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Holistic approach for distributed water and energy management in the cities of the future

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Abstract. The Cities of the Future worldwide initiative represents a major paradigm shift in the way new cities will be built or older ones retrofitted to change from the current unsustainable status to sustainability. The current urban metabolism is linear whereby water and other inputs are brought from large distances, wastewater and part of the stormwater are transported by fast conveyance underground systems to a distant point of disposal which may or may not include a treatment plant. To achieve sustainability, the current linear metabolism must be partially closed to allow water, energy and resources (e.g., fertilizer nutrients) to be *reclaimed, reused and recycled*, which is known as the 3 Rs. The paper summarizes the possible joint water/stormwater/used water and organic solids management in a urban system divided into distributed management clusters or ecoblocks where water and thermal energy can be more efficiently recovered near the point of reuse. However, resource recovery and electricity production can best be accomplished in an integrated resource recovery facility that would accept both organic solids, and concentrated black water flows from the ecoblocks and convert them into biogas followed by conversion into hydrogen, recover fertilizer nutrients, produce electric energy, and also sequester carbon.

Keywords Distributed water system, Integrated resource recovery facility, Carbon emissions, Water conservation, Water reuse, Energy recovery, Nutrient recovery, Water-energy nexus` .

1 Introduction

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 mostly linear in terms of their urban metabolism. Daigger (2009), Novotny (2008) and others agree the current "linear" approach, sometimes called the *take, make, waste* approach in the literature, when applied more broadly to natural resource use and global climatic change, has become increasingly unsustainable and should be replaced by a partially closed (hybrid) system. A fully closed system in which all water would by recycled and all resources recovered is physically unrealistic even on the space station and would lead to accumulation of harmful conservative substances within the system. The linear system discourages reuse, for one, because the source of reclaimed water and energy (e.g., heat) is typically far downstream from the city and the current economic benefit cost or minimum (present value) cost evaluations do not consider social and, in many cases, environmental costs and benefits of reuse traditionally considered as intangible. Societies have realized the current linear paradigm of water management during the last century cannot continue and should be replaced by a semi closed system based on the three R's – reclaim, reuse and recycle. Linear systems produce more pollution (output) and require more resources (water, air, soil and landscape) for dilution and safe assimilation of residuals. Integration of complete water management cannot be fully achieved in a linear system that incorporates long distance transfers, underground subsurface and deep tunnels and distant wastewater treatment plants, although intermediate systems can be proposed. The concept of clustered distributed and decentralized complete water management has been evolving ([1], [2], [3]).

Novotny, Ahern and Brown [4] covered several traditional and more advanced "ecocity" reclamation and reuse systems, including Hammarby Sjöstad and Malmö in Sweden, Singapore, Tianjin in China, Masdar in UAE, Sonoma Mountain Village and Treasure Island in California and Dockside Greens in British Columbia. Systems have been developed for the London 2012 Olympics and other new emerging high recycle systems in Brazil, Portugal, and in the US along with the more traditional centralized systems in Orange County and San Diego in California.

2 Distributed vs. centralized linear systems

2.1 Clusters and ecoblocks

In the holistic hierarchical water/stormwater/used water management system there are layers of management, starting with the smallest unit which is an household or building, continuing to distributed cluster management, and ending with the regional resource recovery and final disposal. For example, water and energy conserving appliances and people's habits to conserve are applied on the household level, most of stormwater management and some resource recovery is done on the cluster level and full resource and energy recovery and final safe disposal of detoxified residues may be best done in a regional facility. Distributed resource management clusters (RMC) (Fig. 1) or ecoblocks are semiautonomous water management/drainage units that receive water, implement water conservation inside the structural components throughout the cluster, capture and store rainfall and stormwater, reclaim sewage for reuse, (such as toilet flushing, irrigation, street washing), provide ecological flow to restored existing or daylighted streams, recover heat energy from used water, and possibly recover 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 ([1], [4], [5]) or an entire (smaller) city or urban watershed.

