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LOCATION SPECIFIC TECHNOECONOMIC ANALYSIS AND LIFE CYCLE ASSESSMENT OF AN EMERGING SANITATION TECHNOLOGY

BY

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THESIS

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ABSTRACT

Target 6.2 of the United Nations' 6th Sustainable Development Goal seeks to achieve adequate sanitation services by 2030 for the 2 billion people who currently live without at least basic access. The high cost of constructing centralized wastewater management systems (including collection systems and treatment facilities) often render these options infeasible in resource-limited settings. This study explores the key sustainability drivers, across countries, for a compact, automated sanitation system designed to treat blackwater for onsite reuse. The system has been shown to effectively meet ISO 30500 standards, but its current cost remains too burdensome for low-income households and small communities. Building off a preliminary technoeconomic analysis (TEA) that elucidated specific technological pathways for improvement, this study integrates country-specific parameters into TEA and life cycle assessment (LCA) to investigate how implementation context affects costs, life cycle greenhouse gas (GHG) emissions, and opportunities to improve system sustainability. The study shows that the drivers of both price and environmental impacts are context-dependent, with electricity acting as the major cost and GHG contributor in most locations. Cost and GHG emissions across countries are not correlated. Accordingly, the prioritization of research and development to improve technology sustainability will depend on the planned location of implementation.

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CHAPTER 1: INTRODUCTION

There are 2 billion people on the planet that live without basic sanitation, resulting in nearly 1 million preventable deaths per year.[1,2] Improving global sanitation practices could help reduce mortality,[3] enhance cognitive development in children,[4] and decrease the risk of assault that women and children face when they must walk to a distant toilet or resort to open defecation.[5] To address the pressing need for safely managed sanitation facilities, several different types of non-sewered sanitation technologies have been designed and continue to be developed (e.g., single and multi-user toilets with onsite treatment, Omni Processors that treat fecal waste). While researcher continues to advance the performance and design of each individual technology, local conditions such as electricity access and market prices may drive the appropriateness of the various technologies.

Centralized wastewater collection and treatment is often viewed as the most efficient solution to sanitation, but the high costs associated with these systems can make them infeasible for many developing communities[3]. Even if centralized treatment were to become affordable, the disparities in some developing communities (e.g., informal settlements) between inconsistent land tenure and fixed collection infrastructure (e.g., sewers) can make centralized systems particularly challenging to implement.[6] Furthermore, wastewater treatment is a major global energy consumer, and the demand is expected to increase by 30% in the next decade.[7,8] Therefore, rethinking wastewater treatment via the implementation of water reuse process and decentralized treatment could greatly reduce global warming potential.[9]

Septic tanks and pit latrines have historically been perceived as plausible alternatives to centralized treatment; however, they can lead to groundwater contamination and are impractical in densely populated urban areas where collection trucks cannot reach some households to remove waste.[10,11,12] Decentralized sanitation systems with onsite treatment is another effective class of technologies. Small-scale onsite treatment facilities can be installed at low cost, facilitate resource recovery, and safely treat waste in rural areas where houses are too far apart to be connected with a sewer system or in regions lacking existing sewer infrastructure.[13] Decentralized waste treatment is considerably cheaper than centralized systems,[14] and the feasibility of separating yellow, black, and gray water creates the opportunity for nutrient and energy recovery from separated and concentrated streams.[15]

The Duke University Center for WaSH-AID designed a decentralized system capable of providing onsite treatment of liquid waste. Urine and flush water, separated via a solid/liquid separator, are pumped through an ultrafiltration membrane for preliminary chemical oxygen demand (COD), suspended solids, nutrient (nitrogen and phosphorus), and pathogen removal. Granular activated carbon and zeolites are then used to further remove COD and nutrients. Finally, the liquid is disinfected via an electrochemical cell and can be reused as flush water. The system has been the potential meet ISO liquid effluent standards,[16] but the total system cost predicted by a preliminary technoeconomic analysis (TEA)[17] is about $\$0.17 \cdot \text{user}^{-1} \cdot \text{day}^{-1}$, representing nearly 10% of total income for a person living at the international poverty line ($\$1.90 \cdot \text{day}^{-1}$).[18] A few adjustments have been made to the original design of the system in accordance with the findings from that initial TEA (e.g., reduced pump size, increased GAC replacement period); however, location-specific cost drivers (e.g., electricity price, diet, labor) represented a large source of uncertainty. Location specific parameters cannot be changed through technology design, but they should be furthered investigated to better understand how they will impact system outcomes.

The objective of this study was to estimate how implementation location will impact financial viability and environmental impacts of the non-sewered sanitation system. The analysis was conducted across 89 countries, using location specific data (e.g. price level ratio (PLR), labor wages, electricity price, diet, income tax) as inputs into a TEA and life cycle assessment (LCA) framework. This study was designed to identify overarching trends across a diverse set of countries, rather than precisely estimate the impacts within a specific country. Therefore, the data used within the study represents country averages. This analysis can provide a general sense for the cost and environmental impacts of a given sanitation technology with respect to different contextual characteristics. The identified trends can pinpoint locations where conditions may be most conducive to the implementation of a specific technology, and further analysis can be conducted to develop more precise estimates. The findings of this work will be used to inform the development and deployment of Duke's Center for WaSH-AID's treatment system, as well as investment in similar decentralized treatment technologies.

CHAPTER 2: BACKGROUND

2.1 Challenges of Centralized Sanitation Systems

Centralized waste treatment systems are commonly viewed as the ideal endpoint sanitation solution; however centralized sanitation has several shortcomings that makes it infeasible in some contexts. The implementation of centralized treatment systems is nearly impossible in rural areas with low population densities[19] that do not have preexisting sewer infrastructure.[20] Even in many urban areas, inconsistent land tenure makes centralized treatment systems infeasible.[6] Furthermore, wastewater treatment is a major global energy consumer, and the demand is expected to increase by 30% in the next decade.[7,8] Therefore, rethinking wastewater treatment via the implementation of water reuse processes and decentralized treatment could greatly reduce global warming potential.[9] Due to the cost burden associated with the installation of centralized (sewer based) waste treatment systems, decentralized treatment systems may be a better option in some developing communities. Septic tanks and pit latrines have historically been perceived as plausible alternatives; however, they are impractical in densely populated urban areas where collection trucks cannot reach some households to remove waste. In this case, maintenance workers are forced to empty the systems manually, endangering both workers and users by increasing the opportunity for pathogen exposure.[11,12] Container based sanitation (CBS), which is "semi-centralized" (decentralized onsite storage and centralized treatment) and fully decentralized systems (onsite waste treatment) are two possible alternatives. Modern CBS systems are dry toilets with removable containers that use dry organic materials and locally available additives to contain waste and suppress odor.[21] Relative to septic tanks and pit latrines, CBS systems require a smaller upfront investment and are more portable, making them attractive to households that may choose or be forced to move.[22] Decentralized sanitation systems with onsite treatment is another effective class of technologies. Small-scale onsite treatment facilities can be cheaply installed, facilitate resource recovery, and safely treat waste in rural areas where houses are too far apart to be connected with a sewer system or in regions lacking existing sewer infrastructure.[13] Even after factoring in the cost of fecal sludge management, the total cost of semi-centralized or decentralized waste treatment is typically cheaper than centralized systems.[14] Furthermore, decentralization makes the separation of yellow, black, and gray water more feasible, creating the opportunity for nutrient and energy recovery from separated and concentrated streams.[15]

2.2 Reinvent the Toilet Challenge

In an effort to meet the UN's Millennium Development Goal to achieve universal access to safe sanitation facilities,[23] the Bill and Melinda Gates Foundation initiated the reinvent the toilet challenge. Through the challenge, the Gates Foundation pledged to fund the development of select sanitation technologies that meet the following criteria: 1. removes harmful pathogens and recovers resources (e.g. nutrients, electricity, treated water) from waste, 2. operates without grid electricity, 3. is universally affordable (less than $0.05 per user per day), 4. creates a sustainable business for local residents, and 5. appeals to users.[24] Funding was allotted to over fifteen research institutes over the course of three years. As a result, a variety of innovative waste treatment technologies have been developed over the last decade. The Reclaimer, a single unit decentralized liquid treatment system uses ultrafiltration, granular activated carbon, and electrochemical disinfection to treat waste so it can be reused as flush water.[25] The Eco-San, a multi-user decentralized toilet, uses anaerobic digestion and electrolysis to treat waste and recover water and nutrients.[26] The Janicki Omni-Processor, a centralized treatment system that uses a Rankine cycle to treat waste while recovering water, nutrients, and energy from local toilets that are not equipped with onsite treatment such as CBS systems.[27]

2.3 International Standards for Non-Sewered Sanitation Systems

To achieve the treatment goals set forward in the Reinvent the Toilet challenge, innovative systems should be designed to conform to ISO Standards 30500 for non-sewered sanitation. Non-sewered sanitation systems should provide adequate treatment of feces, urine, menstrual blood, bile, flush water, anal cleansing water, and toilet paper.[28] If the treated effluent is intended for direct reuse via handwashing or anal cleansing, the treatment requirements are more stringent.[29] For the treatment of microorganisms and parasites, a concentration limit or minimum log-reduction value must be met. The concentration limits for pathogens, viruses, helminths, and protozoa are 100 CFU/MPN, 10 PFU, <1, and <1 respectively, while the minimum log removal value for each class is 6, 7, 4, and 6 respectively. The maximum chemical oxygen demand (COD) and total suspended solid (TSS) concentrations in the effluent are ≤ 50 mg/L and ≤ 10 mg/L for unrestricted urban use or ≤ 150 mg/L and ≤ 30 mg/L for systems that discharge into surface water. International standards require a minimum load reduction of 70% and 80% for total nitrogen and total phosphorus respectively. A pH between 6-9 must be maintained throughout the entire treatment process.

2.4 Reclaimer

The Duke University Center for WaSH-AID designed the Reclaimer (Figure 1), a sanitation system that facilitates onsite liquid waste treatment in accordance with ISO 30500 standards and has the potential to meet the goals outlined in the Reinvent the Toilet Challenge. The original design consisted of a solid/liquid separator that removed up to 86% of the influent TSS. The separated liquid entered a series of settling tanks before undergoing electrochemical disinfection. The treated effluent was then reused for flush water. Lab testing revealed an incremental increase in the energy required for disinfection in consecutive treatment cycles likely due to solids accumulation and an unpleasant color and odor in the treated effluent.[30] A Granular Activated Carbon (GAC) column was introduced to reduce the energy requirement of the treatment process and boost user acceptability.[31] Studies showed that the decreased energy demand was due to the reduction of soluble COD, but GAC was only capable of removing half of the COD present in the blackwater.[32] Therefore, an ultrafiltration membrane was added to enhance COD removal and further decrease the energy required for electrochemical disinfection.[25] The treatment design has worked effectively in South Africa and India.[33,34] Clinoptilolite and Polonite, zeolites capable of removing ammonia and phosphate, have recently been added to the system to meet the ISO 30500 nitrogen and phosphorus removal requirements.[16] Lab testing indicates that the zeolites can meet phosphorus and nitrogen removal requirements.

Figure 1. *The following elements are highlighted in the image of the Duke Center for WaSH-AID liquid waste treatment system: 1. Ultrafiltration pump 2. Ultrafiltration membrane 3. GAC column 4. Electrochemical cell 5. Controls system*

2.5 Reclaimer Technoeconomic Analysis

At this point, the cost of the Reclaimer is too high to be implemented in developing communities that need it most. Therefore, a techno-economic analysis (TEA), the process of valuing the performance of a given technology in conjunction with the economic implications to the assess its financial viability, was performed on the Reclaimer. The valuation highlights areas for future research and development.[35] TEA is a widely used methodology which has been used to quantify the cost of decentralized waste treatment and aid in the development of cost effective sanitation solutions. For example, TEA was used to quantify the cost of a multi-effect distillation plant that could treat brackish water, making it suitable for irrigation purposes. Results from the TEA suggest the most effective way to reduce treatment cost is to optimize the capital costs associated with the installation of the plant and the solar field used to power the plant. Increasing the treatment capacity of the plant was also shown to reduce the unit cost of treatment.[36] TEA of a solar powered desalination plant showed that energy was the main cost driver. Because areas dealing with water scarcity typically receive a lot of sunlight, solar energy is a plausible energy source; however, the cost of solar electricity is high relative to alternative sources. Costs associated with solar energy have steadily declined over the past decade and will likely continue to do so, making a solar powered desalination plant an economical water treatment solution in the future.[37]

A preliminary TEA has been performed on the Reclaimer, demonstrating the high cost of the ultrafiltration system (driven by an oversized pump) and the importance lengthening the GAC replacement period.[17] This analysis was characterized by a large degree of uncertainty, particularly for location specific parameters like electricity cost and labor wages. An enhanced TEA is necessary to reflect technological improvements that have been made by the design team since the preliminary analysis and to more accurately predict major cost drivers using refined location specific data.

2.6 Reclaimer Life Cycle Assessment

The environmental impacts of the Reclaimer were measured using life cycle assessment (LCA), a tool used to quantify the environmental implications of a given system. Performing a LCA helps to identify areas in which the system needs improvements to reduce the overall environmental impacts and shows how impactful a given system will be to the surrounding environment, enabling informed decision making. LCA is broken up into four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation. The boundary of the analysis is established in the goal and scope definition phase. Within the inventory analysis phase, the impacts of the individual components within the system boundary are quantified and input into the process model to calculate the overall system impact in the impact assessment phase. The total impacts are assessed in the interpretation phase using metrics relevant to the particular study (e.g. global warming potential, eutrophication potential, etc.).[38] LCA has been used by researchers in a variety of ways to assess the environmental impacts of waste treatment systems. In an LCA comparing a decentralized waste treatment system that facilitates water reuse to a centralized wastewater treatment plant (WWTP), the decentralized option was shown to have the potential be more environmentally favorable. This was the case when considering water reuse in both systems and an anerobic digestor with gas caption was added to the decentralized system.[39] Another study conducts a comparative analysis of existing WWTP in developing communities using LCA to determine how to reduce the environmental footprint of systems installed in the future. Results showed that direct gas emissions and energy consumption are the largest contributors to overall global warming impacts. To minimize environmental impacts, treatment systems should incorporate water reuse and anaerobic digestion into the activated sludge process.[40] Included in the scope of the Life Cycle Assessment performed on the Reclaimer are the impacts associated with construction materials, energy, GAC media, and zeolite media.

CHAPTER 3: METHODS

TEA and LCA are conducted to link the performance of the treatment system to life cycle costs and environmental impacts, which are compared across different countries. The model tracks the performance of each unit process within the system, including ultrafiltration (UF), granular activated carbon (GAC)/Zeolites, electrochemical cell (EC) disinfection, controls, and other miscellaneous items. Inputs used to generate the TEA and LCA model include data from field tests (GAC lifetime, EC power requirement, etc.), values that are fixed by the system design and/or product specifications (membrane surface area, GAC volume, etc.), and assumptions from literature (daily flushes per user, etc.) (Tables 1-7). Country specific data was collected for five key parameters (PLR, labor cost, electricity price, diet, income tax) to generate location-specific results (Tables 8-9). Only countries with values for all five parameters were included in the study (89 countries).

