

## Water and energy link in the cities of the future – achieving net zero carbon and pollution emissions footprint

V. Novotny

### ABSTRACT

This article discusses the link between water conservation, reclamation, reuse and energy use as related to the goal of achieving the net zero carbon emission footprint in future sustainable cities. It defines sustainable ecocities and outlines quantitatively steps towards the reduction of energy use due to water and used water flows, management and limits in linear and closed loop water/stormwater/wastewater management systems. The three phase water energy nexus diagram may have a minimum inflection point beyond which reduction of water demand may not result in a reduction of energy and carbon emissions. Hence, water conservation is the best alternative solution to water shortages and minimizing the carbon footprint. A marginal water/energy chart is developed and proposed to assist planners in developing future ecocities and retrofitting older communities to achieve sustainability.

**Key words** | one planet living criteria, greenhouse gases emissions, water conservation, water reclamation, LEED criteria, green development, water demand, energy use, carbon footprint

V. Novotny (corresponding author)  
Department of Civil and Environmental  
Engineering,  
Northeastern University,  
Boston,  
MA 02415,  
USA.  
E-mail: [novotny@coe.neu.edu](mailto:novotny@coe.neu.edu)

### INTRODUCTION

#### Goals

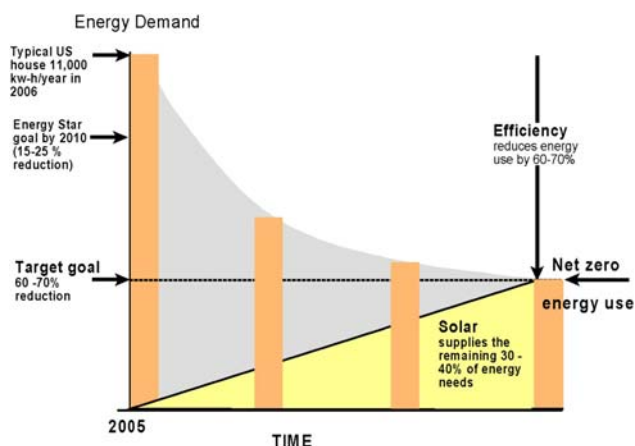
The Cities of the Future or Ecocities represent a major paradigm shift in the way new cities will be built or older ones retrofitted to achieve a change from the current unsustainable status to sustainability. A working definition of an ecocity and the goal of future new urban developments as well as retrofitting the old ones is as follows (Register 1985; Novotny *et al.* 2010):

An ecocity is a city or a part thereof that balances social, economic and environmental factors (triple bottom line) to achieve sustainable development. A sustainable city or ecocity is a city designed with consideration of environmental impact, inhabited by people dedicated to minimization of required inputs of energy, water and food, and waste output of heat, air pollution – CO<sub>2</sub>, methane, and water pollution. Ideally, a sustainable city powers itself with renewable sources of energy, creates the smallest possible ecological footprint, and produces the lowest quantity of pollution possible. It also uses land efficiently,

composts used materials, recycles or converts waste-to-energy. If such practices are adapted, overall contribution of the city to climate change will be none or minimal below the resiliency threshold. Urban (green) infrastructure; resilient and hydrologically and ecologically functioning landscape and water resources will constitute one system.

The current criteria and guidelines used for ecocity certification are LEED (Leadership in Energy and Environment Design) of the [US Green Building Council \(2005, 2007\)](#) and One Planet Living (OPL) by the [World Wildlife Fund \(2008\)](#). OPL criteria, the [National Science and Technology Council \(NSTC\) \(2008\)](#) recommendations and governments of several countries (e.g., Great Britain) call for achieving net zero greenhouse gas (GHG) emissions.

