Urban Water and Energy Use
From Current US Use to Cities of the Future

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ABSTRACT

The article describes and estimates the carbon greenhouse gas and water footprint of the urban water sector to achieving the sustainability goals of future (eco) cities. Specifically, the article focuses on two goals of reducing water use by 50% and zero net carbon (GHG) emissions. Water conservation from the current use to an achievable sustainable use cannot be achieved by water conservation only. Further reduction of the water demand by desalination and high degree treatment (e.g., nanofiltration or reverse osmosis) requires a significant amount of energy and there is a limit on the maximum percent of water that can be reused in a closed water cycle. Cluster semi-distributed water delivery, reclamation and reuse with heat energy recovery is described, followed by presenting a proposal for a regional integrated resource recovery facility (IRRF) which reclaims water for ecologic flow, irrigation and other uses, produces biogas, hydrogen, electric energy, struvite and residual organic solids for soil conditioning. It was estimated that the contribution of the water sector towards the net zero GHG emissions goal could be about 10%.

KEYWORDS

Water use, green house gas emissions, water reuse, integrated resources recovery, anaerobic treatment, biogas production, hydrogen generation, carbon sequestering, cities of the future.

INTRODUCTION

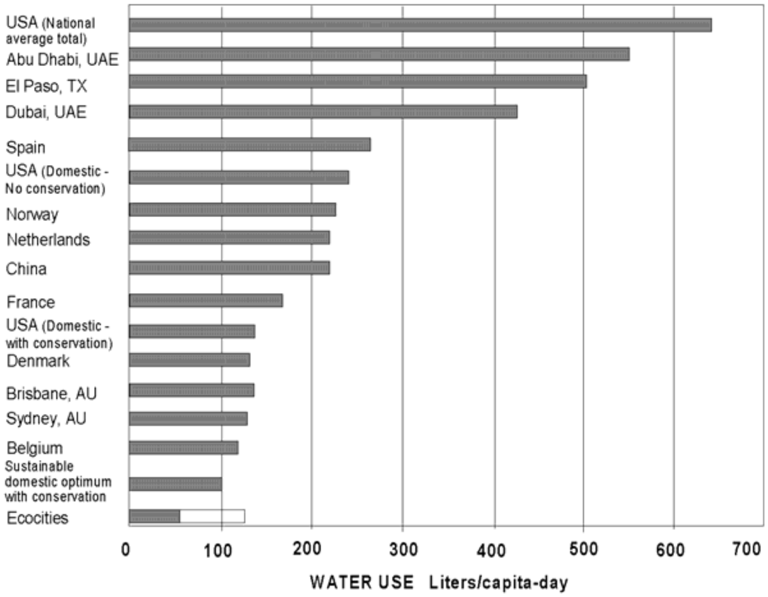
Water Use

Currently, about 7% of energy used in the United States and, consequently, the same proportion of green house gas (GHG) emissions are for providing water and used water disposal to the urban population. Also, many urban areas of the world do not have sufficient water supply to provide water to its inhabitants based on the current water demand for domestic indoor and outdoor, municipal and commercial uses. Population growth in many countries, including the US, is putting additional stresses on municipal water supply systems which are often more than one hundred years old and lose water by leaks and inappropriate use by citizens. Figure 1 shows great discrepancies in urban water demand and use between the countries whereas the US is the leader in the per capita water demand and use.

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 and

136 liters/capita/day for a household practicing water conservation, respectively (Heaney et al., 2000). 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/cap.-day. On the other side of the water use spectrum, Falkermark and Widstrand (1992), proposed more than a decade and half ago, the water use figure of 100 Liters/cap-day to achieve a minimally acceptable urban standard of living, in spite of the fact that in many cities of the developing world urban water use is less.

Figure 1 Per capita water use in selected urban areas and countries (various sources)



Green House Emissions Related to Urban Areas

CO_2 emissions vary widely among nations. Until recently the US was the largest emitter of GHG gases but was overtaken by China. If statistics are presented in emissions per person, the Middle East states are the largest emitters (Table 1) but the US, Australia and Canada are in the top ten. It should be pointed out various statistics differ and the emissions vary year from year, but generally, they seem to be leveling off in this century and, in the US, the GHG emissions have begun to decrease after 2007 (Brown, 2009). Dodman (2009) found large cities emit per capita less GHG than the national average. For example, London's emissions (6.2 tons/capita-year) are 50% less than the national average (9.4 tons/capita-year). Same is true for US data. The average of 100 largest US cities analyzed by Gleaser and Kahn (2008) is 8.5 tons/capita-year, without considering industries, while the national average is 19 tons/capita-year (which includes industries). The median value in the Wikipedia table, listing more than 200 countries, is 3.2 tons of CO_2 per capita in a year and 30 % of the world (poorest) countries had per capita CO_2 annual emissions of less than one ton.

The first line in the table is the total use that also includes rural use including agriculture and industrial emissions. This explains the very high emissions in oil producing countries that are burning natural gas to extract oil and high emissions in refineries. In a sense this is also a virtual inter-country emission value of using fuel in the US and elsewhere (China, Europe) imported from the high emission countries of the Middle East and only accounting for the GHG emitted by burning the fuel in the US but not the emissions in fuel producing countries. Similarly to water use, there are great differences between the GHG emissions between the US and a few developed countries and the rest of the world. While China may be a leading emitter of GHG gases and India is catching up, the per capita GHG emissions in China are only 4.6 tons CO_2 /person-year and that in India is 1.2 tons of CO_2 /person-year, a fraction of the US per capita GHG emissions.

Table 1 Per capita CO_2 emissions statistics

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

More detailed analyses of water use, water conservation and the impact on GHG emissions were published in Novotny et al. (2010).

STEPS TOWARDS SUSTAINABLE INTEGRATED URBAN WATER SYSTEMS

Achieving the Goal of Net Zero Carbon Footprint in New Ecocities and Retrofits

The current criteria and guidelines used for ecocity certification are the LEED (Leadership in Energy and Environment Design) of the US Green Building Council and One Planet Living (OPL) by the World Wildlife Fund. However, the requirement for ecocities is not just to reduce GHG emissions such as expressed in the LEED energy efficiency standards. The demand elucidated in the One Planed Living (OPL) criteria by the World Wildlife Fund requires ecocities to become carbon neutral. The same requirement has also been issued by the National Science and Technology Council (NSTC) (2008) of The US President and by the British government for development and implementation of both net zero carbon footprint and high performance building technologies.

Figure 2 Paths to achieving the net zero energy goals (NSTC, 2008)

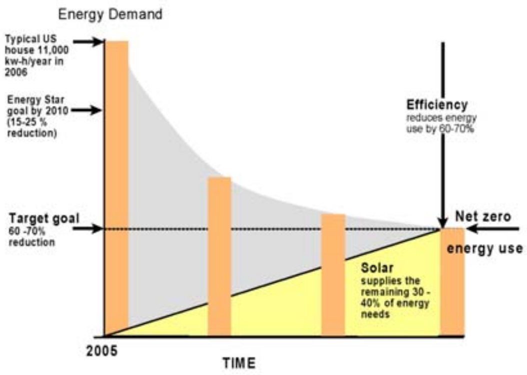


Figure 2 shows the possible paths towards the net zero GHG emissions goal. Current scientific research indicates 60 to 70% of energy reductions can be achieved with more efficient appliances such as better water and space heaters, heat pumps, significant reduction of water demand by water conservation and other improvements. 30 to 40% energy can be produced by renewable sources, including heat recovery from used water or extracted from the ground and groundwater. In this context, raw sewage becomes a resource from which energy, nutrients, solids and other useful constituents can be retrieved (recovered) and reused. Therefore, using the terms “wastewater” or “solid waste” are not appropriate and are being replaced worldwide by the terms “used water” and “resource”. Also the goal of integrated water/stormwater/used water management is not treatment and safe disposal but resource recovery. Implicitly, resource recovery implies a high degree of pollution elimination from the cities of the future.

