Supplementary Materials: Comparing the Life Cycle Energy, Greenhouse Gas Emissions and Nutrient Releases of Several Water and Waste Service Options

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1. Water Balance Calculation

The typical household water and wastewater demand was estimated to be as detailed in Table S1.According to American average values reported by U.S. EPA, the water consumption of the average family of four was estimated [1]. The water consumption of toilet flushing varies with the choices of toilets. With waterless composting toilets and urine diverted flush toilet. The flush water requirement for urine diverted flush toilet is 0.4 L of water per flush [2,3]. Low flush toilet such as the propel air toilet in BE-GR and BE-GRR offers a high performance toilet which only uses 1.5 liters of water per flush.

Table S1. Water Balance Calculations for System Options.

Product/Service			Options					Units	Notes
			BAU	CT	UD	BS	RH		
Water Services	*Drinking water*	*Municipal water*	20	20	20	20	20	Gallon/day	*faucet water (drinking, personal hygiene, cooking, etc.) Same for all options*
	Irrigation water	Municipal water	67	67	67	0	0	Gallon/day	No irrigation during winter months; 100 Gallon/day during the rest of months
		Grey water	0	0	0	67	67	Gallon/day	
	Clothes washing water	Municipal water	59.8	59.8	59.8	59.8	39.8	Gallon/day	
		Grey water treatment and reuse	0	0	0	0	0	Gallon/day	
		Rain water treatment and reuse	0	0	0	0	20	Gallon/day	On-site filtered and UV treated rain water for hot water supply
	Dish washing water	Municipal water	49	49	49	49	29	Gallon/day	
		Rain water treatment and reuse	0	0	0	0	20	Gallon/day	On-site filtered and UV treated rain water for hot water supply
	Shower and bath water	Municipal water	47.2	47.2	47.2	47.2	27.2	Gallon/day	
		Rain water treatment and reuse	0	0	0	0	21.5	Gallon/day	On-site filtered and UV treated rain water for hot water supply
	Toilet water	Municipal water	120	0	20	0	0	Gallon/day	
		Grey water treatment and reuse	0	0	0	32	32	Gallon/day	
		Rain water treatment and reuse	0	0	0	0	0	Gallon/day	

Table S1. *Cont.*

Product/Service			Options					Units	Notes
			BAU	CT	UD	BS	RH		
Waste Services	Human excrement and urine	Conventional flush toilet use	96	96	0	0	0	Gallon/day	
		Composting toilet Use	0	0	0	0	0	Gallon/day	Compost is transported to either local composter (if existing) or landfill.
		Urine diverted flush Use	0	0	16	0	0	Gallon/day	Urine is stored in a urine tank temporarily and then transported to nearby watersheds which are not nitrogen sensitive zones.
		Low flush toilet use	0	0	0	25.6	25.6	Gallon/day	black water collected and transported to the digester
	Clothes washing water	Municipal Wastewater Treatment	47.8	47.8	0	0	0	Gallon/day	
		Grey water Treatment	0	0	47.8	0	0	Gallon/day	On-site treatment in septic tank
		Grey water Treatment and Reuse	0	0	0	47.8	47.8	Gallon/day	On-site filter and UV treatment
	Dish washing water	Municipal Wastewater Treatment	39.2	39.2	0	0	0	Gallon/day	
		Grey water Treatment	0	0	39.2	0	0	Gallon/day	On-site treatment in septic tank
		Grey water Treatment and Reuse	0	0	0	39.2	39.2	Gallon/day	On-site filter and UV treatment
	Shower water	Municipal Wastewater Treatment	37.8	37.8	0	0	0	Gallon/day	
		Grey water Treatment	0	0	37.8	0	0	Gallon/day	On-site treatment in septic tank
		Grey water Treatment and Reuse	0	0	0	37.8	37.8	Gallon/day	On-site filter and UV treatment

Note: The water quantity required for firefighting was assumed to be the same for the investigated water systems. For the comparison purpose, the firefighting water was not listed in the table. The numbers in the water service rows represent the quantities of used water at the household. The numbers in the waste service rows represent the quantities of the treated wastewater at the treatment units/plant. 15% of water loss was assumed during the conventional water transport. 20% of wastewater loss was assumed during the wastewater collection and treatment stages in the conventional BAU option. 20% of loss rate was assumed for the on-site greywater collection, treatment, and distribution system.

Table S2. System Expansion and Functional Unit.

	BAU	CT-SS	UD-SS	BE-GR	BE-GRR
Water service	Household's water and wastewater services, described in Table S1				
Wastewater service					
Energy production	Equivalent amount electricity from national average energy mix	Equivalent amount electricity from national average energy mix	Equivalent amount electricity from national average energy mix	Electricity produced from the combined black water, household food waste, and restaurant grease trap	Electricity produced from the combined black water, household food waste, and restaurant grease trap
Fertilizer production	Equivalent amount of N and P from synthetic fertilizers	N and P from compost	N and P from compost	N and P from digestate	N and P from digestate

2. Rain Water Harvesting Calculation

Table S3. Calculation for rainwater harvesting and rain tank size.