[Figure 1](#) shows the possible paths towards the net zero GHG emissions goal. Current scientific research quoted in the [NSTC \(2008\)](#) report indicates 60 to 70% of energy reductions in buildings in cities can be achieved with more efficient appliances such as better water and space heaters,



**Figure 1** | A path to achieving the net zero energy goals (NSTC 2008). Subscribers to the online version of *Water Science and Technology* can access the colour version of this figure from <http://www.iwaponline.com/wst>

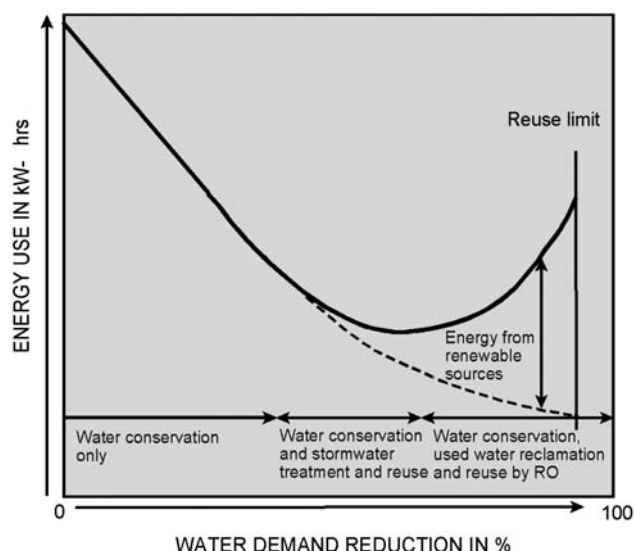
heat pumps, significant reduction of water demand by water conservation and other improvements. NSTC also estimated that 30 to 40% of energy can be produced by renewable sources, including heat recovery from used water or extracted from the ground and groundwater.

The green net-zero GHG and pollution emissions measures in the ecocity developments and retrofits include (Novotny *et al.* 2010):

- passive architectural features for heating and cooling;
- 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 rain-water harvesting and storage;
- distributed stormwater and used (waste) water management to enable efficient used water and reuse and renewable energy production;
- xeriscape of the surroundings that reduces or eliminates irrigation also 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 off-site renewable energy sources such as solar power plants and wind farms;
- organic solids management for energy recovery;
- connection to low or no GHG net emissions heat/cooling sources such as heat recovered from used water or from the ground;
- smart metering of energy and water use providing flexibility between the sources of water and energy; and
- sensors and cyber infrastructure for smart real time control.

## WATER AND ENERGY NEXUS - THE HYPOTHESIS

Figure 2 presents the possible relationship of water demand reduction leading to a closed urban water cycle and energy. This article suggests a hypothesis that there is a minimum inflection point beyond which further reduction of water use will increase energy demand. Consequently, the relationship has three phases: (1) Water conservation phase in which energy and GHG emissions reduction is proportional to the reduction of water use; (2) Inflection phases in which additional and substitute sources of water are brought in, treated and used; and (3) Phase in which energy use is rising while water demand of the development is reduced by used water reclamation and multiple reuse. In the water conservation phase, energy use and GHG emission reduction by reducing water demand are achieved by using more efficient appliances, xeriscape (reducing irrigation) and plugging the leaks and losses. These measures do not require a large amount of extra energy, hence, the energy use reduction is directly proportional to the reduction of the water demand. However, several current ecocities are located or being planned in areas with meager water resources which necessitates using desalinated, brackish and reclaimed water. To further close the water cycle, energy demanding water reclamation processes are needed such as micro and nanofiltration and reverse osmosis. Consequently, larger dependence on renewable zero carbon energy sources (wind, solar, geothermal, energy recovery from used water organic solids) will ensue. The recycle systems cannot be fully closed to prevent accumulation of nondegradable potentially harmful compounds that



**Figure 2** | Relation of water related energy use to water demand of the development.

may pass reverse osmosis and other high degree treatment processes.