Listed below are alternative options and measures to achieve green net-zero GHG and pollution emission goals in the future sustainable city developments and retrofits (Novotny et al., 2010):

- Passive architectural features for heating and cooling
  - ◊ Southern exposure with large windows equipped and regulated by shutters
  - ◊ Cross ventilation
  - ◊ Green roofs
  - ◊ A lot of insulation
  - ◊ Energy efficient lighting
- Renewable energy sources (solar, wind, extracted from used water and stormwater)
- Water conservation and reuse, addressing the entire water (hydrologic) cycle within the development, including rainwater harvesting and storage
- Distributed stormwater and used (waste) water management to enable efficient used water and reuse and renewable energy production
- Considering used water separation (black, gray and yellow)
- Xeriscape of the surroundings that reduces or eliminates irrigation and collects and stores runoff from precipitation
- Energy efficient appliances (e.g., water heaters), treatment (e.g., reverse osmosis) and machinery (e.g., pumps, aerators)
- Connecting to on-site and off-site renewable energy sources such as solar power plants and wind farms
- Integrated resource recovery management of used water and solids to include
  - ◊ Clean water recovery for direct nonpotable reuse and indirect potable reuse, used water separation
  - ◊ Biogas production by anaerobic treatment of concentrated used water and sludge
  - ◊ Conversion of biogas to hydrogen and sequestering carbon dioxide
  - ◊ Considering nutrient removal by algal growth reactors and conversion of algal biomass to biogas and hydrogen that will also sequester carbon dioxide
- Heat and cooling energy recovery from used water by heat pumps
- Connection to low or no GHG net emissions heat/cooling sources such as heat recovered from used water or from ground
- Smart metering of energy and water use and providing flexibility between the sources of water and energy
- Sensors and cyber infrastructure for smart real time control
- Restoration and maintaining the integrity of urban water resources

Water Conservation

Most current water/stormwater/waste water systems are linear. Daiger (2009), Novotny (2008) and others agree the current "linear" approach to urban water management, sometimes called the *take, make, waste* approach in the sustainability literature, when applied more broadly to natural resources use and global climatic change, has become increasingly unsustainable. The most obvious effects are growing water shortages by population increase, pollution and overuse of water resources throughout the world. In the prevailing current linear system, water is taken from upstream sources, delivered to the urban area by underground conduits, used and polluted, then delivered by underground conduits to a regional wastewater treatment facility many kilometers downstream from the points of potential reuse, and finally overwhelming the receiving water body by the effluent discharge, creating often an effluent dominated water body. Traditional simple economic cost analysis for water systems based on economy of scale dogma was leading planners to building large regional facilities and (in the 1970s, after the passage of the Clean Water Act in the US and elsewhere) to abandoning smaller community based treatment plants that were deemed uneconomical and inefficient. The consequences of the linear system are rivers with no flow during the time of shortage and effluent (treated and sometimes untreated, e.g., CSOs) dominated streams by the effluent discharges located often far downstream. Water reuse and recycle in the linear system is very difficult and expensive because of long water transfers by dual systems. Also concerns about the ecologic status of the water bodies impacted by urban development, resource consumption, and the dispersion of nutrients resulting in severe algal blooms are growing. The reason for these problems may not be the linear system per se, it is often the very high water use which ironically commonly happens in water short arid and semi arid regions. Hence, implementing water conservation and saving is the first step, which, by the way, is also the most energy efficient.

Daiger (2009) proposed a hybrid system in which water/stormwater/used water management can be accomplished both in a remnant of a linear system but mostly distributed. This hybrid system concept can be further expanded into home (building), cluster or ecoblock scale and regional scale measures and management, leading to sustainability. This creates a portfolio or a toolkit of measures planners and developers can adopt, adapt and expand on a site specific basis. Malmqvist et al. (2006) published guidelines for developing strategies towards sustainable cities.

Heaney, Wright and Sample (2000) reported the results of the AWWA Research Foundation sponsored nationwide project, referred to as the North American End Use Study (NAREUS), of domestic water use (Table 2). The study monitored in detail 1200 households. The indoor water use ranged between 162 liters/capita-day (in Seattle, WA) and 276 Liters/capita per day (in Scottsdale/Tempe, AZ). The standard deviation of the indoor water use was 38 liters/capita-day. This relatively stable indoor water use study reflected water use for essential purposes is culturally the same among the US population. This range of water use does not reflect any water conservation, e.g., toilet flushing tank content generally was 15 to 19 liters in the 1990s (Heaney, Wright, and Sample, 2000) and no water saving shower heads were used in the tested households. Table 2 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 Sample (2000). Future conservation potential effects of domestic water users in the US are presented in the right side of the table. The conservation options do not include water reclamation and reuse. The values of the conservation option were adjusted using also estimates from a study by (Gleick et al., 2003) of the water conservation potential in California.

Table 2 presents estimates of water use by water experts and monitoring of the potential reduction of water demand achievable by implementing water conservation appliances and measures such as low flow shower heads, low flush toilets, Energy Star certified appliances, etc. After implementing water conservation, based on US water use, the outcome would put the potential indoor water use at the level of that currently in Europe, but the total still being on the higher side. Considering the above expert estimates leads to the conclusion that further savings (reductions) of water demand in water short areas, beyond that achievable by conservation, can be achieved by reuse and recycle which will require energy for treatment, pumping, and delivery. The current water system in most cities is linear, i.e., what water comes in upstream it goes out as wastewater (minus consumptive use) downstream. It is not wise to implement water reclamation and reuse without conservation to satisfy the homeowners' desire for plenty and developers push for more scattered thirsty and water wasting subdivisions. In order to achieve a large water saving partial closure of the water cycle, an exhaustive consideration and implementation of water conservation measures is a necessary prerequisite It will be argued a full 100% closure of the cycle (100% recycle) is physically impossible.

Table 2 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/capita-day	**Percent**	**Liter/capita-day**	**Percent**
Faucets	35	14.7	35	25.8
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	14	10.3
Leaks	30	12.6	15	11.0
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 switch from lawn to xeriscape using native plants and ground covers with no irrigation. Water use is for swimming pools, watering flowers and vegetable gardens, *** Values adjusted by the Pacific Institute estimates for California (Gleick et al., 2003).

It is reasonable to assume cities will provide most water from a centralized water supply grid. But it is illogical and unsustainable to use treated potable water for uses such as irrigation, toilet flushing, or lose it by excessive leaks. Furthermore, citizens should be encouraged (by education and using smart pricing of delivered potable water) not only to conserve but also to implement some simple capture of water from other sources. For example, condensate from air-conditioning and dehumidifiers has a composition of distilled water (it is not potable) but could be used for ironing, battery refilling, or plant irrigation in the house. Captured rainwater has been used as a source of potable and nonpotable water for millennia. Additional sources of water that are being considered and used in water short cities are

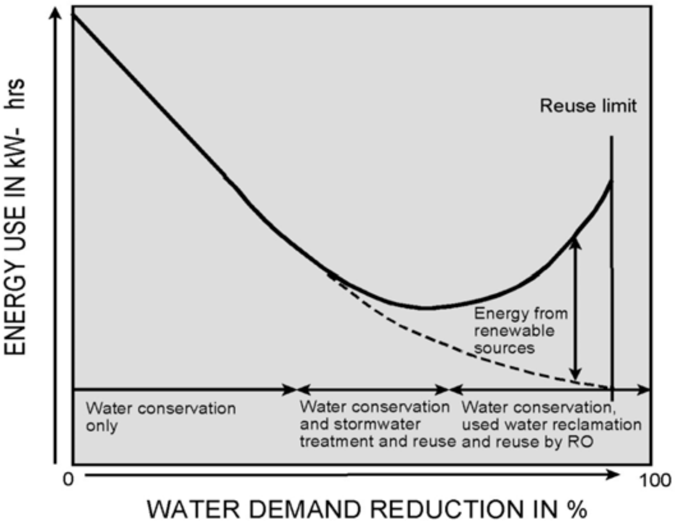
- Rainwater harvesting and captured urban stormwater
- Desalinated water from brackish groundwater and sea
- Graywater reclamation and reuse
- Used (waste) water reclamation by high degree of treatment followed by aquifer recharge for nonpotable and indirect potable water reuses

Using reclaimed water from the above sources will require additional energy as shown on Figure 3.

