PRESENT ADVANCED TECHNOLOGIES IT MIGHT BE POSSIBLE TO MEET NET ZERO CARBON 2050 SUSTAINABILITY GOALS IF

- **Water conservation and grey water reuse is implemented in houses and districts**
- **Aerobic treatment using fossil electric energy and emitting CO_2 is replaced by anaerobic treatment producing biogas**
- **Incinerators are replaced by direct gasification that makes syngas from MSW, plastics and sludge**
- **Power plant is a biogas turbine and generator**
- **Increased recycling and circular economy in production of goods reduce the mass of solid waste into gasifier and landfills (gasifier ash) and saves a lot of energy**
- **Sequestering of CO_2 from flue gases of turbines and combustion engines is difficult because of dilution by air nitrogen and other gases.**
- **Wind and solar panels are used to generate additional green energy to reach net zero carbon goal**
- **Fossil CO_2 from gasifying plastic is a problem.**

How to achieve full decarbonization by ~~2050~~ 2040 ?



How to achieve full decarbonization by ~~2050~~ 2040 ?

Join the thinkers and consider H_2

Design an IRRF that shall generate biogas, H_2 and syngas and GHG free energy

- Methane from
  - UASB Reactors processing concentrated black water and municipal biodegradable wastes (food, brewery, airport, liquid manure, etc,)
  - Codigestion of biodegradable MSW solids with sludge solids from IRRF and other biomass
  - Methane capture from abandoned landfills
- Syngas ($CO + nH_2$) from
  - Indirect gasification of combustible MSW solids and dried sludge from IRRF Lines 1 and 2
  - Intermediate product in steam methane reforming to H_2
- Hydrogen from
  - Microbial Electrolysis Cell (reactors) and dark fermentation of organic solids
  - Syngas reforming to hydrogen
  - Electrolysis from water (steam)

ENERGY CONTENT AND DENSITY OF GASES

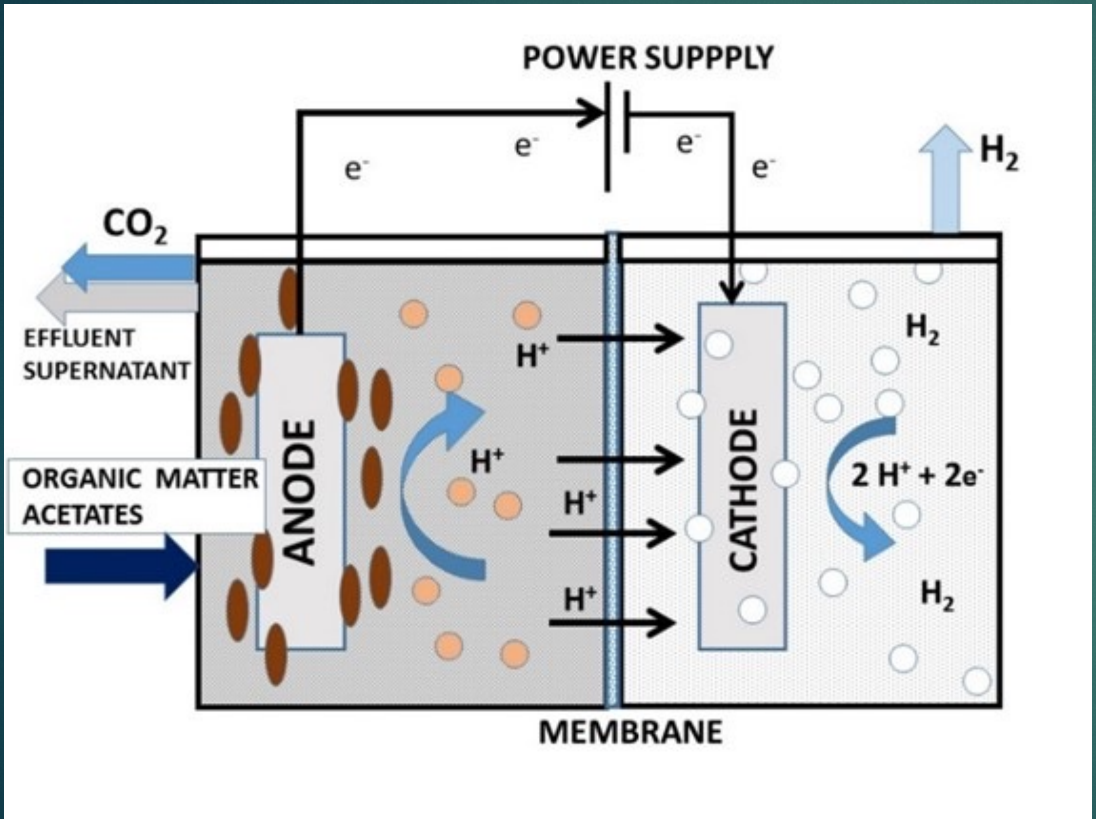
Compound	Heating value (20° C)		Molecular weight Grams per mole	Specific density Kg/m^3
	MJ/kg	kJ/mole		
Air				1.19
Hydrogen	141.8	283.6	2	0.09
Methane	55.5	888	16	0.72
Natural gas	37.9			
Carbon monoxide	11.11	311	28	1.25
Carbon dioxide	0	0	44	1.97

1 KW-hr = 4.2 MJ

H_2 is 20 times lighter than CO_2 and 7 times than methane

- Hydrogen is the most efficient energy source and carrier
- It is safer than methane (natural gas) and does not explode
- Today grey hydrogen is made from natural gas. It becomes *blue hydrogen* when the emitted fosil CO_2 in the flue gas is captured and stored underground and eventually converted to carbonate minerals. *Green hydrogen* is made by electrolysis of water by clean renewable energies such as hydro, wind and solar. This color definition is focused on natural gas as a source of H_2.

