An integrated energy, carbon, water, and economic analysis of reclaimed water use in urban settings: a case study of Austin, Texas

Ashlynn S. Stillwell, Kelly M. Twomey, Rusty Osborne, David M. Greene, Dan W. Pedersen and Michael E. Webber

ABSTRACT

As water supplies become strained, some municipalities have turned to reclaimed water as a potential source to meet non-potable needs. Such reclaimed water – wastewater effluent treated to appropriate quality standards – is not suitable for human consumption without additional treatment, but can be used for purposes such as irrigation and cooling. One reclaimed water distribution system of particular interest is at the University of Texas at Austin (UT), USA, which receives treated effluent from City of Austin wastewater treatment plants. Depending on the embedded energy of existing water sources, existing levels of wastewater treatment, and the extent of the relevant distribution network, water reuse can save energy and carbon emissions compared with conventional drinking water distribution systems, at the expense of higher capital costs. Our analysis uses EPANet modeling software and historical datasets to examine the embedded energy and carbon emissions in drinking water and reclaimed water for non-potable applications at UT. We then examine the overall economics of reclaimed water use, including capital and operating costs for a variety of amortization periods, financing costs, and externality costs using a levelized-cost of water methodology. This integrated analysis serves as the basis for developing principles of sustainable water reuse.

Key words | carbon, economics, energy, reclaimed water, sustainability, water reuse

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INTRODUCTION

In the context of increasing populations and climate change, many municipalities have pursued alternative water resources to fulfill growing water demand. At the same time, many of them are seeking to reduce their overall energy consumption and carbon emissions. Many alternative sources of water, such as long-haul transfer and desalination, increase the supply of drinking water but are typically associated with increased energy consumption. Since less than 10% of household water use is for drinking (AWWARF 1999), many cities have considered or implemented water reuse to meet current and growing non-potable water demands. Such water reuse utilizes reclaimed water – wastewater treatment plant (WWTP) effluent that has been treated to a high quality standard – for non-potable and indirect potable applications, including outdoor irrigation, toilet flushing, aquifer recharge, and reservoir replenishment. A separate non-potable water distribution network – termed 'purple pipe' since the materials are generally purple – is needed to deliver reclaimed water to customers. These networks usually require pumping (and possibly additional treatment), which consumes energy.

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Decisions regarding water systems overlap with management of energy resources. Water and energy are inextricably linked, and reclaimed water is no exception. Treating and pumping water and wastewater requires energy (Table 1). This energy is generally in the form of electricity, but can also come from primary fuels, totaling over 12 quadrillion BTU of energy use for water in the USA (Twomey & Webber 2011). Since a majority of the electricity in the USA is generated from fossil fuel sources, energy for water use has associated carbon emissions. As a result, changes to the water system can have important implications within the water-energy-carbon nexus. In particular, the energy embedded in drinking water increases with increasing distance and elevation change associated with source water collection and conveyance. As the energy associated with drinking water collection and conveyance increases, the energy savings associated with reclaimed water use generally increase also. For example, using locally-generated reclaimed water can save energy compared to using drinking water from distant supplies for non-potable applications. Distribution of reclaimed water can be more energy-intensive than the baseline drinking water distribution, but the collection and treatment of reclaimed water might consume less energy than collection and treatment of other alternative water supplies. Consequently, widespread use of reclaimed water in some cases could yield significant energy savings and avoided carbon emissions over both baseline conditions as well as over alternative water supply scenarios. However, the energy and carbon tradeoffs of reclaimed water are non-obvious and vary significantly for different water reuse distribution systems and geographic locations. Thus, there is a need for an integrated analytical approach to assessing the overall sustainability of reclaimed water use. This paper presents one pathway for filling that need.

Table 1 | Energy use for water and wastewater treatment increases with lower source water quality and higher treated effluent quality (Goldstein & Smith 2002; CEC 2005; Stillwell *et al*. 2011). Wastewater treatment is less energy-intensive than treating new brackish or saline sources

Treatment system	Energy for treatment[a] (kWh/1,000 L)
Water (including distribution)	
Surface water treatment	0.38
Groundwater treatment	0.48
Brackish groundwater treatment	1.3–2.9
Seawater desalination	2.9–4.7
Wastewater (effluent discharge negligible)	
Trickling filter	0.25
Activated sludge	0.34
Advanced treatment without nitrification	0.40
Advanced treatment with nitrification	0.50

[a]US national average value.

Life-cycle assessment of alternative water supplies in Marin and San Diego counties in northern and southern California, respectively, reveals that reclaimed water requires less electricity than imported and desalinated water (Stokes & Horvath 2006). When examining the entire water and wastewater system, life-cycle carbon dioxide equivalent (CO_2e) emissions for reclaimed water are less than emissions from desalinated water and nearly equal or slightly higher than emissions from imported water depending on fugitive emissions associated with wastewater treatment (Stokes & Horvath 2006). For the Marin and San Diego counties analysis, water reuse saves energy over desalination and imported water sources, but requires utilities to implement better practices elsewhere (for example, to avoid fugitive biogas leakage) to reduce carbon emissions as well.

In water and wastewater systems, treatment processes generally use less energy than pumping operations, both of which use significantly less energy than end-use water heating. Since reclaimed water is generally used in non-potable applications that require little, if any, additional treatment or end-use heating, the majority of the energy associated with water reuse is for pumping. Consequently, efficient distribution systems can reduce the overall energy and carbon footprint of a water system, which becomes important in the context of a potential price on carbon emissions. Previous work on single- and multi-objective optimization of water distribution systems shows that optimal design and operations can be highly sensitive to carbon prices. For example, higher carbon prices motivate larger distribution pipe diameters to reduce friction and thus reduce carbon-derived electricity use (Wu *et al*. 2010). Thus, putting a price on externalities can alter reclaimed water system design. Our research aims to combine these concepts of alternative water supply, energy consumption, CO_2e emissions, and economic feasibility into a novel integrated analysis of reclaimed water use (using Austin, Texas, USA, as a geographic testbed) and its implications within the water-energy-carbon nexus.

HISTORY OF RECLAIMED WATER USE IN AUSTIN, TEXAS, USA

Reclaimed water has been used in Austin for decades for a variety of reasons. Historical use of reclaimed water in Austin was primarily for golf course irrigation, dating back to 1974 when wastewater effluent was used at the Jimmy Clay Golf Course. This water reuse was not done to save energy or avoid carbon emissions, but rather as a means of wastewater effluent disposal due to limited assimilative capacity of the receiving stream (Layton *et al.* 2009). In the 1990s and early 2000s, reclaimed water service was added for golf course irrigation at the Cedars Golf Course, Roy Kizer Golf Course, Morris Williams Golf Course, and First Tee of Greater Austin (Layton *et al.* 2009). Thermoelectric power generation units at the Sand Hill Energy Center have also used reclaimed water for cooling since 2006 (Austin Energy 2011a).

As the Austin population grew from approximately 550,000 in 1995 to almost 800,000 in 2005, demand for water rose from 150 billion to 190 billion liters, which was met primarily by increasing withdrawals from the Colorado River basin (Figure 1). Austin has since expanded the reclaimed water system to meet a portion of the non-potable demand, resulting in an estimated peak-day demand savings of almost 2%, or 17 million liters, in 2009. Currently, the City of Austin's motivations for using reclaimed water have changed from only disposing wastewater effluent to now include reducing drinking water demand, especially peak-day demand, decreasing withdrawals from the Highland Lakes and Colorado River water sources, and reducing or delaying the need for new drinking water treatment facilities (Layton *et al.* 2009; City of Austin 2011).