Water-energy Nexus

In general, implementing water conservation, reuse, and recycle is expected to reduces GHG emissions. Some experts advocate that a fully closed water cycle is the most optimal solution to both water and carbon footprint problems. However, this may be true only up to a certain limit. Figure 3 presents the possible relation of water demand reduction leading to a closed urban water cycle and energy. The plot suggests there is a minimum beyond which further reduction of water use will increase energy demand. In the water conservation phase, energy use and GHG emission reduction of water demand by using more efficient appliances, xeriscape and plugging the leaks and losses do not require a large amount of extra energy, hence, the energy use reduction is directly proportional to the reduction of the water demand. Several new urban developments and older cities are located or being planned in areas with meager water resources which necessitates using desalinated, brackish and reused water. To further close the water cycle, energy demanding water reclamation processes are needed such as nanofiltration

Figure 3 Relationship between water conservation, reuse and energy (from Novotny et al, 2010)



and reverse osmosis.

Consequently, larger dependence on renewable zero carbon energy sources (wind, solar, geothermal, and energy recovery from used water organic solids) will ensue. Recycle systems cannot be fully closed to prevent accumu-lation of nondegradable potentially harmful compounds that may pass through reverse osmosis and other high degree treatment processes.

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 represents about 3% of the energy use. However, within the buildings, 8% of the 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 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 which is

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

The Energy Information Administration (2009) estimated 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 billon tons of CO_2 emitted. Using the 3% estimate for providing and treating water, the “water share” of energy use is 124.7 TeraW-hrs and 75.5 million tons of CO_2 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 and boiling, and wet cleaning.

Reducing water use by conservation will not require extra energy. It also does not have to be in a closed system but it works best if it is done in a distributed partially closed urban management system which provides ecological flow to urban streams (restored or daylighted) and allows energy and water reclamation from used water. 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-hr/m^3 attributed to water. Corresponding carbon emission is 1.37 kg CO_2/m^3. This is the linear Phase I of Figure 3. The water saving potential shown in Table 2 is 65% reduction.

In the inflection phase, a city is looking for additional sources of water or brings in sources that have worse quality and will require more treatment and/or 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 water and/or may be located on receiving water bodies that require a higher degree of treatment. For example, pumping 1 m^3 of water from a depth of 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.

In the increasing phase, tapping on higher salinity water sources (brackish sea or groundwater) is supplemented with used (waste) water reclamation and reuse that requires a two or three step high efficiency energy demanding treatment (Figure 3). Table 3 presents energy and CO_2 emissions.

Table 3 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)		

The trend today in water short areas is towards (partially) closed systems that would implement water reclamation and reuse. Furthermore, in countries like China, Middle East, Israel, North Africa, population increases and migration force development of new cities in water short areas (similar to the situation of Los Angeles or Phoenix decades ago) which evolved in deserts or very arid environments. It can be stated that most of the new large urbanization occurs in areas without adequate water resources. The response of urban land use development architects and planners was to introduce the concept of sustainable “ecocities” which are very frugal with the use of water and energy. The most stringent requirements on the limits of water use have been proposed by the World Wild Life Fund (2008) for the future ecocities under the title One Planet Living (OPL). OPL criteria for ecocities are far more broad and stringent than LEED or Low Impact Development Guidelines (USGBC, 2007). Out of the ten OPL criteria, the following two are very pertinent to water – energy nexus.

- net zero carbon emissions with 100% of the energy coming from renewable resources;
- sustainable water use with a 50% reduction from the national average.

From the above discussion it is evident that achieving 50% reduction of water usage in US cities is realistic over a period of 10 – 15 years by water conservation. Without water conservation it might be even questionable, with the exception of reclaiming rainwater and stormwater, to look for additional low quality sources requiring reverse osmosis for treatment. Furthermore, considering used water as a resource and recovering energy from used water and organic solids, as well as developing solar and wind energy sources, is the way to satisfy the net zero carbon emissions.

INTEGRATEDC RESOURCE RECOVERY IN SUSTAINBALE CITIES – A REALISTIC SOLUTION

Review of Ecocities

Novotny and Novotny (2009) presented a review of seven "ecocities" which is an acronym for sustainable urban developments that are approaching or even meeting the OPL criteria. The reviewed cities included two conceptual virtual cities in China (Dongtan and Qingdao) and one already being built in the Tianjin province, two in the US (Treasure Island and Sonoma Mountain Village in California), one in Sweden (Hammarby Sjőstad), and one in the United Arab Emirates (Masdar). Table 4 summarizes the synthesis of the evaluations.

The two Chinese virtual cities (Dongtan and Qingdao) were developed by two leading urban landscape architectural teams (British ARUP and the College of Environmental Systems of the University of California – Berkeley). Realization of the Dongtan ecocity has been indefinitely postponed due to political reasons in China. The Qingdao design has been incorporated into the Tianjin development, a Sino-Singapore joint venture, which is progressing and on schedule. The following findings of the ecocity evaluation study are highlighted herein:

Population Density. With the exceptions of Sonoma Mountain Village (the smallest development) and Qingdao ecoblock (the development with the highest population density), the density of the remaining five developments varied between 117 to 170 people/ha. From the presentations and literature findings it was evident all design teams used some kind of a proprietary model which balances the population and its energy use based on probability of walking and biking instead of driving, energy insulation of buildings and exposure to sun, renewable energy sources and other determinants for GHG emissions from urban areas. Three sites, Dongtan, Tianjin, and Treasure Island were designed by Arup teams. Literature indicates low density "American style" suburban areas with one oversized house on 0.4 ha (1 acre) land are the most wasteful regarding energy use and efficiency (Newman, 2006). The fact of medium design density development being the most optimal refutes, to some degree, the utility of the "low impact" subdivisions which in most cases have an objective of minimizing stormwater impacts and discharges and generally results in low density developments.

Green House Gas Emissions (carbon footprint). Dongtan, Qingdao, Masdar and Sonoma Valley designs are proving ecocities can fulfill the OPL criterion of zero GHG emissions from infrastructure heating and cooling, electricity consumption and traffic.

Water Reclamation and Reuse. All cities use the latest technology for in-house water savings such as low flush toilets, showers, etc. Hammarby Sjöstad is almost a 100 % linear system with recovery of phosphorus and energy. Stockholm is water rich and there is apparently no need for recycle yet they expect to reduce the per capita water use to the "magic" limit of 100 L/capita-day. All other cities use various degrees of water reclamation and reuse but start with a higher per capita water use reduced by reclamation of used water and stormwater.

