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Water and Energy Link in the Cities of the Future – Achieving Net Zero Carbon and Pollution Emissions Footprint

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Abstract

The link between water conservation, reclamation, reuse and energy use as related to the goal of achieving the net zero carbon emission footprint in future sustainable cities is discussed. Sustainable ecocities are defined and the steps towards reduction of energy use due to water and used water flows, management and limits in linear and closed loop water/stormwater/wastewater management systems are outlined. The three phase water energy nexus diagram may have a minimum inflection point beyond which reduction of water demand may not result in a reduction of energy and carbon emissions. A double loop water reclamation/reuse system requiring less than 60 L/cap-day of fresh water input is described; however, such a system would also rely on capturing and reusing rainwater and stormwater. The system would produce concentrated black water that, with the solids, would be conveyed to a regional integrated resource recovery facility where additional clean water, nutrients, energy, and other resources would be recovered from black water and organic solids. Three alternatives of water management are compared. In order to achieve better than net zero GHG green house emissions and produce energy, both used water and organic solids should be co-processed and resources recovered. Hydrogen based energy recovery and conversion to electricity by the integrated resource recovery facility is proposed for the future cities.

Keywords

Greenhouse gases emissions, Water conservation, Water reclamation, Water demand, Used water treatment, Energy use, Carbon footprint, Hydrogen energy, Biogas, Resource recovery, Anaerobic treatment

INTRODUCTION

The Cities of the Future or Ecocities represent a major paradigm shift in the way new cities will be built or older ones retrofitted to achieve a change from the current unsustainable status to sustainability, meet the net zero green house (GHG) emission targets, reuse and recycle water, and recover resources, including nutrients (Register, 1987; Novotny et al., 2010).

Current scientific research quoted in the National Science and Technology Council (NSTC, 2008) report indicates 60 to 70% of energy reductions in buildings in cities can be achieved with passive heating and cooling incorporated in the architecture of the building, more efficient appliances such as better water and space heaters, heat pumps, significant reduction of water demand by water conservation and use of rain and stormwater, organic solids management for energy and resources recovery, and other improvements. NSTC also estimated that 30 to 40% of energy can be produced by renewable sources, including heat recovery from used water and/or extracted from the ground and groundwater.

URBAN METABOLISM

Urban metabolism – Reclaim, reuse and recycle

Cities are complex systems which accept, transform, use, and attenuate inputs and produce and emit outputs. This is called urban metabolism. Current urban systems have been usually linear in terms of their urban metabolism (Figure 1). Daigger (2009), Novotny (2008) and others agree the current “linear” approach, sometimes called the *take, make, waste* approach in the literature has become unsustainable and cannot continue. The linear system discourages reuse because the source of reclaimed water is far downstream from the city and the current economic benefit/cost or minimum cost evaluations do not consider important social and, in many cases, environmental costs and benefits traditionally considered as intangible.

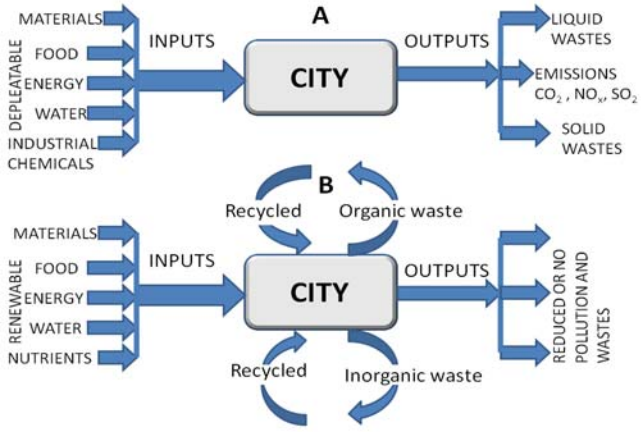


Figure 1 Linear (A) and circular (B) urban metabolism systems (from Novotny et al., 2010)

Furthermore, in our understanding of the water use in a city we cannot just limit ourselves to considering water and its direct use and economics. Providing materials, energy, and food to the city requires additional water at the points of production, manufacturing, retail and fuel for transportation. This represents *virtual water demand* that could exceed the direct water use by an order of magnitude (Hoekstra and Chapagain, 2008). Linear systems produce far more pollution output and need more resources (water, air, soil and landscape) for dilution and assimilation of residuals than a semi closed system based on the three R’s – *reclaim, reuse and recycle*.

Water footprint – Direct use of water

The per capita water use in cities is a local footprint which usually has regional significance. In the US, domestic indoor water use is relatively constant among the major urban areas (Heaney et al., 2000), averaging 242 Liters/capita/day for a household without water conservation but could be reduced to 136 Liters/capita-day in a household practicing water conservation. However, the total per capita water use is magnified by outdoor irrigation (using potable water), pipeline leaks, or swimming pools and in the US reaches almost 650 Liters/capita-day, the highest in the world, as compared to Europe or Australia which is around 150 to 200 Liters/capita-day or less. For example, Drbohlav and Jankovsky (2010) reported billed domestic water use in Prague (Czerch Republic) as 140 Liter/capita-day. The high water use in the US, Middle East, and other affluent countries puts enormous stresses on the water resources and availability. However, water shortages have also occurred in Atlanta (GA), Florida, and other communities in the eastern US located in more humid areas.

Water-energy nexus

In the US, buildings consume 40% of the energy of which 22% is residential and 18% commercial, respectively. Industries consume 32% and transportation 28%, respectively (NSTC, 2008). Providing treated water and disposal of wastewater in the US represents on average about 3% of the energy use but can be as high (California) as 20%. However, within buildings, 8% of the additional energy use is for water related processes such as cooking, wet cleaning, and water heating. A percent or more is needed to pump and transport water and wastewater. The Energy Information Administration (2009) documented the total energy production in the US in 2007 to be 4,157 TeraW-hours (4,157 x 10^9 KW-hrs) which represented about 2.516 billons tons of CO_2 emitted. In 2007, 55 billions m^3 of water was used by the population of 301.3 million in the US. Using the US EPA estimate of 3% energy use for water would result in the unit energy use of 2.26 $kW\text{-}hr/m^3$ attributed to water. Corresponding carbon emission is of 1.37 kg CO_2/m^3. Using the 3% estimate for providing and treating water, “water share” of the energy use is 124.7 TeraW-hrs and 75.5 million tons of CO_2 is emitted as a result of providing clean and disposing polluted water, plus an additional 200 million tons of CO_2 for hot water heating, cooking, boiling, and wet cleaning.

The US Department of Energy (2000) published estimates of carbon equivalent of energy produced by fossil fuel power plants as

0.96 kg of CO_2 / kW-hour produced by coal fired power plants
0.89 kg of CO_2 / kW-hour produced by oil fired power plants
0.60 kg of CO_2 / kW-hour produced by natural gas power plants

Because 30% of energy is produced by processes that do not emit substantial quantities of GHG (nuclear, hydropower and other renewables), a weighted average of the CO_2 will be considered in this analysis as

0.61 kg of CO_2 emitted per kW-hour of energy produced

In contrast, in France, Belgium, Austria and other EU countries, the GHG equivalent of energy is smaller because of much higher reliance on nuclear power (France) or hydropower (Austria, Switzerland). Vestraete et al. (2010) used the GHG equivalent 0.21 kg of CO_2 emitted per 1 kW-hr energy used. Growing use of wind and solar power in Germany, Spain, Czech Republic is further decreasing the GHG equivalent of one kW-hour.