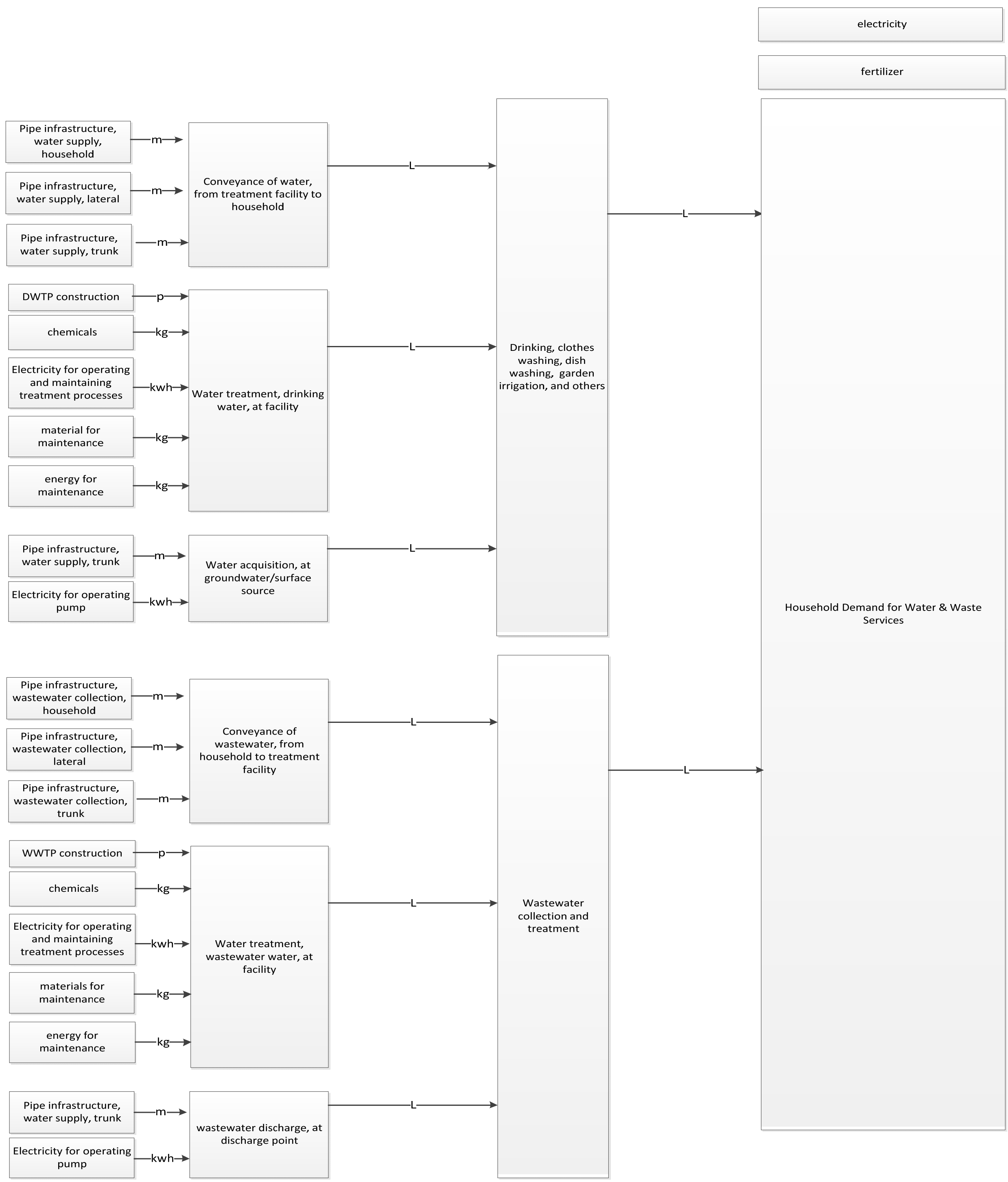
Month	Average Rainfall (Inches/Month)	Rainfall Collected (Gallons/Month)	Treated Rain Water for Household Use (Gallon/Month)
January	4.23	2229.21	2006.289
February	3.98	2097.46	1887.714
March	4.14	2181.78	1963.602
April	3.95	2081.65	1873.485
May	3.71	1955.17	1759.653
June	3.44	1812.88	1631.592
July	3.38	1781.26	1603.134
August	3.33	1754.91	1579.419
September	3.91	2060.57	1854.513
October	4.12	2171.24	1954.116
November	3.89	2050.03	1845.027
December	4.63	2440.01	2196.009
Average	3.8925	2051.348	1846.213

The rainwater storage tank, assuming of a typical roof area of 1000 ft^2, 10 days of storage time, and 85% of roof collection efficiency for 80% reliability of supply was 3000 L.

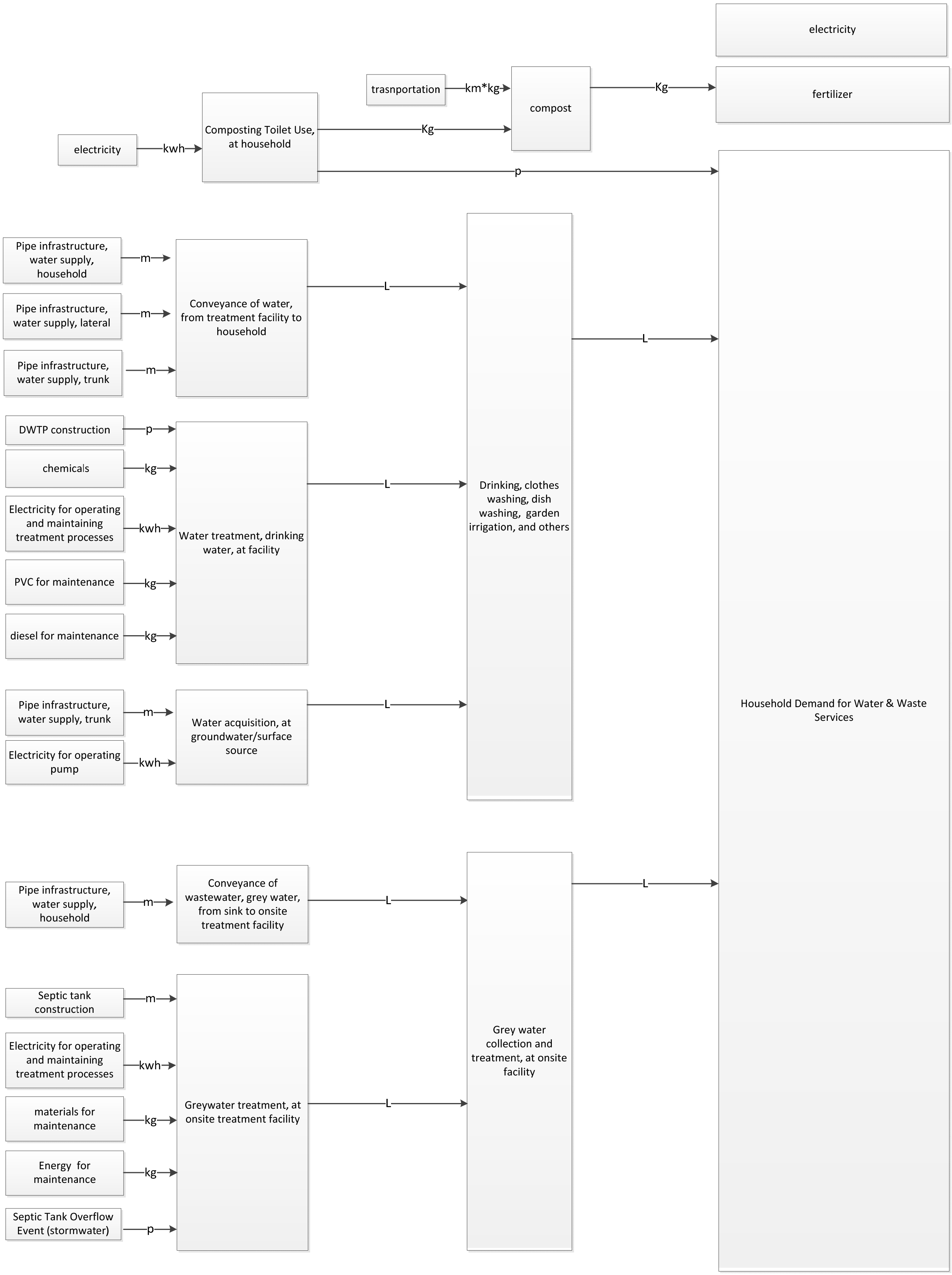
3. Water System Diagram and Description

The five investigated system options are described below. The diagrams reflect 1) unit processes complied and organized for each system; and 2) the system scope and functional unit for this study.