Table 4 Summary of the seven cities evaluation (from Novotny and Novotny, 2009)

City	Population Total	Population Density #/ha	Water use L/cap-day	% water recycle	Water System	% Energy savings renewable	Green area m^2/cap	Cost US$/unit*
Hammarby Sjőstad	30,000	133	100	0	Linear	50	40	200,000
Dongtan	500,000 (80,000)++	160	200	43	Linear	100	100	~40,000
Qingdao	1500+	430 - 515	160	85	Closed loop	100	~15	?
Tianjin	350,000 (50,000)++	117	160	60	Partially closed	15	15	60,000 – 70,000
Masdar	50,000	135	160	80	Closed loop	100	<10	1 million
Treasure Island	13,500	170	264	25	Mostly Linear	60	75	550,000
Sonoma Mountain	5,000	62	185	22	Linear	100	20	525,000

* Based on average 2.5 members per household + Qingdao ecoblock ++ Phase I

A high density Qingdao ecoblock with 430-515 people/ha appears to be an anomaly which should be further researched as to the feasibility and sustainability of the concept regarding used water reclamation. For one, locating free surface wetlands that are supposed to provide treatment to partially treated black wastewater next to the high-rise buildings may not be acceptable in many countries because of health concerns. Qingdao's treatment of black water consists of "sequential batch reactors" described in a promotional video (Green Dragon, 2008) as septic tanks, followed by wetland treatment. Because of health reasons, the acceptable wetland type would have to have a fully submerged flow. Based on the WEF (2001) manual, the minimum area of the wetland serving 1500-1800 people will have to be about ½ hectare or one football field and could not be accessible as a park but could be a part of green environment supporting wildlife. Also the wetlands will have a relatively large evapotranspiration during dry summer days. Constructed wetlands also emit large quantities of GHG methane, nitrous oxide and carbon dioxide (Sovik et al., 2006) that might be counter balanced by carbon sequestering by vegetation and building organic soils.

Surface Drainage for Runoff and Clean Water. All ecocities use surface drainage for collecting urban runoff and clean water inputs and will use extensively best management practices for urban runoff such as pervious pavements for infiltration, capture and storage in underground basins, and reuse for various purposes such as irrigation, fire protection, and some plan to tap into the groundwater resources for reclaimed water. All cities are planning reuse of the captured stormwater for irrigation and in some cities for reuse as nonpotable water supply. Potable reuse off clean stormwater such as harvested rainwater is possible and considered. Use of green roofs has not been planned on a large scale with the exception of Hammarby Sjöstad.

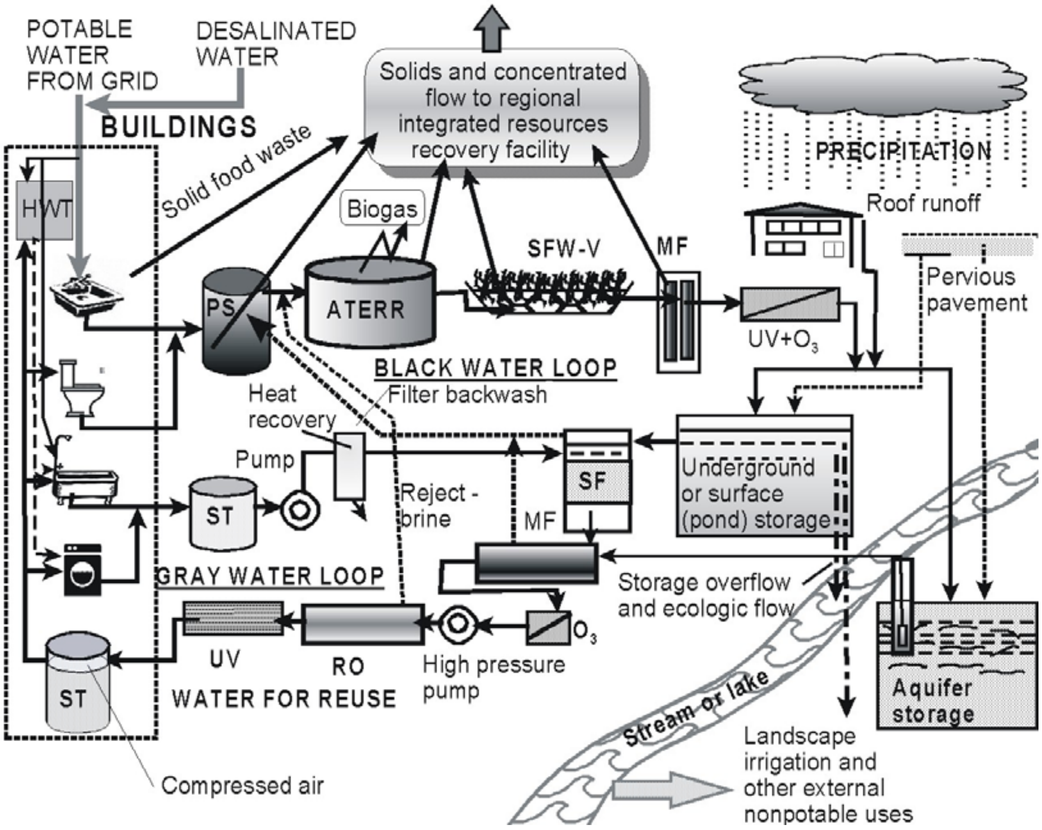
Water Centric Development Opportunities. Hammarby Sjőstad, Dongtan, and Tianjin are clearly water centric whereby water and canals are the architectural centerpieces of the development and will have an aesthetic role, provide recreation and local transportation. By locating the advanced wastewater treatment plant at the fringe of the city and directly discharging the treated used water into Hammarby Lake connected to Stockholm Bay without water reclamation, the city has missed the opportunity for water reuse. The other two cities in China considered using the water bodies inside of the city for discharge and treatment of reclaimed water and reuse in the mostly recreated canals. The desert city, Masdar, will apparently create small artificial streams transecting the city. It is not clear whether or not the Masdar streams will be used for conveyance of reclaimed used water. Qingdao, Sonoma Mountain Village, and Treasure Island will not have permanent streams, natural or artificial, planned within the ecocity boundary. Sonoma Mountain Village is planning to create habitat bioswales with wetlands for stormwater conveyance transecting the village and connected to a storage basin from which water will be reused. Qingdao created two conveyance systems for reuse: one for the reclaimed black water via a chain of wetlands, the other for stormwater both ending in an underground storage facility, followed by reuse. The architectural rendering of the Qingdao ecoblock does not show surface stormwater conveyance to the central storage basin.

Analysis of the Adaptation of the Qingdao Ecoblock

An ecoblock or a cluster is a semiautonomous water management and resource recovery unit (Novotny, 2008; Novotny et al., 2010) that maximizes the potential of resource recovery. The fundamental characteristics of the resource recovery cluster are the geographical size, source separation of both solids (food and organic decomposable solids, combustibles, glass and metals, and items containing toxic compounds) and used water (black, gray, white and yellow streams). Yellow streams (urine) contain nutrients but may not require mandatory separation because nutrients, as it will be documented, can also be separated in the treatment process. Figure 4 is an adaptation of the Qingdao ecoblock water management (Fraker, 2008) which handles black, gray and white (rainwater and stormwater) water sources in a double loop. On the figure the box denoted as “Buildings” does not represent an individual single homeowner building but a cluster (ecoblock) that may have thousands of people living or working therein (highrise apartment building, office/residence towers, large block or subdivision). The suggested number of people residing in the Qingdao ecoblock was 1500 to 1800 (Fraker, 2008).