NEW HYDROGEN ENERGY TECHNOLOGIES



Sources Rabaey and Verstraete (2005) and Liu, Grot and Logan, 2005 with permission of publisher.

Microbial Electrolysis Cell (MEC)

Converts organic biomass directly into hydrogen by adding small electricity to the reactor. 85 % hydrogen energy potential recovery from acetates and sugars is possible .

Produced hydrogen is separated from CO_2 and supernatant .

CO_2 is not emitted, it is dissolved or dissociated as bicarbonate and sequestered

BIOHYDROGEN YIELD POTENTIAL FOR BIODEGRADABLE ORGANIC COMPOUNDS

- **Theoretical Maximal hydrogen yield in anaerobic breakdown of hexose is**

  $$C_6H_{12}O_6 + 6\ H_2O \rightarrow 12\ H_2 + 6\ CO_2$$

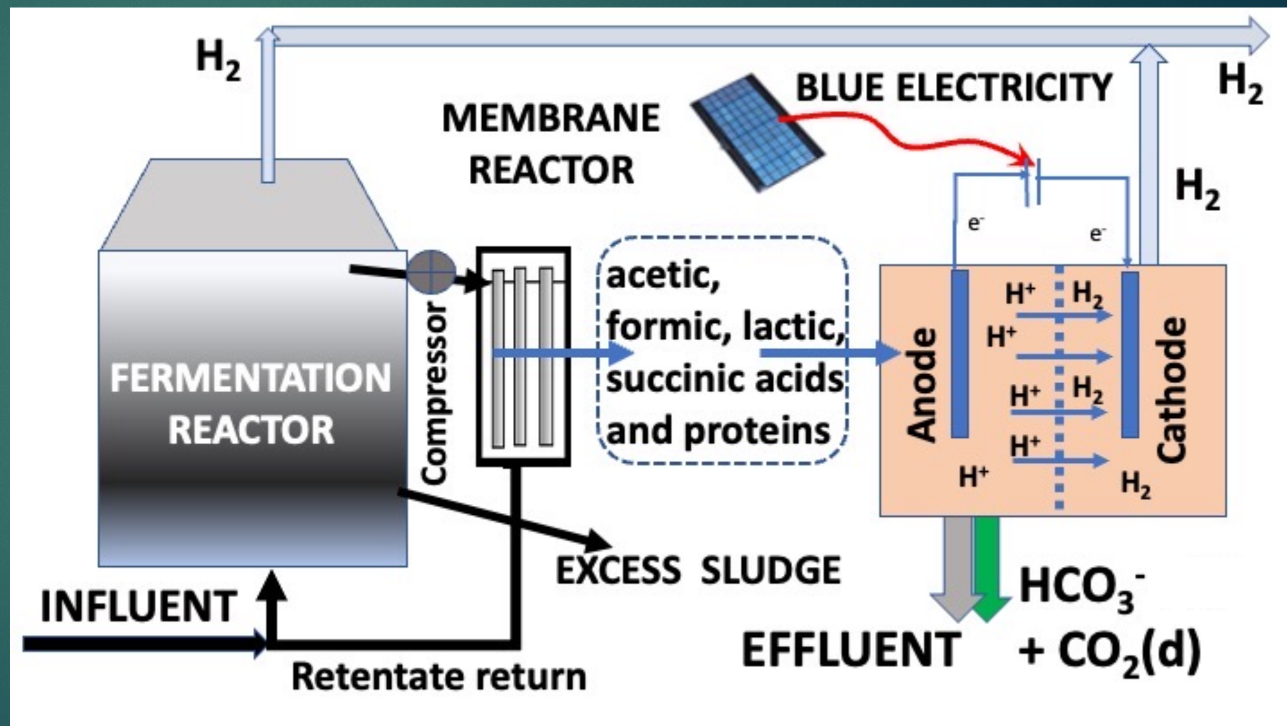
- **Hexose has similar composition of C, H, and O as MSW and sludge**
- **Hydrogen is produced in the fermentation/oxidation phase of anaerobic digestion which also produces acetates and other digestible compounds and restricts H_2 production to about 25% of the potential. This has been identified as acetate barrier. The hydrogen yield is less than 4 moles of H_2 per mole of hexose.**
- **Microbial electrolysis cell converts organics to hydrogen but so far has not been top efficient for complex organic waste other than acetates, organic acids, proteins and sugars.**
- **Combination of low pH (~5.5) fermentation with suppressed methanogenesis followed by MEC maximizes the hydrogen yield to approach the maximum yield.**

Source Logan et al (2008) , Van Lier et al (2008) and Kadier et al (2018, 2020)

Switching from digester methane as energy sources to hydrogen on Line 2

- A low pH (~5.5) fermentation reactor suppressing methano-genesis in combination with the MEC reactor produces hydrogen
- Hydrolysis reactor can be added up front to assist in breaking cellulose.
- Hydrogen in residual solids will be recovered by gasification

Overall efficiency of H_2 recovery is much higher than fermentation or MEC alone



Credit to Professor Logan, Pennsylvania State University for proposing Fermentation/MEC combination

Maximum Hydrogen yield potential for some organic compounds in fermentation/MEC and/or indirect gasification

- **Hydrogen is recovered from steam and H in the molecule of the compound to oxidize**
- $C_m H_n O_p N_x S_y + z\, H_2O \rightarrow m\, CO_2 + x\, NH_3 + y\, H_2S + [z + 0.5*n - (1.5x + y)]\, H_2$

H_2 kg/kg ds = 2*(2m-p+0.5n-(1.5x+y))/(12*m+n+16*p+x*14+y*32)   ds=dry mass.