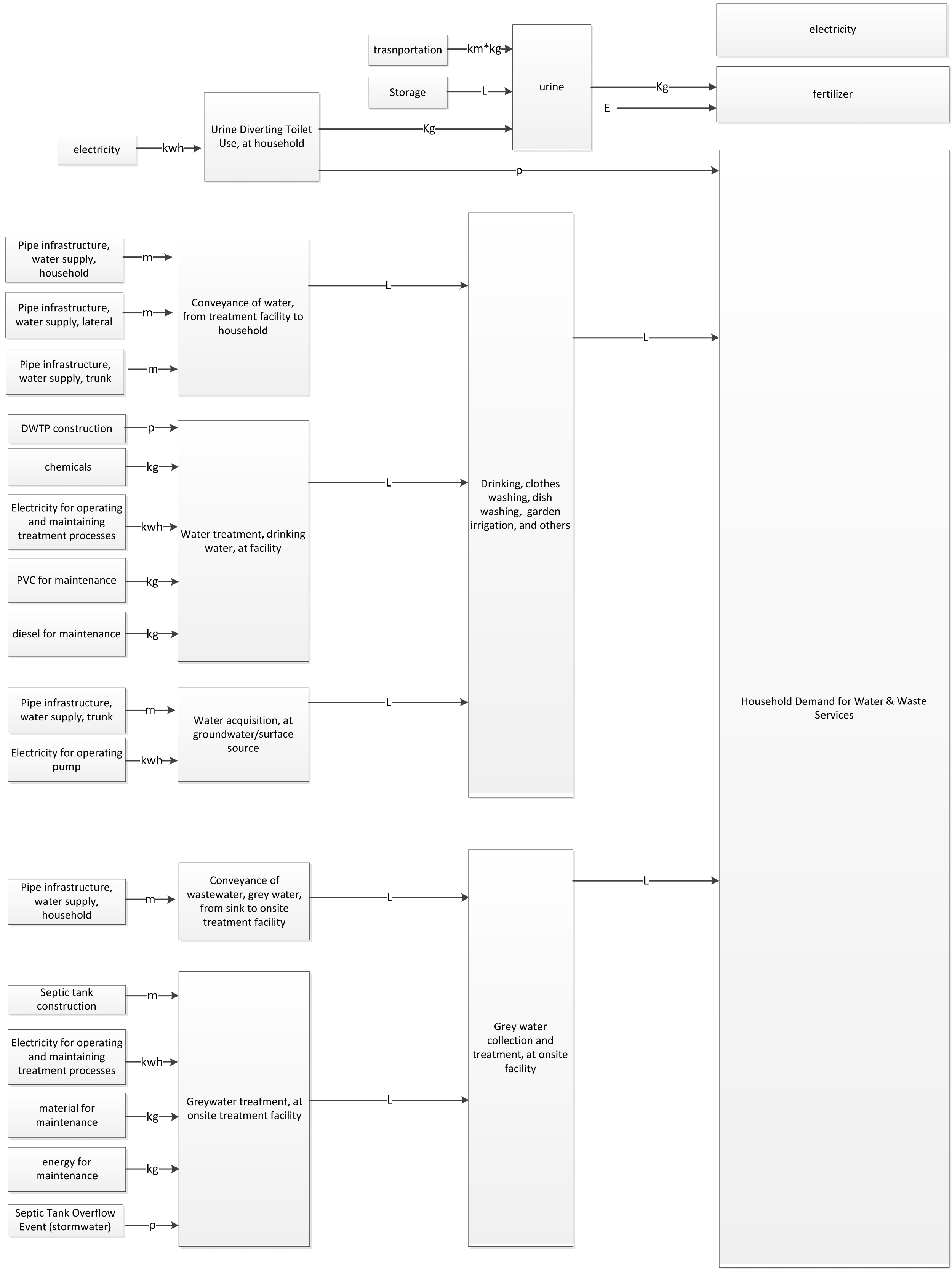
Base case 1: centralized water and wastewater treatment