The difference between the original Qingdao ecoblock and the schematics of Figure 4 is the avoidance of the partial direct potable reuse, rearranging and modifying the treatment processes, inclusion of the ATERR (unheated) unit for biogas on-site recovery, and providing ecologic flow. Also the arrangement of the loops is somewhat different. In this new concept, a significant portion of flow with solids would be diverted to the regional Integrated Resource Recovery facility (see next Section) as a concentrated flow laden mostly with organic solids. Biogas from the ATERR unit will be used locally. Methane and carbon dioxide emitted from the wetland would be counterbalanced by vegetation production and organic soil buildup in the wetland. This could make the system carbon neutral. In the future the biogas could be converted to hydrogen with carbon dioxide sequestering as proposed for the regional integrated resource recovery facility (IRRF) described in the next section. ATERR could be a conventional mezophilic digester, completely mixed activated (anaerobic) reactor or an anaerobic upflow sludge blanket (UASB) reactor. Used water and solids in the black water loop would be concentrated with expected BOD concentrations exceeding 1000 mg/L and high concentrations of nutrients if yellow water is not separated. Such high strength waters are not suitable for conventional aerobic activated sludge treatment that would also demand energy and would emit or cause emissions of GHGs.

Figure 4 Schematics of the adaptation of the Qingdao ecoblock water management (based on Fraker, and Novotny et al., 2010)

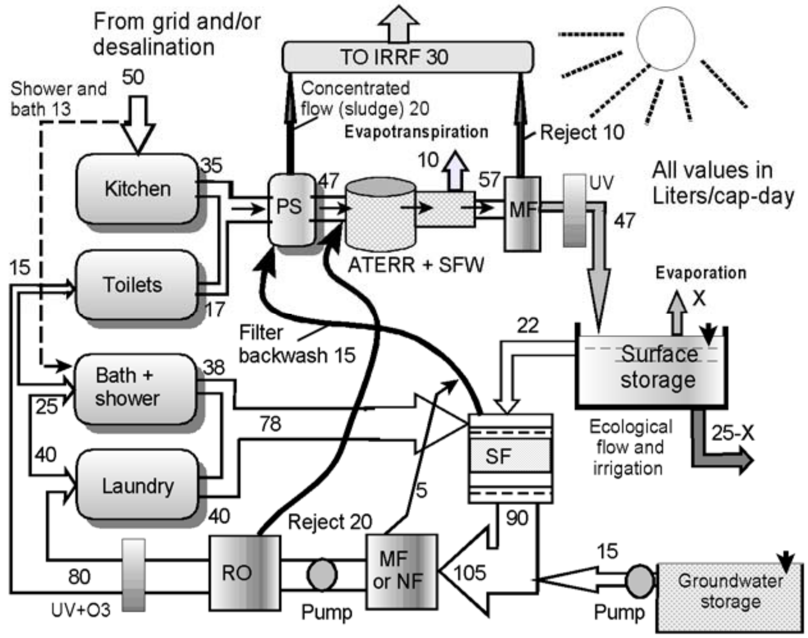


Legend: PS – primary settling, ATERR – anaerobic treatment and energy recovery reactor, SFW-V – vertical subsurface flow wetland, MF-membrane filter, ST – storage tank, SF-sand filter, UV-ultraviolet disinfection, RO – reverse osmosis.

In the graywater loop, a sand filter, followed by finer filtration and reverse osmosis will provide the treatment. Unfortunately, graywater is not clean, it contains highly variable BOD (COD) concentrations, pathogens, pharmaceutical and cleaning chemicals and other pollutants and, in overall, while it goes foul after a day or two, it is not amenable to biological treatment. In order to reuse it, physical and partially chemical (ozone) treatment is needed. The system presented on Figure 4 should result in a water quality that would be comparable to drinking water. For psychological and also other reasons, it should not be used for drinking but its water quality would be more than acceptable for toilet flushing, laundry (the water would be clean and soft) and bathroom uses except the bathroom sink. Water from the grid would also provide dilution to the shower and bath.

Figure 5 shows a water balance of the cluster water and energy recovery unit during dry weather. The numbers of water flows in the figure are in Liters/capita-day so that the system can be scaled up according to the population living in the cluster. The values for each use are those listed in Table 2 for the conservation alternative. It can be seen the system is very frugal with water use which goes beyond just conservation. Although the internal water use within the system is 130 Liters/capita-day, the double loop system receives only 50 Liters/capita-day from the grid (or desalination) and about 15 liters/capita-day from stored rainwater and runoff. During the dry period it would be capable to provide some water for ecological flow and irrigation. 23% of the internal flow would be sent from the black water loop to the regional integrated resource recovery facility. During wet weather, rainwater would be harvested and stored and the runoff would be infiltrated to provide a supplement during dry weather. The flow rates on the figure represent the best judgment under the most stringent water reuse alternative.

Figure 5 Water balance in the dual loop water management within the ecoblock.



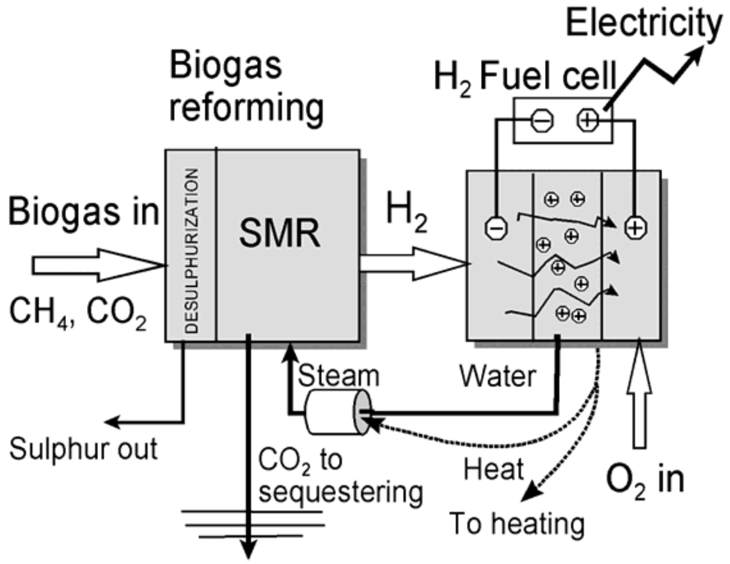
In many other less stringent situations typical for US cities, after maximum water conservation measures are implemented, including rainwater harvesting and runoff storage, the linear system may be converted into a hybrid system in which the sanitary sewers conveying used water to a regional system could be tapped for extra locally needed flow (e.g., toilet flushing, irrigation and ecologic flow). This flow would be treated on site in a smaller less energy requiring satellite water reclamation plant and the solids and the concentrated used water flow sent to the regional integrated resource recovery facility (IRRF) (Asano et al., 2007). In the Qingdao ecoblock all energy was to be provided by renewable sources (solar and wind) installed on the roofs of buildings.

Focus on Resource Recovery – New Paradigm

The traditional "wastewater" treatment unit processes require a lot of energy for aeration, mixing, pumping (e.g. from deep tunnels and interceptors), pressing and dewatering solids and, in a final blow to the energy balance, may emit methane which is far more potent GHG than carbon dioxide. Adding water reclamation and reuse by microfiltration, reverse osmosis, ozonization, and UV radiations without water conservation can make the traditional water reclamation plants an energy black hole and cause big GHG emissions from the plant and the power plants. Visionaries such as Lettinga (2009), Barnard (2007) or Logan (2008), Tchobanoglous (Tchobanoglous et al., 2003) or Asano (2007) are calling for a change of the paradigm of used water reclamation leading to integrated resource recovery.

This new radical change is spurred by new realistic developments in the hydrogen fuel cell technology (Figure 6) that is already widely used also by the new developments in the field of microbial fuel cells (Logan, 2008) which in the future could become the key component of the integrated resource recovery facilities throughout the world. Anaerobic treatment has been in use for more than one hundred years but the work by Lettinga's team (Lettinga et al., 1987), in development of the anaerobic upflow sludge blanket (UASB) reactor and process, has made it the most viable alternative when resource recovery is considered. In addition, membrane filters have become a common practice.