RECLAIMED WATER USE AT THE UNIVERSITY OF TEXAS

The University of Texas at Austin (UT) main campus is over 140 hectares and supports nearly 75,000 faculty, staff, and students (UT 2011). Total campus water use for all purposes has averaged 7.9 million L/d over the last 5 years. Reclaimed water on campus has been pursued to reduce the university's purchase of drinking water for use in non-potable applications. The installation of the reclaimed water purple pipe network on the UT campus was combined with installation of a new fire water main to reduce construction disruptions and minimize costs (Layton *et al.* 2009). Proposed uses of reclaimed water on campus are non-potable applications, including cooling towers and irrigation with possible future use for toilet flushing, with ultimate build-out demand totaling 6.2 million L/d (Klotz Associates 2009; Layton *et al.* 2009).

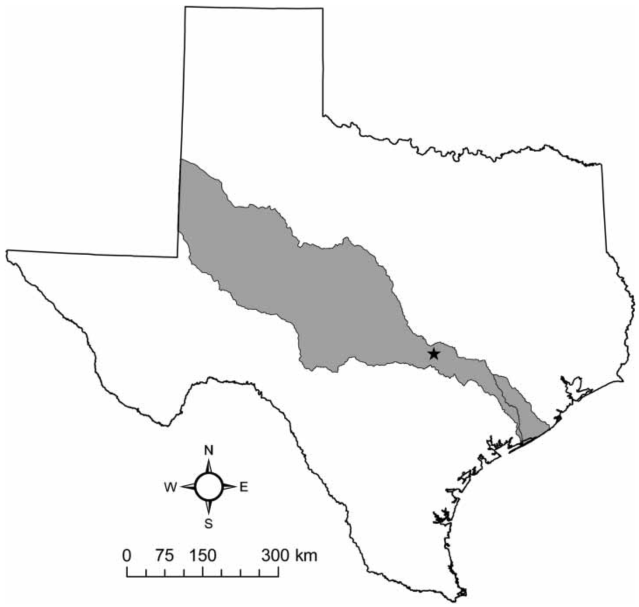

Figure 1 | The City of Austin (represented by the star) collects raw water from the Colorado River basin, shown in grey on this map. After use and treatment, water is returned to the Colorado River as wastewater effluent.

Austin and UT are appropriate testbeds for our reclaimed water analysis for many reasons. High population density in the core urban district, which includes the UT campus, coupled with growing population, create a high demand for water (both potable and non-potable) in a relatively small geographic area. This water demand is for many different purposes – roughly 40% of which are outdoor non-potable uses – due to the diverse economic mix of academia, government, residential, commercial, and manufacturing. Additionally, Austin is large enough to be statistically relevant to other urban regions, yet small enough to model with access to complete data sets and an extensive knowledge base from decades of reclaimed water use. Since both the City of Austin and UT have access to capital to finance reclaimed water infrastructure, our analysis is also timely. While the analytical methodology will be demonstrated with UT and Austin as the geographic testbed, the authors expect that it will have applicability to other regions and water systems.

INTEGRATED ENERGY, CARBON, AND ECONOMIC ANALYSIS

To evaluate use of 6.2 million L/d of reclaimed water at UT and its implications within the water-energy-carbon nexus, we completed an integrated analysis of the embedded energy, associated carbon emissions, and overall economics of the project.

Energy use for reclaimed water

Reclaimed water requires energy for sophisticated treatment of wastewater to produce high-quality effluent and for pumping during distribution. In many US cities, such as Austin, existing wastewater treatment is sufficient to produce suitable quality reclaimed water, but other situations might require new infrastructure for wastewater treatment only, or for an entire water and wastewater infrastructure. Accounting for the energy embedded in reclaimed water depends on these existing conditions and how the system control volume boundary is drawn (Figure 2). Different control volumes will cause energy for different process steps to be included or excluded from the total energy embedded in reclaimed water.

When considering the entire life-cycle energy consumption (the solid line in Figure 2), the energy embedded in reclaimed water includes energy associated with drinking

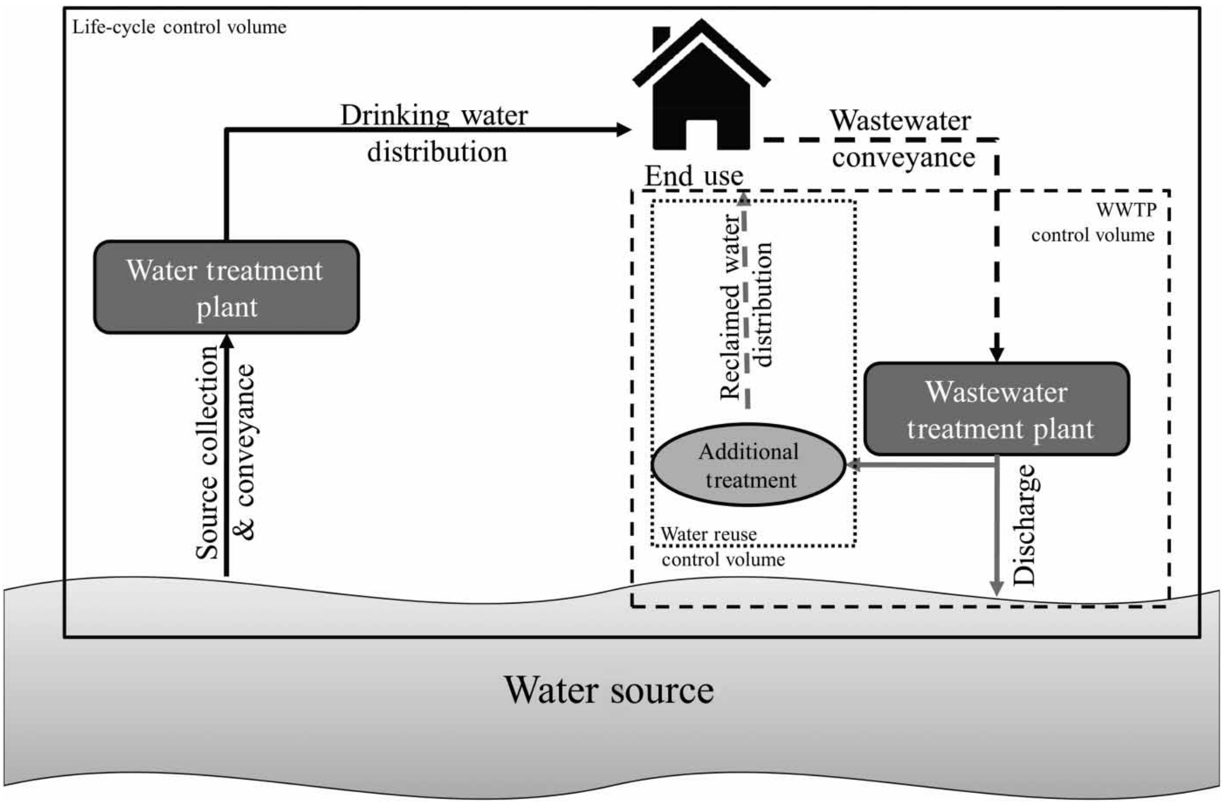

Figure 2 | Accounting for energy use for reclaimed water depends on how the control volume boundary is drawn. When considering the life-cycle control volume (solid line), energy use includes that associated with drinking water, wastewater treatment, and reclaimed water distribution. The wastewater treatment plant (WWTP) control volume (dashed line) includes energy consumption for wastewater treatment and reclaimed water distribution. The water reuse control volume (dotted line) includes only additional treatment (if necessary) and reclaimed water distribution.