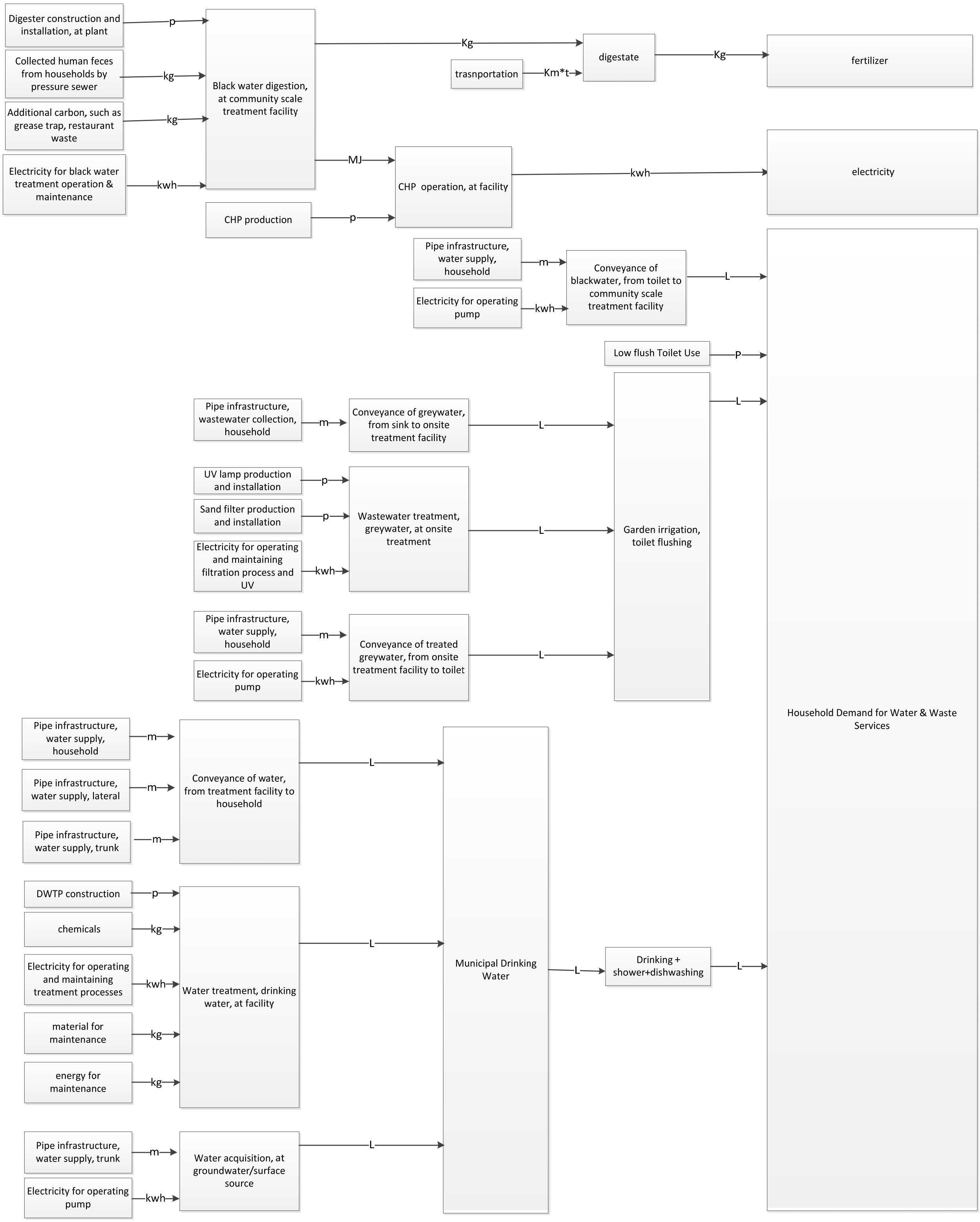
Alternative option 1: composting toilet and grey water treatment via septic tank



Alternative Option 2: urine diverting toilet and grey water treatment via septic tank



Alternative Option 3: Black water, and grey water treatment



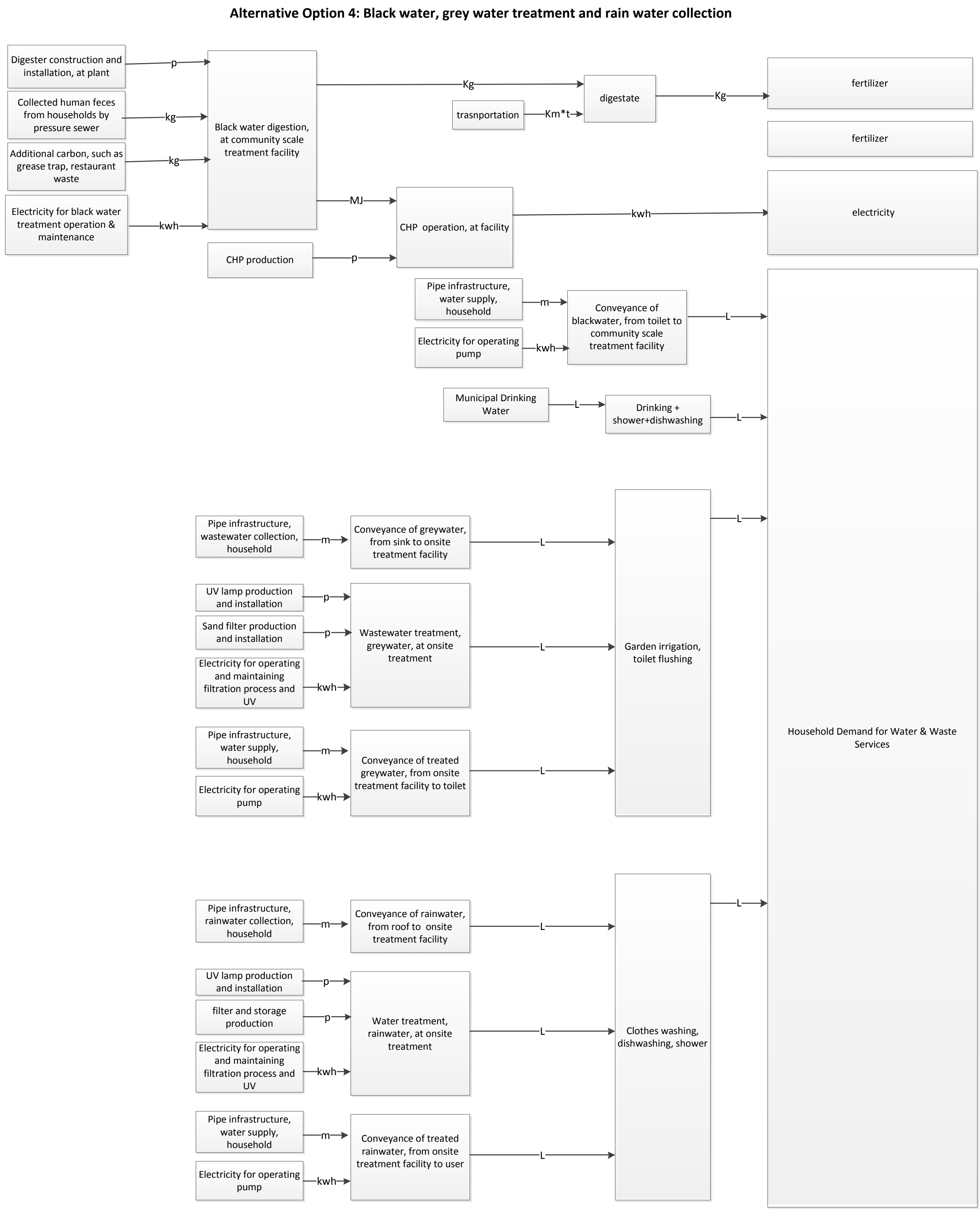


Figure S1. Foreground Unit Processes for Water Systems.