Nitrogen and Sulphur, if present in the compound molecule, are converted into ammonia and sulphide, respectively.

Examples:

- Glycol fermentation + MEC $C_2H_6O_2 + 2\, H_2O \rightarrow 2CO_2 + 5H_2$

  Maximum yield 5 H_2/mole of glycol = 10/ (2*12+6+2*16) = 0.15 kg of H_2/kg of $C_2H_6O_2$
- Used water sludge $C_{4.2}H_{4.4}O_{1.6}N_{0.3}$ Maximum yield potential H_2 kg/kg ds = 0.31 kg H_2/kg ds
- Food waste $C_{3.8}H_{6.3}O_{2.2}N_{0.2}$ Maximum yield potential H_2 kg/kg VSS = 0.21 kg H_2/kg VSS
- Combustible MSW $C_6H_{9.4}O_{3.9}N_{0.06}$ Maximum yield potential H_2 kg/kg ds = 0.18 kg H_2/kg ds
- Polyethylene (PE) plastics $(C_2H_4)_n$ Maximum yield potential H_2 kg/kg = 0.42 kg H_2/kg ds

See Chapter 8 in Novotny (2020)

Maximum Hydrogen yield potential for some organic compounds in fermentation/MEC and/or indirect gasification

- **Hydrogen is recovered from steam and H in the molecule of the compound to oxidize**
- **NH_3 + y H_2S + [z + 0.5*n – (1.5x + y)] H_2**

*x*14+y*32) ds=dry mass.

Nitrogen ulphide,

respectivel

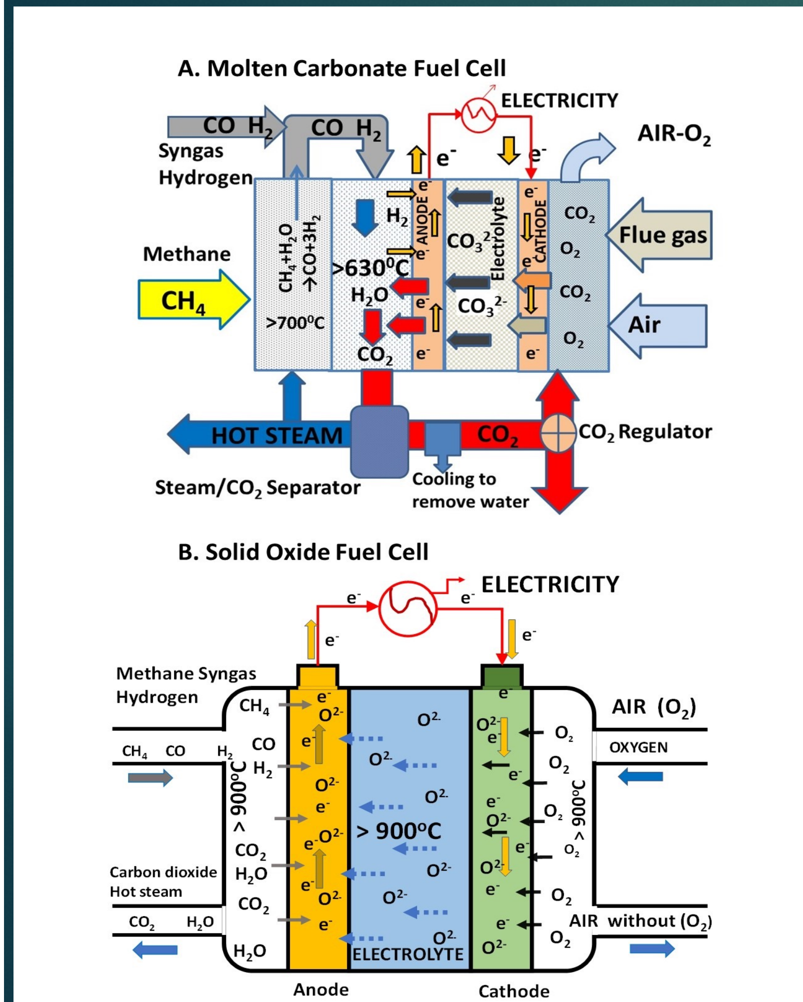
Examples:

- Gl
- kg H_2/kg ds
- waste $C_{3.8}H_{6.3}O_{2.2}N_{0.2}$ H_2/kg VSS
- Combustible MSW $C_6H_{9.4}O_{3.9}N_{0.06}$ Maximum kg H_2/kg ds
- Polyethylene (PE) plastics $(C_2H_4)_n$ Maximum yield potential H_2 kg/kg = 0.42 kg H_2/kg ds

NON-HALOGENATED PLASTICS ARE GREAT SOURCE OF HYDROGEN BUT WILL EMITT FOSSIL GHG IN GASIFICATION . Plastic are made from petroleum and the process uses a lot of energy (~ 17 to 32 kWatt-h/kg plastic – not counted herein)

See Chapter 8 in Novotny (2020)

HYDROGEN FUEL CELLS



Fuel cells are an energy user's dream: an efficient, combustion-less, virtually pollution-free power source, capable of being sited in downtown urban areas or in remote regions that runs almost silently and has few moving parts (US DoE).