Figure 6 Hydrogen fuel cell concept (US Department of Energy)



Daiger (2009) stated dual distribution and source separation practices compliment water reclamation and reuse by delivering “fit for purpose” water for various uses and separating the components of the typical waste stream to facilitate energy and nutrient recovery. Graywater has the largest volume and is relatively less contaminated, facilitating low-energy treatment for reuse. Black water is relatively low in volume and high in concentration when graywater is removed and can be treated directly by anaerobic processes for energy production. Yellow water is very low in volume (about 1 L/capita/day) and contains most of the nutrients. In short, source separation segregates the water, organic matter, and nutrient components for efficient recovery and reuse.

The change of the paradigm would include:

- Concentrating the used water flows by eliminating all clean water inflows such as surface runoff, groundwater and roof downspout inflows, as well as rigorous water conservation. Underground conduits should be capable of transporting not only used water but also other organic solids such as shredded vegetation residues and food waste (frequently done in the US by kitchen in-sink grinder comminuting kitchen waste) as long as the slurry containing mostly organic particles is liquid enough to disperse the particles and the flow follows the hydraulic newtonian flow by gravity without settling (e.g., flow velocity in the sewers should be more than 0.6 – 0.9 m/sec, which is a standard design parameter for conventional sewers).
- Black water, with or without urine separation, would be the best candidate for integrated cluster or regional resource recovery. Graywater can be reclaimed and treated in cluster (ecoblock) reclamation/reuse treatment units employing microfiltration and RO units followed by disinfection by UV radiation and adding ozone. Concentrate reject and sludge from these units would be sent to the ecoblock (cluster) biological resource recovery or with the concentrated biodegradable used water and solids flow to the regional integrated resource recovery facility.
- The benefits of urine separation must be assessed because nutrient recovery, the main reason for urine separation, can also be effectively done in the integrated resource recovery facility described below. However, urine contains 50% of phosphorus and more than 75% of nitrogen load in less than 1% of the total flow, consequently, nutrient recovery from urine is more efficient and less costly than the recovery from the total flow but it still would leave enough nutrients for the follow up treatment and resource recovery in the IRRF.
- Consider anaerobic treatment in a form of an anaerobic digester or upflow anaerobic sludge blanket (UASB) unit as the first step in treatment and water and energy recovery. The product of the digestion would be an effluent laden with nutrients, biogas, and residual solids usable as soil conditioners after removal of excess moisture. The BOD (COD) removal efficiency of well designed and operated anaerobic units is more than 75% and BOD removal efficiencies as high or more than 90% can be achieved (Tchobanoglous, Burton and Stensel, 2003).
- Organic solids can be converted into biofuel either by a chemical heat gasification process producing syngas (a mixture of carbon monoxide, carbon dioxide, and hydrogen) or by anaerobic digestion that produces methane biogas and carbon dioxide. Both carbon monoxide and methane can be reformed into hydrogen and electricity in a hydrogen fuel cell and excess carbon dioxide can be sequestered.

- Biogas from the anaerobic units could be converted by hydrogen fuel cells (HFC) into hydrogen and electricity. CO_2 produced in the biogas reforming process of HFC (Figure 6) could be recycled and the excess sequestered. If the ongoing and future research proves the feasibility of direct large scale and economical H_2 or electricity recovery by microbial fuel cells, the anaerobic step would be a microbioal fuel cell (MEC) which produces electricity or Microbial Electrolysis Cell (MEC) or BioElectrochemically Assisted Microbial Reactor (BEAMR) for hydrogen production (Logan, 2008).
- Aerobic post treatment by treatment units requiring no or less energy such as trickling filters or submerged flow wetlands could be used as a polishing step that could also convert sulfide to sulphate. Aerobic trickling filters can be combined with an anoxic unit for nitrogen removal and biogas can be collected from the anoxic unit. Vegetation from wetlands can be harvested, shredded and sent to the anaerobic reactor.
- Nutrients even after urine separation, if implemented, can be separated by adding magnesium to convert ammonium and phosphate to crystalline ammonium magnesium phosphate – struvite - which can be removed, for example, in an upflow fluidized bed reactor. Struvite is a valuable fertilizer that can be commercially distributed.
- Membrane filters followed by UV radiation (with or without ozone) would be the final step before discharge of the reclaimed water for irrigation and/or as ecological flow into a receiving water body.
- Concentrated solar heat panels could be made a part of the resource recovery process to provide heat for digesters and UASB.
- For indirect potable reuse, the effluent would have to receive additional treatment by reverse osmosis, mixed with good quality dilution water (e.g., treated stormwater), and stored for an extended period in a surface or underground basin or aquifer.

Integrated Resource Recovery Facility (IRRF)

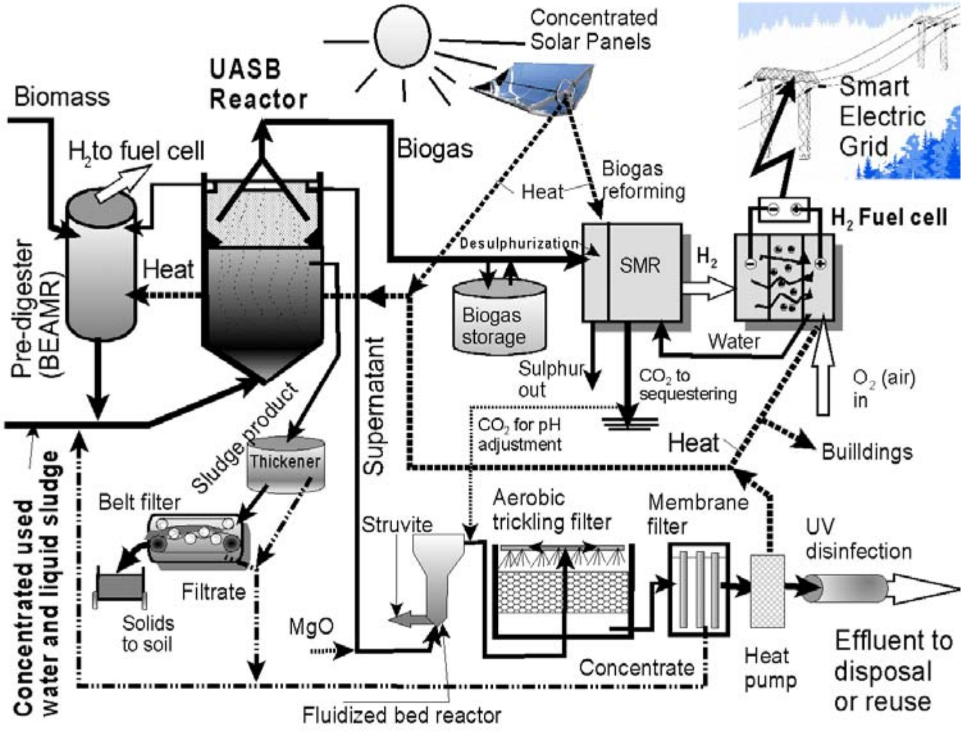
A description of the IRRF is included in Novotny et al. (2010) and one alternative schematics is presented on Figure 7. The IRRF could begin with two reactors, the Lettinga's UASB for the incoming concentrated used water and the predigester for organic solids. The facility will receive flows containing concentrated used water (mostly black water with or without urine) and sludge with solids from the cluster water (and heat) reclamation plants, including comminuted food waste and vegetation residues. The UASB receives the concentrated influent with BOD concentrations of more than one thousand mg/L, COD in several thousands mg/L and high nutrient concentrations, which are the optimum concentration for the UASB influent. The hydraulic residence time in the reactor is between 6 hrs at reactor temperature of 26°C or more and about 10 hrs at temperature of 20°C (Lettinga and Hulshoff Pol, 1991). The reactor may have to be heated during cold weather. 90% removal efficiencies for BOD and COD are achievable.