Material costs and environmental impacts were calculated using the prototype system's bill of materials (Table 14). Price adjustments were made to several items listed in the original bill of materials (Table 15) to reflect anticipated cost reductions from recent technological improvements (e.g. replacing the current pump with a smaller one). Construction materials were separated into two categories: specialized items purchased from global suppliers (using data from vendors in the United States) and other items made from widely available materials that can be purchased where the technology is deployed. The country-specific costs (in USD) of locally-purchased materials are assumed to follow general trends captured by the Price Level Ratio (PLR), which reflects differences in the general prices of goods across countries.[41] The PLR is the ratio between a country's Purchasing Power Parity (PPP, units of local currency per US dollar) and its market exchange rate (relative to US dollars). PPP is an exchange rate like the market exchange rate; however, it also considers the quantity of goods the currency can purchase locally. If PPP is higher than the market exchange rate (PLR > 1), goods cost more in the country of interest than they do in the US. The environmental impact of transporting items that could not be purchased locally was determined using the weight of transported products and both nautical and land transport distances.[42,43]

Labor costs are calculated using occupation specific estimates for monthly wages in each country and estimates of construction and maintenance time and frequency based on the design team's experience.[44] We used wages for the construction and water, sewage, and waste enterprises to represent construction and maintenance wages, respectively. To estimate electricity cost in each country, the average unit price of electricity was gathered from Price Petrol. Values from Price Petrol were compared with classified IEA data to ensure consistency.[45] We used protein consumption data in each country to estimate nutrient concentrations in excreta, which determined the mass of zeolites required for nutrient removal.[41] A country average income tax value was used to calculate the breakeven point in the cost analysis.[41]

With the inclusion of ion exchange media (e.g. zeolites) the technology is capable of meeting ISO liquid effluent standards**,** so we modeled the system based on the operating parameters provided by the design team, assuming the system achieves adequate treatment (S1.1-S7.6). The ultrafiltration unit was modeled, assuming the system was running at steady state with minimal losses, setting the liquid leaving the system as permeate flow equal to the inflow. To scale operation cost relative to the number of users, we estimated the volume of liquid waste generated from a single user (urine excretion plus flush water) and determined the membrane area required to treat the influent generated by a given number of users. In some cases (i.e. when the number of users exceeds about 10), an additional membrane had to be added for adequate treatment. Using parameters listed in the membrane specifications and provided by the design team, we calculated the pump head needed to achieve the required feed flow rate (Table 1). We selected a pump size that could supply the calculated pump head and calculated the cost of the energy demanded by the selected pump.

To model the cost of operating the GAC/zeolite system, we calculate how much of each media is needed for COD and nutrient removal. In the absence of the ultrafiltration system and without stretching the GAC media to the point of failure, GAC could treat about 4500 L of blackwater.[34] For the full system with ultrafiltration in place, we estimated the GAC replacement period to be three times that seen in field tests when stretched to the point of failure. Knowing the volume of GAC within the column, the GAC density, and the liquid flowrate, we determined the costs of the required GAC mass and column length. We then estimated the nitrogen and phosphorus concentrations in the influent based on protein consumption and calculated the cost of zeolites needed to remove it based on measured zeolite capacities (Table 2).[46]

We based our modeling of electrochemical treatment on the typical power requirements for treatment in field testing (Table 3). We used this value to calculate the energy costs associated with running the EC cell based on the time needed to treat each batch and the daily number of batches.

The daily power requirement provided by the design team was used to compute the operational cost of the controls system, which handles the timing and operation of the system (Table 4). The cost of operating the final effluent discharge pump was lumped into the miscellaneous cost category and quantified using the number of batches run by the electrochemical cell and the pump specifications (Table S5).

A discounted cashflow analysis was used to integrate the various types of system costs. A discount rate (or interest rate on a loan) was applied to each cost (e.g. materials, labor, operation) and revenue stream (user fees) to account for the diminishing value of money over time. The overall system cost was calculated in terms of the minimum daily fee users would need to pay to cover all expenses over the course of the system's lifetime.[47]

The scope of the LCA includes impacts from construction materials, GAC media, zeolite media, transportation, and electricity. The environmental impacts were calculated for construction materials, using the mass of each item (Table 14) and the unit impact of the raw material(s) and process(es) used to produce the item (Table 12). Impacts of GAC and zeolite media were quantified from the mass required for treatment and the unit impacts associated with each media (Table 13). The mass of transported goods and estimated sea and land transport distances were used to calculate the transportation impacts. The environmental impact of the electricity required to operate the treatment system was calculated using each country's electricity mix (Table 10-11) and the associated unit impacts for each electricity source (Table 13).[48]

Construction equipment was excluded from the scope of the analysis because the system is small (about 1x0.5x2m), it does not require underground installation, and equipment could be reused for multiple systems. Our transportation calculations (described previously) revealed that impacts were negligible relative to other categories, so we removed them from our analysis for simplicity. As one example, in Ethiopia, in the location where energy impacts are lowest, transporting the 0.25 tonnes of materials that cannot be purchased locally over 2.5 billion nautical km (i.e., circling the globe more than 70 times) would still represent only 5% of the environmental impacts of energy.

The environmental impacts of each component included in the analysis were calculated using values from the ecoinvent database using SimaPro v8.5.2.0.[49] TRACI (2.1 v1.03) was selected among other LCA methodologies to estimate climate change impacts. Among other environmental impacts, TRACI provides results in terms of global warming potential (GWP) (kg CO_2 eq. per user per day).[50]

Due to the potential variability of testing and implementation conditions, the second stage of the process employed a full uncertainty analysis to estimate the range of possible economic and environmental outcomes. Each uncertain parameter was included in the model as a range, encompassing the most probable values for the given parameter, rather than as a single value. The model was run 100 times for each country, selecting a unique value from each input range for every run, using Latin hypercube sampling to generate ranges of outputs that encompass the likely costs and environmental impacts of the system.[51] From the 1,000 outputs, the median cost and GWP values in each country were used for comparison. A multiple linear regression analysis was performed to quantify the degree to which costs were correlated with each country-specific parameter. We did not perform a multiple linear regression to analyze LCA results because only the impacts of zeolite media and electricity vary across countries, and the variance in zeolites is menial relative to that of electricity. We did perform an additional multiple linear regression analysis to gauge the relationship between electricity price and different energy sources within the electricity mix. To further illuminate economic and environmental trends across countries, we grouped countries using several World Bank indicators (e.g. income level, region, human development index), and performed Kruskal Wallis tests followed by Dunn’s tests to determine if there was a statistical difference between cost and environmental impacts in each group.

Because the precise use scenario (e.g., liquid influent from one small household or from multiple households, etc.) and system’s lifetime are unknown but critically important, a separate sensitivity analysis was conducted to determine the quantitative effects of changing these parameters while setting uncertain parameters at their median values. The number of users was varied in increments of five from 5-20 to represent different use cases and evaluated under four different lifetime scenarios (5,10,15, 20 years). When the number of users decreased from 20 to 5, the required daily user fee increased by $0.78 (205%). When the system lifetime was decreased from 20 to 5 years, the required daily user fee increased by $0.35 (43%). The lowest daily user fee ($0.31) resulted when both the number of users and the system lifetime were set to their highest values (20 users, 20-year lifetime), which were the assumed parameters in all other modeling activities in this study.

***Table 1.** The fixed parameters (FP) and uncertain parameters (UP) used to model the UF unit process are listed. Fixed parameters are assigned an exact value because they cannot vary due to design and/or product specification. The exact value for uncertain parameters is unknown, so a range is specified to encompass the most probable value.*

	Parameter	Unit	Value(s)	Distribution	Type	Justification/ Reference(s)
F	Daily flushes	flushes·user^{-1}·day^{-1}	1-7	Uniform	UP	1 assumes flush solids only, 7 assumes flush solids and liquids[52]
V_F	Flush volume	L·flush^{-1}	6-10	Uniform	UP	Assumption
A_{MS}	Membrane surface area	m^2	0.07		FP	Membrane specs
J	Membrane Flux	L·m^{-2}·h^{-1}	114-171	Uniform	UP	Multiply experimental flowrate (8-12 L/h) by membrane surface area (0.07 m^2)
v_c	Crossflow velocity	m·s^{-1}	3.5-5.6	Uniform	UP	Membrane specs
ID	Internal membrane diameter	mm	12.77		FP	Membrane specs
TMP	Transmembrane pressure	bar	0-3.5	Uniform	UP	Membrane specs

Calculate the required permeate flowrate, assuming pump is running continuously (24hr/day)

$$Q_p = Q_{users}$$

(Equation 1.1)

Calculate the daily liquid input

$$Q_{users} = F * V_F * U$$

(Equation 1.2)

Calculate the membrane area needed to achieve the required daily flowrate

$$A_M = \frac{Q_P}{J}$$

(Equation 1.3)

Determine the number of membranes needed to reach the calculated membrane area

$$M = \frac{A_M}{A_{MS}}$$

(Equation 1.4)

Calculate the permeate flowrate for each membrane

$$Q_{PM} = \frac{Q_P}{M}$$

(Equation 1.5)

Calculate the concentrate flowrate for each membrane

$$Q_{CM} = \frac{\pi}{4}(ID)^2 * v_c$$

(Equation 1.6)

Calculate the feed flowrate (water that must be fed through the pump)

$$Q_F = (Q_{PM} + Q_{CM}) * M$$

(Equation 1.7)

Determine the smallest pump (hp) needed to achieve the TMP using best fit equations from the pump curves (Circulation-Pump-Specifications)

$$Head = m(Q_F) + b$$

(Equation 1.8)

Calculate the energy demand from the ultrafiltration system

$$E_{UF} = hp$$

(Equation 1.9)

Table 2. *The fixed parameters (FP) and uncertain parameters (UP) used to model the GAC/zeolite unit process are listed.*

	Parameter	Unit	Value(s)	Distribution	Type	Justification/ Reference(s)
D_C	GAC column diameter	in	4		FP	Measured
V_{GAC}	GAC volume	L	7.7		FP	Assumption
FF	GAC fill fraction	%	75-85	Uniform	UP	Assumption
ρ_{GAC}	GAC density	$kg \cdot m^{-3}$	400-500	Uniform	UP	[53]
L_{GAC}	GAC lifetime	L	4500, 9000, 13500	Triangular	UP	GAC treated 4500 L of blackwater in the field without failing before UF system is added
N_U	Percent of excreted nitrogen in urine	%	86[±10]	Triangular	UP	[54]
P_U	Percent of excreted phosphorus in urine	%	67[±10]	Triangular	UP	[54]
Pr	Protein consumption	$g \cdot person^{-1} \cdot day^{-1}$	Table 8	Triangular	UP	[55]
Pr_A	Animal protein consumption	$g \cdot person^{-1} \cdot day^{-1}$	Table 8	Triangular	UP	[55]
Pr_V	Vegetal protein consumption	$g \cdot person^{-1} \cdot day^{-1}$	Table 8	Triangular	UP	[55]
p_N	Nitrogen content in protein	%	13-19	Uniform	UP	[56], [57]
p_{PA}	Phosphorus content in animal protein	%	0.2,2.2,4.8	Triangular	UP	[56], [58]
p_{VA}	Phosphorus content in vegetal protein	%	0.2,1.1,3.2	Triangular	UP	[56], [58]
W	Household Waste	%	Table 8	Triangular	UP	[59]
ex	Percent of nitrogen and phosphorus intake excreted	%	99-100	Uniform	UP	[60], [61]

Table 2 cont

	Parameter	Unit	Value(s)	Distribution	Type	Justification/ Reference(s)
ε	Solid/liquid separator efficiency	%	80-90	Uniform	UP	Assumption
r	Percent nitrogen and phosphorus removed from UF and GAC	%	30-50	Uniform	UP	Assumption
r_c	Clinoptilolite removal capacity	mg N·g^{-1}	10[±10%]	Uniform	UP	Measured
r_p	Polonite removal capacity	mg P·g^{-1}	10[±10%]	Uniform	UP	Measured

Determine the required GAC column volume

$$V_C = \frac{V_{GAC}}{FF}$$

(Equation 2.1)

Calculate the required GAC column length

$$L_C = \frac{V_C}{\frac{\pi}{4}(D_C)^2}$$

(Equation 2.2)

Calculate the GAC mass in the column

$$m_{GAC} = V_{GAC} * \rho_{GAC}$$

(Equation 2.3)

Calculate the GAC replacement period

$$R_{GAC} = \frac{L_{GAC}}{Q_P}$$

(Equation 2.4)

Calculate the annual required GAC mass

$$GAC = \frac{m_{GAC}}{R_{GAC}}$$

(Equation 2.5)

Calculate the nitrogen concentration in the influent

$$C_N = (Pr * p_N * (1 - W) * ex) * \left(N_U + \left((1 - \varepsilon) * (1 - N_U)\right)\right)$$

(Equation 2.6)

Calculate the phosphorus concentration in the influent

$$C_P = (((Pr_A * p_{PA}) + (Pr_V * p_{PV})) * (1 - W) * ex) * \left(P_U + \left((1 - \varepsilon) * (1 - P_U)\right)\right)$$

(Equation 2.7)

Calculate the mass of clinoptilolite needed to remove nitrogen

$$m_c = \frac{C_N * (1 - r)}{r_c}$$

(Equation 2.8)

Calculate the mass of polonite needed to remove phosphorus

$$m_P = \frac{C_P * (1 - r)}{r_P}$$

(Equation 2.9)

Table 3. *The fixed parameters (FP) and uncertain parameters (UP) used to model the EC unit process are listed.*

	Parameter	**Unit**	**Value(s)**	**Distribution**	**Type**	**Justification/ Reference(s)**
V_{EC}	EC tank volume	Gal	5		FP	BOM
P_{EC}	Power required for EC treatment	$Wh \cdot L^{-1}$	5.6-6.4	Uniform	UP	Assumption
V	EC cell voltage	V	12		FP	Measured
I	Electric current in treated influent	A	4,4,8	Triangular	UP	Assumption
P_S	Power required for mixer	W	18-30	Uniform	UP	Assumption

Calculate the number of batches needed to disinfect the daily influent

$$B = \frac{Q_P}{V_{EC}}$$

(Equation 3.1)

Determine the time required for each batch

$$t_B = \frac{P_{EC} * V_{EC}}{V * I}$$

(Equation 3.2)

Calculate the energy demand for the EC system

$$E_{EC} = [(I * V * B * t_B) + (P_S * B * t_B)]$$

(Equation 3.3)

Table 4. *The fixed parameters (FP) and uncertain parameters (UP) used to model the controls system are listed.*

	Parameter	**Unit**	**Value(s)**	**Distribution**	**Type**	**Justification/ Reference(s)**
P_C	Power required for controls system	W	25		FP	Measured

Calculate the annual energy demand for the Controls system

$$E_C = P_C$$

(Equation 4.1)

Table 5. *The fixed parameters (FP) and uncertain parameters (UP) used to model the operation of miscellaneous components are listed.*

	Parameter	Unit	Value(s)	Distribution	Type	Justification/ Reference(s)
Q_D	Discharge flowrate	$L \cdot min^{-1}$	8-16	Uniform	UP	Assumption
V_D	Discharge pump voltage	V	12		FP	Pump specifications
I_D	Discharge pump current	A	6		FP	Pump specifications

Calculate the discharge pump run time

$$t_D = \frac{V * B}{Q_D}$$

(Equation 5.1)