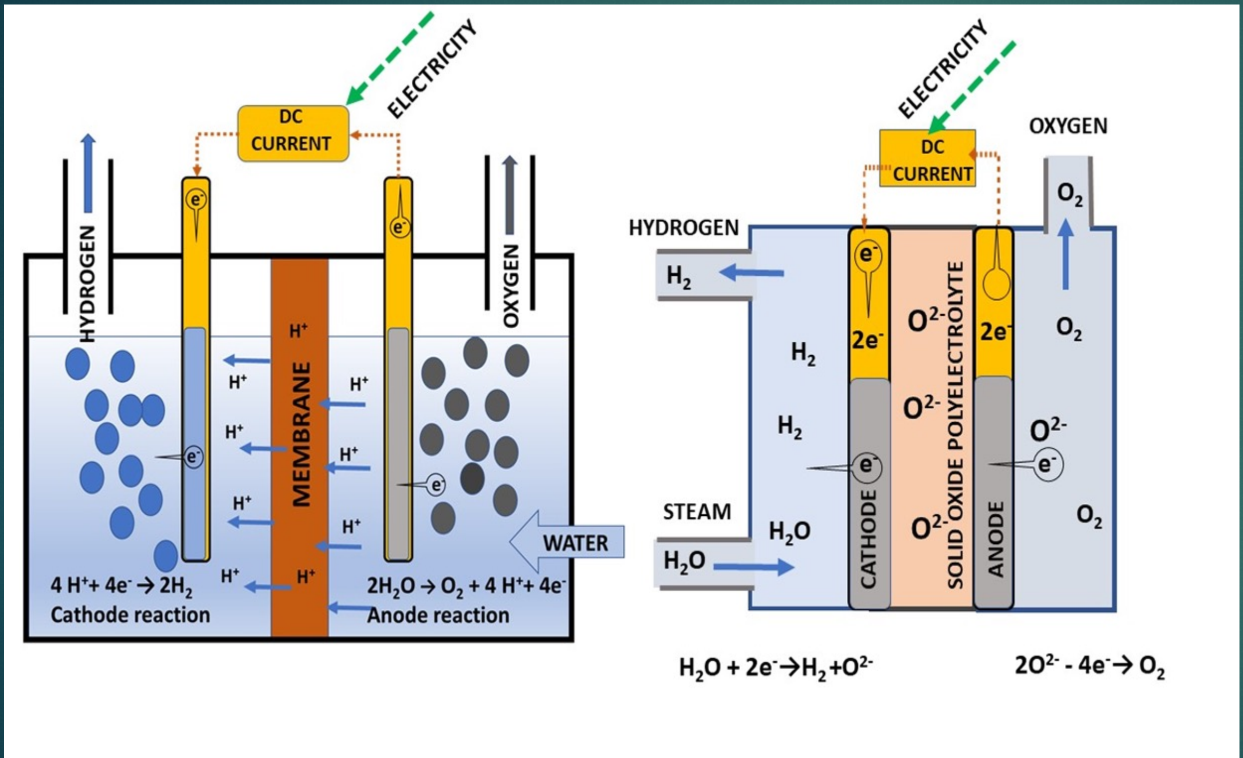
Molten Carbonate (MCFC) and Solid Oxide (SOFC) Fuel Cells are high temperature fuel cells that allow the use of low carbon gaseous hydrocarbon fuels in addition to hydrogen as feed. They produce electricity and steam.

The future MCFC is expected to have high energy efficiency

Hydrogen to electricity 65%. With heat recovery 85 – 95 %

MCFC contains carbonate salts of alkali metals as electrolyte. It can accept dilute flue gas with diluted CO_2 (10%) in cathode and concentrate it to 70% CO_2 and hot steam from anode. SOFC contains solid ceramic oxide.

Electrolyzer produces hydrogen and oxygen by splitting water (steam) molecule



Low temperature membrane electrolyzer splitting water

High temperature SOFC working in reverse to make H_2 and O_2 from steam

Making hydrogen and oxygen by splitting water molecule with DC current is a well-known endothermic process that uses more energy than it produces; hence it is not economical if the electricity is provided by fossil fuel power.