IRRF, which is at this time is a vision, could include the following units:

- UASB reactor receiving concentrated flow

- A pre-digester for digesting biomass with a supernatant conveyed to the UASB reactor
- A reactor on the UASB effluent producing struvite from nitrogen and phosphorus
- A post treatment by a low energy reactor (e.g., trickling filter or a wetland)
- An algal growth reactor to sequester carbon and produce more biomass
- Membrane filter for solids separation
- Disinfection
- Biogas collection and storage
- Biogas reforming into hydrogen
- Hydrogen fuel cell producing electricity
- Residual solids management by dewatering and reuse

Figure 7 A variant of the Integrated Resource Recovery facility proposal producing clean water, struvite, biogas, hydrogen, electricity and organic solids (from Novotny, Ahern and Brown, 2010)



The liquid inflow could be mixed with outflow from the predigester decomposing biomass (decaying vegetation, food waste) to acetates with suppressed methane fermentation. This reactor would require much shorter HRT than a conventional anaerobic digester requiring solids residence times of more than 15 days. Using such a reactor was identified by Lettinga and Hulshoff Pol (1991) as a pre-acidification or acidification and the authors mentioned it as beneficial but not necessary. In view of Logan's (2008) discovery of direct hydrogen or electricity producing microbial cells and the general need for clean energy recovery, pre-acidification of the biomass could be an asset. Under the classic model, pre-acidification produces acetate and hydrogen without forming carbon dioxide but hydrogen may be scavenged by hydrogen scavenging methanogens (McCarty and Mosey, 1991), which can be prevented by lowering the pH. Hydrogen was a useless byproduct until this century but today it is the best source of energy. Hydrogen production can be maximized, for example, by adding cathode and anode with electric current, essentially converting the pre-acidification of the biomass into a MEC – BEAMR reactor (Logan, 2008). The result would be production of hydrogen, preprocessing of organic particulate solids and conversion of the solid biomass into soluble acetates that would then be converted into methane biogas with the incoming concentrated water and liquid in the subsequent UASB reactor. The hydrogen in the pre-acidification reactor from biomass could be conveyed directly to the fuel cell to produce electricity.

A fluidized bed reactor precipitates and removes phosphorus and ammonium in a form of granules of struvite which is facilitated by adding magnesium as magnesium hydroxide, magnesium chloride or magnesium oxide (MgO) (Barnard, 2007; LeCorre et al.,2009; Britton et al., 2005). If magnesium chloride is added, the pH should be increased by adding caustic sodium hydroxide but the salinity increase it would produce may not be desirable in some cases. pH adjustment to the range between 8.5 to 9.0 is needed for efficient (90%) struvite precipitation (Britton et al., 2005). Subsequently, carbon dioxide will be added after struvite precipitation to reduce the pH close to neutral. This CO_2 provided from the biogas reforming is sequestered and will not contribute to global climatic change and would give carbon emission credit to the operating utility.

The effluent from the UASB and struvite forming reactor still will have higher BOD and nutrient concentrations that would not be acceptable for disposal into the environment or for reuse. An optional conventional biological trickling filter can further reduce the concentrations of these constituents by another 85 %. Trickling filters require minimum energy but do emit some carbon dioxide. An alternative or in conjunction with the trickling filter an algal reactor (an algal farm) was proposed by Verstraete, Van de Caveye and Diamantis (2009). The high yield algae producing reactor would remove residual nutrients and sequester carbon. The produced algal biomass could be redirected back to the predigester or exported for biofuel production.

The hydrogen fuel cell shown on Figure 6 has three compartments. In the first anoxic compartment, at a high temperature, biogas (methane) is converted to carbon monoxide and hydrogen. In the second, steam methane reforming compartment (SMR), carbon monoxide is converted to carbon dioxide and more hydrogen. Carbon dioxide will be sent to neutralize pH after struvite production and as a nutrient to produce algae in the algal growth reactor.

After biogas reforms to hydrogen, hydrogen fuel cells could produce clean electricity from hydrogen and oxygen, which react in the presence of an electrolyte. The reactants flow into the cell, and the reaction products flow out of it, while the electrolyte remains within it. The anode side receives hydrogen and the cathode side receives oxygen from air which generates electric potential and electricity is produced by combining hydrogen and oxygen into water. Water is the only product that is returned to the SMR unit for biogas reforming and producing hydrogen. Fuel cells can operate virtually continuously as long as the necessary flows are maintained. Fuel cells do not operate on a thermal cycle like combustion engines and they are not constrained by thermodynamic limits.

In summary, IRRF could be a system that maximizes resource recovery from used water and solids produced by a community under the new paradigm of sustainability. It produces

- clean effluent water ready for reuse, including ecological flow

- biogas for energy production
- fertiulizer struvite
- sequester carbon
- produces hydrogen and electricity
- produces solids rich with organic and nutrient content for soil conditionning

Produced energy in biogas, hydrogen, electricity and heat could be in great excess of the IRRF internal energy heat needs. Electricity can be sold to the regional smart electric grid, biogas can be reformed into biofuel, and hydrogen is the furure energy souce replacing current fossil fuel.

DISCUSSION - ACHIEVING NET ZERO GHG EMISSIONS

Table 5 contains averages of Gleaser and Kahn's (2008) statistical data of GHG emissions for 100 larger US cities which separate household energy use into transportation by vehicles, public transportation, household heating and use of electricity. Heating is by natural gas or oil. Because data are from before 2005, hybrid or electric cars were not available.

Figure 2 taken from the NSTC (2008) report states that based on the current research and knowledge 60 – 70 % energy use reductions can be achieved by better appliances, more efficient and electric cars, reduction of fossil fuel by the power industry and other savings, including water conservation. Approximate calculations in Novotny et al., (2010) estimate reduction of water use from current 0.5 m^3/cap-day to 0.2 m^3/cap-day and making the same assumption of the reduction of GHG emissions by the power industry could bring the CO_2 reduction of 0.2 ton CO_2/cap-year. On the renewable energy recovery and production side of the balance, extracting heat from used water would bring GHG emission reductions of 0.27 tons/capita-year and the contribution of the IRRF was estimated as 0.1 tons/capita-year. The total would represent about 10% of the total needed reduction which would be significant but not fully sufficient to bring the GHG emissions to the net zero level. Hence, as expected, additional energy savings and GHG emission reductions must come from renewable sources such as wind, solar and geothermal power, from converting automobiles to hybrids and plug-ins and other savings which are still in the laboratories.

Table 5 Average statistics of energy use in 100 large US cities (recalculated and modified from Gleaser and Kahn, (2008)

Energy use for	CO_2 emissions in tons/cap-year	% of total
Transportation by cars	4.091	47.0
Public transportation	0.388	4.4
Home heating by gas or oil	1.470	17.0
House electricity including that for cooling	2.751	31.6
Total	8.71	100

CONCLUSIONS

The threats of global warming, water shortages, population increase and other stressors humans and ecology are facing in this century are requiring the urban environmental community (not just engineers) to rethink and boldly change the current paradigm of using and managing water, transporting water and wastewater systems and infrastructure. The current paradigm of large distance water and wastewater transfer and discharging treated (or even untreated) wastewater without reuse is not sustainable. In spite of the progress made by heavy infrastructure developments in the second half of the last century, the water quality goals of the Clean Water Act have not been met and there are serious doubt among the experts that they could not be met using the current fast conveyance end-of – pipe treatment linear systems.

The system solution presented in this paper are not a utopian fantasy, it is already becoming a reality in some countries and even in the US. Experts and public call for water conservation and treating used water as a resource. As an example, California Building Standards Commission just recently approved a new code, dubbed Calgreen, by which newly constructed hospitals, schools, shopping malls and homes in California will have to be built according to the most stringent, environmentally friendly building code standards of any state in the nation.