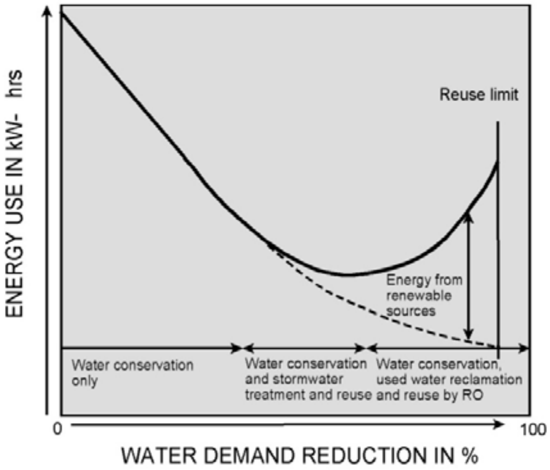


Figure 2 Three phases of the water-energy nexus (without energy recovery)

Figure 2 presents the possible relationship of water demand reduction leading to a closed urban water cycle and energy. Novotny (2010) suggests a hypothesis that there is a minimum inflection point beyond which further reduction of water use will increase energy demand and urban water metabolisms because of increased use of chemicals, energy and infrastructure (materials). A relationship can be developed for relating the cost of providing water to the magnitude of the water demand. The water – energy nexus relationship has three phases (Novotny, 2010; Novotny et al., 2010):

(1) *The water conservation phase* in which energy, and GHG emission reduction is proportional to the reduction of the high water use.

(2) *The inflection phase* in which additional and substitute sources of water demanding more energy are brought in, treated and used.

(3) *Rising energy (cost) phase* in which energy use is increasing while water demand of the development is reduced by used water reclamation and multiple reuses.

Phase I – Water conservation - Linear reduction. Table 1 shows the per capita volumes and proportions of the daily water use in a typical US single family home. The left part of the table is based on the AWWA RF (1999) study as reported by Heaney, Wright and Small (2000). On the right side are the estimates of water savings used by the AWWA RF study and by the Pacific Institute (Gleick et al, 2000) study for California. After implementing mostly common sense water conservation measures (for details see Novotny et al., 2010), the US domestic use can be reduced from the high 550 Liters/capita-day to less than 134 Liters/capita-day which is comparable to the current use in Europe. Because of the prevalence of single houses on more land in the US, the realistic conservation total use is 200 Liters/capita-day.

Reducing water use by conservation may reduce proportionally energy use. It works best if it is done in a distributed urban management system. Most of the water conservation reduction in Table 1 can be achieved by more efficient appliances (water saving shower heads, toilets, laundry wash machines, etc) and xeriscape. Hence for each cubic meter saved, energy in the ideal average household would be reduced by the same proportions. This is the linear Phase I of Figure 2. The water saving potential shown in Table 1 is 65% reduction.

Table 1 Indoor and outdoor water use in a single family home in 12 monitored cities in North America

Water use	**Without water conservation***		**With water conservation**	
	Liter/cap-day	**Percent**	**Liter/cap-day**	**Percent**
Faucets	35	14.7	35	25.7
Drinking water and cooling	3.6	1.2	2.0	1.5
Showers	42	17.8	21	15.4
Bath and Hot Tubs	6.8	2.0	6.0	4.4
Laundry	54	22.6	40	29.4
Dish washers	3.0	1.4	3.0	2.2
Toilets	63	26.4	19	14.0
Leaks	30	12.6	10	7.4
Total Indoor	238	100	136	100
Outdoor	313	132	60**	44
Total	551	232	196	144

Adapted from AWWA RF (1999); Heaney, Wright and Sample (2000) and Asano et al. (2007)

** Reflects converting from lawn to xeriscape using native plants and ground covers with no irrigation**.** Water use is for swimming pools, watering flowers and vegetable gardens.

Phase II – Inflection. In the inflection phase, a city is looking for additional sources of water or brings in sources that have worse quality such as more salty deeper groundwater. This will require more treatment, sometimes by energy demanding reverse osmosis, and/or water will have to be pumped from long distances or from deep geological layers. Many cities in the southwest US cannot meet the water demand using relatively inexpensive sources of fresh water and/or may be located on receiving water bodies that require a high degree of treatment. For example, pumping a volume $V=1\ m^3$ of water from a depth of $H= 500$ meters with a pump that has an overall efficiency of 80% will require work of $W = \gamma\ V\ H = 9{,}819 \times 1 \times 5000/0.8 = 6{,}131{,}125$ Joule = 1.7 kW-hrs (γ=specific density of water in N/m^3) and will result in 1 kg of additional CO_2 emissions. Many water short communities are pumping higher salinity water from depths as deep as 1000 meters, e.g., El Paso, TX. Water sources with low energy demand are rainwater harvesting (negligible energy needs) and stormwater (some pumping and treatment).

Phase III - Increasing energy demand and CO_2 emissions. In the increasing phase, tapping higher salinity water sources (brackish sea or groundwater) is supplemented with water reuse that requires a two or three step high efficiency treatment (Figure 3). Table 2 presents energy and CO_2 emissions.

Table 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	Energy use kw-hr/m^3 (CO_2 emissions kg/m^3) Daily flow volume of treated used water (m^3/day) 10,000	25,000	>50,000
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	~ 25 (15.25)		

In activated sludge processes, for each mole of oxygen consumed in the aeration process, one mole of carbon dioxide is emitted. Hence CO_2 emitted = (12 +2x16)/(2x16) = 1.37 O_2 consumed. For example, if the BOD_5 concentration in used water is 300 mg/L = 0.3 kg/m^3 then the CO_2 emission in the aeration unit removing 95% of BOD_5 (80% by oxidizing carbonaceous matter, 15% by sludge grow) will be

CO_2 emitted (kg/m^3) = 1.4 ($BOD_{ultimate}$/ BOD_5) x 0.80 x 0.3 (kg BOD_5/m^3) x 1.37 (CO_2 emitted/O_2 consumed) = 0.44 kg/m^3 of CO_2 emitted or 1.8 kg of CO_2 emitted/kg of BOD_5 removed.

This value should be added to the CO_2 emissions due to the energy use listed in Table 2 in the GHG balance but some claim that it does not contribute to global warming.

To further close the water cycle, energy demanding water reclamation processes are needed such as highly efficient tertiary treatment with chemical additions followed by micro or nanofiltration and reverse osmosis ((RO). The recycle systems cannot be fully closed in order to prevent accumulation of harmful conservative compounds and the reject (concentrate) water from RO or microfiltration usually cannot be reused. For example, RO water reclamation plants in California or desalination plants in Florida using sea or brackish water reject 20 to 40% of water that has high salinity and concentrated pollutant content. It must be disposed into nearby large water bodies (ocean or sea) with sufficient dilution flow.

Distributed (hybrid) vs. centralized (linear) systems

A distributed Resource Management Cluster (RMC) or ecoblock is a semiautonomous water management/drainage unit that receives water, implements water conservation inside the structural components throughout the cluster, captures and stores rainfall and stormwater, reclaims sewage for reuse, such as toilet flushing, irrigation, street washing and provides ecological flow to restored existing or daylighted streams, recovers heat energy from used water, and possibly recovers biogas from organic solids. Clusters may range from a large high-rise building, larger shopping center, large hotel, to a subdivision or a portion of a city (Furumai, 2007; Lucey and Barraclough, 2007; Heaney, 2007; Novotny et al., 2010; Daigger,

2009) or an entire (smaller) city or urban watershed.