Calculate the annual energy demand for the discharge pump (miscellaneous)

$$E_M = V_D * I_D * t_D$$

(Equation 5.2)

Table 6. *The fixed parameters (FP) and uncertain parameters (UP) used to model system costs are listed.*

	Parameter	Unit	Value(s)	Distribution	Type	Justification/ Reference(s)
i	Interest rate	%	3-6	Uniform	UP	[62]
PLR	Price level ratio		Table 9	Triangular	UP	[41]
w_c	Monthly construction wage	$\$\cdot\text{month}^{-1}$	Table 9	Triangular	UP	[63]
w_m	Monthly maintenance wage	$\$\cdot\text{month}^{-1}$	Table 9	Triangular	UP	[63]
W_m	Work days per month	$\text{days}\cdot\text{month}^{-1}$	20-25	Uniform	UP	Assumption
t_c	Construction time	days	2-4	Uniform	UP	Assumption
t_m	Maintenance time	days	0.25-1	Uniform	UP	Assumption
f_M	Maintenance frequency	$\text{days}\cdot\text{year}^{-1}$	1-2	Uniform	UP	Assumption
t	Income tax	%	Table 9	Triangular	UP	[41]
U_E	Electricity price	$\$\cdot\text{kWh}^{-1}$	Table 9	Triangular	UP	[45]
U_{GAC}	GAC price	$\$\cdot\text{kg}^{-1}$	0.29-1	Uniform	UP	Assumption
U_c	Clinoptilolite price	$\$\cdot\text{kg}^{-1}$	1.08[±10 %]	Uniform	UP	Assumption
U_p	Polonite price	$\$\cdot\text{kg}^{-1}$	1.37[±10 %]	Uniform	UP	Assumption

Start with a basic cost equation

$$Profit = Income - expenses - tax$$

(Equation 6.1)

Calculate the discount rate

$$d = \frac{1}{(1+i)^L}$$

(Equation 6.2)

Adjust for the decreasing value of money over time

$$d * Profit = d * (Income - expenses - tax)$$

(Equation 6.3)

Determine income generated from daily user fee (c)

$$income = U * c$$

(Equation 6.4)

Determine expenses

$$expenses = initial\ capital + OM + Energy$$

(Equation 6.5)

Calculate initial capital costs

$$I = \sum BOM_{CostUS} + \sum BOM_{CostAny} * PLR + construction\ labor$$

(Equation 6.6)

Calculate construction labor costs

$$LC = \frac{w_c}{W_m} * t_c$$

(Equation 6.7)

Calculate OM costs

$$OM = Replacement\ Materials + maintenance\ labor$$

(Equation 6.8)

Calculate maintenance labor costs

$$LM = \frac{w_m}{W_m} * t_m * f_M$$

(Equation 6.9)

Calculate energy costs

$$E = (E_{UF} + E_{EC} + E_C + E_M) * U_E$$

(Equation 6.10)

Calculate the minimum daily user fee required to break even

$$c = I + \frac{\sum_{i=1}^{L} d[((OM + E - D) * (1 - t)) - D]}{\sum_{i=1}^{L} d[365 * U * (1 - t)]}$$

(Equation 6.11)

**D = depreciation—assume all material costs depreciate linearly over its lifetime (20 years if not otherwise specified in the replacement parts table)*

Table 7. *The fixed parameters (FP) and uncertain parameters (UP) used to model system life cycle impacts are listed.*

	Parameter	Unit	Value(s)	Distribution	Type
I_M	Material unit impacts	kg CO_2 eq.	Table 12		UP
I_{GAC}	GAC unit impacts	kg CO_2 eq.·kg GAC^{-1}	Table 13		FP
I_{zeo}	Zeolite unit impacts	kg CO_2 eq.·kg $zeolite^{-1}$	Table 13		FP
I_{EC}	Coal electricity unit impacts	kg CO_2 eq.·kWh^{-1}	Table 13		FP
I_{EO}	Oil electricity unit impacts	kg CO_2 eq.·kWh^{-1}	Table 13		FP
I_{EG}	Gas electricity unit impacts	kg CO_2 eq.·kWh^{-1}	Table 13	Triangular	UP
I_{EB}	Biogas and waste electricity unit impacts	kg CO_2 eq.·kWh^{-1}	Table 13		FP
I_{ES}	Solar electricity unit impacts	kg CO_2 eq.·kWh^{-1}	Table 13	Uniform	UP
I_{EGE}	Geothermal electricity unit impacts	kg CO_2 eq.·kWh^{-1}	Table 13		FP
I_{EH}	Hydroelectric electricity unit impacts	kg CO_2 eq.·kWh^{-1}	Table 13	Uniform	UP
I_{EW}	Wind electricity unit impacts	kg CO_2 eq.·kWh^{-1}	Table 13	Triangular	UP
I_{EN}	Nuclear electricity unit impacts	kg CO_2 eq.·kWh^{-1}	Table 13		FP
p_{EC}	Fraction of electricity generated from coal		Table 10		FP
p_{EO}	Fraction of electricity generated from oil		Table 10		FP
p_{EG}	Fraction of electricity generated from gas		Table 10		FP
p_{EB}	Fraction of electricity generated from biogas and waste		Table 11		FP
p_{ES}	Fraction of electricity generated from solar		Table 11		FP
p_{EGE}	Fraction of electricity generated from geothermal		Table 11		FP
p_{EH}	Fraction of electricity generated from hydro		Table 10		FP
p_{EW}	Fraction of electricity generated from wind		Table 11		FP
p_{EN}	Fraction of electricity generated from nuclear		Table 11		FP

Table 7 cont

	Parameter	Unit	Value(s)	Distribution	Type
I_{TL}	Land transportation unit impacts	kg CO_2 eq.·ton^{-1}· km^{-1}	Table 13		FP
I_{TS}	Sea transportation unit impacts	kg CO_2 eq.·ton^{-1}· km^{-1}	Table 13		FP

Calculate impacts from construction materials

$$Materials_I = \sum BOM_{mass} * I_M$$

(Equation 7.1)

Calculate impacts from GAC

$$GAC_I = GAC * I_{GAC} * L$$

(Equation 7.2)

Calculate impacts from zeolites

$$Zeolites_I = (m_c + m_p) * I_{zeo} * L$$

(Equation 7.3)

Calculate impacts from electricity

$$\begin{aligned} Electricity_I = {} & [(I_{EC} * p_{EC}) + (I_{EO} * p_{EO}) + (I_{EG} * p_{EG}) + (I_{EG} * p_{EG}) + (I_{EB} * p_{EB}) \\ & + (I_{ES} * p_{ES}) + (I_{EGE} * p_{EGE}) + (I_{EH} * p_{EH}) + (I_{EW} * p_{EW}) + (I_{EN} * p_{EN})] * L \end{aligned}$$

(Equation 7.4)

Calculate impacts from transportation

$$\begin{aligned} & Transportation_I \\ & \quad = (I_{TL} * \sum BOM_{mass} * land\ distance) + (*\ I_{TS} \\ & \quad * \sum BOM_{mass} * sea\ distance) \end{aligned}$$

(Equation 7.5)

**Transportation impacts were small enough to exclude from the overall analysis*

Calculate total environmental impacts in terms of kg CO_2 eq./user/day

$$Total_I = \frac{Materials_I + GAC_I + Zeolites_I + Electricty_I}{L * U * 365 days/year}$$

(Equation 7.6)

CHAPTER 4: RESULTS AND DISCUSSION

The median total cost of the treatment system ranges from roughly \$0.17·user^{-1}·day^{-1} (Myanmar) to \$0.69·user^{-1}·day^{-1} (Bermuda) across the 89 countries that were analyzed. The total cost is broken down into five categories (coinciding the country-specific parameter that most influenced each category): energy (unit electricity price), materials (PLR), labor (maintenance wage), zeolites (protein consumption), and GAC (income tax). Of the five cost categories, median energy cost varies the most across countries (with a range of about \$0.39). It should be noted that income tax was the only country-specific parameters used to calculate GAC cost because we did not have data concerning the cost of GAC media in every country. Median material, labor, and zeolite costs vary moderately across countries (ranges of approximately \$0.06, \$0.06, and \$0.04, respectively). The median cost of GAC, on the other hand, is about the same in all 89 countries (about \$0.01 range) (Figure 2 top). While we assumed the cost of zeolites was the same in each country, the mass of zeolite needed to remove nitrogen and phosphorus did range from approximately 0.02 to 0.06 kg zeolite·user^{-1}·day^{-1} across countries based on dietary protein intake (used to estimate nutrient excretion, which determines zeolite demand).

Across countries, we see a lot of variability among the cost categories, and a high overall cost does not necessarily indicate high costs across all categories (Figure 2). However, the larger the magnitude of the cost range, the more closely cost trends will hold for each category. Countries with high overall costs tend to also have high energy costs, because energy represents the largest fraction of total cost and electricity prices vary considerable across contexts. When focusing on cost categories with a smaller range, however, the relative cost of each category becomes less predictable and cost trends become more random (signified by overlapping orange, navy, gray lines in the bottom portion Figure 2). For example, the total cost of the treatment system is the 2nd highest in Denmark (median: $0.60·user^{-1}·day^{-1}, 5th percentile: 0.40, 95th percentile 0.77), which has the 3rd highest energy cost ($0.37·user^{-1}·day^{-1}, 0.19, 0.77), 5th highest materials cost ($0.13·user^{-1}·day^{-1}, 0.10, 0.15), and 4th highest labor cost ($0.04·user^{-1}·day^{-1}, 0.02, 0.07), but the 16th highest zeolite cost ($0.04·user^{-1}·day^{-1}, 0.03, 0.06), and 36th highest GAC cost ($0.03·user^{-1}·day^{-1}, 0.01, 0.07). Egypt has the 2nd lowest total cost ($0.19·user^{-1}·day^{-1}, 0.13, 0.25), the third lowest energy cost ($0.03·user^{-1}·day^{-1}, 0.02, 0.04), the lowest materials cost ($0.08·user^{-1}·day^{-1}, 0.06, 0.10), the 11th lowest labor cost ($0.001·user^{-1}·day^{-1}, 0.001, 0.002), and the 14th highest zeolite cost ($0.04·user^{-1}·day^{-1}, 0.03, 0.06), but the 36th highest GAC cost ($0.03·user^{-1}·day^{-1}, 0.01, 0.07).

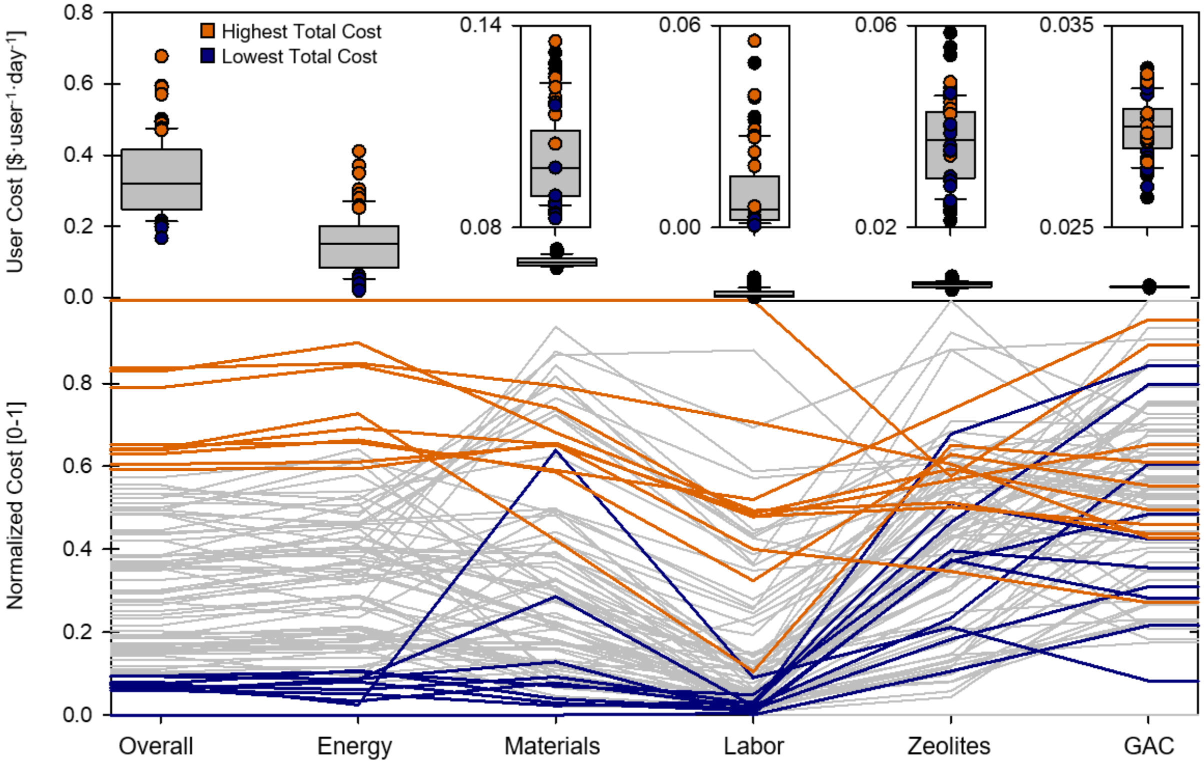


Figure 2. *The median user cost in all 89 countries is displayed as a box and whisker plot (top) for overall cost and each cost category. Boxplot tails represent the 10th and 90th percentiles. Orange and navy dots correspond with the 10 countries that have the highest and lowest overall cost respectively. Each line in the parallel line plot (bottom) represents a country. Orange and navy lines represent the 10 countries with the highest and lowest overall cost respectively. The gray lines represent the other 69 countries. Overall cost and each cost category are normalized, so that 0 and 1 represent the minimum and maximum value for each category respectively.*

4.1 Variations in electricity price control overall system cost

We further analyzed the energy cost in each country, due to its large role in determining the overall cost of the system. The variability of the unit price of electricity across countries explains the large range of energy costs (Figure 2 top). We can predict that energy will make up 10-65% of the overall system cost when the unit electricity price is between $0.04 and $0.40·kWh^{-1} (using 5th and 95th percentiles) (Figure 3). As the electricity price increases, the electricity portion of the total cost also increases. When the cost of electricity is low, the energy cost makes up a lower percentage of the total cost. For example, in Bermuda, Germany, and Denmark, where the unit cost of electricity is highest ($0.4, $0.35, $0.34·kWh^{-1}), electricity makes up about 60%, 63%, and 59% of the total cost, respectively. In countries where the cost of electricity is low such as Myanmar, Venezuela, and Egypt ($0.02, $0.028, $0.03·kWh^{-1}), energy makes up 12%, 14%, and 16% of the total cost, respectively.

In an attempt to identify electricity price trends, countries were grouped according to several World Bank classifications: income level, region, human development index, basic sanitation coverage, urbanization. Of the categories considered, a relationship was most apparent between country income level and electricity price. The price of electricity is typically higher in high income countries as compared to lower middle and upper middle income countries ($p<0.001$). Statistical tests did not reveal a meaningful difference between high income and low income countries ($p = 0.16$), but only four of the 89 countries included in the study (due to data availability) were in the low income group, which could explain the lack of statistical significance. These relationships are not significant enough to suggest a clear trend that would relate energy cost (driven by electricity price) to income level, as residents in some lower income countries appear to face relatively high electricity prices. However, material, labor, and zeolite costs show more substantial differences between income level groupings. PLR, wages, and protein consumption tend to be higher in high income countries than in any of the other three income groups ($p<0.001$). Thus, if electricity cost played a smaller role and/or if one of the other three cost categories were more prominent than electricity (for example, in a different type of treatment system that is less energy-intensive), it might be possible to predict cost based on economic or geographic indicators.