An advantage of using OpenLCA is that the software is freely and publicly available and the datasets developed for this study can be easily transferred to promote transparency and easily updated to incorporate future modeling efforts. With the OpenLCA software package, we created modular unit processes to describe system elements, and connected them with background datasets to represent the full supply chains and life cycle implications and estimated the greenhouse gas and energy use implications of each. A diagram depicting connections between foreground unit processes is included in the S1.

Table S4. Unit processes and utilized data sources.

Unit Processes	Data Sources
Water services including water extraction, treatment and supply	water utility datasets, ecoinvent database, peer-reviewed articles
Composting toilet, low-flush toilet, urine diversion toilet	pilot studies, peer-reviewed articles, product specifics
Blackwater collection, digestion and energy recovery	ecoinvent database, EPA Coeat Model, peer-reviewed articles
Greywater collection, treatment and reuse	ecoinvent database, peer-reviewed articles,
Rainwater harvest and use	ecoinvent database , peer-reviewed articles

Based on consultation with multiple toilet manufacturers (such as Sun-mar and Phoenix), the average electrical load for operating a fan for the composting toilets was 5 $W \cdot d^{-1}$. Low-volume flush toilet use for options BE-GR and BE-GRR (Figure 1) was assume to use 500 $J \cdot flush^{-1}$ (provided for the PropelAirTM) and to be used four times for each of three household members.

For the options utilizing a septic tank (CT-SS, UD-SS, Figure 1), the energy consumption required for pumping and transporting residuals from the household was estimated at 5 $MJ \cdot (year \cdot household)^{-1}$ and 68 $MJ \cdot (year \cdot household)^{-1}$, respectively. The energy estimates for septic tank cleaning and transporting residuals were based on the assumption that a 2500 gallon vacuum truck was utilized to clean a septic tank every 3 years. Additionally, for the annual collection and transport of compost (CT-SS) and urine (UD-SS), the estimated energy consumptions were 440 $MJ \cdot household^{-1}$ for CT-SS and 1280 $MJ \cdot household^{-1}$ for UD-SS. These estimates were based on an adult producing 0.5–2.5 L of urine per adult per day and flushwater volumes of 0.2–0.6 $L \cdot flush^{-1}$. We assumed a 3 m^3 urine storage tank, based on 20 $L \cdot d^{-1}$, 70% of urine collection rate, and 3 months of storage time before collection. Further, we assumed the worst-case for transporting urine and compost up to 200 km from the household to farms where they could be used as soil amendments, given that these products may be transported to a less nutrient sensitive watershed.

For options using decentralized greywater treatment (biological treatment, UV disinfection) and household reuse (pumped to the household for toilet flushing/clothes washing), the energy consumption depended on the type of biological filtration process and head height pressure for reuse within the household. We consulted several manufactures and utilized the likely range (1.44–5.4 $MJ \cdot m^{-3}$) for on-site filtration. Small-scale medium pressure UV lamps were assumed for greywater disinfection, operating at 0.02–0.08 $mJ \cdot m^{-2}$ at 35% of UV light efficiency to reach water quality requirement for toilet flushing. The additional energy required for pumping treated greywater to its destination was estimated based on the flow rate, water pressure, pump and motor efficiencies described in Table S5.

For the rainwater harvesting (BE-GRR, Figure 1) option, we assumed a typical roof area of 90 m^2 with 85% of that area connected to the collection system, 80% reliability of supply with a 3 m^3 rainwater tank (Table S2). The on-site rain water treatment processes include in-line filtration (nominal 20 μm household water filter), household UV disinfection, and pressure distribution of treated rainwater to the hot water heater system. The energy consumption for infiltration and disinfection processes was calculated based on manufacturing and pilot testing datasets. In addition, the energy consumption for redistributing the treated rainwater was estimated according to the pump performance curve of a Grundfos CH2 pump, as adopted for multiple Australian on-site rainwater treatment systems (Table S6).

4. Material Requirements for Treatment Infrastructure

Table S5. Material requirements for the infrastructure.

Material Requirements	Unit	Water and Wastewater Infrastructure					
		Septic Tank	Water Treatment Plant	Wastewater Treatment Plant	Greywater Tank	Rainwater Storage Tank	Digester
Brick	lbs	0	660,000	1,100,000	0	0	0
Concrete	ft^3	530	900,000	1,500,000	350	140	65,000
steel	lbs	66	160,000	270,000	0.66	0.18	1500
Cast iron	lbs	44	88,000	150,000	0.15	0.088	0
Brass	lbs	0.0066	8.8	11	0	0	0
Aluminium	lbs	0.044	52.9	88	0	0	0
Copper	lbs	8.8	13000	22000	0	0	0
Synthetic rubber	lbs	0.0044	6.6	13	0	0	0
Bronze	lbs	0.0088	15	20	0.088	0.022	0
Sand	lbs	600	990,000	1,700,000	18	13	0
PVC	lbs	0	0	0	4.4	3.3	0

The energy used to dig the trenches for water and wastewater infrastructure was estimated according to the evacuation volume and diesel requirement by a John Deere 135G excavator. The associated greenhouse gas emissions were estimated based on diesel consumption and the NONROAD model. The shipping distance for materials from storage to construction sites was assumed to range from 10 to 70 km.

6. Energy Calculation for Onsite Distribution Processes

Table S6. Calculation for energy requirement for greywater distribution from on-site treatment to toilet.

Pump Type	Davey 50Hz
Flow rate	0.057 Gallon/min
Water head	50 ft
Pump efficiency	75%
Motor efficiency	90%
Energy consumption	0.000512 horsepower

Table S7. Calculation for energy requirement for greywater distribution from on-site treatment to toilet.

Pump Type	Grundfos CH2 Pump
Flow rate	0.123 Gallon/min
Water head	50ft
Pump efficiency	75%
Motor efficiency	90%
Energy consumption	0.000768 horsepower

7. Energy and GHGs Calculation for Digestion and Energy Production

This section describes the assumption and data sources which were utilized to calculate the energy and GHGs for digestion and CHP processes under Cape Cod's context. We assumed that the digestion feedstock includes the food waste from all households and local restaurants, and blackwater from residential areas. The assumptions for estimating digestion feedstock are detailed below.

Table S8. Residential Feedstock Availability.

Food Waste Feedstocks	Pounds/Capita/Year
Household Food Scraps—Red Meat	37.01
Household Food Scraps—Poultry	27.26
Household Food Scraps—Fresh and Frozen Fish	3.62
Household Food Scraps—Canned Fish and Shellfish	4.02
Household Food Scraps—Total Tree Nuts	0.31
Household Food Scraps—Eggs	3.49
Household Food Scraps—Total Dairy	44.28
Household Food Scraps—Total Fats, Oils, Greases (FOG)	14.46
Household Food Scraps—Fruit	60.86
Household Food Scraps—Vegetable	84.87
Household Food Scraps—Grains	35.6
Household Food Scraps—Sugars, Honey, Sweeteners	24.3

Table S9. Restaurant Feedstock Availability.