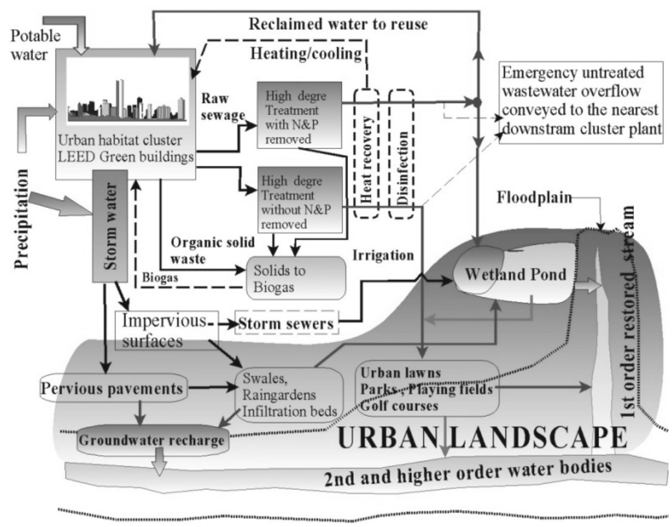

Fig. 1 Concept of a water centric resource management cluster (RMC) incorporating landscape and natural water features (from Novotny [6] and Novotny et al. [4]).

The treatment level within the RMC is "fit for reuse". If, for example, 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 and would have much larger carbon footprint. For all practical reasons, toilet flushing may require reduction of turbidity and disinfection, primarily to control bacterial growth in the toilets and urinals. 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 as commercial fertilizer (e.g., struvite) and not just removed (e.g., as nitrogen gas and/or sludge put in a landfill). However, water reclaimed within the ecoblock should not be reused for direct or even indirect potable use because of the short time between the reclamation and reuse. Landscape application and receiving water discharge quality requirements may have separate discharge quality requirements.

For groundwater recharge, and subsequent indirect potable reuse, reclaimed water from a centralized integrated resource recovery facility (IRRF) can be used. On a local cluster/ecoblock scale, aquifer recharge will be accomplished by infiltration of captured stormwater treated by best management practices which are the foundation blocks of the Low Impact Development (LID) concepts, including rainwater harvesting, pervious pavements, ponds, wetlands, infiltration rein gardens, etc. ([4], [7]).

Possible alternatives of RMC. Asano et al. [8] 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 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 solids from the cluster are then conveyed to a central (regional) IRRF where more concentrated waste flows are converted to biogas (e.g., by upflow anaerobic sludge blanket (UASB) reactors) and/or hydrogen/electricity, nutrients recovered by converting phosphorus and ammonium into struvite, and solids recovered for soil conditioning.

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 2. The Qingdao three hectare ecoblock would house 1500 – 2000 inhabitants out of the total 40,000 planned to live in the (future) ecocity. Masdar in United Arab Emirates, operating as a single water/used water management cluster, will have a population of 50,000. If water reclamation and reuse with energy recovery are contemplated, the population density is a more important parameter determining the cluster size than the total population the cluster may serve. The Qingdao ecocity cluster inhabitants are proposed to live in several high-rise and medium height buildings. These ecoblocks are then combined to form the entire development [9]. The water management shown on Fig. 2 reaches a maximum limit of reuse and would be applicable to regions with severe shortages of fresh water resources (Middle East, northeast China, inland Australia, some Southwest US states, and many future cities in developing countries with burgeoning population).