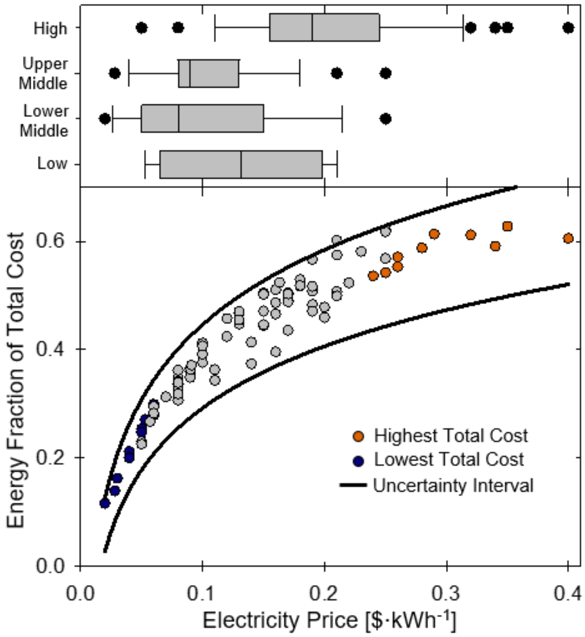


Figure 3. *The relationship between electricity price and the energy portion of the total cost is displayed. Orange and navy dots correspond to the 10 counties with the highest and lowest overall cost respectively (same as figure 2). The black lines represent the uncertainty interval, generated from best fit lines for the 5th and 95th percentiles of the energy fraction of total cost. All 89 countries are categorized by income level (top).*

4.2 Variations in electricity mix control overall environmental impacts

The median total global warming potential (GWP) of the treatment system ranges from 0.22 kg CO_2·user^{-1}·day^{-1} (Ethiopia) to 1.32 kg CO_2 eq·user^{-1}·day^{-1} (Botswana) across the analyzed countries. The daily average CO_2 consumption from fuel in Ethiopia and Botswana is 0.27 kg CO_2·user^{-1}·day^{-1} and 9.3 kg CO_2·user^{-1}·day^{-1}, respectively.[64] Total environmental impacts in each country are divided into four impact sources: energy, materials, zeolites, and GAC. Across all 89 countries, the median environmental impact of the energy was largest among the four impact categories (approximately 75% energy, 9% materials, 9% zeolites, 7% GAC). As the CO_2 intensity of electricity increases across countries, the energy portion of the system's total GWP also increases (Figure 4). When the CO_2 intensity of electricity is low, greenhouse gas emissions (GHG) due to energy consumption becoming less important relative to the other sources of emissions in the system (materials, zeolites, and GAC). The difference in total GHG emissions across countries is due to the use of different electricity sources (Figure 5). Coal is the most CO_2 intensive electricity source while nuclear is the least intensive. In countries with high GWP, the electricity mix is mostly made up of fossil fuels (coal, oil, and gas). Whereas in countries with low GWP, the electricity mix consists mostly of renewable electricity sources (hydro, solar, wind, geothermal, waste, and nuclear) (Figure 5). The total GWP is highest in Botswana (1.32 kg $CO_2 \cdot user^{-1} \cdot day^{-1}$, 0.74, 1.58), where 52% of electricity is generated from oil and the other 48% is produced from coal. Ethiopia has the lowest total GWP (0.22 kg $CO_2 \cdot user^{-1} \cdot day^{-1}$, 0.18, 0.25). Most of its electricity is generated from hydropower (about 94%), and the remainder comes from nonhydroelectric renewable resources (6%). In Botswana, Bermuda, and Hong Kong, where the CO_2 intensity of electricity is highest (1.00, 0.95, 0.94 kg $CO_2 \cdot kWh^{-1}$), 87%, 85%, and 84% of total GHG emissions come from energy. In contrast, only 28%, 24%, and 26% of total GHG emissions stem from energy in Ethiopia, Albania, and Paraguay, where the CO_2 intensity of electricity is lowest (0.056, 0.057, 0.058 kg $CO_2 \cdot kWh^{-1}$). We can predict that approximately 40-85% of the overall GHG emissions will come from energy consumption when the CO_2 intensity of electricity is between 0.2 and 0.8 kg CO_2 eq.$\cdot kWh^{-1}$ (using 5th and 95th percentiles). Statistical tests do not reveal differences between the CO_2 intensity of electricity in each income group (all $p>0.45$).

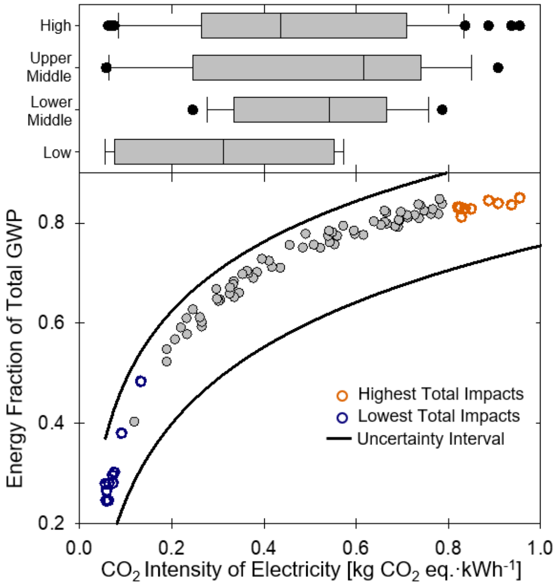


Figure 4. *The relationship between the CO_2 intensity of electricity and the energy portion of the total GWP is displayed. Orange and navy circles correspond to the 10 counties with the highest and lowest total global warming potential. The black lines represent the uncertainty interval, generated from logarithmic best fit curves for the 5th and 95th percentiles of the energy fraction of total GWP. All 89 countries are categorized by income level (top).*

The difference in total GHG emissions is due to the difference in electricity sources in each country (Figure 5). Coal is the most CO_2 intensive electricity source while nuclear CO_2 is the least intensive. In countries with high GWP, the electricity mix is mostly made up of fossil fuels (coal, oil, and gas). Whereas in countries with low GWP, the electricity mix consists mostly of renewable electricity sources (hydro, nonhydro renewables, and nuclear). The median total GWP in is highest in Botswana (1.32 kg CO_2/person/day, 0.74, 1.58), where 52% of electricity is generated from oil and the other 48% is produced from coal. Ethiopia has the lowest median total GWP (0.22 kg CO_2/person/day, 0.18, 0.25). Most of its electricity is generated from hydropower (about 94%), and the remainder comes from Nonhydroelectric renewable resources (6%). Oddly enough, in countries where the projected cost of the Reclaimer is high do not coincide with countries where the expected global warming potential is high. The same is true for low cost and low global warming potential countries. The global warming potential of electricity, resulting from the electricity mix, does not reveal any additional information regarding how electricity prices are set. A multiple linear regression confirmed that there was no statistical correlation between electricity price and source (all p values > 0.4).

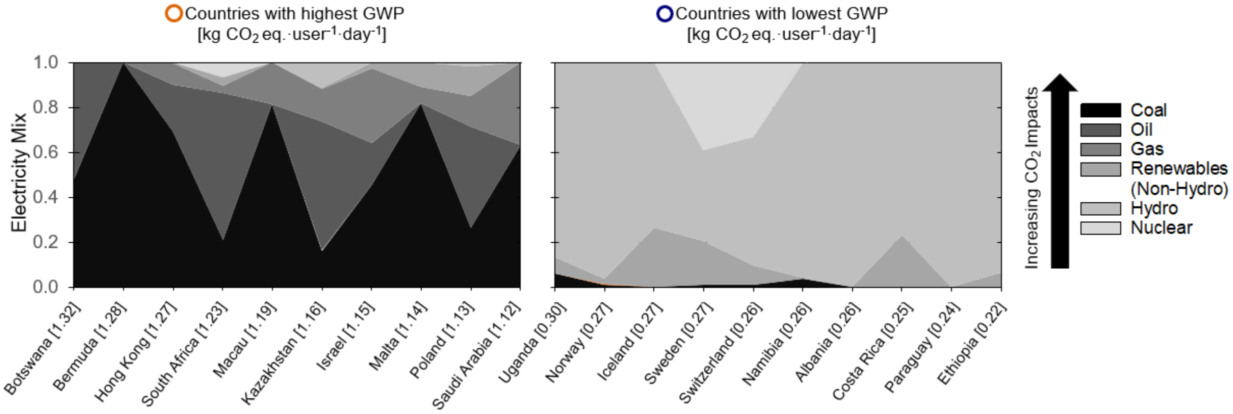


Figure 5. *The electricity mix of the 10 countries with the highest (left) and lowest (right) total global warming potential are displayed. Values for total warming potential in each country are shown in brackets, following the name of each country on the x-axis. The relative* CO_2 *impact of each electricity source is shown in the legend.*

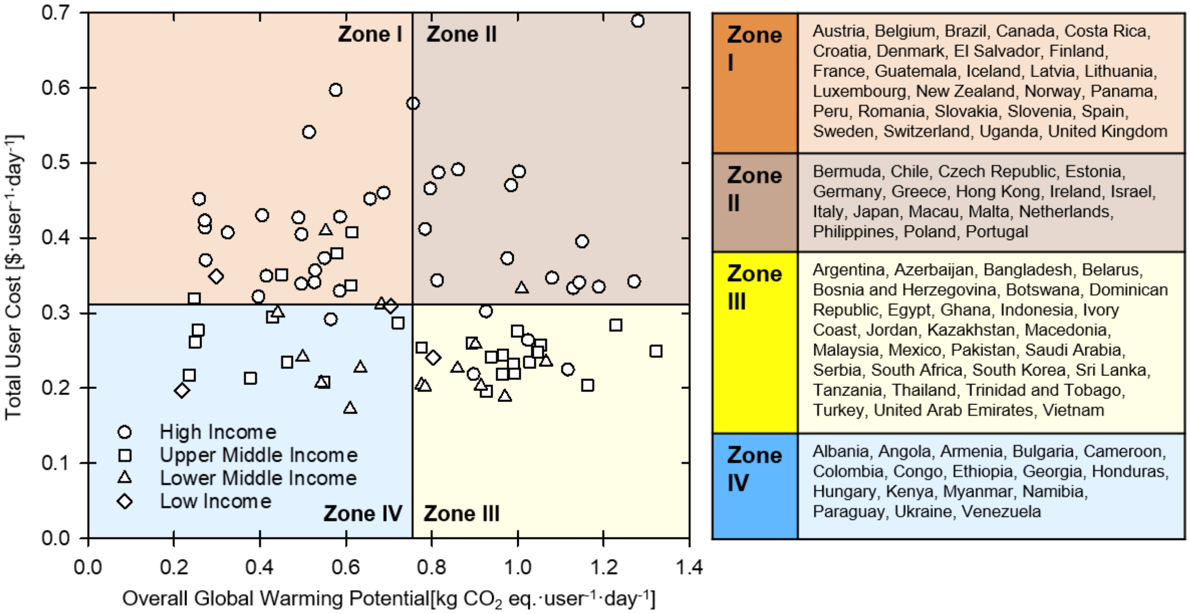
Oddly enough, countries where the projected cost of the technology is high do not coincide with countries where the expected global warming potential is high. The same is true for low cost and low global warming potential. The global warming potential of electricity (dependent on the electricity mix) does not reveal any additional information regarding how electricity prices are set. A multiple linear regression confirmed that there was no statistical correlation between electricity price and source (all p values > 0.4). While the unit cost of electricity drives total user cost and the CO_2 intensity of the electricity mix drives overall global warming potential, the relationship between total user cost and overall global warming potential is not straight forward (Figure 6). Total user cost and overall global warming potential do not appear to be linked, meaning that a high total user cost is not indicative of high overall global warming potential or vice versa. Accordingly, it may be difficult, to improve the economic and environmental viability of the system by changing a single aspect of the system.

In contexts like Vietnam, where cost is low but impacts are high (zone III), reducing the carbon intensity of electricity by switching to renewable electricity sources will bring about the greatest reduction in impacts. However, the cost effects of this shift are unknown, and such a change in electricity source will likely necessitate large-scale changes in the country's energy infrastructure. Perhaps the easiest way to reduce environmental impacts is with the introduction of a solar home system (SHS), which are the most widespread renewable energy alternative for low-income rural areas and can be adapted to accommodate a wide ranges of uses.[65,66] One kilowatt of power generation requires about 8-10 m^2 of roof space.[67] For this treatment technology, which requires about 0.5-1.2 kW, we would need between 4 and 11 m^2 of area. While this space requirement is feasible, households would likely want to install enough panels to power more than their waste treatment system. Alternatively, a SHS could be installed to power waste treatment systems for multiple houses within a community. Unfortunately, switching from grid electricity to a SHS could increase the overall system cost, which might make it less appealing for users.

For countries such as El Salvador where the system cost is high and impacts are low (zone I), finding a low-cost electricity source is the best way to improve the system's viability. Relative to grid electricity and other renewable alternatives, the price of electricity generated from solar tends to be high. In some cases, it can reach as a high $\$2.10 \cdot kWh^{-1}$.[68] The LUCE (levelized unit cost of electricity) for a SHS can be more than 20 times greater than the average price paid for conventional electricity. Due to high costs, users will likely be unwilling or unable to pay for a SHS. Without assistance from governments or aid organizations or cost sharing programs, SHSs will likely be unable to compete with conventional fossil fuel based electricity.[69,70,71] There are other household scale renewable energy options that can be more economically viable, such as pico hydropower[72], small-scale hydroelectric systems, whose installation costs 50% of what it costs to install the cheapest solar home system, and energy costs ($\$\cdot \text{kWh}^{-1}$) are less than 15% of those generated via a SHS.[73] Unfortunately, pico hydropower is only feasible in areas with an available water source.

In areas such as Poland, where cost and impacts are both high (zone II), system implementors should focus on finding an electricity source that is cost-effective with a low carbon intensity. Because a decrease in one could lead to an increase in the other, implementation organizations will likely have to prioritize reducing either cost or environmental impacts. If attempting to optimize for both cost and impacts, pico hydro may be the best option to achieve electrification in low-income, rural communities. Of all the electricity sources, hydro power has the third lowest impact, behind wind and nuclear electricity. Unfortunately, nuclear power really only works for large-scale power generation. While wind power would reduce global warming potential, it is less reliable and cost-effective than pico hydro.[67]

Finally, for countries such as Venezuela, where both cost and impacts are low (zone IV), developers should prioritize further reducing costs. For systems with the lowest total costs, energy makes a smaller contribution to the overall total (Figure 2), so the focus can shift to reducing the cost of materials, GAC/zeolite medias, and labor.