Equation	Number of Employees
Food waste (lbs/year) = N of employees × 3000 lbs/employee/year	1000

Table S10. Parameters utilized to calculate the heat and energy generation.

Parameters	Value	Unit
Food Waste Biogas Yield	6.65	ft^3 CH^4/lb TS
Food Waste Total Solids	30.00%	solids
Food Waste Volatile Solid (VS)	27.90%	of total solids
Food Waste % of Total Waste	1.47%	total substrate
Weighted Total Feedstock Loading (TS)	46,636.50	lbs/day
Weighted Total Feedstock Loading (VS)	13,011.58	lbs/day
Blackwater Solids Mass	1559	short tons/day
Blackwater Solids Yield	2.12	ft^3 CH^4/lb TS
Blackwater Total Solids	3.00%	solids
Blackwater Volatile Solid(VS)	70.00%	of total solids
Blackwater % of Total Waste	98.53%	total substrate
Weighted Total Feedstock Concentration (% TS)	3.4%	solids
Weighted VS Content of Total Feedstock	69%	volatile solids
Biogas Production Rate	15	ft^3 biogas/lb VS destroyed
VS Destruction Efficiency (Food Waste)	80%	
VS Destruction Efficiency (Wastewater Solids)	56%	
Methane to Biogas Ratio	0.6	
High Heat Value of Methane (Btu/cubic foot)	1011	Btu/ft^3

The BE-GR and BE-GRR systems differ from CT-SS and UD-SS in their capability for CHP generation from the source-separated blackwater and food co-digestion components. The energy consumption for black water transport within a pressure sewer was estimated from basic design principles and case studies conducted in Europe. Several reports commissioned by the U.S. Environmental Protection Agency (EPA), Department of Energy, Department of Agriculture, and the State of Massachusetts together with the U.S. EPA's CoEAT model were used to estimate the availability of additional inputs for the bioreactor sourced from household food waste and restaurant grease traps in Falmouth, and the electricity generation capacity of the associated methanogenic digestion and electricity generation processes. Based on blackwater, household waste, and restaurant grease trap residuals, the total daily digester load was estimated at 1.4×10^6 kg·d^{-1} (Table S9). The biogas generation rate was estimated to be 0.75 to 1.12 m^3·kg^{-1} of volatile solid converted. Approximately 10% of biogas produced from co-digestion process was assumed to be used to operate the plant and provide electricity for the associated buildings. We estimated the biogas methane content to be 60%, used 3.5×10^4 kJ·m^{-3} as the heat value of methane gas, and estimated a 55% methane-to-electricity conversion efficiency. To allow for comparison of the systems, the landfilling of restaurant grease trap and household food wastes were included in the functional unit of the BAU, CT-SS, and UD-SS systems. Since the assumptions for collecting and transporting restaurant grease trap and house food wastes were the same for all scenarios, the calculations of collecting and transporting solid waste were not included in the inventory due to the comparison purpose of this study.

8. Material Requirement for Pipe Infrastructure

This section describes the assumption and data sources which were utilized to calculate the energy and material requirements for manufacturing pipes, and piping requirements for municipal water supply, municipal wastewater collection and treatment, black water transport, greywater, and rainwater systems.

Table S11. Pipe requirements for water and wastewater systems at various scales.

System	Scale	Diameter	Unit	Material	Comments
drinking water system	household	1	in	PVC	
				PEX	
		1	in	ductile Iron	
				Galvanized iron	
		0.5–0.75	in	copper	for hot water only
	lateral	6–12	in	PVC	
				HDPE/PE	
				ductile iron	bitumen or cement lining
				cast iron	
	trunk	12–60	in	PVC	
				ductile iron	bitumen or cement lining
wastewater system	household	2-3	in	PVC	
				Galvanized iron	
				cast iron	
	lateral	8–24	in	cement	
				concrete	
				ductile iron	
				PVC	
	trunk	24–80	in	PVC	
				ductile iron	

Table S12. Assumptions for pipe length for water and wastewater systems.

System	Length Assumption		Unit
	Scale	Length	
black water piping	Household	21.8	yard
	Lateral	327	yard
grey water piping	Household	21.8	yard
rain water piping	Household	21.8	yard
municipal drinking water piping	Household	10.9	yard
	Lateral	327	yard
	Trunk	763	yard
municipal waste water piping	Household	21.8	yard
	Lateral	327	yard
	Trunk	763	yard

Table S13. Constitutes of water and wastewater pipes.

Constituents	Pipe Types							
	PVC	Polyethylene	CPVC	PEX	PVC	PVC Cell Core	ABS	ABS Cell Core
PVC resin	92.50%	0	66%	0	92.40%	87.30%	0	0
PE resin	0	0	0	74.30%	0	0	0	0
HDPE resin	0	94.70%	0	0	0	0	0	0
LLDPE resin	0	5.30%	0	0	0	0	0	0
PEX-b compound	0	0	0	25%	0	0	0	0
ABS resin	0	0	0	0	0	0	100%	97.70%
steel	0	0	0	0	0	0	0%	0.00%
ductile iron	0	0	0	0	0	0	0%	0.00%
cast iron	0	0	0	0	0	0	0%	0.00%
concrete	0	0	0	0	0	0	0%	0.00%
copper	0	0	0	0	0	0	0%	0.00%
zinc	0	0	0	0	0	0	0%	0.00%
Chlorine	0	0	18%	0	0	0	0	0
Impact modifier	0	0	6.30%	0	0	0	0	0
Calcium carbonate	4.70%	0	4.20%	0	4.70%	7.90%	0	0
Other additives	2.80%	0	5.50%	0.70%	2.90%	4.80%	0	2.30%
Polyethylene wax	0.56%	0	1.10%	0.14%	0.58%	0.96%	0	0.46%
Paraffin wax	0.56%	0	1.10%	0.14%	0.58%	0.96%	0	0.46%
Titanium dioxide	0.56%	0	1.10%	0.14%	0.58%	0.96%	0	0.46%
Calcium stearate	0.56%	0	1.10%	0.14%	0.58%	0.96%	0	0.46%
Peroxide	0.56%	0	1.10%	0.14%	0.58%	0.96%	0	0.46%

Table S14. Input flows for manufacturing pipes.