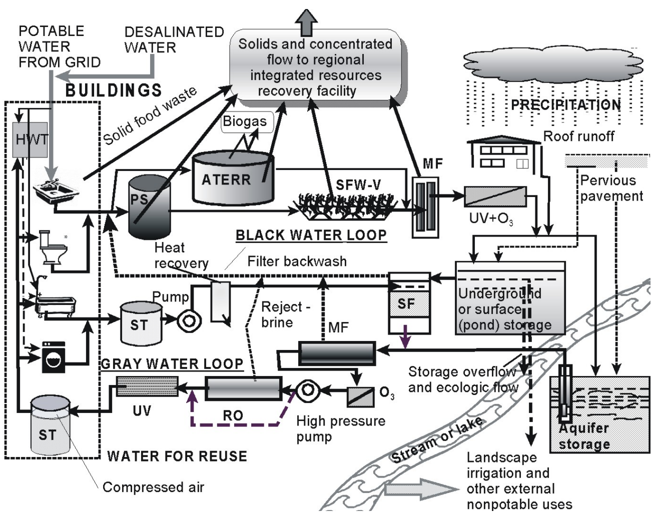

Fig. 2 A double loop hybrid cluster (ecoblock) system that recycles gray water and some black water for reuse within the cluster based on the Qingdao ecoblock proposed by Harrison Fraker [9]. Legend: SFW – subsurface flow wetland; PS-primary settler with solids removal, ATERR – anaerobic treatment and energy recovery reactor; MF-membrane filter; SF-sand filter; NF nanofilter; RO-reverse osmosis, UV-ultraviolet radiation; O_3 – ozone addition; X – water lost by evapotranspiration

The Qingdao double loop on Fig. 2 was modified from the original system proposal to avoid a possibility of direct potable reuse and includes restored surface water bodies and underground storage. The figure represents the management within the ecoblock. Water reclamation and reuse is carried in a double loop consisting of black and gray water reclamation. Black water flow includes water from toilets, kitchen sinks and dishwashers. ATERR is a generic anaerobic treatment unit that produces biogas. In the original Qingdao system proposal, sequencing batch reactors or septic tanks were proposed [9]. Verstraete, Van der Caveye, and Diamantis [10] and Verstraete, Bundervolt, and Eggermont [11] suggested an anaerobic upflow sludge blanket reactor (UASB) combined with a septic tank. In this application, PS reactor (e.g., an Imhoff primary settler with suppressed digestion [12]) 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 (alkalinity) and will be harvested, and nitrification will be minimal because of reducing conditions in the wetland whereby all nitrogen entering the wetland will be in the form of Total

Kjeldahl Nitrogen (a sum of organic N and ammonium).

The system accomplishes several objectives: (1) it treats the gray water to almost potable water quality for several in-house uses although direct potable use is not contemplated, (2) concentrates black water, including filter backwash and RO rejects from the gray water loop, and sends a part of the black water with almost all removed solids and colloids to a regional IRRF (see next section). A part of the black water is further treated on site to supplement the water flow lost in reject and filter backwash flows; (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 the form of biogas and heat.

Heat recovery is important because household water heating for washing, shower, laundry and dishwasher represents the largest domestic energy expenditure related to water [11] and, consequently, the largest energy recovery which can be done efficiently (e.g., by a heat pump) on a local household or cluster level but would be uneconomical in a linear system in a regional facility. In the context of "fit for reuse" recycle, the Qingdao ecoblock would provide water of a quality that could be used for all nonpotable uses within the building including laundry, shower and bath (mixed with some fresh water from the grid). Potable water could be provided for the bathroom faucet from the potable water supply grid. If water is reused only for toilet flushing and/or irrigation, less rigorous treatment would be required (e.g., sand and membrane filter with ozonization).

2.2 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 reason is that, as eluded 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 a 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.

In most cases, current regional "water reclamation plants" do not really reclaim and reuse water, they only make effluent discharge safe for disposal into the receiving water bodies and, in an unplanned water-sewage-water cycle [13], the effluent can then be found in the water intakes of downstream communities. Even in Singapore, the infrastructure and energy intensive closure is only partial.

A pioneer of the new revolutionary zero waste used water treatment, reclamation and reuse, Professor Willy Verstrate (University of Ghent, Belgium) stated: "*Conventional systems based on (aerobic) activated sludge wastewater treatment (ASWT) are the wrong road towards sustainability*". An IRRF is 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 that it is possible in the traditional "water reclamation plants". Essentially, IRRF does not generate waste; it produces resources and energy. A needed prerequisite is concentration of the used water flow which implies on-site water reclamation at the cluster level and water conservation on the domestic level.