### Water conservation and its effect

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<sub>2</sub>/kW-hour produced by coal fired power plants
- 0.89 kg of CO<sub>2</sub>/kW-hour produced by oil fired power plants
- 0.60 kg of CO<sub>2</sub>/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<sub>2</sub> will be considered in this analysis which is

0.61 kg of CO<sub>2</sub> emitted per kW-hour of energy produced

The Energy Information Administration (2009) documented the total energy production in the US in 2007 was 4,157 TWh (4,157 × 10<sup>9</sup> kWh) which represented about 2.516 billions tons of CO<sub>2</sub> emitted. Using the 3% estimate for providing and treating water, “water share” of the energy use is 124.7 TWh and 75.5 million tons of CO<sub>2</sub> were emitted as a result of providing clean and disposing polluted water, plus an additional 200 million tons of CO<sub>2</sub> for hot water heating, cooking and boiling, and wet cleaning.

### Phase I – Water conservation - Linear reduction

The first phase of the water – energy nexus is a linear or near linear nexus relationship between water conservation and energy reduction, The building and community water use systems range from linear systems in which water is extracted from the source, brought to the city where it is polluted, then transferred to a treatment plant where it is treated and discharged into a receiving water body, to closed loop systems

reclaiming and reusing water. It will be subsequently shown that a 100% closed system is potentially possible on a space station but unrealistic in cities. Table 1 shows the per capita volumes and proportions of the daily water use in a typical US single family home. The left part of the table is based on the AWWA RF (1999) study as reported by Heaney *et al.* (2000). On the right side are the estimates of water savings used by the AWWA RF study and by the Pacific Institute (Gleick *et al.* 2003) study for California. The table shows high water use in the US of 550 L/cap-day, which is much higher than in most other developed countries. After implementing mostly common sense water conservation measures (for details see Novotny *et al.* 2010), the US use can be reduced to less than 200 L/capita-day, still high but comparable to European values. The largest water use is for lawn irrigation that can be reduced or eliminated by xeriscape landscaping using native plants and landscaping not requiring water.

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 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<sup>3</sup> 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 kWh/m<sup>3</sup> attributed to water. Corresponding carbon emission is of 1.37 kg CO<sub>2</sub>/m<sup>3</sup>. Most of the water conservation reduction in Table 1 can be achieved by more efficient appliances (water saving shower heads, toilets, laundry wash machines, etc) and xeriscape. Hence for each cubic metre saved, energy in the ideal average household would be reduced by the above amount. This is the linear Phase I of Figure 2. The water saving potential shown in Table 1 is 65% reduction.

In addition to emissions by power plants producing energy for water, CO<sub>2</sub> is also emitted in the biological treatment process that oxidizes organic matter. Changing to anaerobic treatment saves the energy and allows to recover biogas and nutrients (Verstraete *et al.* 2009)

### Phase II – Inflection

In the inflection phase, a city is looking for additional sources of water or brings in sources that have worse quality, 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

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

Water use	Without water conservation*		With water conservation	
	L/cap-day	Percent	L/cap-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 *et al.* (2000) and Asano *et al.* (2007)

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

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<sup>3</sup> of water from a depth of 500 m with a pump that has an overall efficiency of 80% will require work of  $W = \gamma VH = 9,819 \times 1 \times 5000/0.8 = 6,131,125$  J = 1.7 kW-hrs ( $\gamma$  = specific density of water in N/m<sup>3</sup>) and will result in 1 kg of additional CO<sub>2</sub> emissions. Many water short communities are pumping higher salinity water as deep as 1000 m.

Low energy demanding sources of water are rainwater harvesting (negligible pumping energy needs) and stormwater (some pumping and treatment).

### Phase III - Increasing energy demand and CO<sub>2</sub> emissions

In the increasing phase, tapping on higher salinity water sources (brackish sea or groundwater) is supplemented with water reuse that requires a two or three step high efficiency treatment (Figure 3). Table 2 presents energy and CO<sub>2</sub> emissions.