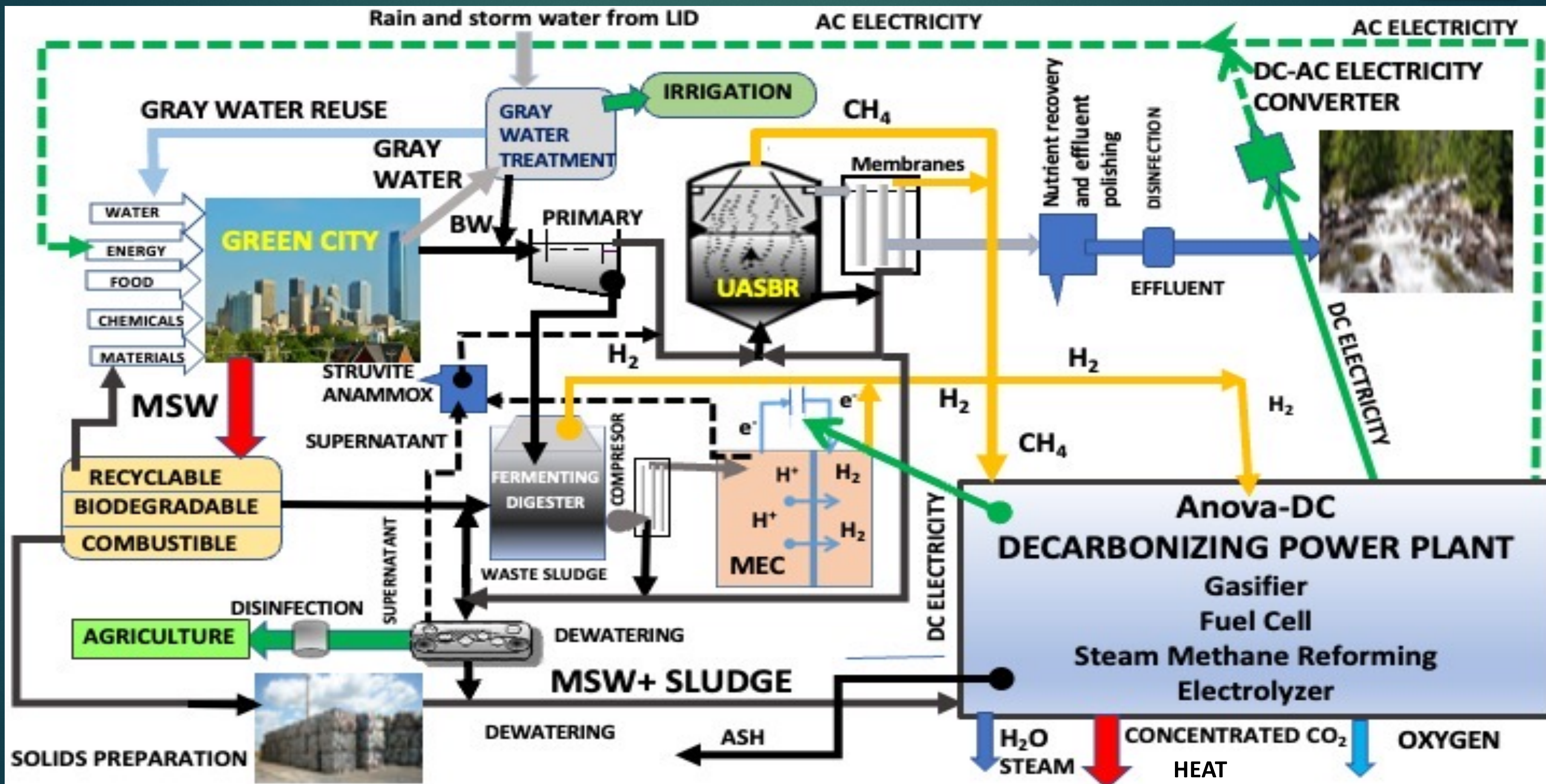
However, it may become very attractive when excess renewable green or blue energy is available. Both hydrogen and oxygen can be stored. Using high temperature SOFC is attractive because it can work in both directions.

Pure oxygen is a commercial commodity and is used in making ozone for disinfection and in medicine.

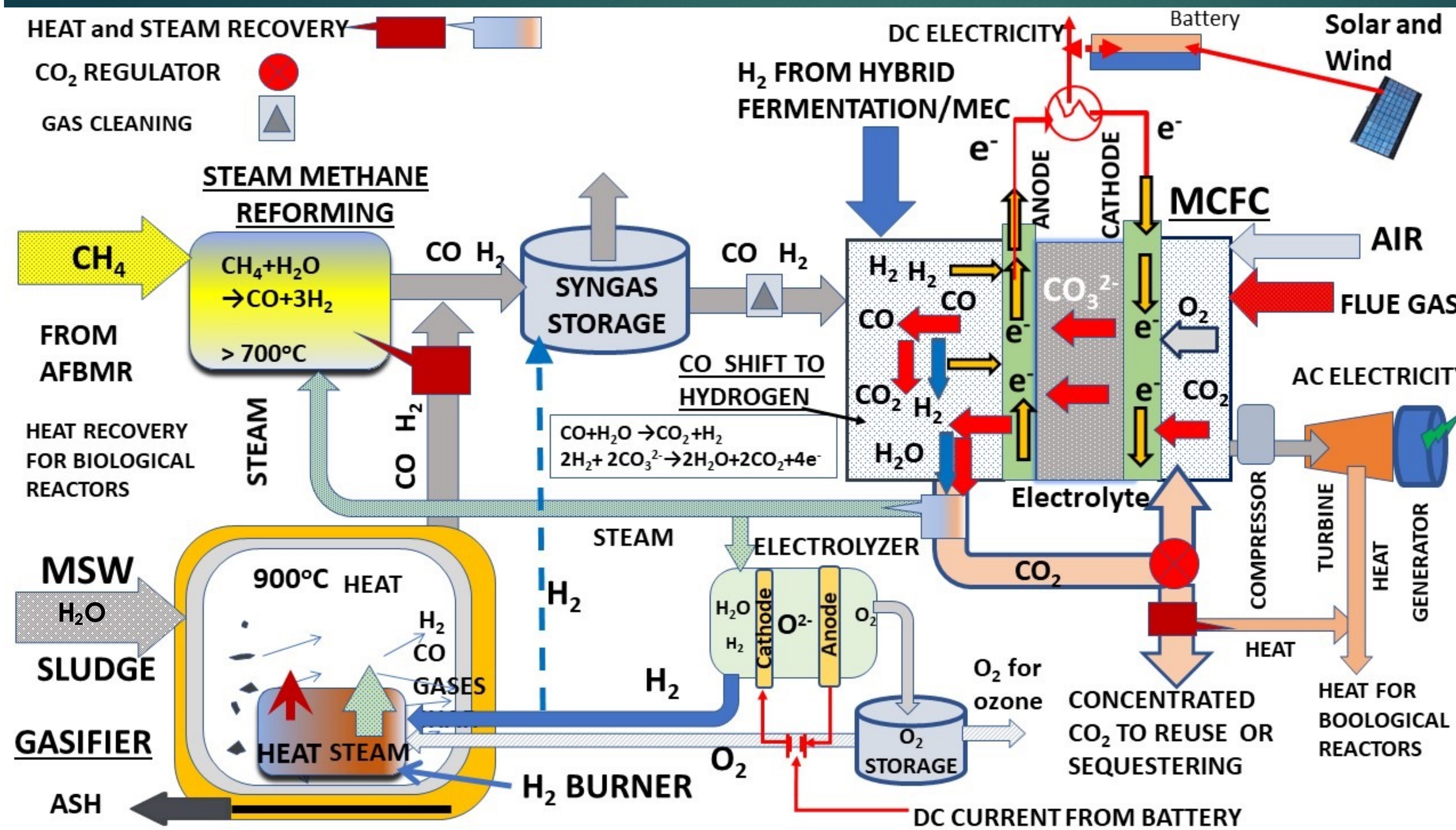
Developing H_2 based decarbonizing Integrated Resource Recovery Facility