The treatment level within the RMC is "fit for reuse". If, for example, in an RMC reused water is used for landscape irrigation, removing nutrients does not make sense because the nutrients eliminated from reclaimed water would have to be replaced by industrial fertilizers, which would defy the purpose of reclamation and reuse. For all practical reasons, toilet flushing may require reduction of turbidity, disinfection, primarily to control bacterial growth in the toilets and urinals, and adding some colour. On the other hand, if reclaimed water is used for providing ecological flow to lakes or streams, nutrient removal may be necessary but nutrients should be recovered and not just removed (e.g., as sludge put in a landfill).

On a local ecoblock scale, aquifer recharge will be accomplished by infiltration of captured stormwater by best management practices which are foundation blocks of the Low Impact Development (LID) concept. LID practices include enhanced rainwater infiltration (raingardens), pervious pavements, and infiltration ponds (Novotny et al., 2010).

Asano et al. (2007) suggested alternatives for retrofitting decentralized water management into existing urban environments. By starting with building satellite treatment in upstream portions of the urban drainage area, used water (wastewater from the local collection system) can be intercepted and treated to a high degree required for various reuse alternatives such as toilet flushing in houses, landscape irrigation, and ecological flow enhancement. This concept not requiring dual or triple plumbing and water separation into black and gray used water was implemented at the Solaire Battery Park multi unit residential complex in New York City where reclaimed water is used for toilet flushing, irrigation and cooling. The residual effluent with solids from the cluster water reclamation facility is then conveyed to a central (regional) treatment plant and discharged into the environment. At this time, there are no guidelines that would establish the size of the ecoblock.

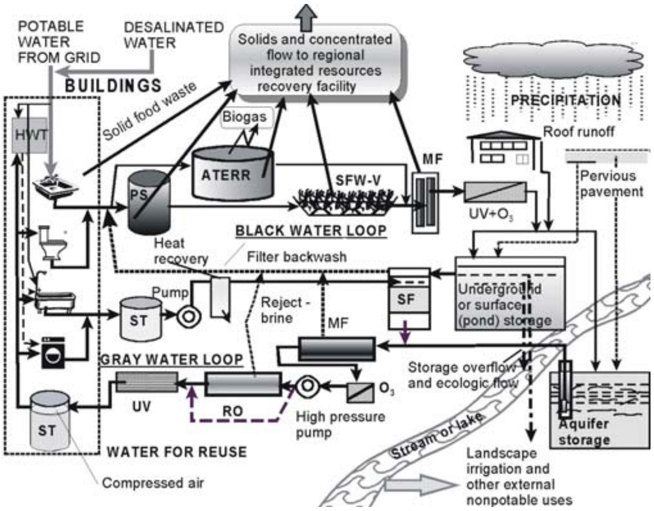


Figure 3 A double loop hybrid cluster (ecoblock) system that recycles gray water and some black water base on Qingdao Ecoblock (Fraker, 2008). From Novotny et al. (2010). Legend: ATERR – a generic anaerobic treatment and energy (methane) recovery reactor; HWT – hot water tank; MF – Membrane filter; NF – nanofilter; O_3 – ozone addition; PS- primary settler with solids removal; RO – reverse osmosis; SF – sand filter; SFW – subsurface flow multicell wetland

A double loop hybrid system – source separation

Source separation of used water is gaining popularity in some countries, e.g., Sweden. Planners of the water frugal ecocities in Qingdao (China) and Masdar (UAE) considered a partially closed (hybrid) system similar to that shown on Figure 3. The Qingdao three hectare ecoblock would have contained 1500 – 2000 inhabitants out of the total 40,000 planned to live in the (future) ecocity (Fraker, 2008). Masdar in United Arab Emirates, operating as a single water/used water management cluster, will have a population of 50,000 permanent residents and 40,000 commuters. Population density is a more important parameter determining the cluster size than the total population the cluster may serve. The Qingdao ecocity cluster inhabitants were to live in several high-rise and medium height buildings. These ecoblocks are then combined to form the entire development (Fraker, 2008).

The water management shown on Figure 3 reaches a maximum limit of reuse and would be applicable to regions with severe shortage of fresh water resources (Middle East, northeast China, inland Australia, some southwest US states, and many future cities in developing countries with burgeoning population and meagre or unusable water resources).

The Qingdao double loop (Fraker, 2008) was modified from the original one to avoid the possibility of direct potable reuse and includes restored surface water bodies and underground storage (Figure 3). The water reclamation and reuse is carried in black and gray water double loops. Black water flow includes water from toilets, kitchen sinks and dishwashers. In the original Qingdao system proposal sequencing batch reactors or septic tanks were proposed (Fraker, 2008). Verstraete, Van der Caveye, and Diamantis (2009) and Verstraete, Bundervolt, and Eggermont (2010) suggested an anaerobic upflow sludge blanket reactor (UASB) combined with a septic tank. In this application, the PS reactor, e.g., an Imhoff primary settler with suppressed digestion (Novotny et al., 1989), is optional. The subsurface flow wetland treatment may emit small quantities of GHGs carbon dioxide, methane and nitric oxide but vegetation growth in the wetland will assimilate CO_2, by converting it to alkalinity, biomass will be harvested for energy production, and nitrification will be minimal because of reducing conditions in the wetland and all nitrogen entering the wetland being in a form of Total Kjeldahl Nitrogen. The system accomplishes several objectives: (1) it treats the gray water to potable water quality for several in-house uses although direct potable use is not contemplated, (2) concentrates black water, including filter backwash from the gray water loop, and sends a part of the black water with solids to a regional integrated resource recovery facility (see next section); a part of the black water is further treated on site to supplement the gray water flow lost in reject and filter backwash flow; (3) in addition to providing water to inhabitants, the double loop system also provides some ecological flow to the surface water bodies within the ecocity and garden irrigation; and (4) it recovers some energy in a form of biogas and heat.

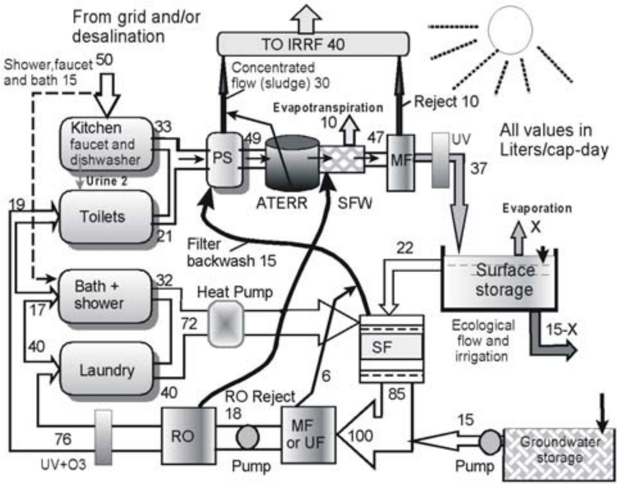


Figure 4 Mass balance of flows of the double loop hybrid water cycle system on a dry day. The numbers represent water flows and uses in Liters/cap-day. IRRF – integrated resource recovery facility; X – water lost by evaporation. From Novotny et al., 2010)

The water cycle balance of the double loop is presented on Figure 4. The figure shows the total water use in the cluster as 126 Liters/capita-day, which is similar to the conservation alternative from Table 1 without the leaks and outdoor use, but the municipal water supply grid provides only 50 Liters/capita-day. It can be seen that 50 L/capita-day water input from the municipal grid is not sufficient to sustain the total demand of 126 L/cap–day during dry weather. Rainwater harvesting and stormwater capture and infiltration (via pervious pavements and infiltration rain gardens) is needed to supplement the dry weather flow (Novotny and Novotny, 2009). Consequently, surface and/or subsurface storage is needed. Surface ponds, wetlands and architectural water features (Dreiseitl and Grau, 2009) could store collected surface runoff and a portion of the highly treated black water; subsurface storage should collect infiltration, excess clean water from dewatering basements and cooling condensate, and harvested rainwater.