water collection and conveyance, treatment, and distribution; in-home end use; wastewater conveyance, treatment, and discharge; and reclaimed water additional treatment and distribution. In this whole-system scenario, the energy embedded in reclaimed water using life-cycle accounting is always additional to, and thus greater than, the energy embedded in drinking water. When wastewater treatment facilities do not already exist (for example, in locations where WWTPs are not required), then the boundaries can be drawn such that only the energy for wastewater conveyance, treatment, and discharge, and reclaimed water additional treatment and distribution are included, as shown in the WWTP control volume represented by a dashed line in Figure 2. Such circumstances would likely be found only in developing countries with freshwater systems but without existing sanitation infrastructure. In many urban areas (such as Austin) both water and WWTPs exist and only the marginal energy for using reclaimed water needs to be included in the control volume, as shown in the dotted line in Figure 2. This allocation is representative of energy for water reuse in the United States where wastewater treatment is required by law and, therefore, the facilities already exist.

Since wastewater would have been conveyed, treated, and discharged regardless of reuse, the energy embedded in reclaimed water includes only the marginal energy investment: additional tertiary treatment (if necessary) and distribution of reclaimed water. The analysis for the work described in this paper uses the water reuse control volume represented by the dotted line in Figure 2. The Walnut Creek and South Austin Regional Wastewater Treatment Plants in Austin (Figure 3) treat wastewater effluent to

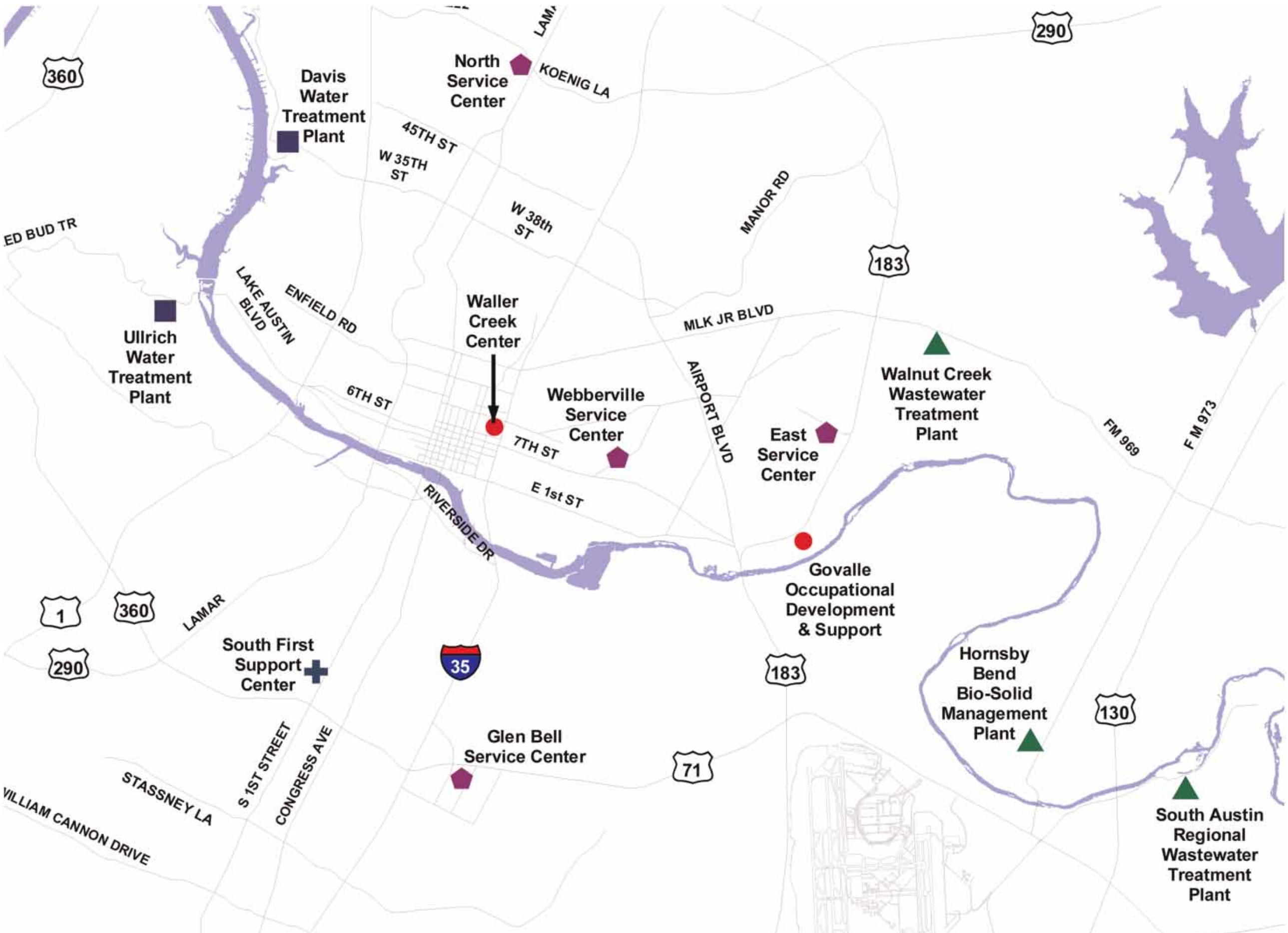

Figure 3 | Water (squares) and wastewater (triangles) treatment facilities are located on the west (higher elevation) and east (lower elevation) sides, respectively, of the Austin core.

a standard sufficient for Type I reclaimed water use under the Texas Administrative Code. Such Type I reclaimed water is approved for urban irrigation and toilet flushing, among other uses where human contact is possible (Texas SOS 2009). As a result, no additional treatment is necessary before reclaimed water enters the purple pipe distribution system and only the energy necessary for reclaimed water pumping is included.

The difference between reclaimed and drinking water pumping energy is expected to be the major source of energy savings from the Austin reclaimed water program since existing levels of wastewater treatment are sufficient for water reuse. Austin water treatment plants are located on the west side of town and WWTPs are on the east side with 40–80 m of elevation change between water and wastewater facilities. Therefore, water generally moves uphill for treatment and distribution while wastewater moves downhill for collection, treatment, and discharge. Based on historical data, Austin Water Utility consumes 0.46 kWh/1,000 L for drinking water collection, treatment, and distribution to the central, north, and south pressure zones, which closely overlap the anticipated build-out area for reclaimed water distribution (Greene 2011). Drinking water for UT is supplied by the Davis Water Treatment Plant, which has an average measured energy consumption of 0.44 kWh/1,000 L for treatment and distribution (using pumps) over the past 10 years. Of that, an estimated 5% (0.02 kWh/1,000 L) is for treatment, while the balance (0.42 kWh/1,000 L) is for pumping (Greene 2011).