- Regional grey water treatment and recovery
- MSW separation into biodegradable, combustible and recyclable solids
- Anaerobic treatment to produce biogas
- Fermentation of biodegradable MSW with sludge followed by Microbial Electrolysis Cell to produce hydrogen
- Struvite (P) and N recovery from supernatant
- Indirect gasification of organic waste solids to produce syngas (CO and H_2)
- Hydrogen fuel cell for electricity and heat production with methane and carbon monoxide reforming into biohydrogen and CO_2
- Flue gas CO_2 separation and sequestering
- Producing hydrogen and oxygen by electrolysis to provide endothermic heat to gasification and oxygen for ozone
- Heat recovery by heat pumps and exchangers

Three Lines Integrated Resource Recovery Facility with ANova DC Power Plant



ANova DC three-line fuel entry power plant with CO_2 free indirect gasifier, steam methane reforming and electrolyzer.



ANova DC produces electricity, clean steam (water), concentrated sequester able CO_2 , heat energy and pure oxygen that has a commercial value.

Electrolyzer can be SOFC working in reverse.

Gasifier ash is less than 5% of the feed solids. It is methane free, may not be landfilled and could be used as fertilizer or in construction .

The MCFC can accept diluted flue gas and concentrate CO_2 to 70%

Alternative System 3 - CO_2 Emissions and Credits in kg CO_2 $capita^{-1}day^{-1}$ and energy (kWatt-h $capita^{-1}day^{-1}$) for Three Lines system utilizing hydrogen-based technologies