Zone I	Austria, Belgium, Brazil, Canada, Costa Rica, Croatia, Denmark, El Salvador, Finland, France, Guatemala, Iceland, Latvia, Lithuania, Luxembourg, New Zealand, Norway, Panama, Peru, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, Uganda, United Kingdom
Zone II	Bermuda, Chile, Czech Republic, Estonia, Germany, Greece, Hong Kong, Ireland, Israel, Italy, Japan, Macau, Malta, Netherlands, Philippines, Poland, Portugal
Zone III	Argentina, Azerbaijan, Bangladesh, Belarus, Bosnia and Herzegovina, Botswana, Dominican Republic, Egypt, Ghana, Indonesia, Ivory Coast, Jordan, Kazakhstan, Macedonia, Malaysia, Mexico, Pakistan, Saudi Arabia, Serbia, South Africa, South Korea, Sri Lanka, Tanzania, Thailand, Trinidad and Tobago, Turkey, United Arab Emirates, Vietnam
Zone IV	Albania, Angola, Armenia, Bulgaria, Cameroon, Colombia, Congo, Ethiopia, Georgia, Honduras, Hungary, Kenya, Myanmar, Namibia, Paraguay, Ukraine, Venezuela

Figure 6. *The median total user cost vs. the median overall global warming potential for each of the 89 countries included in the analysis are represented by a point on the scatter plot. Shapes are used to show each country's income group. The median total user cost and median overall global warming potential of all 89 countries are used to divide the countries into four groups: Zone I: high cost, low impacts; Zone II: high cost, high impacts; Zone III: low cost, high impacts; Zone IV: low cost, low impacts.*

CHAPTER 5: CONCLUSION

Addressing the global sanitation crisis and achieving safe sanitation coverage in low income communities are difficult tasks that require innovative solutions.[1] Traditional centralized wastewater treatment plants are expensive and rely on the presence or implementation of costly sewer infrastructure, making them unaffordable for many low income communities and unsuitable for rural areas with low population densities.[3,6] Although pit latrines and septic tanks are affordable alternatives to centralized waste treatment, they can lead to groundwater contamination[10] and still face issues in densely populated areas, where some households cannot be reached by waste collection trucks.[11,12] In certain contexts, decentralized waste treatment may be an appropriate strategy for addressing sanitation needs, as it is affordable, can be quickly implemented, reduces the risk of pathogen exposure, and can be portable (making it beneficial for transient populations such as refugees).[14,74] Decentralized systems can easily facilitate resource recovery and water reuse; therefore, they have the potential to reduce global energy consumption and environmental impacts.[15,75]

Using TEA and LCA, this study showed that the economic and environmental outcomes of decentralized waste treatment technologies like the system designed by the Duke Center for WaSH-AID are highly dependent on context. The cost of the technology in Bermuda (most expensive) is more than four times higher than it is in Myanmar (cheapest). The environmental impacts associated with the technology in Botswana (highest impacts) are six times higher than they are in Ethiopia (lowest impacts). Energy is the main driver of both the overall cost and environmental impacts of the system. The overall cost of the system is driven by a given country’s electricity price, while the total environmental impacts are driven by the carbon intensity of the electricity mix. Because there is no clear relationship between the price and carbon intensity of electricity, simultaneously reducing the cost and environmental impacts associated with the system in each country may not be straight forward (i.e. reducing the environmental impacts of the system could result in an increase in cost). This study also shows that it is possible to determine context-specific cost and environmental outcomes of a technology without extensive data collection for each context. Using a simple performance model for a given technology, TEA, LCA, and a few key location-specific parameters, preliminary comparative cost and environmental implications of the technology can feasibly be generated across a plethora of contexts before performing more detailed analyses on locations of interest.

If grid electricity is unreliable, and the cost is unpredictable, it will be nearly impossible to advance safe sanitation coverage in low income communities using energy-intensive treatment technologies that rely on a grid connection. Over the last decade, global access to grid electricity has continued to increase. However, improvements may be concentrated in several key countries such as India and Bangladesh, whereas areas such as sub-Saharan Africa have seen less progress.[76] Integrating innovative sanitation technologies with reliable access to renewable energy may be a key step toward advancing access to global sanitation. Furthermore, the use of renewable energy is a promising way to limit the environmental impacts that are traditionally associated with development. This study shows that it is possible to estimate comparative country-specific cost and environmental outcomes using a relatively small amount of data for each location (e.g. electricity price, protein consumption, electricity mix, etc.) to identify locations to perform in-depth analyses. Unfortunately, data needed to generate the results (particularly electricity data) were not available for every country, so our analysis was limited to 89 countries. In the future, understanding the factors that contribute to determine electricity prices (e.g. GDP, electricity source, etc.) could make it possible to estimate electricity cost from other known parameters and extend the scope of similar analyses.

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APPENDIX A: SUPPLEMENTAL INFORMATION

Table 8. *The total, animal, and vegetal protein consumption, and household waste for each country included in the analysis are listed. Triangular distributions, using the value listed in the table as the midpoint and ±10% for the min and max values are used for total, animal, and vegetal protein. Triangular distributions using the range listed in the table is used for household waste.*

Country	**Total Protein Consumption ($g{\cdot}person^{-1}{\cdot}day^{-1}$)**	**Animal Protein Consumption ($g{\cdot}person^{-1}{\cdot}day^{-1}$)**	**Vegetal Protein ($g{\cdot}person^{-1}{\cdot}day^{-1}$)**	**Household Waste**
Myanmar	82.61	33.72	48.89	1-7%
Venezuela	73.01	38.12	34.89	2-10%
Egypt	103.24	26.34	76.9	2-12%
Azerbaijan	93.15	30.08	63.07	4-25%
Kazakhstan	96.41	57.06	39.35	2-12%
Ukraine	88.62	43.15	45.47	4-25%
Saudi Arabia	91.63	39.93	51.7	2-12%
Ghana	64.57	17.21	47.36	0.1-5%
Trinidad and Tobago	83.36	43.12	40.24	3-16%
Ethiopia	60.4	7.69	52.71	0.1-5%
Paraguay	70.72	34.19	36.53	2-10%
Georgia	80.53	28.81	51.72	4-25%
Malaysia	81.58	45.39	36.19	1-7%
Bangladesh	55.84	9.92	45.92	1-7%
Pakistan	65.49	27.27	38.22	1-7%
Vietnam	81.61	31.06	50.55	1-7%
Macedonia	78.51	32.25	46.26	3-16%
Serbia	82.22	39.94	42.28	4-25%
Armenia	90.04	43.25	46.79	4-25%
United Arab Emirates	104.62	41.69	62.93	2-12%
Sri Lanka	59.71	16.31	43.4	1-7%
Mexico	87.63	40.66	46.97	2-10%
Cameroon	69.96	11.69	58.27	0.1-5%
Argentina	102.64	66.95	35.69	2-10%
Belarus	93.82	54.96	38.86	4-25%
Jordan	79.59	27.18	52.41	2-12%
Botswana	64.86	26.41	38.45	0.1-5%
Turkey	108.12	36.31	71.81	2-12%
Angola	57.26	18.4	38.86	0.1-5%
Bosnia and Herzegovina	91.64	30.43	61.21	4-25%
Albania	111.42	59.42	52	4-25%
Indonesia	62.18	17.7	44.48	1-7%

Table 8 cont

Country	Total Protein Consumption ($g \cdot person^{-1} \cdot day^{-1}$)	Animal Protein Consumption ($g \cdot person^{-1} \cdot day^{-1}$)	Vegetal Protein ($g \cdot person^{-1} \cdot day^{-1}$)	Household Waste
Dominican Republic	58.2	26.4	31.8	2-10%
Tanzania	57.8	10.21	47.59	0.1-5%
Korea	96.2	10.06	44.94	4-20%
Canada	104.95	54.7	50.25	4-33%
Ivory Coast	58.51	13.67	44.84	3-16%
South Africa	85.33	36.39	48.94	0.1-5%
Hungary	78.85	42.11	36.74	4-25%
Bulgaria	83.53	41.31	42.22	4-25%
Thailand	60.88	24.85	36.03	1-7%
Namibia	57.69	19.55	38.14	0.1-5%
Hong Kong	129.18	94.41	34.77	4-20%
Norway	110.9	65.99	44.91	4-25%
Macau	94.84	61.11	33.73	4-20%
Costa Rica	75.07	40.99	34.08	2-10%
Kenya	61.84	15.9	45.94	0.1-5%
Colombia	64.38	33.48	30.9	2-10%
Malta	110.36	61.75	48.61	3-16%
Lithuania	124.49	76.5	47.99	4-25%
Croatia	84.35	47.98	36.37	4-25%
Iceland	133.54	96.48	37.06	4-25%
Honduras	64.88	23.2	41.68	2-10%
Congo	51.66	22.24	29.42	0.1-5%
Romania	103.02	47.2	55.82	4-25%
Poland	101.47	53.27	48.2	4-25%
Estonia	103.9	53.24	50.66	4-25%
Israel	128.14	72.46	55.68	2-12%
Panama	79.44	41.64	37.8	2-10%
Chile	87.36	45.27	42.09	2-10%
Latvia	91.39	50.97	40.42	4-25%
Slovakia	72.51	34.95	37.56	4-25%
Brazil	94.99	52.59	42.4	2-10%
Slovenia	96.19	51.81	44.38	4-25%
Finland	117.72	73.03	44.69	4-25%
Greece	108.8	59.24	49.56	4-25%
Philippines	59.93	24.86	35.07	1-7%
France	110.52	69.34	41.18	4-25%
Switzerland	93.08	59.77	33.31	4-25%
Sweden	107.72	70.83	36.89	4-25%
Luxembourg	113.88	72.12	41.76	4-25%
New Zealand	92.54	54.82	37.72	4-33%

Table 8 cont

Country	Total Protein Consumption (g·person^{-1}·day^{-1})	Animal Protein Consumption (g·person^{-1}·day^{-1})	Vegetal Protein (g·person^{-1}·day^{-1})	Household Waste
Peru	74.92	27.04	47.88	2-10%
Uganda	52.68	12.39	40.29	0.1-5%
Austria	106.21	62.86	43.35	4-25%
Czech Republic	87.47	50.48	36.99	4-25%
United Kingdom	103.21	58.28	44.93	4-25%
Guatemala	63.73	17.83	45.9	2-10%
Netherlands	111.72	75.76	35.96	4-25%
Spain	104.88	65.15	39.73	4-25%
El Salvador	71.9	25.25	46.65	2-10%
Ireland	110.02	64.83	45.19	4-25%
Italy	108.51	58.25	50.26	4-25%
Japan	87.73	48.46	39.27	4-20%
Portugal	110.88	67.29	43.59	4-25%
Belgium	99.59	58.11	41.48	4-25%
Denmark	108.88	69.81	39.07	4-25%
Germany	101.59	61.48	40.11	4-25%
Bermuda	90.79	60.27	30.52	3-16%

Table 9. *The energy price, price level ratio, construction and maintenance wage, and income tax for the 89 countries included in the analysis are listed. All values are input as triangular distributions, using the value listed in the table as the midpoint and ±10% for the min and max values.*

Country	**Energy ($\$\cdot\text{kWh}^{-1}$)**	**PLR**	**Construction Labor Wage ($\$\cdot\text{person}^{-1}\cdot\text{month}^{-1}$)**	**Maintenance Labor Wage ($\$\cdot\text{person}^{-1}\cdot\text{month}^{-1}$)**	**Income Tax**
Myanmar	0.02	0.287283	131.79	89.71	25%
Venezuela	0.028	0.886867	693.66	910	34%
Egypt	0.03	0.205735	242.15	182.05	23%
Azerbaijan	0.04	0.262108	509.42	201.41	20%
Kazakhstan	0.04	0.33528	523.75	274.3	20%
Ukraine	0.05	0.335224	185.16	158.07	18%
Saudi Arabia	0.05	0.421248	1170.24	2248.56	20%
Ghana	0.05	0.464788	321.82	194.57	25%
Trinidad and Tobago	0.05	0.522644	773.61	1252.83	25%
Ethiopia	0.053	0.382603	74.74	70.64	30%
Paraguay	0.057	0.432652	337.16	827.73	10%
Georgia	0.06	0.38042	534.89	300.61	15%
Malaysia	0.06	0.354559	493.94	489.84	24%
Bangladesh	0.06	0.389149	147.16	173.03	25%
Pakistan	0.06	0.265678	126.53	209.75	31%
Vietnam	0.07	0.344846	215.88	259.56	20%
Macedonia	0.08	0.371896	488.38	522.32	10%
Serbia	0.08	0.415645	312.47	305.49	15%
Armenia	0.08	0.407951	237.93	174.76	20%
United Arab Emirates	0.08	0.573838	1680.48	1680.48	21%
Sri Lanka	0.08	0.305019	168.31	241.49	28%
Mexico	0.08	0.487637	419.96	493.36	30%
Cameroon	0.08	0.404894	257.83	231.78	33%
Argentina	0.08	0.566558	590.03	845.45	35%
Belarus	0.09	0.315134	383.4	397.47	18%
Jordan	0.09	0.454407	743.66	849.3	20%
Botswana	0.09	0.44442	527.48	1575.55	22%
Turkey	0.09	0.33383	859.02	1144.6	22%
Angola	0.091	0.532898	411.86	499.78	30%
Bosnia and Herzegovina	0.1	0.414784	468.05	390.35	10%
Albania	0.1	0.394252	337.24	280.4	15%
Indonesia	0.1	0.29821	145.14	239.82	25%
Dominican Republic	0.1	0.429808	473.36	591.56	27%
Tanzania	0.1	0.325585	193.14	341.79	30%
Korea	0.11	0.781884	2835.15	2686.93	25%

Table 9 cont

Country	**Energy ($\$\cdot$kWh^{-1})**	**PLR**	**Construction Labor Wage ($\$\cdot$person^{-1} $\cdot$month^{-1})**	**Maintenance Labor Wage ($\$\cdot$person^{-1} $\cdot$month^{-1})**	**Income Tax**
Canada	0.11	0.960581	3767.53	3767.53	27%
Pakistan	0.06	0.265678	126.53	209.75	31%
Vietnam	0.07	0.344846	215.88	259.56	20%
Ivory Coast	0.12	0.408492	221.71	164.72	25%
South Africa	0.12	0.464229	235.13	587.82	28%
Hungary	0.13	0.519636	797.43	897.14	9%
Bulgaria	0.13	0.422244	437.77	461.53	10%
Thailand	0.13	0.382462	281.1	447.71	20%
Namibia	0.13	0.532695	301.32	369.12	32%
Hong Kong	0.14	0.755452	2125.67	2125.67	17%
Norway	0.14	1.247085	5047.02	4935.41	22%
Macau	0.15	0.705317	1502.02	2253.03	12%
Costa Rica	0.15	0.68158	648.56	997.72	30%
Kenya	0.15	0.494161	79.47	165.92	30%
Colombia	0.15	0.443436	309.9	526.49	34%
Malta	0.15	0.706524	1937.03	2048.88	35%
Lithuania	0.16	0.540121	791.45	877.4	15%
Croatia	0.16	0.540602	1149.92	1369.42	18%
Iceland	0.16	1.277264	5910.03	5380.28	20%
Honduras	0.16	0.483992	286.14	386.33	25%
Congo	0.163	0.603719	27.06	91.66	35%
Romania	0.17	0.436114	516.11	589.77	16%
Poland	0.17	0.492105	840.34	1005.19	19%
Estonia	0.17	0.646759	1230.04	1267.65	20%
Israel	0.17	1.044987	2344.45	3188.85	24%
Panama	0.17	0.61058	748.52	737.69	25%
Chile	0.17	0.631315	759.64	1107.36	27%
Latvia	0.18	0.589365	1126.4	1022.91	20%
Slovakia	0.18	0.576312	1044.21	1011.02	21%
Brazil	0.18	0.555187	490.8	565.6	34%
Slovenia	0.19	0.686592	1431.36	1736.66	19%
Finland	0.19	1.035843	3321.66	3516.85	20%
Greece	0.19	0.686812	858.82	983.04	28%
Philippines	0.19	0.347242	225.15	270.78	30%
France	0.19	0.914456	3001.61	3162.97	31%
Switzerland	0.2	1.216506	6655.2	6739.43	18%
Sweden	0.2	1.026302	5027.7	4871.31	21%
Luxembourg	0.21	1.029138	3161.38	3999.84	27%
Iceland	0.16	1.277264	5910.03	5380.28	20%
Honduras	0.16	0.483992	286.14	386.33	25%