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 regional (level three) IRRF could be:

1. Treating and reclaiming water for
    a. Ecological flow for 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) and, in the future, converting them to hydrogen
5. Producing organic solids for soil conditioning
6. Providing water and nutrients to algal aquaculture producing biomass for biogas and oils 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 could be carbon negative; i.e., net sequesters [11]. Technologies that allow proposing this revolutionary resource recovery system, summarized in Novotny et al. [4], include (a) 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 [14]; Verstraete et al. [10]); (b) microbial fuel cells that convert organic matter to hydrogen or electricity (Rabaney and Verstraete [15]; Logan [16]; Call and Logan [17]; Wagner et al. [18]); (c) hydrogen fuel cells converting biogas to hydrogen and electricity (US Department of Energy [19]) ; (d) heat recovery from water by heat pumps and other heat reclamation devices; (e) production of struvite (ammonium magnesium phosphate) fertilizer from used water effluents and digester supernatants (Barnard [20]) (f) improved production of nutrient rich solids from sludge (Verstraete et al. [11]) (g) production of algal biomass and subsequently hydrogen (James et al. [21]); (h) new and more efficient capture of renewable solar energy by concentrated solar panels and photovoltaics.

These technologies have been already tested in on pilot and/or laboratory scales. Hand in hand with these new technologies go the developments in smart electric grids already in place on a large scale in Europe that can accept (buy) into the grid electric energy produced by the renewable sources.

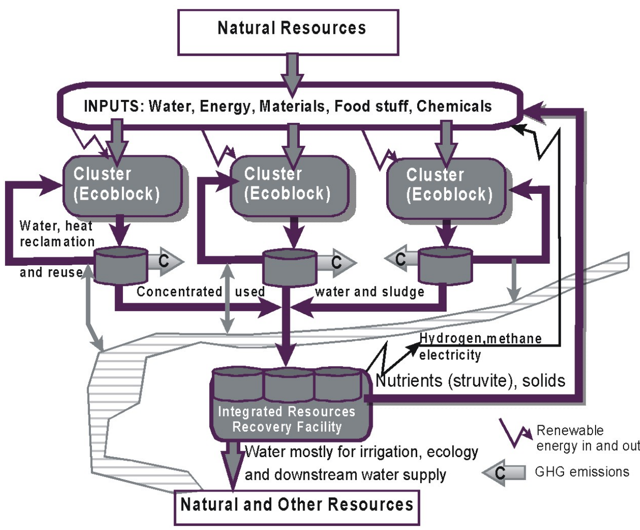

Fig. 3 Distributed urban water/stormwater/used water management system with IRRF.

Fig. 3 is a schematic of such a system composed of ecoblocks interconnected with IRRF. It may be advisable to interconnect the clusters for safety against the failure so that, during emergency, flow from the impacted cluster may be redirected to the nearest interconnected cluster water/energy reclamation plant.

A traditional energy recovery system which is used in most water reclamation plants employing aerobic/anoxic (with nitrification) or aerobic/anoxic/anaerobic treatment units with N and P removals, may recover biogas by digestion of sludge solids separated in the primary treatment and excess sludge solids grown in the secondary treatment units. This energy recovery is offset by the energy needed to provide aeration to the treatment units, dewater sludge, heating the digesters and transport water and solids. In some systems, heat dried organic sludge solids are mixed with other organic solids (vegetation, woodchips, food solid wastes) and heated to high temperature in oxygen deficient tanks to generate syngas (a mixture of carbon monoxide and hydrogen) which can be either used as a fuel in a combustion energy recovery process or, after further processing, converted to liquid biofuel. According to O'Riordan et al. [1] energy recovery via syngas production from organic solids and methane production from sludge digestion can provide about 25% of the energy needs of the integrated water and energy reclamation facility in the Dockside Green community in Victoria (British Columbia).