2040

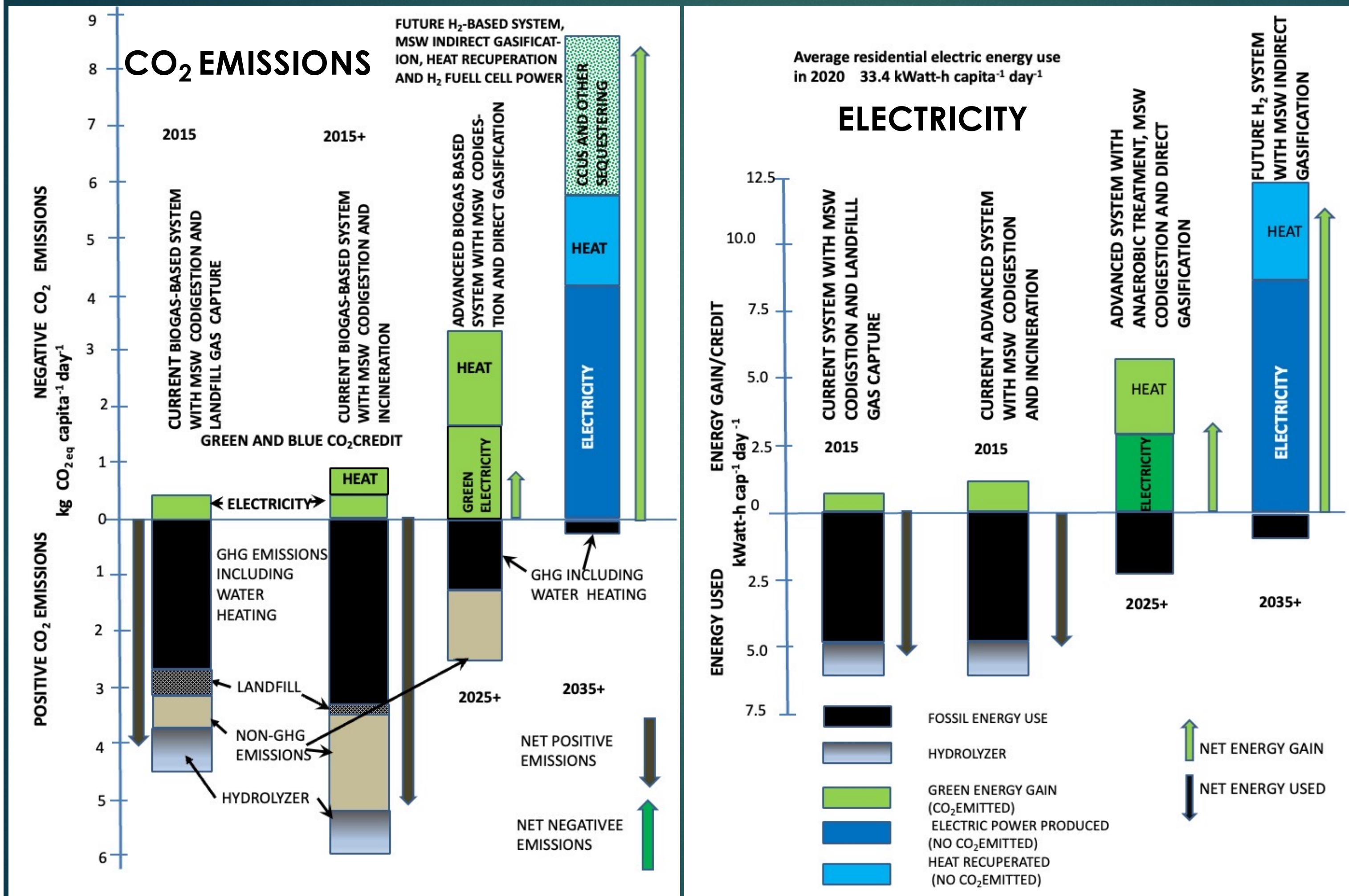
Fossil CO_2 per kWwatt-h energy in 2040

$\frac{0.02 \text{ kg } CO_2}{\text{kWatt-h}}$

0 in 2050

Line	GHG CO_{2eq} emissions	Non GHG CO_2 emissions	GHG CO_2 and energy credit	Comment
	Positive emissions		Negative emissions	
1 Liquid black water	0.02 (0.11)			Fossil energy for water delivery and graywater treatment. Low ratio of fossil CO_2/kWatt-h.
		No CO_2 emission	- 0.03	CO_2 produced by methanogenesis sent with biogas to power plant where it is sequestered
2 High COD biodegradable flow		No CO_2 emission	-0.53	Fermentation CO_2 is dissolved and disso-ciated and sequestered as bicarbonate in supernatant and Line 1 effluent
3 Combustible solids		No CO_2 emission		Prepares solids for gasification
Power plant ANova DC			- 4.2 (-8.32)	Electric energy CO_2 credit
			- 1.5 (-3.09)	Heat energy CO_2 credit
	0.76	1.64	-2.4 CO_2 is sequestered	Concentrated sequester able and reusable CO_2 emissions in the flue gas separated from steam
Subtotals	0.02 (0.11)		-8.66 (11.42)	99 % negative CO_2 emission system
Water heating	0.1 (0.6)		- 0.08(-0.4) Heat recovery (??)	Water heating for dishwasher, shower and laundry in homes conserving water. Heat energy is recovered by heat pumps.
Total	0.12 (0.61)		- 9.74 (-12.22)	Highly negative emission system. The system is fully decarbonized.

Comparison of the four alternatives



The differences between the Alternatives 1 and 2 and 3 and 4 are due to switching from landfilling of MSW, limited MSW processing by co-digestion, incineration and producing electricity by waste heat of incineration to MSW and sludge gasification and hydrogen fuel cells.

In 2050 the fossil energy and CO_2 emissions will be zero

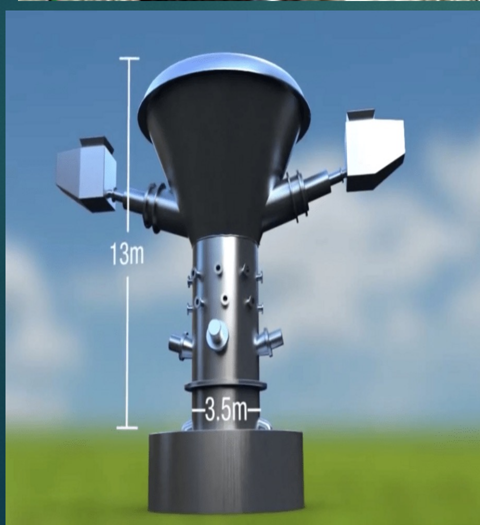
Important hydrogen energy components are already being implemented

1.2 MW DFC 1500 Fuel cell MCFC power plant with internal biogas reforming manufactured by FuelCell Energy installed in Riverside, CA water reclamation plant.

This energy source is combined with battery to store excess energy. Fuel Cell Energy operates similar plants in Connecticut and abroad.

Many hydrogen fuel cell power plants have been already installed around the world and larger 100+ MW are planned in the Republic of Korea, US and other countries. These plants use natural gas as fuel**.**

Picture source and credit City of Riverside public domain.



Start-up Solena Group builds a SGH2 plasma indirect gasifier in Lancaster California for making green hydrogen from wastepaper stocks. The plant will process 40,000 tons of waste every year and have the capacity to produce up to 3.8 million kilograms of hydrogen per year. A preliminary lifecycle carbon analysis, which found that for every ton of hydrogen produced, SPEG technology reduces emissions by 23 to 31 tons of carbon dioxide equivalent, which is "13 to 19 tons more carbon dioxide avoided per ton than any other green hydrogen process," the company stated. SGH2 hydrogen is five to seven times cheaper than other green hydrogen. MSW and other solids gasifiers are made in China, Japan, India and Europe.