		PVC	Polyethylene	CPVC	PEX	PVC	PVC Cell Core	ABS	ABS Cell Core
Electricity	Btu/lbs	473	770	731	1853	343	413	671	340
Transportation, truck	Ton·mile/lbs	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031
Transportation, rail	Ton·mile/lbs	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53
Transportation, ocean freighter	Ton·mile/lbs	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95

The energy consumption for extracting raw materials and manufacturing pipes was estimated from various sources, however, the energy consumption for producing toilets was excluded due to the similarity of material use for the different types of toilets and their negligible influences on comparative life-cycle impacts. More detail regarding the material and construction requirements for the centralized water treatment plant, wastewater treatment plant, on-site septic tank-leach fields, greywater storage and treatment, and rainwater storage and treatment systems is provided in the Supporting Information (Table S4) as well as the life-cycle inventories of pipes and water distribution scenarios (Table S10). In order to estimate the total pipe material requirements, a length-weighted average cross-sectional area was calculated to determine an equivalent average pipe diameter and then multiplied by the total length of the distribution network. The calculations of pipe materials included uPVC, PVC, HDPE, galvanized iron, copper, ductile iron cement lined, and cast iron pipes with various diameters (ranging from 0.5 inch to 60 inches for water pipes, and 2 to 80 inches for wastewater pipes described in Table S11) and fittings following the Plastic Pipe and Fitting Association data provided in the BEES database.

9. Nutrient Contents of Compost, Urine and Digestate

The nutrient contents of greywater, feces, urine and digestate are estimated based on previous lab and field experiments. The table listed the nutrient contents of greywater and fresh excreta. The 5% of nutrient loss is assumed during urine storage. In addition, the bio-availability of various nutrient sources was considered as well. The bio-availability of urine was assumed as 95%. According to Meinzinger, 5% to 15% of the compost nitrogen is plant-available in the first year with releases of 2% to 8% in the following years [4]. The nitrogen bioavailability of digestate is around 78%–80% based on the IEA bioenergy report [5].

Table S15. Nutrient contents of greywater, feces, urine and digestate.

	Greywater	Feces	Urine	Digestate after Black Water Digestion
N lbs/(p·d)	0.0022	0.0033–0.0042	0.019–0.020	
P lbs/(p·d)	0.0011	0.0012–0.0014	0.0019–0.0023	
N lbs/lbs fresh matter				0.0012–0.0091
P lbs/lbs fresh matter				0.0004–0.0026

10. Carbon Intensity of Electricity Sources

Table S16. Carbon Intensity of electricity sources, lb $CO_2/10^3$ BTU electricity [6].

Statics	Bio	Solar-PV	Solar-CSP	Geothermal	hydro	Ocean	wind	nuclear	Natural gas	oil	coal
Min	−409	3	5	4	0	1	1	1	187	329	436
25th	233	19	9	13	2	4	5	5	273	466	567
50th	12	30	14	29	3	5	8	10	303	543	647
75th	24	52	21	37	5	6	13	29	354	586	730
max	48	140	57	51	28	15	52	142	601	756	1091

Table S17. Electricity mix of Falmouth and national average.

	National Electricity Mix	Falmouth Electricity Mix
coal	45%	12%
natural gas	24%	42%
nuclear	20%	30%
hydro	8%	7%
others	3%	9%

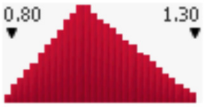
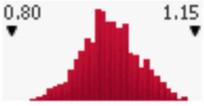
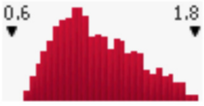
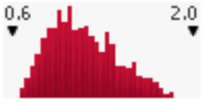
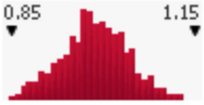
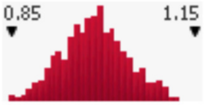
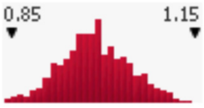
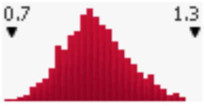
11. Stochastic Distributions of Parameters

Monte Carlo analysis was used to quantify variability and uncertainty of the energy inventory and greenhouse gases emissions. The probability distribution is determined for each independent input parameter relevant with energy consumption of water systems. These input parameters include coagulant usage in municipal water treatment, disinfectant usage in municipal water treatment, disinfectant usage in municipal wastewater treatment, pump efficiency, motor efficiency, UV energy intensity, carbon intensity of electricity from grid, and electricity production from co-digestion. When sufficient datasets present, best-fit probability distributions were simulated for the input parameters. Otherwise, triangle distributions with max, most likely, and min values were assigned for parameters. The distributions of global warming potentials of water systems are functions of input parameters. @Risk software was used to perform the MCA. Anderson Darling sampling methods and 10,000 iterations were used to simulate the stochastic distributions of global warming potentials of water systems.

Table S18. Statistics distributions for inputs parameters.

Inputs	Distribution Type	Min	Mean	Max	5%	95%
water acquisition, pump, efficiency variation factor	Triangular distribution	0.903	1	1.096	0.93	1.07
water distribution from treatment to household, pump, efficiency variation factor	Triangular distribution	0.904	1	1.097	0.93	1.07
treated greywater distribution from treatment to toilet, pump, efficiency variation factor	Triangular distribution	0.902	1	1.1098	0.93	1.07
treated rainwater distribution from treatment to shower head, pump, efficiency variation factor	Triangular distribution	0.903	1	1.098	0.93	1.068
black from toilet to digester, pump, efficiency variation factor	Triangular distribution	0.903	1	1.097	0.93	1.068
greywater treatment without disinfection, energy use	Triangular distribution	0.73	1.66	3.24	0.896	2.73
water treatment, energy use	Triangular distribution	0.805	1.035	1.29	0.87	1.21
rainwater treatment without disinfection, energy use	Triangular distribution	0.78	1.11	1.541	0.87	1.407
rainwater treatment, flow rate variation factor	Triangular distribution	0.927	0.997	1.05	0.945	1.035
water acquisition, pump, flow rate variation factor	Triangular distribution	0.922	0.99	1.05	0.94	1.03
water distribution from treatment to household, pump, flow rate variation factor	Normal distribution	0.922	0.99	1.052	0.945	1.03
greywater treatment, disinfection, flow rate variation factor	Normal distribution	0.923	0.99	1.048	0.943	1.03
treated greywater distribution from treatment to toilet, pump, flow rate variation factor	Normal distribution	0.922	0.99	1.049	0.943	1.03
treated rainwater distribution from treatment to showerhead, pump, flow rate variation factor	Normal distribution	0.922	0.99	1.048	0.943	1.03
blackwater transport, pump, flow rate variation factor	Normal distribution	0.92	0.99	1.048	0.943	1.03
greywater disinfection, UV dose, variation factor	Triangular distribution	0.735	1.180	1.80	0.845	1.60
rainwater disinfection UV dose, variation factor	Triangular distribution	0.736	1.180	1.807	0.846	1.604
Carbon intensity of electricity (national average)	Triangular distribution	0.51	0.67	0.84	0.56	0.80

Table S19. Statistics distributions for outputs parameters.