A concept of a future state-of the art IRRF. A future possible IRRF alternative was conceptually presented in Novotny [22] and Novotny et al [4]. This facility would accept both concentrated liquid used water flows from the clusters and organic solids such as food and yard organic solids, vegetation residues and, in developing countries, manure. The energy output could be biogas that could be converted to electricity by a combustion engine and generator, or, in the near future, biogas and hydrogen would be generated and then converted to electricity in hydrogen fuel cells similar in principle to those already used in electric automobiles. As stated before, energy can be recovered in a form of biogas, syngas, hydrogen. It is anticipated that hydrogen based systems will be the future because such systems can recover the maximum energy output, produce the smallest (or close to none) carbon and methane emissions, both being GHGs, and have the highest economic benefit.

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, leachate from abandoned solid waste landfill (which may not be necessary but still might be producing highly concentrated legacy liquid flows), waste airport deicing fluids (glycol based) (Zitomer et al. [23]), etc;
- a pre-digester for fermentation of organic solids that could be in a form of a Bio-electrically Assisted Microbial Reactor (BEAMR) [16] or a traditional fermentation digester without methanogenesis.

This arrangement will allow 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 to hydrogen in the SMR process. Both UASB and BEAMR reactors work efficiently in the temperature range of 20-30^{o}C, which is well below the mesophilic (35^{o}C) range of traditional anaerobic digesters, and require much smaller hydraulic residence time (HRT). 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 energy overall output even in colder climatic conditions.

Struvite precipitation recovers nutrients from liquid used water and digester supernatant (rich in nutrients). Struvite is chemically an ammonium magnesium phosphate which grows in sewers that carry flows high in magnesium (hardness) but can be, under controlled condition, precipitated and recovered in an upflow fluidized bed reactor. If not enough magnesium is present in the flow it can be added in the form of magnesium oxide or 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. Adding MgO or $Mg(OH_2)$ increases pH. 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.

Methane conversion to hydrogen and electricity is accomplished in the hydrogen fuel cell whereby methane is first converted to hydrogen and carbon dioxide by the process of steam methane reforming (SMR) and the hydrogen is converted in an exothermic reaction into electricity and water. 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 and energy/electricity production from hydrogen is clean energy. The energy production is facilitated by hydrogen fuel cells that today are revolutionizing transportation and convert hydrogen into electricity more efficiently than combustion engines and generators. Electric cars with hydrogen fuel cells will be common in the near future.

A hydrogen fuel cell (HFC) produces clean electricity from hydrogen and oxygen, which react in the presence of an electrolyte. The reactants flow into the cell, and the reaction product – water - flows out. The anode side receives hydrogen, and the cathode receives oxygen from air which generates electric potential, and electricity is produced by combining hydrogen and oxygen. Water and heat are the only by-products. Hence a hydrogen fuel cell produces no polluting emissions.

3 Comparison of three alternatives

Three alternative solutions have been analyzed to illustrate the water and energy use and associated GHG emissions and included in the water-energy nexus Table 1. 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 Heaney [2]. Methods and parameters for the calculation and original reference sources are included in Novotny et al. [4]. It should be noted that a typical American household uses has one of the largest water demand and uses in the world (average 550 L/capita-day) while in most

European and developed Asian urban areas (e.g., Japan, China) the use is about one third of that in the US.

Alternative I a conventional average US household with a large outdoor lawn sprinkler irrigation water demand, practicing no water and energy conservation and discharging its wastewater into a conventional underground conveyance system connected to a conventional activated sludge treatment plant with nitrification that applies residual sludge on land or deposits them in a landfill. Water demand for this alternative 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 US household practicing water conservation indoor and xeriscape planting (minimal or no irrigation) outdoor. Water conservation reduces the total water demand to 146 L/capita –day which would be a typical current water demand in Europe and Japan. This house is located in a cluster which has a capability to reclaim water and reuse some water for toilet flushing (20 L/capita-day) and about ½ of the irrigation needs of estimated outdoor use of 30 L/capita-day. One half of outdoor use would be from captured rainwater. Per AWWA RF study [2] the heated water volume is reduced to 71 L/capita-day. On the cluster level a portion of heating energy can be recovered by a heat pump. Reclaimed water for toilet flushing would be treated by microfiltration and ozonization. The rest of used water would be delivered to a regional treatment conventional activated sludge treatment plant with nitrification that would produce methane from sludge for heating of the digesters and the treatment plant buildings. This alternative necessitates separate piping, storage and a pump 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 Fig. 2. Black water cycle (BWC) on the cluster level includes solids separation and treatment of a portion of the BWC flow for the local supplement of the gray water cycle (GWC) needs for make-up water to replace water lost in backwash and reject water of the filtration (including reverse osmosis) units of the GWC and for irrigation and ecological outdoor flow. The daily volume of fresh water from the grid provided by freshwater sources or desalination is 50 L/ capita-day.