We estimated the energy embedded in reclaimed water use on the UT campus using EPANet software from the US Environmental Protection Agency. EPANet is a network modeling software that simulates water distribution systems using hydraulic properties and water quality data with user-defined water demand nodes and water sources linked by pipes and pumps. We modeled Austin's reclaimed water distribution system with the UT campus network, simulating water demand and distribution energy consumption at full system build-out. To determine the amount of reclaimed water used, we integrated under the EPANet system flow balance curve (flow versus time) to calculate the total volume of reclaimed water produced during the simulation time period of 12 days. The modeled total energy consumption of all pumps in the distribution system was then divided by the total volume produced to determine the energy embedded in distribution of reclaimed water in kWh/1,000 L. Here we make the distinction between embedded energy per volume produced versus pumped; dividing total energy consumption for pumping by the total volume pumped gives a low value of embedded energy that is not indicative of the system energy use since some water may be 're-pumped' to reach successively higher pressure planes within the distribution system. Results of the EPANet energy analysis show an embedded energy of 0.44 ± 0.01 kWh/1,000 L produced for the reclaimed water pumps, with uncertainty based on the peak and average day models. Embedded energy is variable depending on reclaimed water customer usage and elevation, as varying flow rates change friction in distribution pipes and flow direction in looped systems. This electricity requirement for reclaimed water pumping represents the total marginal energy investment in reclaimed water use, since additional treatment is not necessary.

As a result of the difference in energy consumption between drinking water (measured at 0.44 kWh/1,000 L) and reclaimed water (modeled at 0.44 ± 0.01 kWh/1,000 L), water reuse on the UT campus is anticipated to save up to 0.007 kWh/1,000 L or consume up to 0.01 kWh/1,000 L. That is, reclaimed water can be a net energy saver or consumer, depending on the energy embedded in reclaimed water, the final determination of which is within the uncertainty of this analysis for Austin. The energy embedded in the marginal liter of drinking water, however, might change in future years with stricter treatment standards or degraded source water quality. Nominally, this embedded energy would likely go higher, which would make reclaimed water a definitive net energy saver; however, these increases might be offset since Austin Water Utility is also actively identifying and mitigating inefficiencies in the existing distribution system. Furthermore, increased reclaimed water use at UT and elsewhere can introduce uncertain impacts to the energy for drinking water distribution. For example, as reclaimed water use displaces drinking water use, it is unclear whether energy needs for drinking water will decrease (because of lower volumes that are pumped) or increase (because of sub-optimal pumping that will be a consequence of lower flow volumes). Consequently, whether the net energy impacts of reclaimed water use in

Austin will be positive or negative in the future is uncertain due to these variables, but trends suggest net energy savings.

For 6.2 million L/d of reclaimed water use on the UT campus, water reuse nominally has an energy equivalence of drinking water (the full range of uncertainty in the analysis suggests that reclaimed water's impact ranges from avoiding 44 kWh/d or causing 68 kWh/d of energy consumption) using average estimates for the last decade. In other words, to first order, reclaimed water use in Austin does not directly avoid energy consumption or associated carbon emissions, though as noted before, reclaimed water use is expected to save energy and carbon in the future as drinking water systems become more energy-intensive. Furthermore, these results vary globally by location, and water reuse circumstances in Austin are peculiar with relatively high wastewater energy intensity and comparatively low drinking water energy intensity.

While reclaimed water might be net neutral in terms of energy for these particular conditions, water reuse is a preferred alternative water source for various reasons. When water reuse is compared to development of the marginal 'next' water source, reclaimed water use can become a net energy saver. If cities similar to Austin currently using surface water for drinking water met increasing water demand with groundwater instead, for instance, additional energy would be embedded in the drinking water supply due to groundwater pumping. Groundwater pumping from a depth of 37 m requires 0.14 kWh/1,000 L for source water collection (DOE 2006), while source water collection of surface water requires minimal energy investment. As a result, using groundwater for drinking water in Austin would make reclaimed water use a net energy saver – an estimated 0.13–0.15 kWh/1,000 L at groundwater depths of 37 m – in non-potable applications. These energy savings increase as the energy embedded in drinking water increases through use of marginal water sources such as long-haul interbasin transfer and desalination. Since reclaimed water directly offsets drinking water for non-potable purposes, water reuse can avoid or delay development of such alternative marginal water sources. Additionally, reclaimed water quality matches well with most non-potable water uses, reserving high quality water for high-value purposes. In the context of climate change and population growth, reclaimed water also represents a reliable local water supply that is resistant to droughts. Notably, even in locations where reclaimed water might be a net energy consumer (for example in cities with comparatively low energy requirements for drinking water), these benefits might still be sufficient enough to motivate water reuse.

Carbon emissions associated with reclaimed water

Saving energy also avoids the carbon emissions associated with generation of electricity. Based on the current fuel mix from Austin Energy (Figure 4), the energy impacts of reclaimed water use will also impact carbon emissions from the natural gas and coal power plants that are used to provide a significant portion of the electricity for the treatment facilities. Since nearly one-third of Austin Energy's electricity generation is from natural gas, the average CO_2e emissions rate is lower than if production were dominated by coal facilities.

Based on 2008 emissions and generation, Austin Energy's reported CO_2e emissions rate was 0.491 kg/kWh (California Climate Action Registry 2011). While this emissions rate is based on average electricity generation, some water and WWTPs use more electricity at night by shifting operations to off-peak hours. Overnight electricity generation is primarily from coal, nuclear, and wind sources during the winter and natural gas sources during the summer. These seasonal variations mean that small shifts in energy consumption during different seasons can potentially avoid higher than average rates of CO_2e emissions. Current and future expanded use of biogas from anaerobic digesters at Austin's Hornsby Bend

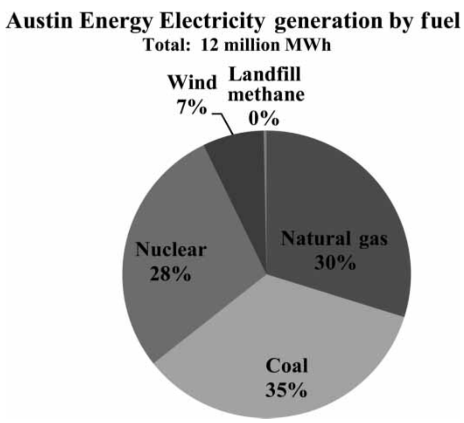

Figure 4 | Austin Energy's 2008 electricity generation is dominated by fossil fuels and has a CO_2 equivalent emissions rate of 0.491 kg/kWh (Austin Energy 2008; California Climate Action Registry 2011).

Biosolids Management Plant also avoids carbon emissions by offsetting grid electricity (Austin Energy 2011c).

For the previously calculated electricity savings and expenditures of 44 and 68 kWh/d, respectively, the associated carbon emissions total 21 kg CO_2e/d avoided and 34 kg/d generated, respectively. That is, using reclaimed water instead of drinking water on the UT campus could avoid up to 7.8 metric tons or generate up to 12 metric tons of carbon dioxide equivalent emissions annually, depending on the system pumping demand and mix of electricity fuels at Austin Energy power plants that are used at the times the treatment is occurring. If the energy (and carbon) embedded in drinking water increases in the future due to stricter treatment standards, water reuse would become a definitive approach to avoiding increased carbon emissions.

Economics of non-potable water use

Cost estimates for installation of the reclaimed water distribution system on the UT campus were completed by Klotz Associates in 2009. Engineering estimates for the university connection to the city distribution system, including mobilization and contingency, total $1,270,000 (Klotz Associates 2009). The UT Utilities and Energy Management's additional investment for on-campus distribution pipe purchases, treatment, and miscellaneous equipment was $1,600,000, bringing the total capital investment to $2,870,000. We analyzed this capital cost estimate in terms of the overall payback period and levelized cost of water (LCOW) – accounting for capital, operating, and externality costs – to determine the profitability of reclaimed water use in non-potable applications.