The Qingdao ecoblock also saves energy by passive heating and cooling and producing energy by solar panels, voltaics, and wind turbines. It could also produce biogas from digested sludge and provide organic solids harvested from the wetland, fallen leaves and gardens that can be transported to IRRF for processing to recover more efficiently energy and nutrients. The black water loop contains most nutrients and "fit for reuse" nutrients can be left in the treated black water effluent flow which may eliminate the need for industrial fertilizer if the reclaimed effluent is used for irrigation. In the overall scheme, the ecoblock should have net zero carbon emission and no pollution footprints. The Qingdao ecoblock concept is now being implemented in Tianjin (China) Ecocity 150 km southwest of Beijing (Harrison Fraker, personal communication) built by a China-Singapore consortium.

Heat recovery from used water. Water heating is one of the largest domestic energy uses. Total used water leaving the house has a temperature of about 27^oC. Gray water is warmer; about $38\text{-}40^oC$ because of warm showers, baths, and hot laundry (Roest et al, 2010); therefore, it may be more efficient to retrieve heat from gray water after separation in the cluster. Actually, simultaneous warming and cooling can be accomplished in a 'water to water' heat pump. Water to air heat pump will provide space heating and cooling. The net energy extracted from water is then (Novotny et al., 2010)

$$\Delta E = E_{ac} - E_{ap} = V\ \rho\ \Delta T\ C_p\,(1 - 1/COP)$$

where V is volume of water, ΔT is the temperature difference in the heat pump between incoming and leaving water, C_p is specific heat of water and COP is the coefficient of performance of the heat pump which is a ratio of energy acquired, E_{ac}, to energy applied, E_{ap}, to the compressor in the heat pump. COP ranges from 2 to 5, depending on temperature. The above equation works for both heating and cooling. For the volume of 1 m^3 of gray water in the cycle the energy recovered, assuming COP = 4 and $\Delta T = 25^oC$, becomes

$$\Delta E = 1[m^3] \times 10^6\,[g/m^3] \times 25\,[^oC] \times 4.2\,[J/\,g\,^oC]\,\{1 - \tfrac{1}{4}\} = 78.75 \times 10^6\ J = 78.75\ MJ =$$

$$78.75\ MJ/(3.6\ MJ/kW\text{-}hr) = 21.87\ kW\text{-}hr/m^3$$

which is a very significant energy component. Recovering heat from black water flow is counterproductive. It would significantly reduce treatment efficiency and, if anaerobic treatment is selected, black water would have to be reheated in the reactor. Recovering heat from used water provides energy for water heating. For the above calculation of energy recovery from 1 m^3 the carbon emission reduction would be $(21.87\ kW\text{-}hr/m^3) \times 0.61 kg\ CO_2/kW\text{-}hr = 13.3\ kg\ CO_2/m^3$. This is a significant energy gain and GHG emission reduction.

Energy (CO_2) balance for a city switching to sustainable water management

In this illustrative analysis the starting reference point of water and energy use is a community with no water conservation, an open linear water management system and no reuse. The city and the subdivision type cluster is located in southwestern US. The available fresh groundwater source is unsustainably mined and surface source is ephemeral and uneconomical for development. In this analysis the water heating and cooling is not included. The illustrative assumptions are:

Total population in the cluster	10,000
Water demand without conservation	500 L/cap-day
Sustainable water available from freshwater source	100 L/ cap-day
Sustainable rainwater and stormwater reclamation with storage	20 L/cap-day
Sustainable brackish groundwater (TDS ~1500 mg/l)	30 L/cap-day
Maximum water conservation limit (Table 1)	200 L/cap-day

Because the sustainable water from surface and freshwater groundwater sources can only provide 150 L/cap-day, water use must be reduced by water conservation and reuse. Wastewater treatment includes the activated sludge process with nitrification. Reuse will be done by filtration of the effluent, followed by reverse osmosis and ozonization. Reused water will not be available for potable use.

Calculations. A marginal and total water/energy nexus chart presented on Figure 5 has been prepared for carbon emissions. Marginal carbon is the CO_2 emission per one extra m^3 of water.

Current unsustainable situation:

Water use 0.5 m^3/cap- day - Total water use 0.5 x 10,000 = 5,000 m^3/day
Marginal energy use - 2.26 kW-hr/m^3 x 0.5 m^3/cap- day = 1.16 kW-hr/cap- day
Carbon emissions - 0.61 (kg of CO_2 /kW-hr) x 2.26 = 1.37 kg of CO_2/m^3
Total carbon emissions - 5,000 (m^3) x 1.37 (kg of CO_2/m^3) = 6,936 kg CO_2/day.

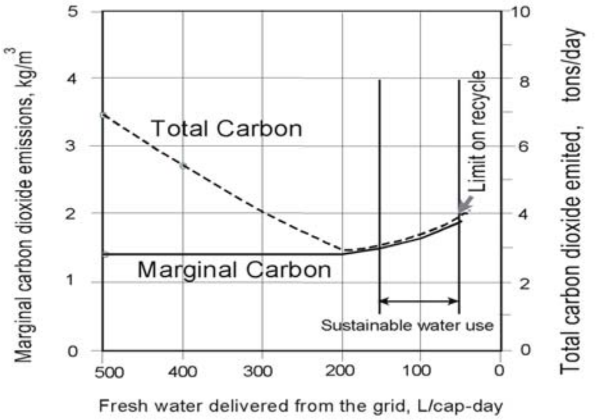


Figure 5 Water energy nexus chart that includes total and marginal carbon emissions related to water demand reductions by water conservation, additional sources and recycle without heat energy recovery.

Reduction to 200 L/cap-day (60% reduction) or 2,000 m^3/day can be achieved solely by water conservation but the water use is still unsustainable and the available sources cannot provide enough water. At 100 L/cap-day of water available from the fresh treated water supply grid, additional water will originate from stored rainwater/stormwater (20), sustainable brackish water (30) and reuse (50) to provide 200 L/cap-day of water. Rainwater/stormwater use will require storage, pumping and filtration which will result in estimated carbon emissions of 0.1 kg of CO_2/m^3. Brackish water has to be pumped (1.6 kw-hrs/m^3 = 1 kg CO_2 /m^3 if pumping depth is 500m) and treated by reverse osmosis and UV/ozonization (1.7 kg CO_2 /m^3). Reuse will approximately emit 2.0 kg of CO_2/m^3.