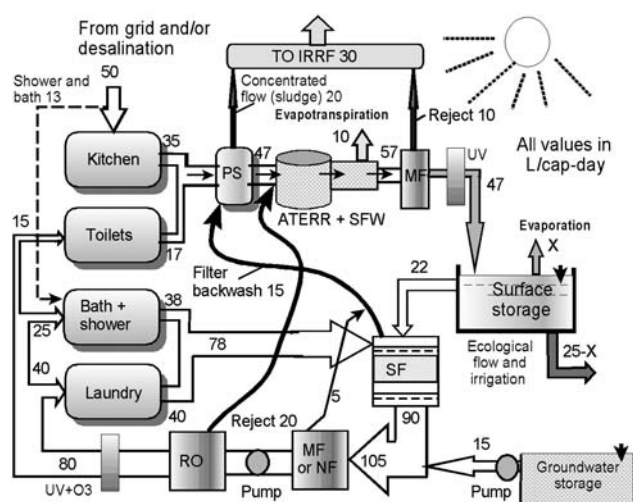
In activated sludge processes, for each mole of oxygen consumed in the aeration process, one mole of carbon dioxide is emitted. Hence CO<sub>2</sub> emitted = (12 + 2 × 16) / (2 × 16) = 1.37 O<sub>2</sub> consumed. For example, if the BOD<sub>5</sub> concentration in used water is 300 mg/L = 0.3 kg/m<sup>3</sup> then

the CO<sub>2</sub> emission in aeration unit removing 95% of BOD<sub>5</sub> will be

$$\begin{aligned} \text{CO}_2 \text{ emitted (kg/m}^3\text{)} &= 1.4(\text{BOD}_{\text{ultimate}}/\text{BOD}_5) \times 0.95 \\ &\times 0.3(\text{kg BOD}_5/\text{m}^3) \\ &\times 1.37(\text{CO}_2 \text{ emitted}/\text{O}_2 \text{ consumed}) \\ &= 0.53 \text{ kg/m}^3 \text{ of CO}_2 \text{ emitted.} \end{aligned}$$

This value should be added to the CO<sub>2</sub> emissions due to the energy use listed in Table 2. However, some may claim this CO<sub>2</sub> emission component does not originate from burning fossil fuel and should be counted as a neutral carbon footprint as it should for methane burning from sludge digestion or biofuel production.

Planners of water frugal ecocities in Qingdao (China) and Masdar (UAE) consider a fully closed loop similar to that shown on Figure 3. The Qingdao double loop (Fraker 2008) was modified to avoid direct potable reuse. The numbers on the plot represent daily water use in L/person-day living in the cluster of the ecocity. The Qingdao ecocity cluster has about 1500 to 2000 inhabitants proposed to live in several highrise and medium height buildings. The figure shows the total water use in the cluster as 130 L/capita-day but the municipal grid supplies only 50 L/capita-day. It is assumed



**Figure 3** | Mass balance of flows in L/cap-day for the system in a closed water cycle ecocity on a dry day. 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 disinfection; O<sub>3</sub> – ozone addition; X – water loss by evaporation, IRRF – integrated resource recovery facility.

maximum water saving practices are implemented in the cluster ecoblock. The water reclamation and reuse is carried in a double loop consisting of black and grey water reclamation and reuse. Black water flow includes water from toilets, kitchen sinks and dishwashers. The subsurface flow wetland treatment is assumed to emit minimal quantities of carbon dioxide and nitric oxide, both GHGs. 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. It can be seen that 50 L/capita-

day water input from the municipal grid is not sufficient to sustain the total demand of 140 L/cap-day during dry weather. Rainwater harvesting and stormwater capture and infiltration (via pervious pavements and infiltration raingardens) is needed to supplement the dry weather flow (Novotny & Novotny 2009). Hence, one can consider the 50 L/cap-day as the minimum inflow from the grid and 130 L/cap-day as the optimal water demand after implementing a suite of water conservation measures.