Outputs	Distribution Type	Min	Mean	Max	5%	95%
water acquisition, energy use variation factor		0.80	1.03	1.29	0.87	1.21
water distribution from treatment to household, pump, energy use variation factor		0.85	0.99	1.13	0.91	1.07
greywater treatment, energy use variation factor		0.73	1.17	1.78	0.84	1.60
rainwater treatment, energy variation factor		0.71	1.17	1.82	0.83	1.60
treated greywater distribution to toilet, energy use variation factor		0.86	0.99	1.13	0.91	1.07
treated rainwater distribution to shower head, energy use variation factor		0.86	0.99	1.12	0.914	1.07
blackwater transport, energy use variation factor		0.85	0.99	1.14	0.912	1.07
water treatment, total electricity, energy use variation factor		0.71	0.98	1.26	0.835	1.15

12. Carbon Intensity of Various System Components

The global warming intensity of each component of the anthropogenic water cycle is represented in Figure S3. The most carbon intensive stage is black water transport via pressure sewer, with average value as 0.06 kg CO_2/L black water. The following carbon-intensive stages are rainwater treatment and grey water treatment, whose average intensities are 0.04 kg CO_2/L rainwater, and 0.035 kg CO_2/L greywater, respectively. In contrast, the lowest carbon intensity occurs in the stage of centralized water treatment and distribution with an average value as 0.018 kg CO_2/L. The intensive energy use of operating grinder pumps for transporting black water from households to the community digester caused its high carbon intensity. It is interesting to note that on-site rainwater collection and treatment is the most carbon intensive option to supply water for households, compared with municipal centralized water treatment and distribution, and onsite greywater treatment and distribution Due to the energy intensive characteristics of both pump operation and UV disinfection, the rain water treatment demonstrated high carbon emissions. Previous studies in Australia and United Kingdom reported that the carbon intensity of rainwater treatment ranges from 0.03 to 0.07 kg CO_2/L treated rainwater, which agrees with our results [7–9].

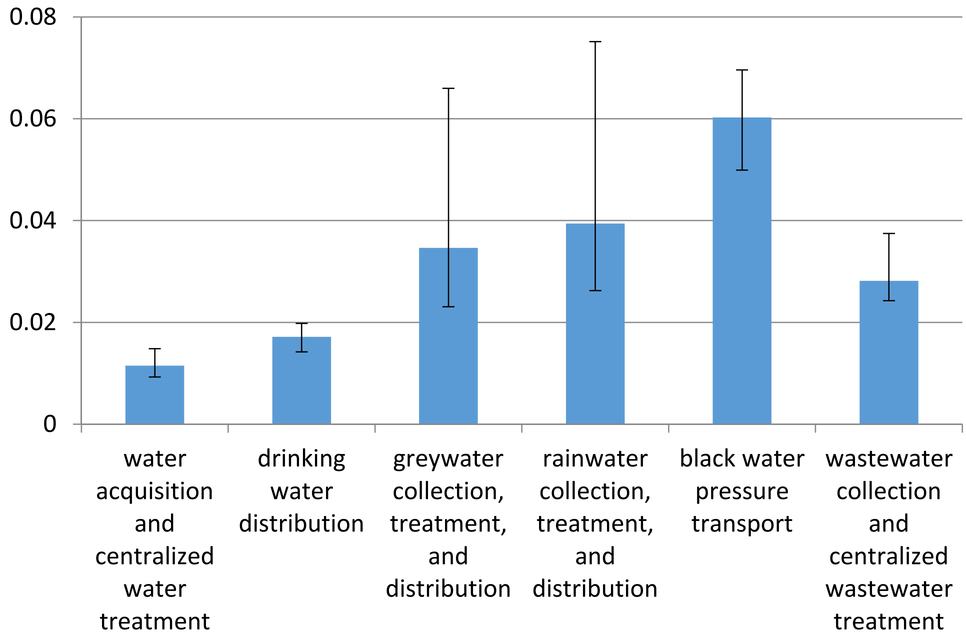


Figure S3. Carbon intensity of various system components, kg CO_2/L.

13. Comparison to Selective Prior Studies

We compared previous studies focusing on either one or few stages of the engineered water cycle with the according stages in this study. Our estimate is close to the range reported by River network [10], which stated that the average value for electricity needed for centralized water supply in the US is 0.38 kwh/m^3 with minimum and maximum values of 0.26 kwh/m^3 and 0.47 kwh/m^3, respectively. The differences between our estimates with other studies [11,12] are resulted from the difference choices of system boundary, life cycle assessment methods, and water treatment technologies. Our results are relatively higher than the embodied energy provided by Mo *et al*. [11,13] and Racoviceanu *et al.* [14], partly due to the different system boundaries selected. While Mo *et al.* [13] included municipal water treatment and distribution and excluded the water extraction; Racoviceanu *et al.* [14] only considered the operation phase of the treatment plant. Besides the influences of system boundary, the estimated embodied energy varies significantly based on different estimation methods used, different raw water qualities and treatment technologies, and different geographical locations. For instance, even the energy embodiments of the similar three water supply options studied by Stokes and Horvath [15,16] and Lyons *et al*. [17] differed by 2 to 4 fold.

Few studied have quantified the energy and global warming potentials of decentralized wastewater treatment elements [18,19]. We compared our studies with studies reported by Remy et al, whose results demonstrated that the separation systems have a life cycle energy demand of 930–1182 MJ/(person·yr) depending on their configuration, which is in accordance with our estimates. In addition, Remy et al reported that the recovered energy and nutrients from co-digestion process nullified around 53% to 70% of the energy consumed during operational stage. This study found that the black water and food co-digestion could recover at least 50% of energy consumed during wastewater treatment, which is approximately the lower bound of Remy's estimates.

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