At 100 L/cap-day of fresh water from the grid the marginal kg CO_2/m^3 emissions become (0.1 [freshwater] x 1.37 + 0.02 [rain] x 0.1 + 0.03 [brackish] x 2.7 + 0.05 [reuse] x 2)/0.2 = 1.6 kg CO_2/m^3. The total carbon emissions at 200 L/cap-day demand and 100 L/cap-day fresh water availability from the grid will be 1.6 kg CO_2/m^3 x 2,000 m^3 = 3,200 kg CO_2/day. The marginal kilograms of CO_2/m^3 and the total CO_2 emissions based on additional calculations are plotted on Figure 5.

Additional energy saving and carbon emission reductions can be achieved if reclaimed water is treated to the fit for use level and by recoering heat. For example, water for irrigation outdoor use (60 L/cap-day) does not have to be treated by reverse osmosis and nutrients can remain in the reclaimed water. This would require dual piping but this is already common in some US cities located in arid zones (e.g., Salt Lake City, UT).

INTEGRATED RESOURCE RECOVERY FACILITY (IRRF)

A completely distributed water/stormwater/used water management system with independently operated clusters fully reclaiming and recycling all water is unrealistic. The major reasons are, as eluded to previously, the cycle needs make-up water to prevent accumulation of salts and of "new" conservative contaminants (pharmaceuticals, nanopollutants, endocrine disrupting compounds) in the system and the need for safe disposal of reject water from RO systems. Also sludge management and biogas recovery may not be advisable in small cluster size reclamation facilities and may be objectionable to the citizens living in the cluster. An IRRF will be a new complete water/energy recovery and management facility which accepts organic solids, concentrated excess used water and recovers water, nutrients, solids, electric energy, heat in much greater quantities than it is possible in the traditional "water reclamation plants".

In the proposed double loop distributed system a large volume of water and some energy are reclaimed/recovered and reused on site in the cluster/ecoblock. Consequently, the main objectives of the IRRF could be:

1. Treating and reclaiming water for
    a. Ecological flow of the receiving water body
    b. Beneficial downstream uses for
        i. Irrigation
        ii. Water supply from alluvial deposit
        iii. Recreation
    c. Providing water and nutrients to algal aquaculture producing biomass and energy
2. Recovering phosphorus and removing nitrogen
3. Recovering and producing heat energy for heating the anaerobic treatment and fermentation units as well as the buildings in the facility and nearby
4. Producing biogas that may include methane or syngas (a mixture of carbon monoxide and hydrogen) (O'Riordan et al, 2008) and/or hydrogen
5. Producing organic solids for soil conditioning
6. Providing water and nutrients to algal aquaculture producing biomass for biogas and oil production and, in the future, hydrogen
7. Converting biogas and hydrogen into electricity
8. Deriving all energy needs from on-site energy recovery, additional renewable sources (solar) and sequestering carbon

Such facilities will generate no pollution, produce excess electricity and will be net sequesters of carbon. Laboratory and field tested technologies that enable to propose this revolutionary resource recovery system, summarized in Novotny et al. (2010), include

- new developments of the more than century old anaerobic treatment and digestion of organic solids and sludge in upflow anaerobic sludge blanket (UASB) reactors (Lettinga and Hulshoff-Pol, 1991; Verstraete et al., 2009);
- microbial fuel cells that convert organic matter to hydrogen or electricity (Rabaey and Verstraete, 2005; Logan, 2004 and 2008; Call and Logan, 2008; Wagner et al., 2009);
- hydrogen fuel cells converting biogas to hydrogen and electricity (US Department of Energy, 2009);
- heat recovery from water by heat pumps and other heat reclamation devices;
- production of struvite (ammonium magnesium phosphate) fertilizer from used water effluents and digester supernatants (Barnard, 2007; Parsons et a., 2001);
- improved production of nutrient rich solids from sludge (Verstraete et al., 2010);
- more efficient biogas and biofuel production;
- production of algal biomass and subsequently hydrogen (James et al., 2009); and

- new and more efficient capture of renewable solar energy by concentrated solar panels and photovoltaics.

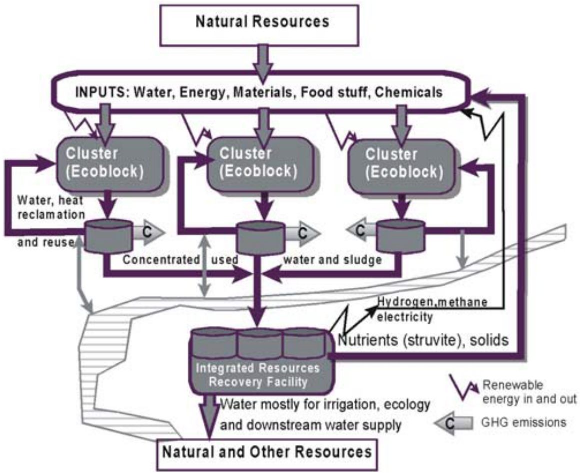


Figure 6 Distributed urban water/stormwater/used water management system with IRRF.

Figure 6 is a schematic of the system composed of ecoblocks interconnected with IRRF. Note the important role of surface water bodies in the system.

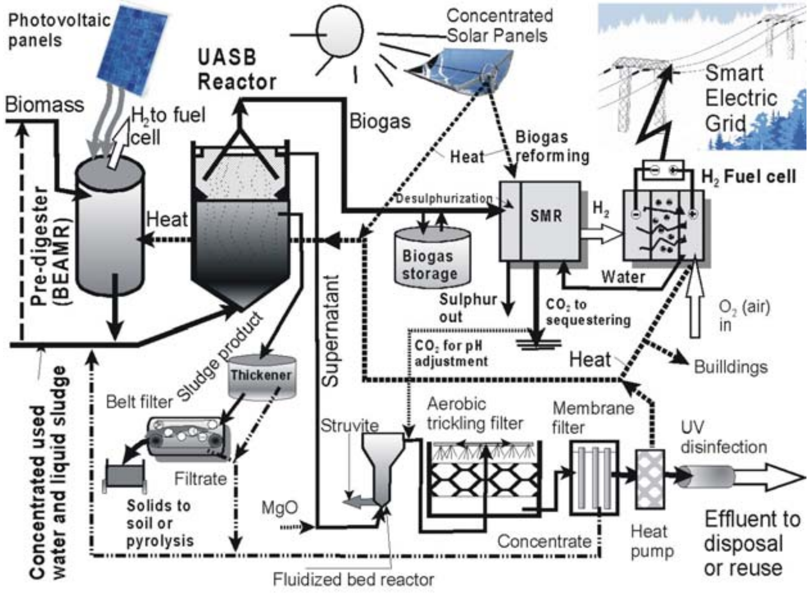
A concept of a future IRRF

A future possible IRRF alternative was conceptually presented in Novotny (2010) and Novotny et al (2010) and is shown on Figure 7. This facility would accept both concentrated liquid used water flows from the clusters and organic solids (vegetation residues, food waste, and manure in developing countries). The produced biogas could be converted to electricity by a combustion engine and generator, or, in a more distant future, biogas and hydrogen would be generated and converted to electricity in a hydrogen fuel cell. Energy can be recovered in a form of biogas, syngas, heat, or hydrogen. It is anticipated that hydrogen based systems will be the future because such systems can recover the maximum energy output and produce the smallest or no GHG emissions. The two key energy producing anaerobic reactors in this proposed IRRF are

- the upflow anaerobic sludge blanket (UASB) reactor for liquid concentrated used water containing mostly black water and reject and backwash solids from the cluster water and reclamation plants, legacy leachate from abandoned solid waste landfills, etc. UASB reactors work efficiently in the temperature range of 20-30^{o}C, which is below the mesophilic (30 - 40^{o}C) range of traditional anaerobic digesters, and require much smaller hydraulic residence time (HRT).