Table 9 cont

Country	**Energy ($\$\cdot kWh^{-1}$)**	**PLR**	**Construction Labor Wage ($\$\cdot person^{-1} \cdot month^{-1}$)**	**Maintenance Labor Wage ($\$\cdot person^{-1} \cdot month^{-1}$)**	**Income Tax**
New Zealand	0.21	1.022922	3487.58	3585.04	28%
Peru	0.21	0.482668	439.08	550.39	30%
Uganda	0.21	0.316305	122.4	107.31	30%
Austria	0.22	0.928	2819.58	3065.15	25%
Czech Republic	0.23	0.580687	1070.22	1098.98	19%
United Kingdom	0.24	0.9341	3592.87	3669.83	19%
Guatemala	0.25	0.538507	290.93	335.36	25%
Netherlands	0.25	0.941329	3266.93	4389.89	25%
Spain	0.25	0.764712	2023.13	2333	25%
El Salvador	0.25	0.487946	269.99	341.6	30%
Ireland	0.26	0.947154	3541.91	3950.76	13%
Italy	0.26	0.824357	2339.89	2568.71	24%
Japan	0.28	0.918044	3075.57	2989.18	31%
Portugal	0.29	0.700512	852.84	884.92	21%
Belgium	0.32	0.924343	3305.18	3776.4	29%
Denmark	0.34	1.102013	5791.39	5978.65	22%
Germany	0.35	0.896909	3684.59	3942.32	30%
Bermuda	0.4	1.631825	5129.3	7547.9	0%

Table 10. *The portion of electricity generated by each coal, oil, gas, and hydroelectric in each country is listed.*

Country	Coal	Oil	Gas	Hydroelectric
Myanmar	0.242174	0.007987	0.173801	0.571678
Venezuela	0.194276	0.000812	0.185884	0.618094
Egypt	0.391092	0.016149	0.503131	0.072709
Azerbaijan	0.311725	6.12E-05	0.602939	0.075302
Kazakhstan	0.162157	0.575334	0.143841	0.113738
Ukraine	0.06729	0.152033	0.154685	0.06079
Saudi Arabia	0.63199	0.000256	0.367265	0
Ghana	0.462687	0.002969	0.119809	0.41106
Trinidad and Tobago	0.132592	0.000141	0.866881	0
Ethiopia	0.000273	1.84E-05	0	0.933477
Paraguay	3.38E-05	0	0	0.997619
Georgia	0.074948	0.0097	0.101022	0.806546
Malaysia	0.359312	0.178857	0.285726	0.168614
Bangladesh	0.185232	0.037434	0.759597	0.014977
Pakistan	0.282354	0.054666	0.33126	0.219322
Vietnam	0.206831	0.318146	0.067762	0.404907
Macedonia	0.358645	0.332046	0.068266	0.206153
Serbia	0.165823	0.43773	0.13145	0.260936
Armenia	0.058732	0.000128	0.307889	0.30508
United Arab Emirates	0.391015	0.015432	0.587254	0
Sri Lanka	0.572291	0.12594	0	0.2638
Mexico	0.432839	0.054621	0.31223	0.104027
Cameroon	0.307767	0	0.142726	0.547224
Argentina	0.297577	0.006367	0.350481	0.284658
Belarus	0.290944	0.014347	0.670638	0.012343
Jordan	0.576707	0.00715	0.345374	0.001939
Botswana	0.480664	0.518632	0	0
Turkey	0.2498	0.205526	0.241211	0.20485
Angola	0.242065	0	0.027886	0.709629
Bosnia and Herzegovina	0.225642	0.492478	0.026287	0.251578
Albania	0	0	0	0.999777
Indonesia	0.404707	0.256117	0.206269	0.076436
Dominican Republic	0.654764	0.072984	0.113981	0.120477
Tanzania	0.368749	0.023066	0.297555	0.305381
Korea	0.34717	0.229713	0.120734	0.005337
Canada	0.088275	0.011849	0.082931	0.606892
Ivory Coast	0.429798	0	0.396155	0.155553
South Africa	0.209248	0.656203	0.030962	0.003623

Table 10 cont

Country	Coal	Oil	Gas	Hydroelectric
Hungary	0.163246	0.049401	0.180896	0.006881
Bulgaria	0.175601	0.227092	0.107502	0.065398
Thailand	0.426802	0.109441	0.291377	0.053259
Namibia	0.037669	4.36E-05	0	0.959246
Hong Kong	0.68982	0.21015	0.096871	0
Norway	0.012449	0.000648	0.004388	0.959732
Macau	0.815216	0	0.184784	0
Costa Rica	0.00312	5.40E-08	0	0.765665
Kenya	0.186343	0.008277	0	0.313884
Colombia	0.116931	0.032537	0.057007	0.773894
Malta	0.819315	0	0.074414	0
Lithuania	0.12112	0.005991	0.082889	0.180909
Croatia	0.220491	0.022715	0.140091	0.459032
Iceland	9.86E-05	7.57E-06	0	0.737133
Honduras	0.407843	0.002176	0	0.328127
Congo	0.249432	0	0.389356	0.360909
Romania	0.176491	0.089519	0.166442	0.234541
Poland	0.262346	0.453946	0.133935	0.015865
Estonia	0.647038	0.009912	0.18491	0.002122
Israel	0.455269	0.188223	0.329861	6.30E-06
Panama	0.266018	0.005622	0	0.665524
Chile	0.331845	0.129633	0.087668	0.273983
Latvia	0.166697	0.003275	0.093564	0.590212
Slovakia	0.078179	0.054648	0.072258	0.166982
Brazil	0.131828	0.01401	0.027943	0.635352
Slovenia	0.189547	0.077988	0.057358	0.248275
Finland	0.123707	0.034096	0.025001	0.223757
Greece	0.459973	0.14456	0.133632	0.075173
Philippines	0.391373	0.299315	0.05274	0.10572
France	0.070632	0.007473	0.032408	0.092283
Switzerland	0.009343	4.96E-05	0.002713	0.572296
Sweden	0.009092	0.000959	0.000402	0.401576
Luxembourg	0.187107	0.002763	0.046225	0.093076
New Zealand	0.109334	0.014795	0.056903	0.580563
Peru	0.235632	0.0067	0.150702	0.560373
Uganda	0.060514	0	0	0.86626
Austria	0.127996	0.022229	0.080037	0.567821
Czech Republic	0.170821	0.25741	0.123512	0.022778
United Kingdom	0.234785	0.027147	0.214019	0.018359
Guatemala	0.228479	0.062026	0	0.455721
Netherlands	0.42224	0.082263	0.294421	0.000548

Table 10 cont

Country	Coal	Oil	Gas	Hydroelectric
Spain	0.282677	0.045959	0.12531	0.070663
El Salvador	0.248535	0	0	0.305235
Ireland	0.393751	0.055157	0.243572	0.023328
Italy	0.281132	0.045809	0.299096	0.127276
Japan	0.360745	0.215853	0.218324	0.085111
Portugal	0.338069	0.091727	0.161998	0.104622
Belgium	0.190312	0.01479	0.089947	0.003299
Denmark	0.165626	0.031063	0.061948	0.000589
Germany	0.23269	0.135943	0.156965	0.032278
Bermuda	1	0	0	0

Table 11. *The portion of electricity generated by each coal, oil, gas, and hydroelectric in each country is listed.*

	Nonhydroelectric Renewables				
Country	**Biogas and Waste**	**Geothermal**	**Wind**	**Solar**	**Nuclear**
Myanmar	0.000642	0	0	0.003717	0
Venezuela	0	0	0.000867	6.74E-05	0
Egypt	0.001673	0	0.014094	0.001152	0
Azerbaijan	0.007404	0	0.000958	0.001611	0
Kazakhstan	0.000492	0	0.003474	0.000963	0
Ukraine	0.001442	0	0.006748	0.00508	0.551932
Saudi Arabia	0	0	1.53E-05	0.000474	0
Ghana	0.001405	0	0	0.00207	0
Trinidad and Tobago	0	0	0	0.000386	0
Ethiopia	0.002038	7.28E-06	0.062586	0.001601	0
Paraguay	0.002347	0	0	0	0
Georgia	0	0	0.007784	0	0
Malaysia	0.005377	0	0	0.002115	0
Bangladesh	0.000116	0	7.26E-05	0.002571	0
Pakistan	0.024347	0	0.016668	0.007053	0.064331
Vietnam	0.000439	0	0.001864	5.19E-05	0
Macedonia	0.009754	0	0.020634	0.004502	0
Serbia	0.002304	0	0.001382	0.000374	0
Armenia	0	0	0.000272	0.000407	0.327493
United Arab Emirates	4.74E-05	0	7.90E-06	0.006243	0
Sri Lanka	0.00444	0	0.024187	0.009343	0
Mexico	0.007093	0.018528	0.032491	0.00352	0.034651
Cameroon	0.00036	0	0	0.001923	0
Argentina	0.015116	0	0.004445	0.000115	0.041242
Belarus	0.006002	0	0.002986	0.00274	0
Jordan	0.000204	0	0.02296	0.045666	0
Botswana	0	0	0	0.000704	0
Turkey	0.007525	0.018071	0.063034	0.009983	0
Angola	0.018734	0	0	0.001686	0
Bosnia and Herzegovina	0.002613	0	6.37E-05	0.001339	0
Albania	0	0	0	0.000223	0
Indonesia	0.003435	0.052891	2.49E-05	0.00012	0
Dominican Republic	0.008479	0	0.021613	0.007703	0
Tanzania	0.002756	0	0	0.002493	0
Korea	0.013018	0	0.004091	0.013316	0.266621

Table 11 cont

	Nonhydroelectric Renewables				
Country	**Biogas and Waste**	**Geothermal**	**Wind**	**Solar**	**Nuclear**
Canada	0.011477	0	0.044488	0.005536	0.148551
Ivory Coast	0.017775	0	0	0.000719	0
South Africa	0.001248	0	0.021393	0.013912	0.063411
Hungary	0.075301	3.22E-05	0.023696	0.011221	0.489325
Bulgaria	0.009249	0	0.035034	0.032769	0.347355
Thailand	0.087195	1.13E-05	0.006262	0.025653	0
Namibia	0	0	0.003041	0	0
Hong Kong	0.003074	0	5.74E-05	2.87E-05	0
Norway	0.003387	0	0.019396	0	0
Macau	0	0	0	0	0
Costa Rica	0.016401	0.099652	0.114805	0.000357	0
Kenya	0.01246	0.470332	0.004747	0.003956	0
Colombia	0.019399	0	4.09E-05	0.000191	0
Malta	0.006425	0	0.000257	0.099589	0
Lithuania	0.177879	0	0.410909	0.020303	0
Croatia	0.045947	0	0.104822	0.006901	0
Iceland	0	0.262337	0.000424	0	0
Honduras	0.0839	0.010376	0.064487	0.10309	0
Congo	0	0	0	0.000303	0
Romania	0.008581	0	0.12112	0.030337	0.172968
Poland	0.04228	0	0.090602	0.001026	0
Estonia	0.096206	0	0.058996	0.000816	0
Israel	6.30E-06	0	0.002835	0.023799	0
Panama	0.002966	0	0.045412	0.014458	0
Chile	0.07951	0.000839	0.046116	0.050405	0
Latvia	0.126009	0	0.020189	5.42E-05	0
Slovakia	0.066507	0	0.000232	0.019554	0.541639
Brazil	0.090415	0	0.073312	0.00144	0.025701
Slovenia	0.019464	0	0.000391	0.018487	0.388491
Finland	0.18893	0	0.073437	0.000659	0.330413
Greece	0.005882	0	0.105056	0.075723	0
Philippines	0.011244	0.114109	0.012155	0.013344	0
France	0.019017	0.000224	0.046198	0.017897	0.713868
Switzerland	0.052645	0	0.002255	0.028535	0.332163
Sweden	0.085451	0	0.109377	0.001429	0.391713
Luxembourg	0.281498	0	0.266742	0.122588	0
New Zealand	0.013644	0.173675	0.049362	0.001723	0
Peru	0.020102	0	0.0209	0.00559	0
Uganda	0.057717	0	0	0.01551	0

Table 11 cont

	Nonhydroelectric Renewables				
Country	**Biogas and Waste**	**Geothermal**	**Wind**	**Solar**	**Nuclear**
Austria	0.085855	1.56E-06	0.097285	0.018774	0
Czech Republic	0.062209	0	0.007158	0.026677	0.329434
United Kingdom	0.112838	0	0.156632	0.036101	0.200119
Guatemala	0.200272	0.020203	0.017408	0.015891	0
Netherlands	0.056476	0	0.094942	0.019799	0.029312
Spain	0.026222	0	0.183476	0.052743	0.212949
El Salvador	0.135324	0.27594	0	0.034965	0
Ireland	0.030275	0	0.253542	0.000375	0
Italy	0.077838	0.020731	0.062567	0.08555	0
Japan	0.042217	0.002282	0.006694	0.056799	0.011975
Portugal	0.063315	0.003487	0.218857	0.017925	0
Belgium	0.088128	0	0.078637	0.04018	0.494707
Denmark	0.232177	0	0.484003	0.024593	0
Germany	0.094064	0.000254	0.167556	0.063659	0.116591
Bermuda	0	0	0	0	0

Table 12. *The unit impacts for materials taken from ecoinvent (corresponds with Table 15) are listed.*[49] [a] *To estimate the impacts of the polyvinylflouride membrane, we used the ecoinvent entry for a polysulfone membrane, removed from polysulfone and added those of polyvinylflouride.* [b] *The ecoinvent entry for polysulfone was created using the same process for polyvinylflouride and substituting polysulfone.*

Reference Number	Description	GWP (kg CO_2 eq.)
1	1 kg Steel, chromium steel 18/8 {RoW}| steel production, converter, chromium steel 18/8 | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)	4.648881684
2	1 kg Casting, steel, lost-wax {RoW}| casting, steel, lost-wax | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)	28.21992258
3	1 kg Polyvinylchloride, bulk polymerised {RoW}| polyvinylchloride production, bulk polymerisation | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)	2.067379863
4	1 kg Polyethylene, high density, granulate {RoW}| production | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)	1.929999303
5	1 kg Extrusion, plastic pipes {RoW}| production | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)	0.528488748
6	1 kg Polycarbonate {RoW}| production | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)	7.783234426
7	1 kg Synthetic rubber {RoW}| production | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)	3.038223217
8	1 kg Nylon 6, glass-filled {RoW}| production | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)	7.329118161
9	1 kg Light emitting diode {GLO}| production | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)	310.1262855
10	1 kg Electric connector, peripheral type buss {GLO}| production | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)	8.847460033
11	1 m Cable, three-conductor cable {GLO}| production | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)	4.379021875
12	1 kg Polypropylene, granulate {RoW}| production | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)	1.973949156
13	1 kg Aluminium, primary, ingot {RoW}| production | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)	6.94807609
14	1 kg Casting, aluminium, lost-wax {RoW}| casting, aluminium, lost-wax | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)	110.0822059