This code requires builders to install plumbing that cuts indoor water use, divert 50 percent of construction waste from landfills to recycling, use low-pollutant paints, carpets and floorings and, in nonresidential buildings, install separate water meters for different uses. It mandates the inspection of energy systems by local officials to ensure that heaters, air conditioners and other mechanical equipment in nonresidential buildings are working efficiently. And it will allow local jurisdictions, such as San Francisco, to retain their stricter existing green building standards, or adopt more stringent versions of the state code if they choose. Although the code deals with buildings, the urban planners must adjust the municipal water/stormwater/used water management to these new rapidly expanding trends.

Building new sustainable cities and retrofitting the old ones will be challenge of this century that will not only include affluent nations but also the cities in rapidly developing countries. The new paradigm will also be far friendlier to ecology of urban aquatic and terrestrial ecosystems. The ideas presented in the paper may assist to these efforts.

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REFERENCES

Asano, T., F.L. Burton, H.L. Leverenz, R. Tsuchiashi, and G. Tchobanoglous (2007) *Water Reuse, Technologies, and Application, Metcalf & Eddy,* McGraw-Hill, New York

AWWA RF (1999) *Residential End Use of Water,* American Water Works Association Research Foundation, Denver, CO

Barnard, J. (2007) *Elimination of Eutrophication Through Resource Recovery*, The 2007 Clarke Lecture, National Water Research Institute, Fountain Valley, CA

Brritton, A. F.A. Kocj, D.S. Mavinic, A. Adnan, W.K. Oldham, and B. Udala (2005) Pilot scale struvite recovery from anaerobic digester supernatant at an enhanced biological phosphorus removal wastewater treatment plant, *J. Environ. Eng. Sci.,* **4**(4):265-277

Brown, L.R. (2009) U.S. Headed for a massive decline in carbon emissions, Plan B update, Earth Policy Institute, www.earthpolicy.org/index.php?/plan_b_updates/2009/update83, accessed October 2009

Daigger, G. (2009) Evolving urban water and residuals management paradigms: Water reclamation and reuse, decentralization, and resource recovery, *Water Environ. Research***81**(8):898-823

Dodman, D. (2009) Blaming cities for climate change? An analysis of urban greenhouse gas emissions inventories, *Environment and Urbanization,* **21**(1):185-2001

Falkermark, M. and C. Widstrand (1992) Population and water resources – A delicate balance, *Population Bulletin* **47**(3):1-36

Fraker, H., Jr. (2008) The Ecoblock-China Sustainable Neighborhood Project, Power point presentation – Connected Urban Development Conference, September 24, 2008, Amsterdam, http://bie.berkeley.edu/ecoblocks

Glaeser, E.L. and M.E. Kahn (2008) *The Greenness of Cities: Carbon Dioxide Emissions and Urban Development,* Working Paper 14238, National Bureau of Economic Research, Cambridge, MA, http://www.nber.org/papers/w14238, accessed march 2009

Gleick, P.H., D. Haasz, C, Henges-Jeck, V. Srinivasan, G. Wolff, K. Kaocushing, and A. Mann (2003) *Waste Not, Want Not: The Potential for Urban Water Conservation in California,* Pacific Institute for Studies in Development, Environment and Security, Oakland, CA (http://www.pacinst.org/reports/urban_usage/waste_not_want_not_full_report.pdf

Green dragon (2008) www.greendragonfilm.com/qingdao_ecoblock_project.html, accessed March 2009

Heaney, J.P, L. Wright, and D. Sample (2000) Sustainable urban water management, Chapter 3 in *Innovative Urban Wet-Weather Flow Management Systems (R. Field, J. P. Heaney, and R. Pitt, eds.)* TECHNOMIC Publ. Comp., Lancaster. PA

Le Corre,K.S., E. Valsami-Jones, P. Hobbs, and S.A. Parson (2009) Phosphorus recovery from wastewater by struvite crystallization: A review, *Critical Reviews in Environmental Science andTtechnology* **39**(6):433-477

Lettinga, G., A.F. M. Van Velsen, S.W. Hobma, and W. de Zeeuw (1980) Use of upflow sludge blanket (USB reactor for biological wastewater treatment, especially for anaerobic treatment, *Biotechnol. And Bioeng*, **22**:699-734

Lettinga, G., and L. W. Hulshoff Pol (1991) UASB – process design for various types of wastewater, *Wat. Sci. & Technol.* **24**(8):97-109

Lettinga, G. (2009) Urgent need for integration of aerobic and anaerobic treatment, Power point web presentation, www.leaf-water.org/files/symposium/2%20Gatze%20**Lettinga**.pdf, accessed September 2009

Logan, B.E. (2008) *Microbial fuel cells*. Wiley-Interscience, Hoboken, N.J.:.

Messenger, R.A. and J. Ventre (2004) *Photovoltaic System Engineering*, CRC press, Boca Raton, Fl

McCarty, P.L., and F.E. Mosey (1991) Modeling of anaerobic digestion processes (A discussion of concepts), *Wat. Sci. & Technol.*, **24**(8):17-33

National Science & Technology Council (2008) Federal Research and Development Agenda for Net-Zero Energy, High Performance Green Buildings, Committee on Technology, Office of the President of the United States, Washington, DC

Newman, P. (2006) The environmental impact of cities, *Environment and Urbanization* **18**(2):275-295

National Science & Technology Council (2008) Federal Research and Development Agenda for Net-Zero Energy, High Performance Green Buildings, Committee on Technology, Office of the President of the United States, Washington, DC

Novotny, V. (2008) Sustainable urban water management, In *Water & Urban Development Paradigms (J.Feyen, K. Shannon, and M. Neville, eds.)* pp. 19-31, CRC Press, Bocca Raton, FL

Novotny, V. and E.V. Novotny (2009) Water centric ecocities – Towards macroscale assessment of sustainability, *Water Practice and Technology,* Vol. 4, No. 4, ISSN Online: 1751-231X

Novotny, V., J. F. Ahern, and P. R. Brown (2010) Water Centric Sustainable Communities: Planning, Retrofitting and Constructing the Next Urban Environments, J. Wiley & Sons, Hoboken, NJ (expected publication August 2010)

Sheehan, J., T. Dunahy, J. Benemann, and P. Roesler (1998) *A Look at the U.S. Department of Energy's Aquatic Species Program – Biodiesel from Algae,* National Renewable Energy Laboratory, NREL/TP-580-24190, Golden, Colorado

Sovik, A.K., et al (2006) Emissions of greenhouse gases nitrous oxide and methane from constructed wetlands in Europe, *Journal. Environ. Quality* **35:**2360-2375

Tchobanoglous, G., F.L. Burton, and H.D. Stensel (2003) *Wastewater Engineering – Treatment and Reuse, Metcalf & Eddy,* McGraw-Hill, New York

US Department of Energy (2000) *Carbon Dioxide Emissions from the Generation of Plants in the United States,* also published by US EPA, Washington, DC

USGBC (2007) *LEED for Neighborhood Development Rating System, Pilot version,* US Green Building Council, Washington, DC. , http://www.usgbc.org

Verstraete, W., P. Van de Caveye, and V. Diamantis (2009) Maximum use of resources present in domestic "used water, *Bioresource Technology***100:**5337-5545

Wikipedia (2009) List of countries by carbon dioxide emissions per capita, http://wikipedia.org/wiki/List_of_countries-by_carbon_dioxide_emissions_per_capita , accessed October 2009

Water Environment Federation (2000) *Natural Systems for Wastewater Treatment,* MOP FD-16, WEF, Alexandria, Virginia

WWF (2008) One planet living, http://www.oneplanetliving.org/index.html