- a pre-digester for fermentation of organic solids that could be in a form of a Bio-electrically Assisted Microbial Reactor (BEAMR) (Logan, 2008) or a traditional (black) fermentation digester with suppressed methanogenesis. Organic solids digesters producing methane have been installed in many countries ranging from small installations in India and China to large digesters for manure in The Netherlands. In the first ten years of the 21st century, BEAMR digesters have been built only on a small laboratory scale (Cheng and Logan, 2011; Call and Logan, 2008; Logan, 2004). The pre-digester producing acetates and/or hydrogen may work satisfactorily in the psychophilic temperature range of < 10-30^{o}C (Kotsyurbenko et al., 1993; Nozhevnikova et al., 2001), hence, this reactor may not need heating.

This dual symbiotic arrangement allows co-processing both liquid and solid organic wastes, eliminating the need for landfills and recovering the resources in one facility. Furthermore, the heat recovered in the conversion of organic matter into energy will exceed the need for heating the reactors and converting water into steam for methane conversion into hydrogen in the SMR process. Additional heating energy can be provided by the concentrated solar panels installed on the premises (roof) of the IRRF. Hence, the proposed IRRF could operate with an excess overall energy output even in colder climatic conditions.



IRRF for concentrated used water and organic solid waste. Credit Novotny (2010) and Novotny et al. (2010). BEAMR- Bio-electrically assisted microbial reactor (Logan, 2008); SMR – steam methane reforming

The UASB reactor proposed by Lettinga and his co-workers (1980) is a suspended growth reactor in which the primary COD removal mechanism is by absorption, biological action of bacteria and fermentation of organic suspended and dissolved solids in the active anaerobic biological sludge blanket. Typical HRT at the temperature range between 20 to 26°C is 7 – 10 hrs and above 26°C is 6 hrs, which is far less that that required for anaerobic digesters operating at higher temperatures and requiring HRT in weeks. UASBs do not remove nutrients beyond that incorporated into sludge nor do they convert ammonium into nitrate. Input COD concentrations into UASB should be between 0.6 to 15 g/L and maximum input total suspended solids (TSS) should be less than 8 g/L. Methane production ranges between 0.2 to 0.4 m^3/ kg of COD removed (Lettinga and Hulshoff Pol, 1991; Tchobanoglous et al., 2003).

Typical COD removal efficiencies of UASB reactors (75 to 85%) are somewhat smaller than those of a typical aerobic activated sludge unit but it has to be realized that the influent COD and TSS concentrations will be much higher, more than 1000 mg/L, and a typical aerobic activated sludge process, even with pure oxygen aeration, cannot accept such high concentrations of organic matter. The smaller COD (BOD) removals could also be caused by dissolved methane in the effluent. Tandukar et al. (2007) proposed and used for post treatment after UASB a downflow hanging sponge (DHS) filter (similar to a trickling filter with plastic media). A sequence of UASB and DHS reactors provided removals of 94% of BOD and 90% of COD, respectively. Solids separation by membrane filters should provide effluent quality commensurate to a well functioning activated sludge membrane reactor.

Because the treated effluent from IRRF will be relatively warm (> 20°C) heat, can be extracted by a heat pump and, after disinfection, the effluent should be ready for disposal into the environment or nonpotable reuse.

Predigester or bio-electrically assisted microbial reactor (BEAMR). A pre-digester is a (black) fermentation digester accepting organic solids, food waste, vegetation residues, etc. Its role is wetting and pre-processing the solids using a portion of the influent or effluent from the UASB reactor which would provide moisture and nutrients. The traditional anaerobic digestion process progresses in three stages: (1) Hydrolysis and fermentation of organic solids into organic acids; (2) Fermentation of organic acids into acetates and hydrogen; and (3) Methanogenesis in which acetates are broken down and hydrogen is scavenged by methanogenic microorganisms to form methane and carbon dioxide. The third step, methanogenesis, is endothermic and requires heating and longer HRT otherwise acetates with small amount of hydrogen are the "dead end" products of fermentation (Call et al., 2009). Without assistance of electricity providing electrons, the hydrogen yield is relatively small, a few percent of unrecoverable H_2. Dark fermentation products (organic acids) can be utilized by specific species of bacteria in a photo fermentation process to develop additional H_2 under nitrogen deficient and illuminated conditions (Hallenbeck and Banemann, 2002; Lu et al., 2010). The rates of hydrolysis and fermentation in the predigester are much greater than those for methane generation; therefore, the particle breakdown and formation of acetates and hydrogen can occur in much shorter HRT than in a typical digester and, after a shorter HRT, the preprocessed mixture full of acetates can be sent into the UASB influent.

A future alternative to a pre-digester is *BEAMR* which is an enhanced anaerobic fermentation reactor capable of producing far more hydrogen (Logan, 2004,d 2008; Call and Logan, 2008) directly from organic matter and concentrated wastewater (Wagner et al., 2009). Logan and co-workers and other researchers discovered that if electricity is added to the reactor by DC current the hydrogen production by electrogenesis in a microbial fuel cell can be much greater than that in the fermentation process without electricity assistance. Wagner et al. (2009) found that by adding electricity providing electrons, hydrogen was produced at a high rate. Furthermore, COD removals comparable to conventional digesters were achieved. The energy equivalent of the produced hydrogen is also much higher than the used electricity which, to a large degree, could be provided by solar photovoltaics (with a storage battery). The produced gas in the swine wastewater BEAMR treatment was 87% pure hydrogen. Hydrogen production from acetates per reactor volume was about 2.5 to 3 m^3 H_2/m^3-d (Call and Logan, 2008) but by decreasing electrodes spacing Cheng and Logan (2011) achieved production rates as high as 17 m^3 H_2/m^3-day in a laboratory setting with applied voltage of 1 V. The production rate of 10 m^3 H_2/m^3- day would be very attractive for full scale applications and seems to be achievable (Cheng and Logan, 2011).

The needed DC electricity of 0.3 to 0.8 Volts is much smaller than the electricity needed in the electrolysis of water without microorganisms. For the swine wastewater in Wagner et al. research, energy used in BEAMR per COD removed was about equivalent to the energy used for COD removal in a traditional active sludge plan which is 0.2 – 2 KW-hr/kg COD (Tchobanoglous et al., 2003), but the net energy in hydrogen produced by BEAMR was more than twice the energy used.

Nutrient recovery. Nitrogen in the atmosphere is abundant and can be converted to fertilizer forms of nitrate and ammonium by the energy demanding Haber-Bosh process. However, the world is running out of phosphate resources and it is expected that shortly after 2040, the world reserves of mineral phosphate will be exhausted which could be devastating to the world agriculture feeding a substantially larger population (approximately 10 billion) than today. Hence, the main task of the future IRRFs is to recover phosphorus. If nitrogen recovery can be accomplished simultaneously, it would save money and reduce GHG emissions of the Haber-Bush process (Barnard, 2007). Traditional oxic/anoxic nitrogen removal by Bardenpho process requires energy.