Using the reclaimed water infrastructure capital cost estimate of $2,870,000 (Klotz Associates 2009) for use of 6.2 million L/d, the reclaimed water project on the UT campus has a 1.4 year simple payback period. That is, UT would recoup all capital investments after 1.4 years of using reclaimed water instead of drinking water in non-potable applications. This payback period might be extended slightly, as it assumes full system build-out in the first year of operations; full use of 6.2 million L/d is not planned until following the first year.

Comparing alternatives in water resources planning and management – here, (1) the 'do nothing' scenario using drinking water versus (2) the reclaimed water scenario – requires capital cost to be annualized over the lifetime of the project such that annual savings and expenditures are directly comparable. We calculated annualized capital cost using Equation (1) below:

$$A = P\left[\frac{i(1+i)^N}{(1+i)^N - 1}\right] \tag{1}$$

where A is the annualized capital cost ($/yr), P is the present capital cost ($), i is the annual interest rate, and N is the amortization period (yr) (based on Loucks & van Beek 2005). Using Equation (1), we directly compared the do nothing scenario using drinking water with the reclaimed water use scenario (Table 2), for a range of annual interest rates and amortization periods. Current drinking water service rates for UT are $1.27/1,000 and $1.16/1,000 L for peak (July through October) and off-peak (November through June) use, respectively (Austin Water Utility 2010). The reclaimed water rate for the 2010/11 fiscal year is $0.30/1,000 L (Austin Water Utility 2010), making reclaimed water more economical than drinking water in non-potable circumstances. Since the total annualized costs (in $/yr) for drinking water exceed those for reclaimed water (Figure 5), we conclude that use of reclaimed water in non-potable applications is economically feasible for UT, saving $1,780,000 to $2,030,000 annually. The 6.2 million L/d University of Texas reclaimed water network becomes economically infeasible over the range of annual interest rates and amortization periods when reclaimed water rates exceed $1.08/1,000 L, making the project moderately sensitive to reclaimed water service rates.

Beyond simple economic comparison, we calculated the LCOW to combine the cost of water, capital investment, and externality expense into a single metric. This LCOW is adapted from the levelized cost of electricity measure commonly accepted in the energy sector (Masters 2004). The LCOW for drinking water and reclaimed water was calculated using Equation (2):

$$\text{LCOW} = \frac{A + f \times \text{IDC}(i_{\text{constr}}, N_{\text{constr}}, A) + \text{AOM}}{Q} \tag{2}$$

where $\text{IDC}(i_{\text{constr}}, N_{\text{constr}}, A) = A \times i_{\text{constr}} \times N_{\text{constr}}$ is interest during construction using the annual interest rate during

Table 2 | Economic analysis of the reclaimed water project on the University of Texas campus shows non-potable use of reclaimed water (at 6.2 million L/d) in place of drinking water to be profitable over a range of interest rates and amortization periods. Levelized cost of water (LCOW) is used for a direct comparison between drinking and reclaimed water

				Reclaimed water project			
Interest rate (annual)	Amortization period (yr)	Do nothing Drinking water[a] ($/yr)	Drinking water LCOW[b] ($/1,000 L)	Capital for reclaimed infrastructure[c] ($/yr)	Reclaimed water[d] ($/yr)	Total reclaimed water cost[e] ($/yr)	Reclaimed water LCOW[b] ($/1,000 L)
0.0%	30	$2,760,000	$1.22	$95,700	$678,000	$774,000	$0.38
	45	$2,760,000	$1.22	$63,800	$678,000	$745,000	$0.37
	60	$2,760,000	$1.22	$47,800	$678,000	$726,000	$0.36
2.5%	30	$2,760,000	$1.22	$137,000	$678,000	$815,000	$0.40
	45	$2,760,000	$1.22	$107,000	$678,000	$785,000	$0.39
	60	$2,760,000	$1.22	$92,900	$678,000	$771,000	$0.38
5.0%	30	$2,760,000	$1.22	$187,000	$678,000	$865,000	$0.42
	45	$2,760,000	$1.22	$161,000	$678,000	$839,000	$0.41
	60	$2,760,000	$1.22	$152,000	$678,000	$830,000	$0.40
7.5%	30	$2,760,000	$1.22	$243,000	$678,000	$921,000	$0.44
	45	$2,760,000	$1.22	$224,000	$678,000	$902,000	$0.44
	60	$2,760,000	$1.22	$218,000	$678,000	$896,000	$0.43
10.0%	30	$2,760,000	$1.22	$304,000	$678,000	$982,000	$0.47
	45	$2,760,000	$1.22	$291,000	$678,000	$969,000	$0.47
	60	$2,760,000	$1.22	$288,000	$678,000	$966,000	$0.46

[a]Based on an average of peak (July through October) and off-peak (November through June) rates of $1.27 and $1.16 per 1,000 L (Austin Water Utility 2010) and assumed to remain constant over the project lifetime.
[b]Calculated using Equation (2). Drinking water LCOW assumes cost of additional energy and associated carbon emissions (at $50/metric ton CO_2e) are passed on directly to the consumer. Interest during construction is assumed to have a 3% annual rate for the 1 year construction period.
[c]Calculated using $2,870,000 capital cost and Equation (1) (based on Loucks & van Beek 2005).
[d]Based on the approved reclaimed water rate of $0.30 per 1,000 L (Austin Water Utility 2010) and assumed to remain constant over the project lifetime.
[e]Presented numbers might not sum exactly due to rounding.

construction i_{constr} time of construction N_{constr} (yr), and annual capital cost A ($/yr);

$$f = \left[\frac{i_{\text{constr}}(1+i_{\text{constr}})^{N_{\text{constr}}}}{(1+i_{\text{constr}})^{N_{\text{constr}}}-1}\right]$$

is the amortization factor for the construction period from Equation (1), AOM represents annual operations and maintenance costs ($/yr), and Q represents annual flow rate (L/yr). In Equation (2), costs of energy and externalities, such as a set price on carbon dioxide equivalent emissions, can be included in AOM and reflected in the resulting LCOW.

Using Equation (2), we calculated LCOW for drinking water and reclaimed water (Table 2). Using the EPANet model range of 0.44 ± 0.01 kWh/1,000 L for reclaimed water distribution, additional energy is required for drinking water (0.007 kWh/1,000 L) and reclaimed water (0.01 kWh/1,000 L), respectively, as well as associated carbon emissions (0.003 and 0.005 kg/1,000 L, respectively). These costs are included in the drinking water and reclaimed water AOM cost in the LCOW calculation at the current Austin Energy electricity rate for water and wastewater (Austin Energy 2011b) and an assumed fee of $50 per metric ton of carbon. Typical speculated values for carbon prices range from $0–$100 per metric ton (EIA 2010); therefore, we selected $50 as a mid-range estimate of potential carbon-related expenses. Including additional electricity and carbon expenses in the AOM cost for drinking water (at the low end of the range of reclaimed water embedded energy) and reclaimed water (at the high end of the range of reclaimed water embedded energy) assumes that the full cost of using drinking water for non-potable purposes would be directly passed on to the consumer. Note that the uncertainty in estimates of energy for reclaimed water distribution (0.44 ± 0.01 kWh/1,000 L) yields the same estimates of LCOW as found in Table 2 when calculations are rounded to two decimal places.