Picture source Solena group

Advantages of hydrogen based IRRF-H_2

- Very high energy recovery from hydrogen, methane and carbon monoxide by hydrogen fuel cells.
- Hydrogen fuel cell efficiency is much better than combustion (near future >90% total energy, up to 65% electricity)
- Water (steam) and concentrated CO_2 are the only emissions from the fuel cell and from the entire system
- Hot steam can be converted by hydrolysis to hydrogen and oxygen.
- Hot high pressure concentrated CO_2 flue gas from fuel cell exhaust can be sequestered by CCUS or reused
- IRRF can gasify plastics without GHG emissions. Plastic are good source of H_2
- Better efficiency can be achieved if a part of needed heat and DC energy needed for IRRF is provided by solar energy (with battery) that is not an option in the traditional processing of used water and MSW .

CONCENTRATED CO_2 SEQUSTERING AND REUSE

- *Carbon Capture Utilization and Storage* (CCUS) (USDOE, 2010a) means using captured CO2 for *Enhanced Oil Recovery (EOR)* to increase oil or natural gas production, which implies fracking, wherein CO2 and other gases from coal and natural gas incineration in power plants are returned liquified under pressure back into the geological zones and force the oil or gas to the surface (similar to fracking). This practice results in some positive emissions.
- *Deep saline formations and saline aquifers.* These formations consist of porous rock filled with brine. A key advantage is their abundance, allowing for large quantities of CO2 to be stored. Both saltwater aquifers and abandoned salt mines are good prospects for sustainable CO2 storage.
- *Basalt formation*. When CO2 is pushed into basalt volcanic rocks it turns into carbonate mineral ankerite. Because basalts are widely found in North America and throughout the world, these volcanic rock formations could help permanently sequester carbon on a large scale.
- *Conversion of CO_2 flue gas into soluble bicarbonate and carbonate*, which can be sequestered as solid mineral carbonate after reacting with alkaline clay, a by-product of aluminum refining, or become dissolved and dissociated as bicarbonate when discharged into receiving water with higher pH. The carbonate product can be utilized as construction fill material, soil amendments, and green fertilizer.
- *Dry ice manufacturing*

Sequestering into underground formation requires pipeline systems that collect concentrated waste CO_2 and delivers it to the storage area where it has to be stored for thousands of years or converted to solid carbonate (e.g., ankerite). To transport the gas in pipelines the CO_2 is pressurized into liquid and pumped by the pipeline to the storage area.

OTHER CARBON CREDITS

Low Impact Development (LID) RELATED CREDITS Biophilic designs for a city	Kg CO_2/cap-day
Green infrastructure, green roofs, and vertical forests with passive energy savings - (50% of cooling and heating)	-2.2
Reducing irrigation requirement by xeriscape by 112 L/c-d	-0.17
Providing 10 % of in-house domestic use from rainwater and treated stormwater for toilet flushing and laundry 10 L/c-d	-0.02
OTHER CREDITS AND ENERGY USES	
Water conservation and reuse (77% of domestic use = 200 L/c-d)	-0.28
Heat recovery by heat pump from gray water (gray water flow 125 L/c-d, 12^{o}C differential)	-1.84
Pumping energy for reverse osmosis and microfiltration (1.5 kW-h/m^3 for 82 L/c-d gray water recycle) (about 1/3 can be recovered)	+ 0.05
TOTAL CREDITS	**-4.5**

NEGATIVE EMISSIONS

Proposal of biophilic remaking of Philadelphia that would have negative CO_2 emissions enhanced also by traffic using renewable sources of energy (electricity and hydrogen). Picture credit Mike Maimone, CDM-Smith.

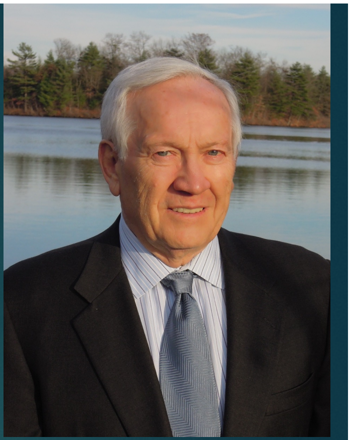
Green roofs and vertical forests reduce need for cooling energy for buildings and green surfaces and vegetation absorbs CO_2.

Vertical forest picture credit Stefano Boeri Architects, Milan, Italy

Conclusions

- US is one of the top states that have the highest per capita and total GHG carbon footprint
  - Low density urban centers
  - High automobile use
  - Great reliance on fossil fuel power production (natural gas and coal)
- China, India, Indonesia have the highest and growing total GHG emissions
- Plastics are a very serious problem that is threatening biota and when burnt emit GHG and toxics
- Converting to H_2 systems will significantly increase energy and resources production from renewable sources
  - Water conservation reduces energy demand (water- energy nexus)
  - Biogas conversion to hydrogen and electricity with carbon sequestering is very effective
  - Wind turbines and large inclusion of solar power will become main sources of energy
  - Integrated electricity and heat energy recovery from used water and municipal solid waste can provide a significant portion of residential energy demand
  - More efficient water use appliances and heating (e.g., heat pumps) will reduce household energy use and recover heat
  - Recovery of phosphorus and potentially other resources are possible and will be implemented
- The goals of net zero carbon footprint from integrated urban water, energy and waste solids systems are achievable by 2035 and decarbonization by 2040 in the US and other countries

Additional Sources of Information



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