A portion of the BWC with all solids separated in BWC and GWC is conveyed to the regional integrated resource recovery facility (IRRF). Admittedly, this is a visionary concept still lacking prototype testing and parameter derivations. Nevertheless, as pointed out previously, the system units have been developed and tested. The IRRF also accepts yard and food solid waste that are co-digested with the concentrated black water influent.

The energy needed to extract, treat and deliver potable water deliver water from the grid is based on the US average of 2.26 kW-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. The energy recovery calculations, methodologies, supporting references and values of parameters are all included in Novotny et al. [4]. Table 1 presents the water and energy balances for the three alternative systems.

3.1 Discussion of the alternatives

Unlike most other literature sources (e.g., Verstraete et al. [11]), both water heating energy and heat energy recovery (less than the former) from used water were included in the balance. The heating energy is responsible for the largest portion of the overall energy use and corresponding energy gain when heat is recovered.

Alternative I, which is the worst, is a baseline against which the other two, or any other improving alternative, will be measured. This currently common linear management alternative would result in one ton of CO_2 emissions per capita and year, which represents about 10% of the average US per capita emissions. This average water use is also unsustainable and cannot be repeated in most countries. Achieving net zero carbon emissions goal is impossible with this alternative which would also result in water shortages that would not be limited only to the arid southwest regions of the US.

Alternative II could be a near future (less than ten years) goal. It incorporates reasonable water and energy saving measures. This alternative implies that, by implementing reasonable water saving measures with a modest reuse and rain water reclamation, the per capita water demand 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, concentrated heat panels that are already being commonly installed 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 25% would be about

Table 1 Water and energy balance of three alternative water/used water management systems. Methodology and parameters are included in Novotny et al. [4]

Parameter		Alternative I Traditional Linear System with no Conservation	Alternative II Linear System with Water Conservation and Small Reuse	Alternative III Hybrid System with Energy Recovery
Water flow from the grid	L/cap-day	551	146	50
Energy to deliver and use water	kW-h/cap-d	1.245	0.330	0.113
Water used for irrigation from grid	L/cap-d	313	30[1]	0
Energy use for irrigation[1]	kW-h/cap-d	0.300	0.016	0
Total heating water flow	L/cap-d	106	71	71
Energy use for heating	kW-h/cap-d	3.101	2.077	2.077
Total wastewater (WW) flow[3]	L/cap-d	297	116	
Pumping WW in the sewers [4]	kW-h/cap-d	0.030	0.012	
COD content of wastewater	g/cap-day	95	95	95
Energy used to treat WW[5]	k W-h/cap-d	0.125	0.072	
Gray water (GW) recycle	L/cap-d	0	20[6]	76
Energy to treat recycle	kW-h/cap-d		0.015[7]	0.160[8]
Heat recovery from used water	kW-h/cap-d	0	-1.22	-1.00
Methane recovery in WTP	kW-h/cap-d		-0.15	
Concentrated BW flow to IRRF	L/cap-d	0		69
Pumping BW to IRRF,	kW-h/cap-d			0.007
Methane recovery from BW	kW-h/cap-d			-0.33
Methane recovery from solids[9]	kW-h/cap-d			-1.46
Heat recovery from BW effluent	kW-H/cap-d			-0.60
Total energy expenditure (production) kW-h/cap-d		**4.67**	**1.15**	**(-1.14)**
Carbon GHG emissions (credit) kg CO_2/cap-year		1080	259	(416)