A process simultaneously removing both N and P without energy is available by struvite precipitation from liquid used water and digester supernatant rich in nutrients (Barnard, 2007; Cecchi et al., 2003). Struvite is chemically an ammonium magnesium phosphate which grows in sewers carrying flows high in magnesium (hardness). Magnesium is added to the treatment/recovery process as magnesium hydroxide or magnesium chloride. Struvite precipitates at pH greater than 9; hence, if magnesium chloride is added, pH has to be increased by sodium hydroxide which adds another chemical to the process. After precipitation in the reactor and struvite removal, pH has to be adjusted back to neutral which can be done by carbon dioxide produced in the treatment process. Struvite is recovered in fluidized bed or pellet reactors.

Methane conversion to hydrogen and electricity. Hydrogen is a highly valuable commodity which also has the highest energy content. Also, using hydrogen for producing electricity is more efficient than electricity production by combustion of methane. Furthermore electricity production from hydrogen is clean energy.

Hydrogen has a very high heating value per unit of mass as seen in the Table 3 below and has a high economic value estimated as US $6/kg which far exceeds that of methane given as US $ 0.47/kg of CH_4 (Logan, 2004). Hydrogen, if needed, can be stored compressed or liquefied.

Table 3 Heating value of common fuels common in energy recovery from used water and organic solids (Source www.engineeringtoolbox.com)

	Heating value		
Fuel	MJ/kg	MJ/m^3	kW-hr/kg
Hydrogen	141.8	13.00	39.4
Methane	55.5	39.80	15.42
Gasoline	47.3		13.14
Natural gas (US)	37.9		18.53
Carbon monoxide	10.11		2.80

A hydrogen fuel cell (HFC) produces clean electricity from hydrogen and oxygen, which react in the presence of an electrolyte by combining hydrogen and oxygen into water. Water and heat are the only by-products. Hence the hydrogen fuel cell produces no polluting emissions (Sammers, 2006).

Hydrogen fuelling the cell is produced from methane by the steam methane reforming (SMR) process. In the first step of SMR, biogas is cleaned by removing sulphides, which produces a purified mixture of methane and carbon dioxide (CO_2) (Sammers, 2006). Altogether, four molecules of H_2 are produced from one molecule of CH_4 or, theoretically, one kg of CH_4 produces 0.5 kg of hydrogen. Carbon dioxide can be sequestered by injecting underground or used to (1) neutralize reclaimed water after production of struvite, and/or (2) grow algae in algal ponds and reactors to produce more energy biomass. SMR is the most common method for producing commercial bulk hydrogen.

About 30 % of energy in incoming methane would be lost for heating the SMR unit. This can be remedied by a solar heat powered SMR unit (Bakos, 2005). Since the SMR unit uses less water than produced in the HFC unit, the joint twin system produces clean water which can be reused. Each molecule of CH_4 produces net 2 molecules of water, or for each kg of CH_4 reformed to hydrogen 1.8 kg of water is produced.

Additional process units of the IRRF are:

- disinfection by ultraviolet radiation
- post treatment and polishing units such as aerobic trickling filter and membrane filters for solids separation
- thickener and belt filter for residual solids dewatering
- pyrolysis (produces syngas and charcoal from dewatered residual solids)
- algal farm producing biomass from carbon dioxide generated by IRRF
- heating system and its computerized real time control, including energy from renewable sources
- heat pump to recover heat from the warm effluent

COMPARISON OF THREE ALTERNATIVES

Three alternative solutions have been analyzed to illustrate the water and energy use, production and associated GHG emissions. Water demand and its division into domestic (kitchen, bathroom, dishwasher, laundry, etc.) and outdoor (irrigation) components for average US households without water conservation and after installing water conserving appliances and water conserving practices were based on the study of the American Water Works Association Research Foundation reported in Table 1. Methods and parameters for the calculation and original reference sources are included in Novotny et al. (2010).

Alternative I is an average end-of-the-century US household with a sprinkler lawn irrigation water demand, practicing no water and energy conservation and discharging its wastewater into a conventional sewer system connected to a conventional activated sludge treatment plant with nitrification that deposits residual sludge on land or in a landfill. Water demand is 550 L/capita-day of which 313 L/capita-day is for outdoor irrigation. Heated water daily volume is 106 L/capita-day and there is no heat energy recovery.

Alternative II is a household practicing water conservation indoor and xeriscape outdoor planting with minimal irrigation. Water conservation reduces the total water demand to 166 L/capita –day, similar to a typical demand in Europe and Japan. This house is located in a cluster which has a capability to reclaim some water and reuse it for toilet flushing (20 L/capita-day) and about ½ of the irrigation needs of the estimated outdoor use of 30 L/capita-day. One half of outdoor use would be from captured rainwater. Per Table 1 the heated water volume is reduced to 71 L/capita-day. On the cluster level a portion of heating energy can be recovered by heat pumps. Reclaimed water for toilet flushing would be treated by microfiltration and ozonization. The rest of used water would be delivered to a regional activated sludge treatment plant with nitrification that would produce methane from sludge for heating of the digesters and buildings. This alternative needs separate piping, storage and a pump with a pressure tank for delivering reclaimed water to the toilets.

Alternative III is a hybrid distributed system that on the cluster (ecoblock) level separates water into black and gray water cycles as shown on Figures 4 and 5. The black water cycle (BWC) includes solids separation and treatment of a portion of the BWC flow for the local supplement of the gray water cycle (GWC) which needs make-up water to replace water lost in backwash and reject water of the filtration (including RO) units of the GWC and for irrigation and ecological outdoor flow. The daily volume of fresh water from the grid provided by freshwater sources is 50 L/capita-day.

A part of the BWC with all solids separated in BWC and GWC is conveyed to the regional IRRF shown on Figure 7. Admittedly, this is a visionary concept still lacking prototype testing and parameter derivations. Nevertheless, the system units have been developed and tested. The IRRF also accepts yard and food solid waste. The IRRF includes UASB reactor that accepts concentrated liquid flows and a BEAMR reactor in which solid waste (sludge, yard and food waste) is diluted by a portion of the BW flow to provide optimum moisture for fermentation. Because of the uncertainty with the future hydrogen yields in the BEAMR, the assumed yield is 5 m^3/m^3-day (Cheng and Logan, 2011) and HRT 5 days.

The energy needed to extract, treat and deliver potable water from the grid is based on the US average of 2.26 $kW\text{-}hr/m^3$ and the GHG CO_2 emissions average equivalent from the power generating plants in the US is 0.61 kg CO_2/kW-hour. If the grid water is provided by desalination, energy use by the system may increase by about 0.15 KW-hr/cap-day.

Table 4 presents the water and energy balances for the three alternative systems.

Table 4 Water and energy balance of three alternative water/used water management.