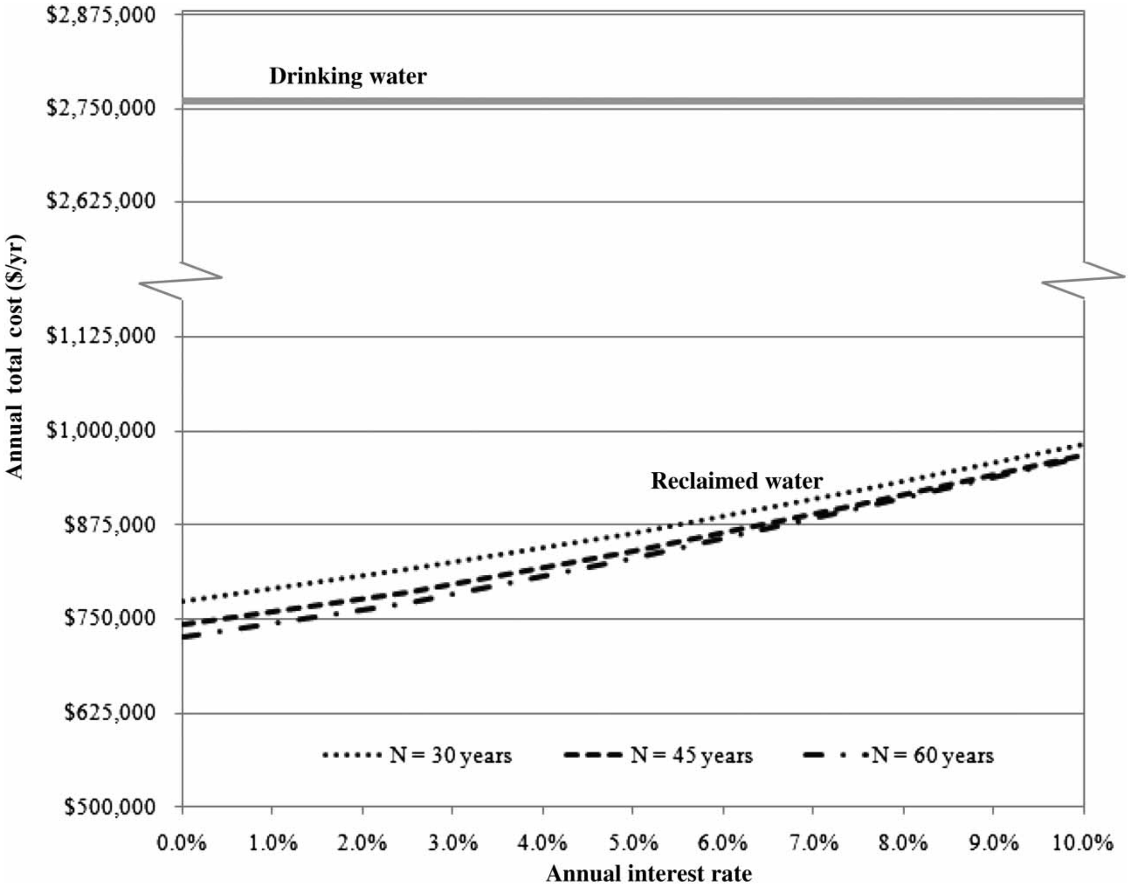

Figure 5 | Total annual costs for drinking water exceed those for reclaimed water over a range of annual interest rates and amortization periods, making reclaimed water use for non-potable purposes economically feasible.

Since the LCOW for drinking water exceeds that of reclaimed water, we again conclude that reclaimed water use is economically feasible at UT in Austin, regardless of any remaining potential savings of energy and carbon. Ranging from $0.36 to $0.47/1,000 L, the LCOW for reclaimed water is greater than the current City of Austin rate for reclaimed water service of $0.30/1,000 L (Austin Water Utility 2010). This finding supports the acknowledgment from Austin Water Utility that the full cost of reclaimed water service is not recovered under the current rate structure. Reasons for discounted reclaimed water rates include encouraging water reuse and reducing or delaying the need for development of additional drinking water supplies and treatment facilities. In a recent survey regarding water reuse, a majority of responding water utilities indicated that less than 25% of annual operating costs for reclaimed water service were recovered in the price of reclaimed water (AWWA 2008). Notably, if reclaimed water service rates were equal to the cost of service, most reclaimed rates would exceed drinking water rates, thus discouraging water reuse (AWWA 2008).

The overall sustainability of water reuse is typically a function of energy use, carbon emissions, and cost. Other benefits, such as increased drought resiliency, potential offsetting of fertilizer use for landscaping, and reduced nutrient loading from effluent discharge, can still make the use of reclaimed water worthwhile. When considering energy savings and carbon emissions reductions alone, water reuse in Austin is neutral, yet these other benefits motivate sustainable reclaimed water use. The 6.2 million L/d of reclaimed water use at UT alone translates to reduced freshwater withdrawals from the Colorado River of over 2.3 billion liters annually. This increase in water self-sufficiency reveals that the sustainability of water reuse projects extends beyond energy savings and avoided carbon emissions. Thus, this case study demonstrates the importance of a holistic and integrated analysis. That is, while one or two sustainability parameters might be negative or neutral, other parameters might be beneficial. Only with a complete assessment will the full picture of sustainability emerge. Consequently, Austin serves as a convenient testbed for: (1) demonstrating our methodology for analyzing reclaimed water systems; (2) illustrating the value of integrated systems analysis to reveal non-obvious conclusions; and (3) uncovering insights that could be useful in formulating guiding principles regarding water reuse. A qualitative analysis of other geographic locations reveals similar complexity in sustainable water reuse.

DISCUSSION OF REGIONAL IMPLICATIONS OF RECLAIMED WATER USE

The energy implications of reclaimed water projects vary a great deal regionally as the anticipated benefits or costs are very dependent on factors such as freshwater availability and regional topography. Water-scarce regions are more likely to benefit from water reuse projects than those that have an abundance of freshwater, since these regions are more likely to require alternative water supplies to meet water demand. These alternatives, which might include desalination, interbasin transfer, and deep groundwater pumping, typically require more energy than local water sources, and in many cases, more energy than reclaimed water. Thus, many water-scarce areas of the USA, such as Orange County, CA (Torrice 2011) and Tucson, AZ (Perrone *et al.* 2011), are turning toward reclaimed water as an alternative to these more energy-intensive options. Particularly in very flat regions, the marginal energy cost to pump water from a wastewater facility to an end-user might be very little in comparison to the costs of acquiring water from alternative water sources. Likewise, in areas of large elevation changes, water reuse becomes less attractive since wastewater treatment facilities tend to be built in low-lying areas, and thus, require energy-intensive pumping to move water to end-users at higher elevations. Such is the case with Austin, where the altitude gain between the WWTPs and water treatment plants is 40–80 m.

Although numerous analyses have attempted to quantify the energy-intensity of regional reclaimed water distribution networks, it is difficult to compare the results of these studies since there is often no transparency as to the boundaries of the control volume being analyzed. Without defining the boundaries of the analysis, it is unclear whether embedded energy estimates include only the marginal treatment (if any) and distribution of the wastewater effluent (in the dotted line in Figure 2) or the entire water supply cycle (in the solid line in Figure 2). Therefore, comparing the energy embedded in reclaimed water with that of other alternative sources is difficult without consistency and clarity in the reporting of results.