The ATERR is a generic anaerobic treatment unit that produces biogas. In the original Qingdao system proposal sequencing batch reactors were proposed. Verstraete *et al.* (2009) suggested anaerobic upflow sludge blanket reactor combined with a septic tank. In this application, PS reactor is optional. The Qingdao ecoblock also saves energy by passive heating and cooling, producing energy by solar panels, voltaics, and wind turbines. It will also produce biogas from digested sludge and organic solids harvested from the wetland, fallen leaves and gardens. In the overall scheme, the planners claim the ecoblock to have a net zero carbon emission footprint. The Qingdao ecoblock concept is now being implemented in Tianjin Ecocity 150 km southwest of Beijing (Harrison Fraker, personal communication).

### Energy (CO<sub>2</sub>) balance for an ecoblock

An ecoblock or a cluster is a semiautonomous water/stormwater/used subdivision or a part of a city that manages water in a semi closed water cycle and produces energy to achieve the net zero carbon footprint. At this time, there is no

**Table 2** | Energy use of treated volume of municipal used (waste) water and corresponding CO<sub>2</sub> emissions. Raw data from Asano *et al.* (2007) and from Novotny *et al.* (2010)

Treatment process	Energy use kw-hr/m <sup>3</sup> (CO <sub>2</sub> emissions kg/m <sup>3</sup> )		
	Daily flow volume of treated used water (m <sup>3</sup> /day)		
	10,000	25,000	> 50,000
Activated sludge without nitrification and filtration	0.55 (0.33)	0.38 (0.23)	0.28 (0.17)
Membrane bioreactor with nitrification	0.83 (0.51)	0.72 (0.44)	0.64 (0.37)
Reverse osmosis desalination			
Brackish water (TDS 1–2.5 g/L)	1.5 (0.91)–2.5 (1.52)		
Sea water	5 (3.05)–15 (9.15)		
Ozonization (ozone produced from air)			
Filtered nitrified effluent	0.24 (0.15)–0.4 (0.24)		
Desalination by evaporation (using waste heat)	~25 (15.25)		

guideline that would establish the size of the ecoblock. The Qingdao ecoblock would contain 1500–2000 inhabitants out of the total 40,000 living in the (future) ecocity. In this illustrative analysis the starting reference point of water and energy use is the alternative with no water conservation and open linear no reuse water management system. The city and the ecoblock would be located in south-western US. The freshwater source (groundwater and nearby stream) is mined and is unsustainable. The illustrative assumptions are:

Total population	100,000
Original water demand	500 L/cap-day
Sustainable water available from fresh water source	100 L/ cap-day
Sustainable rainwater and stormwater reclamation	20 L/cap-day
Sustainable brackish groundwater (TDS 1500 mg/l)	30 L/cap-day
Maximum water conservation limit	200 L/cap-day

Because the sustainable water is available only to satisfy 150 L/cap-day demand, water use must be reduced by water by conservation and reuse.

Wastewater treatment includes activated sludge process with nitrification. Reuse will be done by filtration of the effluent, followed by reverse osmosis and ozonization. Reused water will not be available for potable use.

## Calculations

A marginal water/energy nexus chart has been prepared and presented on Figure 4 for carbon emissions. Marginal carbon/energy is the carbon emission per one extra m<sup>3</sup> of water demand reduction.

Current unsustainable : water use 0.5m<sup>3</sup>/cap-day

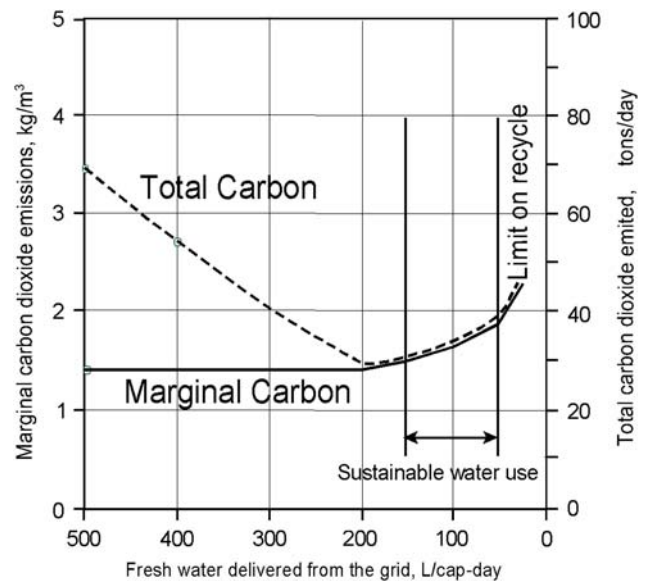
Total water use  $0.5 \times 100,000 = 50,000\text{m}^3/\text{day}$