Table 12 cont

Reference Number	Description	GWP (kg CO_2 eq.)
15	1 kg Electronics, for control units {RoW}| production | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)	26.79636172
16	1 kg Electronic component, active, unspecified {GLO}| production | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)	640.9497198
17	1 kg Electronic component, passive, unspecified {GLO}| production | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)	64.4857983
18	1 kg Switch, toggle type {RoW}| production | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)	18.56098966
19[a]	1 kg Polyvinylfluoride {GLO}| polysulfone production, for membrane filtration production | Alloc Def, U (of project Becca_Gates)	10.73043251
20	1 kg Electric motor, for electric scooter {GLO}| production | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)	9.970347121
21	1 kg Transformer, low voltage use {GLO}| production | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)	4.535300995
22	1 p Pump, 40W {RoW}| production | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)	8.593704116
23[b]	1 kg Polysulfone {RoW}| production | Alloc Def, U (of project Becca_Gates)	16.03471691
24	1 kg Nylon 6 {RoW}| production | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)	9.279255342
25	1 kg Titanium zinc plate, without pre-weathering {RoW}| production | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)	6.03509508
26	1 kg Zinc {GLO}| primary production from concentrate | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)	5.054710999
27	1 kg Glass fibre reinforced plastic, polyamide, injection moulded {RoW}| production | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)	8.779946528
28	1 kg Expanded clay {RoW}| production | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)	0.436778747
29	1 kg Polyurethane, flexible foam {RoW}| production | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)	4.932492605

Table 13*. The unit impacts for GAC/Zeolite Media, Transportation, and Electricity taken from ecoinvent are listed.*[49]
[a] *There is no entry for GAC media in the ecoinvent 3.2 database, so the GAC media impacts from ecoinvent 3.3 were manually entered.*

Component	Global Warming Potential (kg CO^2 eq.)	Units/Description
Transportation		
Land Transport	0.1708143	1 tkm Transport, freight, lorry 16-32 metric ton, EURO5 {RoW}| transport, freight, lorry 16-32 metric ton, EURO5 | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)
Sea Transport	0.0115463	Transport, freight, sea, transoceanic ship {GLO}| processing | Alloc Def, U
GAC/Zeolites		
GAC Media[a]	8.3886483	1 kg activated carbon production, granular from hard coal (Eco-Invent 3.3)
Zeolite and Waste	1.7787768	1 kg Zeolite, slurry, without water, in 50% solution state {RoW}| production | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)
		1 kg Waste zeolite {RoW}| treatment of, inert material landfill | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)
Electricity		
Nuclear	0.0118602	1 kWh Electricity, high voltage {RoW}| electricity production, nuclear, pressure water reactor | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)
Hydroelectric	0.0498731	1 kWh Electricity, high voltage {RoW}| electricity production, hydro, reservoir, non-alpine region | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)
	0.0650941	1 kWh Electricity, high voltage {RoW}| electricity production, hydro, reservoir, tropical region | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)
Geothermal	0.075102	1 kWh Electricity, high voltage {RoW}| electricity production, deep geothermal | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)
Wind	0.0153475	1 kWh Electricity, high voltage {RoW}| electricity production, wind, <1MW turbine, onshore | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)
	0.0155458	1 kWh Electricity, high voltage {RoW}| electricity production, wind, 1-3MW turbine, onshore | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)
	0.032336	1 kWh Electricity, high voltage {RoW}| electricity production, wind, >3MW turbine, onshore | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)

Table 13 cont

Component	Global Warming Potential (kg CO^2 eq.)	Units/Description
Solar	0.0700261	1 kWh Electricity, low voltage {RoW}| electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)
	0.0832806	1 kWh Electricity, low voltage {RoW}| electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)
Biogas and Waste	0.4141763	1 kWh Electricity, medium voltage {RoW}| electricity, from municipal waste incineration to generic market for | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)
Coal	1.0469683	1 kWh Electricity, high voltage {RoW}| electricity production, hard coal | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)
Oil	0.9548412	1 kWh Electricity, high voltage {RoW}| electricity production, oil | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)
Gas	0.4409781	1 kWh Electricity, high voltage {RoW}| electricity production, natural gas, combined cycle power plant | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)
	0.6125631	1 kWh Electricity, high voltage {RoW}| electricity production, natural gas, conventional power plant | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)
	0.6995301	1 kWh Electricity, high voltage {RoW}| electricity production, natural gas, 10MW | Alloc Def, U (of project Ecoinvent 3 - allocation at point of substitution - unit)

Table 14. *The items used to build the system prototype are listed. An uncertainty of 10% is factored into each material cost because prices are subject to change. The uncertainty for material impacts (listed in "LCA Uncertainty") is based on the similarity of each material to items in ecoinvent. The number for ecoinvent materials and processes used to estimate the impacts of each material (listed in "Unit Impacts" column) correspond with Table 12. Items highlighted in yellow must be purchased in the US. Items highlighted in blue can be purchased locally in any country.*

Description	Qty	Total Cost	Total Mass (kg)	Unit Impacts	LCA Uncertainty
UF SYSTEM		**1,821.5**			
Goulds LB0712TE LB Series Booster Pump, 3/4 HP, 115-230 Volt, 60 Hz, Single Phase, 3500 RPM, Noryl 5" Impeller, TEFC - Totally Enclosed Fan Cooled Motor Enclosure, 1 1/4" NPT Suction, 1" NPT Discharge, Dual Rated 50/60 Hz	1	519.68	17.2 (1 p)	22	25
PE substrate/PVDF membrane/PVC housing/0.5" id/0.02 um/72"L/1 tube, Filtrate Port (Qty 1) 3/4" NPT Female, Retentate Ports 1 1/4" pipe stub, Housing Diameter 1 1/4" Sc80, Module Length 72" (1829 mm), Max Differential Pressure 120 psi (827 kPa) at 25°C	1	212	8.72	19	15
Motorized Electric Ball Valve - 2-Way DC - 1", 2.5N.m, Stainless Steel, 12V - ON/OFF	1	100.5	0.798	1, 2	15
Vibration- and Corrosion-Resistant Pressure Gauge, 1/4 NPT Male Bottom Connection, 2-1/2" Dial, 0-60 PSI	1	58	0.22	1, 2	15
Gems CAP100 Non-Contact Capacitive Level Switch, L-type Non-Embeddable (no shielded for aqueous solution), 10-48 VDC Supply Voltage, 78" 3-wire Cable, Current Sourcing PNP, Max Load Current 300 ma	3	330	1.22 (total); 1.21 (nylon); 0.0133 (LED)	8, 9	15
PE substrate/PVDF membrane/PVC housing/0.5" id/0.02 um/72"L/1 tube, Filtrate Port (Qty 1) 3/4" NPT Female, Retentate Ports 1 1/4" pipe stub, Housing Diameter 1 1/4" Sc80, Module Length 72" (1829 mm), Max Differential Pressure 120 psi (827 kPa) at 25°C	1	70.91	0.2	23	15
1" NPT Female Loose Thread x Thread PVC Bulkhead Fitting w/EPDM Gasket - 1.88" Hole Size, Maximum tank wall thickness is 1.08". Minimum flexible tank radius is 10.10" and minimum rigid tank radius 11.75". Hole size required is 1.88".	1	19.77	0.408	3, 5	15

Table 14 cont

Description	Qty	Total Cost	Total Mass (kg)	Unit Impacts	LCA Uncertainty
3/4" PVC Bulkhead Standard Length Fitting/EPDM Standard Flange Gasket; Threaded x Threaded, 1.63" Installation Hole Size	1	18.31	0.163	3, 5	15
1-1/4" Loose Thread x Thread PVC Bulkhead Fitting w/EPDM Gasket, Maximum tank wall thickness is 1.00". Minimum flexible tank radius is 12.19" and minimum rigid tank radius 16.25". Hole size required is 2.63".	1	26.89	0.363	3, 5	15
Sheet Metal Counting Bracket	1	30.24	0.181	1, 2	10
1" Socket Male x 1" NPT Male SCH 40 Standard-Wall PVC Pipe Fitting for Water, White, Adapter with Hex Body, .68" Thread Engagement	3	3.63	0.082	3, 5	15
1.25" SCH 40 Standard-Wall PVC Pipe Fitting for Water, Union Connector, 1-1/4 Pipe Socket-Connect Female	4	35.44	0.463	3, 5	15
Standard-Wall SCH40 PVC Pipe Fitting for Water, White, Adapter with Hex, 1-1/4 Socket Male x NPT Male, .71" Thread Engagement	1	1.49	0.082	3, 5	15
1-1/4 Socket Male x 1-1/4 Socket Female, SCH 40, Standard-Wall PVC Pipe Fitting for Water, 90 Degree Adapter	3	6.54	0.172	3, 5	15
1-1/4" Standard-Wall SCH40 PVC Pipe Fitting for Water, 90 Degree Elbow Connector, White, 1-1/4 Socket Female	2	2.16	0.2	3, 5	15
Standard-Wall SCH 40 PVC Pipe Fitting for Water, Bushing Adapter with Hex, 1-1/4 Socket Male x 1 Socket Female	2	1.98	0.054	3, 5	15
1" SCH 40 Standard-Wall SCH 40 PVC Pipe Fitting for Water, 90 Degree Elbow Adapter, 1 Socket Male x 1 Socket Female	7	12.74	0.365	3, 5	10
1-1/4" SCH 40 Standard-Wall PVC Pipe Fitting for Water, 45 Degree Elbow Connector, White, 1-1/4 Socket Female	1	1.31	0.064	3, 5	15
Precision Flow-Adjustment Valve with Push-to-Connect Fittings, PVC, for 3/8" Tube OD	1	23.6	0.041	3, 5	15
1" SCH 40 Standard-Wall PVC Pipe Fitting for Water, Union Connector, 1 Pipe Size Socket-Connect Female	5	17.5	0.454	3, 5	15

Table 14 cont

Description	Qty	Total Cost	Total Mass (kg)	Unit Impacts	LCA Uncertainty
1" SCH 40 Standard-Wall PVC Pipe Fitting for Water, Side-Outlet Elbow Connector, 1 Socket-Connect Female	2	5.76	0.132	3, 5	15
1" SCH 40 Standard-Wall PVC Pipe Fitting for Water, 90 Degree Elbow Connector, White, 1 Socket-Connect Female	6	3.66	0.327	3, 5	15
1" Socket-Connect Female × Threaded NPT Female SCH 40 Standard-Wall PVC Pipe Fitting for Water, White, Adapter with Hex Body, 1 Socket Female x 1 NPT Female	2	1	0.064	3, 5	15
1" SCH 40 Standard-Wall PVC Pipe Fitting for Water, Cross Connector, 1 Pipe Size Socket-Connect Female	1	2.41	0.084	3, 5	15
1" Pipe Male to 1/4" NPT Female SCH 40 Standard-Wall PVC Pipe Fitting for Water, Bushing Adapter with Hex, 1 Socket Male x 1/4 NPT Female	2	2.08	0.059	3, 5	15
1/4" NPT SCH 80 Thick-Wall PVC Pipe Fitting for Water, Plug with Hex Drive Style, 1/4 NPT Male	1	2.21	0.008	3, 5	15
Standard-Wall PVC Pipe Fitting for Water, Bushing Adapter, 3/4 NPT Male x 3/8 NPT Female	1	0.9	0.016	3, 5	15
Push-to-Connect Fitting for Food and Beverage, Swivel Elbow, for 3/8" Tube OD x 3/8 NPTF Male, White. PP Plastic	3	20.04	0.041	12, 5	10, 15
Standard-Wall SCH40 PVC Pipe Fitting for Water, White, Adapter with Hex, 1-1/4 Socket Male x NPT Male, .71" Thread Engagement	1	1.49	0.082	3, 5	15
1-1/4 Socket Male x 1-1/4 Socket Female, SCH 40, Standard-Wall PVC Pipe Fitting for Water, 90 Degree Adapter	2	4.36	0.172	3, 5	15
1" SCH 40 Standard-Wall PVC Pipe Fitting for Water, White, Adapter with Hex Body, 1 Socket Female x 1 NPT Male	1	0.55	0.032	3, 5	15
1" SCH 40 Standard-Wall PVC Pipe Fitting for Water, 45 Degree Elbow Connector, White, 1 Socket-Connect Female	2	1.88	0.082	3, 5	15
Snug-Fit Vibration-Damping Loop Clamp, 304 Stainless Steel with Neoprene Rubber	1	2.33	0.033	1, 2	10

Table 14 cont

Description	Qty	Total Cost	Total Mass (kg)	Unit Impacts	LCA Uncertainty
Cushion, 2" ID					
Standard-Wall PVC Pipe Fitting for Water, Bushing Adapter with Hex, 1 Socket Male x 3/4 NPT Female	1	0.81	0.027	3, 5	15
Chemical-Resistant Barbed Tube Fitting for 3/4" Tube ID x 3/4 NPT Male, 150°F Maximum	2	2.32	0.017	12, 5	15
Vibration-Resistant Pinch Clamps for Firm Hose/Tube, Tight-Seal, 15/16" to 1-1/16" ID	4	1.94	0.017	1, 2	10
316 Stainless Steel Flanged Button Head Screw, 10-32 Thread, 1" Long	4	3.77	0.018	1, 2	10
Chemical-Resistant Plastic Routing Clamp for 2 Lines, 3/8" ID. PP Plastic	4	2.11	0.526	12, 5	15
18-8 Stainless Steel Button Head Hex Drive Screw, 1/4"-20 Thread Size, 3/4" Long	4	0.57	0.02	1, 2	10
18-8 Stainless Steel Button Head Hex Drive Screw, 5/16"-18 Thread Size, 1/2" Long	8	0.72	0.057	1, 2	10
18-8 Stainless Steel Socket Head Screw, 1/4"-20 Thread Size, 5/8" Long	4	0.77	0.023	1, 2	10
18-8 Stainless Steel Button Head Hex Drive Screw, 10-32 Thread Size, 1/4" Long	2	0.12	0.003	1, 2	10
PVC On/Off Valve for Drinking Water, PTFE/HDPE Seat, 1-1/4 Socket-Weld Female	1	16.34	0.25	3, 5	15
18-8 Stainless Steel Socket Head Screw, 10-32 Thread Size, 3/8" Long	1	0.08	0.0024	1, 2	10
Super-Corrosion-Resistant 316 Stainless Steel Socket Head Screw, 5/16"-18 Thread Size, 1/2" Long	4	1.76	0.039	1, 2	10
316 Stainless Steel Washer for 5/16" Screw Size, 0.344" ID, 0.75" OD	4	0.41	0.008	1, 2	10
Washdown DC Connector Set, Crimp on, Male Plug and Female Socket, 2 Poles, 25 Amps	1	16.84	0.032	24, 5	15
Washdown DC Connector Set, Crimp on, Male Plug and Female Socket, 3 Poles, 13 Amps	1	7.56	0.027	17	25
316 Stainless Steel Button Head Hex Drive Screw, Super-Corrosion-Resistant, 10-32 Thread Size, 3/8" Long	2	0.34	0.004	1, 2	10
18-8 Stainless Steel Button Head Hex Drive Screw, 1/4"-20 Thread Size, 7/8" Long	4	0.59	0.022	1, 2	10