Studies do exist that are transparent in their energy accounting. A 2009 study by Stokes & Horvath indicates that water recycling in Southern California, USA, requires approximately 2.14 kWh/1,000 L, about half that of seawater desalination, which typically requires over 5 kWh/1,000 L. However, 0.45 kWh/1,000 L, or 21%, of this reclaimed water energy-intensity value represents the energy for surface water and wastewater conveyance, treatment, and distribution, thus some transparency exists in reported energy values. The analysis also assumes that reclaimed water is pumped an average of 35 km to its end-user, representing 70%, or 1.5 kWh/1,000 L, of this total value (Stokes & Horvath 2009). While these results assume a hypothetical case study in Southern California, previous results indicate that the energy used to distribute water is highly dependent on location. For example, two case studies that quantified the energy embedded in the water supplies of the Marin Municipal Water District in Northern California and the Oceanside Water Department in San Diego County concluded that the former typically required significantly more energy for water distribution from the point of treatment to its customers (Stokes & Horvath 2006).

Energy-intensity comparisons of drinking water sources of the Costa Brava Water Agency in Northeastern Spain indicate that the energy-saving benefits of water reuse systems vary widely among its 27 municipalities. Three of these municipalities supply a large percentage of their water demand by desalinating seawater, which requires approximately 4.9–5.4 kWh/1,000 L (includes pumping, treatment, and distribution) to prepare water for end-use. Reclaimed water systems in these three municipalities average 0.002 kWh/1,000 L (includes energy for tertiary treatment only, no distribution), 0.36 kWh/1,000 L (includes energy for tertiary treatment, distribution, and agricultural irrigation), and 0.71 kWh/1,000 L (includes energy for tertiary treatment and distribution), respectively (Serra & Sala 2003). Thus, when compared to seawater desalination, reclaimed water systems offer large energy savings. The energy savings or consumption of reclaimed water systems in municipalities that have access to local surface water and groundwater reservoirs vary. Six of the 11 municipalities analyzed required less than 0.5 kWh/1,000 L for surface or groundwater pumping, treatment, and distribution (Serra & Sala 2003). Tertiary treatment and distribution of reclaimed water typically required more than 0.5 kWh/1,000 L, on average, for the entire region; however, energy consumption varies among different municipalities.

The authors of the Costa Brava Water Agency study note that the large range in the reclaimed water embedded energy was largely influenced by proximity of the WWTP to the non-potable water user. Those areas that required reclaimed water to be pumped up large elevation gains required substantially more energy than those that could distribute reclaimed water by gravity. One municipality pumping water 100 m above the elevation of the WWTP used 1.26 kWh/1,000 L for tertiary treatment and pumping, while another, using only gravity to distribute reclaimed water, required only 0.001 kWh/1,000 L for treatment (Serra & Sala 2003). The decision to implement reclaimed water systems is not only a function of energy savings or consumption, but also the availability of water. Although the Costa Brava Water Agency in Spain has many municipalities whose local drinking water sources are less energy-intensive than reclaimed water, large fluxes in water use between tourist and off-seasons often mean that water is scarce in some seasons and abundant in others. Depending on the time of year, the agency supplies between 150,000 and 1.1 million inhabitants, and as such, reclaimed water is an effective way to supplement the water supply during the dry, tourist season (Serra & Sala 2003). The same notion is true in Southern California, where drought, hot temperatures, and agricultural water demands reduce the availability of urban water in the summer.

In some urban areas in desert climates, water reuse can save large amounts of energy compared to drinking water use in non-potable applications. Cities in the Middle East are of particular interest since many rely on seawater as a drinking water source, using relatively inexpensive energy and waste heat from thermoelectric power plants to drive thermal desalination processes. For example, drinking water in Abu Dhabi, United Arab Emirates, requires 26 kWh/1,000 L for multi-stage flash distillation and is significantly more energy-intensive than reclaimed water at 0.66 kWh/1,000 L (Scott 2011). The energy embedded in drinking water, however, is highly dependent on what is included in the control volume boundary. High summer electricity demand for air conditioning leads to excess desalination capacity using waste heat; low electricity demand in the winter requires gas turbines to be dispatched solely for desalination to supply municipal water (Scott 2011). Consequently, accurate energy accounting becomes difficult when considering multiple uses of energy fuels and varying seasonal demands for both energy and water. In an urban area where approximately 80% of municipal water use is for outdoor irrigation, the value of reclaimed water in Abu Dhabi can approach that of drinking water (Scott 2011). Water reuse projects in areas like Abu Dhabi can make environmental and economic sense by offsetting demand for energy-intensive drinking water, meeting a portion of the non-potable water demand in a sustainable manner, and saving energy and associated carbon emissions for municipal water treatment.

PRINCIPLES OF SUSTAINABLE WATER REUSE

Based on our analysis of reclaimed water use in Austin, Texas, with a qualitative look at other regions, we suggest three main principles of sustainable water reuse: analysts should use transparency in the control volume boundary definition, reclaimed water decision makers should consider the relative sustainability of the baseline drinking water source, and managers should encourage and facilitate reclaimed water use for the customer.

Use transparency in control volume boundary definition

How the control volume boundary is defined, as was illustrated in Figure 2, is important for determining the energy savings or expenditures, and corresponding carbon emissions, associated with water reuse. In order for energy values for drinking water and reclaimed water to be accurately compared, aspects of each process that are included or excluded should be explicitly defined. For example, a value of drinking water embedded energy (in kWh/1,000 L) that includes only water treatment energy and not electricity for distribution pumping would appear mistakenly low compared to a value of reclaimed water embedded energy that includes additional tertiary wastewater treatment and distribution pumping. Without transparency in the control volume boundary for determining embedded energy, this example might discourage water reuse due to likely higher reclaimed water embedded energy when compared to that of drinking water.

Understanding which aspects of the water and wastewater process are or are not included in a control volume boundary becomes important when comparing different embedded energy values. Many literature sources report the embedded energy or energy-intensity of a particular water supply, yet most of these reported values are given as a single number out of context. For example, one author might report a value of 0.06 kWh/1,000 L for drinking water, including only the drinking water treatment, while another author might report a value of 0.38 kWh/1,000 L for drinking water, including source collection, treatment, and distribution. Such distinctions of scope are rarely made in the literature. Directly comparing these two embedded energy values would be erroneous to say the least. Making quantitative energy comparisons between two water supply options requires clearly defining the appropriate control volume boundary and making that definition transparent when reporting values.

Consider the relative sustainability of baseline drinking water source

With a clearly defined control volume boundary, comparisons can be made between drinking water and reclaimed water to determine the sustainability of water reuse projects. Whether reclaimed water turns out to be the preferred alternative depends on the relative sustainability of the baseline drinking water supply from environmental, economic, and societal perspectives. Environmentally speaking, higher embedded energy of the baseline drinking water source facilitates sustainable water reuse. That is, when the drinking water embedded energy is comparatively high, reclaimed water use is a net energy saver; when the drinking water embedded energy is low, reclaimed water is a net energy consumer. In the case of Austin, the drinking water embedded energy is within the modeled range of the reclaimed water embedded energy, making water reuse less sustainable than in Abu Dhabi, for example, where the drinking water embedded energy is relatively high due to use of desalination. Stress on the baseline drinking water source also plays a role in water reuse sustainability, since many competing uses for a particular water source, regardless of the embedded energy, might motivate conservation and water reuse. Implementing sustainable water reuse would decrease withdrawals from an over-stressed water source, although this initial reduced impact on water sources is offset by there being reduced return flows, so that downstream impacts are unchanged.