Marginal energy use  $2.26\text{kWh}/\text{m}^3 \times 0.5\text{m}^3/\text{cap-day}$   
 $= 1.16\text{kWh}/\text{cap-day}$

Carbon emissions  $0.61(\text{kg of CO}_2/\text{kWh}) \times 2.26$   
 $= 1.37\text{kg of CO}_2/\text{m}^3$

Total carbon emissions  $50,000 \times 1.37$   
 $= 69,3580\text{kg of CO}_2/\text{day}$

Reduction to 200 L/cap-day (60% reduction) or 20,000 m<sup>3</sup>/day can be achieved solely by water conservation but the water use is still unsustainable and the available sources cannot provide enough water. At 100 L/cap-day of



**Figure 4** | Water energy nexus chart that includes total and marginal carbon emissions related to water demand reductions by water conservation, additional sources and recycle.

water available from the fresh treated water supplying grid, additional water will originate from rainwater/stormwater (20), sustainable brackish water (30) and reuse (50) to provide 200 L/cap-day of water. Rainwater/ stormwater use will require storage, pumping and filtration which will result in estimated carbon emissions of 0.1 kg of CO<sub>2</sub>/m<sup>3</sup>. Brackish water has to be pumped (1.6 kWh/m<sup>3</sup> = 1 kg CO<sub>2</sub>/m<sup>3</sup> if pumping depth is 500 m) and treated by reverse osmosis and UV/ozonization (1.7 kg CO<sub>2</sub>/m<sup>3</sup>). Reuse will approximately emit 2.0 kg of CO<sub>2</sub>/m<sup>3</sup>.

At 100 l/cap-day of fresh water availability from the grid the marginal kg CO<sub>2</sub>/m<sup>3</sup> emissions become  $(0.1 \text{ [freshwater]} \times 1.37 + 0.02 \text{ [rain]} \times 0.1 + 0.03 \text{ [brackish]} \times 2.7 + 0.05 \text{ [reuse]} \times 2) / 0.2 = 1.6 \text{ kg CO}_2/\text{m}^3$ .

The total carbon emissions at 200 L/cap-day demand and 100 L/cap-day fresh water availability from the grid will be  $1.6 \text{ kg CO}_2/\text{m}^3 \times 20,000 \text{ m}^3 = 32,000 \text{ kg CO}_2/\text{day}$ . The marginal kg of CO<sub>2</sub>/m<sup>3</sup> and the total CO<sub>2</sub> based on additional calculations are plotted on Figure 4.

## CONCLUSIONS

Water and energy uses are intertwined and represent a significant portion of the total carbon emissions reaching the environment. Water conservation is the best alternative solution to a water availability problem because it does not increase carbon emissions. Hence, it should be maximized.

Furthermore, energy can be extracted from used water by heat pumps for a carbon credit. A common water to water heat pump provides 4–5 times more energy than it uses. The extracted heat can be used to warm water in the buildings or generate carbon emission free energy. If water conservation can accomplish the water use reduction goals without reuse it will be done best in a linear distributed water management system whereby highly treated effluents, after heat energy is extracted, provide ecological flow to the receiving water and water for downstream uses. Such a system has been implemented in Hammarby Sjöstad in Stockholm (Novotny & Novotny 2009).

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

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