Legend:

1 Water use for xeriscape and pother 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 for toilet flushing only
7 Water recycle treated by microfiltration and ozonization
8 Gray water recycle treated by microfiltration, reverse osmosis and ozonization
9 Per US EPA [24] food and yard organic waste is 0.56 kg/capita-day and the recovery is 39%.

$$A = 1.15\ [\text{kW-hr/cap.-day}]*365[\text{days}]/(4[\text{kw-hr/m}^2)*0.25*320(\text{days})] = 1.3\ \text{m}^2 \quad (1)$$

Alternative III represents a more distant future (>15 years) whereby a switch from current aerobic treatment process to anaerobic energy and resource recovery will become a reality. This alternative has a double loop separating gray water and black water and on site cluster/ecoblock treatment. Concentrated BW with all solids would be discharged to the regional IRRF where water, nutrients, and heat energy would be extracted. Without a co-digestion methane is the main product in the IRRF. In the next generation IRRFs, organic solids from yard and food waste could be predigested, which could produce hydrogen and acetates if methanogenesis is suppressed. This would give an impetus to hydrogen based IRRF.

The energy balance in Table 1 indicates that even after source separation and no energy use for (anaerobic) treatment and no major CO_2 emissions by the treatment and transport processes the used water only does not have enough energy to counterbalance the energy used for heating on the domestic level and heating fermentation predigester and/pr UASB reactor. Although the excess energy used by this system is relatively small (0.32 kW-hr/capita-day) and not economically significant, nevertheless, it is not net zero. However, it could be easily compensated by more solar energy produced on the premises of the IRRF and by co-processing the organic solids with concentrated BW and solids in used water. This would be a very attractive solution resulting in excess energy produced by the system and commercially attractive byproducts hydrogen, electricity and commercial grade nutrients. Furthermore, the process can accomplish some carbon sequestering. In this analysis, the energy gains were based on the methane production only. Carrying out the entire analysis to hydrogen production and electricity is a work in progress and will be published soon elsewhere.

It is also interesting to compare the base line (current) alternative with the more sustainable Alternatives II and III. Implementing Alternative II would eliminate almost 0.8 ton CO_2/cap-year from the current emissions. This is even more impressive with Alternative III that would eliminate almost 1.5 tons of CO_2/cap-year or about 15% from the current total emissions, while producing commercially valuable products.

4 Conclusions

This paper quantitatively documents what has been known for some time; i.e., the current paradigm of urban water, stormwater and waste water infrastructure and management based on centuries old concepts, further exaggerated by last century regulations emphasizing more hard infrastructure, is not sustainable and would result in significant contributions to the emissions of greenhouse gases. Current paradigm of fast mostly underground conveyances of water and wastewater in the linear urban metabolism is becoming archaic. One can also add to the problem the disposal of solid waste whereby the societies are running out of suitable land fill sites. Linear urban metabolism prevalent today in most urban areas is unsustainable and should be replaced by a hybrid system based on four R's – reclamation, reuse, recycling and restoration. "Restoration" refers to the need for restoring the more natural surface drainage which would include restored streams, ponds, wetlands, and other natural ecological features (stream corridors, buffers, etc.) as indicated on Fig. 3.

The new paradigm is holistic whereby management, conservation, recoveries, and reuse occur holistically on the household, cluster and regional levels. Used water and solids are a resource from which clean water with a "fit for use" quality can be reclaimed, energy in a form of heat, methane, hydrogen, and electricity can be produced, and nutrients in a form of nutrient rich solids, and/or struvite extracted and some carbon can be sequestered. The two most effective means to reduce GHG emissions are water conservation (especially in the US) and heat recovery. Used water alone does not have energy content high enough to compensate for the energy used to heat water in domestic water management. The current treatment systems relying on primarily aerobic secondary activated sludge treatment which use a lot of energy should be replaced by anaerobic system producing methane and, in the future, also by microbial fuel cells producing hydrogen and electricity.

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