From an economic perspective, sustainable water reuse prevents or delays development of the marginal next drinking water source. While reclaimed water use might not save energy when compared to the current baseline drinking water source, offsetting non-potable water demand with reclaimed water might decrease the need for new water supplies, which are likely more energy intensive than the baseline water source. Development of marginal drinking water sources also requires upfront capital investments and ongoing operational and maintenance costs that might be avoided by use of reclaimed water in non-potable applications.

Society also plays a role in the sustainability of water reuse when compared to the baseline drinking water supply. Though technologies exist for water reuse in potable applications, typical uses of reclaimed water are for non-potable applications, generally focused on outdoor irrigation. The sustainability of a water reuse project depends on the existing non-potable water demand. Water reuse is more likely to be sustainable in a society with high non-potable water demand that is currently met by drinking water. Without existing non-potable water demand, finding end-use applications for reclaimed water might prove unsustainable.

Encourage and facilitate reclaimed water use for customer

Securing a customer base is the last step in ensuring sustainable water reuse. High ease of reclaimed water use for the customer is key in gaining and retaining customers. Infrastructure connections through piped networks are required for sustainable delivery of reclaimed water to customers. Investment in such infrastructure might be best achieved by targeting large non-potable water users, such as golf courses, and coordinating installation with other construction efforts. Both drinking water and reclaimed water service rates also affect the sustainability of water reuse. All costs are generally not recovered with reclaimed water service rates, as discussed previously, but reclaimed water rates must be less than drinking water rates to encourage water reuse. As a result, cities with large non-potable water use and high existing drinking water rates might be better suited to water reuse projects.

Sample circumstances that make water reuse projects more or less sustainable are listed in Table 3.

POLICY IMPLICATIONS

Overall success of alternative water resources depends on mutual feasibility in all aspects of the society – environment – economy triple bottom line triangle. Water projects might be economically feasible, but adverse environmental impacts or societal distaste for a project can hinder or halt development. Similarly, projects with positive impacts on the environment and high public acceptance can fail from an economic perspective, inhibiting their ability to proceed beyond the concept phase. Simultaneously satisfying the societal, environmental, and economic aspects of a reclaimed water project can prove both challenging and rewarding.

Table 3 | Various circumstances, some of which are listed here, can make water reuse projects more or less sustainable

More sustainable water reuse	Less sustainable water reuse
• Well-defined boundary conditions for energy, carbon, and monetary flows • High marginal energy costs • Limited freshwater availability • Energy-intensive ‘next’ source of drinking water • Drinking water rates that exceed reclaimed water rates • Existing demand for non-potable water	• Murky boundary conditions for energy, carbon, and monetary flows • Low marginal energy costs • Abundant freshwater • Relatively inexpensive drinking water rates • Lack of demand for non-potable water for irrigation or industrial uses

Research shows that the public is generally interested in water reuse when projects are environmentally, economically, and human health friendly (Hartley 2006), yet the public perceives reclaimed water to be riskier than other alternative water sources, such as desalination, from a human health perspective (Dolnicar & Schafer 2006). Additionally, support for water reuse tends to decrease as projects are constructed in local communities where human contact is more likely; gaining and maintaining public support for water reuse systems is dependent on information dissemination, organizational commitment, public dialogue, fairness, and trust (Hartley 2006).

Policies that promote water reuse for indirect potable or non-potable purposes must focus on societal impacts and public education to ensure success. Evidence of water reuse projects with good intentions and unsuccessful outcomes is all too common when water planners and public officials do not handle adverse public sentiment properly, as was seen with San Diego’s proposed indirect potable reuse project in the 1990s coining the ‘toilet to tap’ phrase (Hartley 2006). By addressing societal concerns with public education campaigns, water planners can make strides in the development and acceptance of water reuse.

Use of reclaimed water presents vast potential for positive sustainability impacts within the water-energy-carbon nexus. Reclaimed water use reduces drinking water withdrawals and preserves supplies for potable purposes by meeting a portion of the non-potable water demand. Additionally, depending on the energy and carbon embedded in a particular water source, reclaimed water can save both energy and carbon by avoiding sophisticated drinking water treatment when lower quality water is well-suited for a particular purpose. While reclaimed water distribution systems require energy for pumping, this energy investment can offset the energy required for the next increment of drinking water, especially when that next increment of drinking water might come from desalination or long-haul water transfer.

Investment in reclaimed water distribution systems and use can promote overall system sustainability by reducing source water withdrawals for drinking water and decreasing nutrient loading from wastewater effluent discharges to surface water bodies. Potential secondary benefits of reclaimed water use for irrigation purposes include reduced fertilizer demand, also avoiding associated CO_2e emissions, due to the nutrient content of reclaimed water. Reducing wastewater effluent discharge also reduces the overall impact of the WWTP, since most of a plant's environmental footprint is due to eutrophication of water bodies receiving nutrient-rich effluent (Venkatesh & Brattebø 2011). Innovation in water reuse can also promote matching intended end use with level of water quality (i.e., using high quality water for potable purposes and lower quality water for irrigation, institutional cooling, and toilet flushing). In the context of climate change, reclaimed water serves as a drought-resistant local water supply to meet a portion of non-potable water demands. While motivations for pursuing water reuse vary, benefits of such systems support sustainability and efficient use of water resources.

CONCLUSIONS

In the context of resource sustainability, reclaimed water use in Austin, Texas, benefits local surface water quality and quantity through decreased nutrient loading from wastewater effluent discharge and reduced drinking water withdrawals. Potentially saving energy for water treatment reduces the strain the water and wastewater systems pose for satisfying electricity demand. Reclaimed water use can reduce carbon emissions associated with water treatment, thus mitigating the climate change impacts of the water and wastewater sectors. These potential mutual benefits within the water-energy-carbon nexus make use of reclaimed water feasible and sustainable for the City of Austin. Looking forward to higher energy requirements for water treatment, the savings are more pronounced.

Reclaimed water use at the University of Texas at Austin for non-potable applications saves significant volumes of money and water despite being roughly neutral (according to today's operational parameters) in energy savings and associated carbon emissions. For the university's proposed 6.2 million L/d reclaimed water use, water reuse can save up to 44 kWh or consume up to 68 kWh of electricity per day, based on the range of energy embedded in reclaimed water (0.44 ± 0.01 kWh/1,000 L). Associated carbon dioxide equivalent emissions estimates are up to 21 kg avoided and up to 34 kg generated daily, in response to the range in electricity values. After proceeding with the capital investment in the UT reclaimed water network, cost savings range from $1,780,000 to $2,030,000 annually, depending on the project interest rate and amortization period. Thus, while reclaimed water use is neutral by some sustainability measures, water reuse in Austin is highly beneficial for the resiliency of water systems, as revealed through our integrated analysis.

Based on our quantitative analysis of Austin and qualitative analysis of other areas worldwide, we suggest three main principles of sustainable water reuse: analysts should use transparency in the control volume boundary definition, reclaimed water decision makers should consider the relative sustainability of the baseline drinking water source, and managers should encourage and facilitate reclaimed water use for the customer. Thoughtful selection of a control volume boundary is important for accurate energy accounting to determine the energy sustainability of a particular water reuse project. After clearly defining a control volume boundary, reclaimed water use can be compared to drinking water use in non-potable applications to determine energy savings or consumption associated with water reuse. Finally, ensuring ease of customer use of reclaimed water is essential to promoting water reuse. Such sustainable water reuse can help meet growing water demands with finite resources.

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