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	0.55	0.17	0.113
Water used for irrigation from grid L/cap-d	313	30^{1}	0
Energy use for irrigation^{2} kW-h/cap-d	0.17	0.016	0
Total heating water flow L/cap-d	106	71	71
Energy use for heating kW-h/cap-d	3.88	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	0.12	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 by SMR 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	**4.75**	**1.05**	**(-0.89)**
Carbon GHG emissions (credit) kg CO_2/cap-year	**1263**	**234**	**(-198)**
Area of a solar concentrated panel to provide 50% energy for water heating (line 6) m^{2}/cap	NA	1.2	1.2
GHG credit with ½ solar heat kg CO_2/cap-year	NA	**(-55.5)**	**(-710)**

Legend:

[1] Water use for xeriscape and other outside uses assuming 50% irrigation demand satisfied by captured rainwater

[2] Includes sprinkler flow pumping energy and lawn mower energy estimate

[3] Includes indoor water use + 25 % increase of sewer flow by infiltration/inflow into sewer

[4] Pumping in lift stations for 30 meters head loss to keep minimum velocities to prevent solids settling and providing hydraulic head in the treatment plant

[5] Assuming extended aeration and nitrification

[6] Water recycle only for toilet flushing treated by filtration and ozonization

[7] Water recycle treated by microfiltration and ozonization

[8] Gray water recycle treated by microfiltration, reverse osmosis and ozonization

[9] Per US EPA [2010] food and yard organic waste is 0.68 kg/capita-day and the recovery is 60%

[10] Total effluent for Alternative II, IRRF effluent for Alternative III

Discussion of the alternatives

Both water heating energy and heat energy recovery (less than the former) from used water were included in the balance. Heating energy is responsible for the largest portion of the overall energy use and corresponding energy gain when heat is recovered.

Alternative I is a baseline against which the other two, or any other improving alternative, are measured. This currently common linear management alternative would result in 1.26 ton of CO_2 emissions per capita per year, which represents about 12% of the average US per capita emissions, including also traffic and home space heating. Its average water use is unsustainable and cannot be repeated in most countries and arid regions. Achieving the net zero carbon emissions goal is impossible and the alternative may also result in widespread water shortages.

Alternative II could be a near future (less than ten years) goal. It incorporates reasonable water and energy saving measures. Methodology, parameters and pertinent references are included in Novotny et al. (2010) water saving measures with a reuse and rain water reclamation the per capita water use can be reduced in the US to the levels common in some European countries and Japan. By these measures the CO_2 equivalent emissions can be reduced by 75%. Furthermore the net zero carbon emissions goal would be achievable if about 50% or more of water heating energy is derived from renewable sources, for example, by installing concentrated heat panels that are already common in many environmentally conscious communities in California, Europe, Australia, China, and elsewhere. The size of the panel for a community in the southwestern US which has approximately 320 insolation days, average insolation rate of 4 kW-hrs/m^2 and heat recovery efficiency of 30% (a near future estimate) would be about

$$A= 1.26\ [\text{kW-hr/cap.-day}]*365[\text{days}]/(4[\text{kw-hr/m}^2)*0.3*320(\text{days})] = 1.2\ \text{m}^2/\text{capita.}$$

Alternative III represents a more distant future (>15 years). It has a double loop separating gray water and black water flows and on site cluster/ecoblock treatment. The water demand of this alternative is very low, 50 Liters/capita-day, which is deemed to be the lowest limit for urban water delivery needed for providing adequate water supply and water based sanitation and some irrigation and ecologic flow. However, there is not enough energy in the used water to satisfy the needs for the high recycle without co-digestion of organic solids and/or using renewable (solar) energy for heating water. The energy deficiency without these auxiliary energy sources would be about 0.3 kW-h/cap-day.

Alternative III with co-digestion is a very attractive and efficient solution with better than net zero GHG emissions. It results in excess energy produced by the system and commercially attractive production of hydrogen, electricity and commercial grade nutrients. Furthermore, the process can accomplish some carbon sequestering. Implementing solar power similarly to Alternative II for heating would further improve the energy balance. For a community of 10,000 the IRRF energy production would then be approximately equivalent to a 1 MW power plant that would provide, based on average 2010 electricity consumption (12 146 kW-h/capita), electric power to 725 people which could be improved in the future.

It is also interesting to compare the base line (current) Alternative I with the more sustainable Alternatives II and III. Implementing Alternative II would eliminate almost 1 ton CO_2/cap-year from the current US emissions. This is even more impressive with Alternative III that would eliminate almost 1.4 ton of CO_2/cap-year or about 12% from the current total household emissions (including car use and space heating), while producing commercially valuable products (water, fertilizers, hydrogen, biogass, electricity) and save money on dumping fees for organic solid wastes and water delivery fees.

CONCLUSIONS

Water and energy uses are intertwined and represent a significant portion of the total carbon emissions reaching the environment. About 3 – 7 % of the total energy use and the equivalent portion of GHG emissions are attributed to water and used water delivery, treatment and disposal. Water conservation is the best alternative solution to a water availability problem because it reduces proportionally energy use and carbon emissions. Furthermore, energy can be extracted from used water by heat pumps for a carbon credit. A common water to water heat pump provides 4 -5 times more energy than it uses. The extracted heat can be used to warm water in the buildings or generate energy. If the water use reduction goals water can be met by water conservation without reuse, a distributed water management system is the best solution whereby highly treated effluents, after heat energy is extracted, provide irrigation, ecological flow to receiving waters and water for downstream uses. Such a system has been implemented in Hammarby Sjőstad in Stockholm (Novotny and Novotny, 2009). Total urban water management is best carried out in a hybrid system whereby in local clusters (ecoblocks) used black and gray waters are separated, gray water and a portion of black water are reclaimed for reuse and concentrated black water with other solids is sent to a regional integrated resource recovery facility for further resource and energy recovery.

Used water has recoverable energy content larger than that needed to satisfy energy needs of the water conveyance, reclamation and reuse. However, heating energy requirements, typically not accounted for in the water-energy nexus analyses, would result in the overall energy balance in energy deficit and GHG emissions. This deficit can be more than compensated by co-processing food and yard waste in the IRRF. The co-digestion and hydrogen production would produce energy in excess of the energy consumption in the hybrid urban water/used water cycle. The produced energy could be commercially sold along with nutrients and other resources produced by the IRRF and count as credit.

Reuse with high efficiency solids and pollutant removals (e.g., microfiltration and reverse osmosis) in a closed cycle (e.g., Masdar in UAE or Orange County in US) relying on desalination for water supply requires more energy because of the energy requirement by desalination employed in the treatment processes and multiple cycle reuse (i.e., the water is reclaimed and treated more than once). This leads to a higher marginal carbon emission rate and total energy use. In order to stay sustainable, the extra energy has to be provided by renewable energy sources as it is done in Masdar or proposed for Qingdao. Methane production in the treatment and recycle process, if burned to produce energy, is carbon neutral.

The regional hydrogen based integrated resource recovery facility (H_2-IRRF) would

- treat concentrated used water and solids to a level commensurate for safe disposal into the environment and safe regional reuse;
- produce excess energy in a form of biogas, commercial hydrogen, and electricity
- recover nutrients in the form of commercial grade struvite;
- sequester carbon and provide carbon dioxide for a possible algal biomass production that can be used in the IRRF to produce more energy or commercially processed for biofuel; and
- produce nutrient rich organic solids for farms or for production of syngas and charcoal by pyrolysis.

For all practical purposes the H_2-IRRF would not use outside energy and the entire system could be a carbon sequester and energy producer. The net produced energy could be counted towards credit for a net zero GHG emission goal. The H_2-IRRF is a vision and implementation challenge. All components have been tested in laboratories and practice for some time, some for decades. The conception of H_2-IRRF should now be followed by a translational research, pilot testing and full scale implementations.

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