Table 14 cont

Description	Qty	Total Cost	Total Mass (kg)	Unit Impacts	LCA Uncertainty
Compact Plastic Submersible Cord Grip, NPT Threads, for 0.24"-0.47" Cord OD, 1/2 Knockout Size (.875")	1	3.34	0.145	24, 5	15
Suction Bell, Make from MCM #4880K685, Standard-Wall PVC Pipe Fitting for Water, Reducer, 2 Socket Female x 1-1/2 Socket Female	1	5	0.187	3, 5	50
Return Line Diffuser (Make from Clear SCH 40 PVC Pipe)	1	10	0.363	3, 5	50
Inlet Drop Pipe	1	1	0.1	3, 5	50
Level Switch Nut Plate	2	10	0.25	1, 2	50
Level Switch Mounting Bracket	1	10	0.25	1, 2	50
Level Switch Bracket Standoff	2	20	0.0223	4, 5	15
5 Gallon Rinse Tank, White Polyethylene Semi-Translucent, 5/16-18 UNC Inserts, This 5 gallon cone bottom tank is 11" L x 11" W x 19" H. This tank has six 5/16-18 UNC inserts on one side and gallon graduations on the opposite side.	1	81.43	2.72	4, 5	15
1-1/4" Loose Thread x Thread PVC Bulkhead Fitting w/EPDM Gasket, Maximum tank wall thickness is 1.00". Minimum flexible tank radius is 12.19" and minimum rigid tank radius 16.25". Hole size required is 2.63".	1	26.89	0.363	3, 5	15
1" NPT Female Loose Thread x Thread PVC Bulkhead Fitting w/EPDM Gasket - 1.88" Hole Size, Maximum tank wall thickness is 1.08". Minimum flexible tank radius is 10.10" and minimum rigid tank radius 11.75". Hole size required is 1.88".	2	39.54	0.408	3, 5	15
1" SCH 40 Standard-Wall PVC Pipe Fitting for Water, 90 Degree Elbow Connector, White, 1 Socket-Connect Female	2	1.22	0.327	3, 5	15
1" Socket Male x 1" NPT Male SCH 40 Standard-Wall PVC Pipe Fitting for Water, White, Adapter with Hex Body, .68" Thread Engagement	3	3.63	0.082	3, 5	15
1" SCH 40 Standard-Wall PVC Pipe Fitting for Water, White, Adapter with Hex Body, 1 Socket Female x 1 NPT Male	1	0.55	0.032	3, 5	15

Table 14 cont

Description	Qty	Total Cost	Total Mass (kg)	Unit Impacts	LCA Uncertainty
1" SCH 40 Standard-Wall PVC Pipe Fitting for Water, Cap, White, 1 Pipe Size Socket-Connect Female	1	0.5	0.033	3, 5	15
Standard-Wall SCH40 PVC Pipe Fitting for Water, White, Adapter with Hex, 1-1/4 Socket Male x NPT Male, .71" Thread Engagement	2	2.98	0.082	3, 5	15
18-8 Stainless Steel Button Head Hex Drive Screw, 5/16"-18 Thread Size, 5/8" Long	6	1.32	0.048	1, 2	10
18-8 Stainless Steel Flanged Button Head Screw, 10-32 Thread, 3/8" Long	4	1.48	0.009	1, 2	10
Phillips Rounded Head Thread-Forming Screws for Plastic, 18-8 Stainless Steel, Number 10 Size, 3/4" Long	4	1.65	0.015	1, 2	10
1-1/4" Standard-Wall SCH40 PVC Pipe Fitting for Water, 90 Degree Elbow Connector, White, 1-1/4 Socket Female	1	1.08	0.2	3, 5	15
Standard-Wall SCH40 PVC Pipe Fitting for Water, White, Adapter with Hex, 1-1/4 Socket Male x NPT Male, .71" Thread Engagement	1	1.49	0.082	3, 5	15
GAC SYSTEM		**214.4**			
Standard-Wall SCH 40 PVC Pipe Fitting for Water, Union Connector, 4 Pipe Size Socket-Connect Female	2	88.2	1.61	3, 5	15
GAC Support Bracket	2	62	1.12	1, 2	10
#40 GAC Mesh Retainer, Make from MCM #9241T42, Wire Cloth, Sheets, 304 Stainless Steel, 40 x 40 Mesh, 0.0185" Opening	1	5	0.113	1, 2	50
Mesh Reinforcement, Make from MCM #85385T28, 304 Stainless Steel Wire Cloth, 4 x 4 Mesh Size, 0.203" Opening Size	1	5	0.114	1, 2	50
Foam Diffuser, Make from 80 PPI ZE80 CHAR FOAMEX RETICULATED POLYETHER OPEN CELL FOAM.	1	2	0.61	29	50
GAC Filter Diffuser Plate	1	10	0.27	1, 2	50
Diffuser Top Cap	2	40	1.16	3, 5	15
18-8 Stainless Steel Socket Head Screw, 1/4"-20 Thread Size, 1/2" Long	8	1.54	0.04	1, 2	10
Super-Corrosion-Resistant 316 Stainless Steel Socket Head Screw, 6-32 Thread Size, 1/4"	6	0.66	0.009	1, 2	10

Table 14 cont

Description	Qty	Total Cost	Total Mass (kg)	Unit Impacts	LCA Uncertainty
Long					
EC SYSTEM		**717.91**			
Gems CAP100 Non-Contact Capacitive Level Switch, L-type Non-Embeddable (no shielded for aqueous solution), 10-48 VDC Supply Voltage, 78" 3-wire Cable, Current Sourcing PNP, Max Load Current 300 ma	2	220	0.82 (total); 0.78 (nylon); 0.04 (LED)	8, 9	15
Stirrer Motor Mount	1	25	0.127	4, 5	10, 15
Ampflo Standard Series Motor, 150 Watt (.2 HP) Continuous Output, 79% Efficiency, No Load RPM at 24 VDC 3800, 3.0 lbs,12-24 VDC, with Pulley, 12 in Flying Leads	1	46	1.36	20*(1.36 kg/5.8kg)	25
MIXER TROEMNER INC 5/16 IN WX12 IN L, 303/304 Stainless Steel, 2" Blade Diameter, (Vendor: Grainger)	1	41.6	0.25	1, 2	10
303 Stainless Steel Set Screw Shaft Coupling for 5/16" Diameter Round Shaft	1	18	0.027	1, 2	10
Thick-Wall PVC Pipe Fitting for Water, Plug with Hex Drive Style, 3/8 NPT Male	1	2.21	0.005	3, 5	15
18-8 Stainless Steel Socket Head Screw, 10-32 Thread Size, 3/4" Long	3	0.34	0.011	1, 2	10
18-8 Stainless Steel Socket Head Screw, 10-32 Thread Size, 2-1/2" Long	3	1.04	0.029	1, 2	10
Washdown DC Connector Set, Crimp on, Male Plug and Female Socket, 2 Poles, 25 Amps	1	16.84	0.032	24, 5	15
Titanium EC Electrode Plate	3	40.62	0.084	25	25
EC Plate Mounting Rod, Make from MCM #89145K11 (Ultra-Corrosion-Resistant Grade 2 Titanium Rod, 1/8" Diameter x 6 Feet Long)	2	10	0.035	25	50
Titanium EC Rod Separator	2	10	0.91	25	50
Chemical-Resistant Polypropylene Socket Head Screws, 6-32 Thread Size, 1/2" Long	5	2.41	0.001	12, 5	15
Chemical-Resistant Polypropylene Hex Nut, 6-32 Thread Size	5	2.76	0.001	12, 5	15
Electrical-Insulating Polypropylene Plastic Isher for Number 6 Screw Size, 0.14" ID, 0.312" OD	20	9.34	0.005	12, 5	15
Non-insulated Screw-Down Butt Splices for 14-2 Wire Gauge, 1.19" Lg, 600V	2	7.48	0.018	13, 14	10

Table 14 cont

Description	Qty	Total Cost	Total Mass (kg)	Unit Impacts	LCA Uncertainty
Washdown DC Connector Set, Crimp on, Male Plug and Female Socket, 2 Poles, 25 Amps	1	16.84	0.032	24, 5	15
5 Gallon Rinse Tank, White Polyethylene Semi-Translucent, 5/16-18 UNC Inserts, This 5 gallon cone bottom tank is 11" L x 11" W x 19" H. This tank has six 5/16-18 UNC inserts on one side and gallon graduations on the opposite side.	1	58.75	2.72	4, 5	10, 15
Custom EC Tank Lid	1	30	0.594	4, 5	10, 15
Level Switch Nut Plate	2	10	0.25	1, 2	50
Level Switch Mounting Bracket	2	20	0.25	1, 2	50
Level Switch Bracket Standoff	4	40	0.0223	4, 5	10, 15
1-1/4 NPT Male x 1 NPT Female, SCH 40 Standard-Wall PVC Pipe Fitting for Water, Bushing Adapter	1	1.86	0	0	0
1" Socket Male x 1" NPT Male SCH 40 Standard-Wall PVC Pipe Fitting for Water, White, Adapter with Hex Body, .68" Thread Engagement	1	1.21	0.082	3, 5	15
1" SCH 40 Standard-Wall PVC Pipe Fitting for Water, Union Connector, 1 Pipe Size Socket-Connect Female	1	3.5	0.454	3, 5	15
18-8 Stainless Steel Flanged Button Head Screw, 10-32 Thread, 3/8" Long	4	1.48	0.009	1, 2	10
Easy-to-Clean Muffler, 1/4 NPT Male, Polyethylene, 60 scfm Flow Rate	1	3.42	0.002	12, 5	15
Push-to-Connect Fitting for Food and Beverage, Swivel Elbow, for 3/8" Tube OD x 3/8 NPTF Male, White. PP Plastic	1	6.68	0.041	12, 5	10, 15
18-8 Stainless Steel Button Head Hex Drive Screw, 5/16"-18 Thread Size, 5/8" Long	6	1.32	0.048	1, 2	10
Phillips Rounded Head Thread-Forming Screws for Plastic, Corrosion-Resistant 316 Stainless Steel, Number 8 Size, 3/4" Long, No. 29 0.136" Drill Bit Size, Drive Size #2, Plastite style	16	7.04	0.038	1, 2	10
18-8 Stainless Steel Twist-Resistant Hex-Shaped Inserts for Plastics, 10-32 Thread Size, 1/4" Drill Bit Size	3	1.58	0.002	1, 2	10

Table 14 cont

Description	Qty	Total Cost	Total Mass (kg)	Unit Impacts	LCA Uncertainty
1 IPS&1-1/4 CTS CLIC TOP GRAY PIPE CLAMP (CAD mounting hole dimensions are approximate)	5	25.25	0.05	3, 5	15
1-3/8 CLIC TOP SPACER/35 MM	5	18.55	0.05	6, 5	15
Mounting Flange Nut - Stainless Steel, 1/4-20, Fits Hanger Base to provide 1/4"-20 threaded rod, stud or bolt connection	5	3.3	0.023	1, 2	10
18-8 Stainless Steel Button Head Hex Drive Screw, 1/4"-20 Thread Size, 1-3/4" Long	5	1.32	0.045	1, 2	10
1" SCH 40 Standard-Wall PVC Pipe Fitting for Water, Tee Connector, White, 1 Size Socket-Connect Female	3	2.43	0.211	3, 5	15
1" Pipe Male to 1/4" NPT Female SCH 40 Standard-Wall PVC Pipe Fitting for Water, Bushing Adapter with Hex, 1 Socket Male x 1/4 NPT Female	3	3.12	0.059	3, 5	15
1/4" NPT SCH 80 Thick-Wall PVC Pipe Fitting for Water, Plug with Hex Drive Style, 1/4 NPT Male	3	6.63	0.008	3, 5	15
CONTROLS SYSTEM		**1560.91**			
Unitronics Jazz PLC, 24 VDC, 18 Digital Inputs, 20 PNP Digital Outputs, 117 x 89mm Panel Cutout, 5mm Max Panel Thickness	1	199	0.907	15	25
Socomec SIRCO M series rotary disconnect switch, load break capable, 3-pole, 600 VAC, 40A, 65kA SCCR, DIN rail or panel mount, UL 508 rated, front or side operated, accepts 5 x 5mm size shaft.	1	22.25	0.227	18	25
Enclosed AC DC Converter 1 Output 24V 10A 90 ~ 264 VAC, 127 ~ 370 VDC Input, Efficienty 88.5%, Digi-Key #1866-3520-ND	1	57.58	1	21*(1kg /0.03kg)	25
Enclosed AC DC Converter 1 Output 12V 10A 90 ~ 264 VAC, 127 ~ 370 VDC Input, Efficiency - 85.5%, DIN Rail Mounting, Digi-Key #1866-3517-ND	1	34.01	1	21*(1kg /0.03kg)	25
IronHorse GSD4 series DC general purpose drive, 120/240 VAC 1-phase, Output Voltage 0–90/180 VDC, 1/8 to 1/2hp at 90 VDC and 1/4 to 1hp at 180 VDC, 5.5A	1	71	0.298	15	25

Table 14 cont

Description	Qty	Total Cost	Total Mass (kg)	Unit Impacts	LCA Uncer tainty
Solid state relay, 35mm DIN rail mount, 3.5-32 VDC input voltage, SPST, N.O. MOSFET, 15A contact rating, DC Switching, LED indicator(s), hazardous location certified, 3-150 VDC Load Voltage	2	113.5	0.181	16	25
Fuji Electric IEC contactor, 18A, (3) N.O. power poles, 24 VDC coil voltage, 1 HP at 100-120 VAC Single Phase, 3 HP at 220-240 VAC Single Phase	1	34	0.59	17	25
Fuji Electric thermal overload relay, 5-7.5A adjustable, bi-metallic. For use with Fuji SC-E02(G), SC-E03(G), SC-E04(G), SC-E05(G) 43mm contactors.	1	25	0.118	17	25
WEG Electric CWC series IEC miniature contactor, 16A, (3) N.O. power poles, 24 VDC coil voltage, low consumption. (1) N.O. auxiliary contact included.	1	19	0.227	17	25
Polycarbonate Washdown Enclosure with See-Through Lift-Off Cover, 22" x 15" x 7", NEMA Class NEMA 1, 3, 3S, 4, 4X, 6, 6P, 12, MCM #69945K98	1	219.39	2	6, 5	10, 15
Electrical Enclosure Panel	1	50	1.48	13, 14	10
Wire Duct, Make from MCM #75835K13 Narrow-Slotted Wire Duct with Snap-on Cover, 3" High x 1" Wide, Grey	1	28.15	0.667	24, 5	10, 15
DIN Rail, Make from MCM #8961K19 Steel DIN 3 Rail, 15mm Deep, 2m Long	1	9.15	1.111	1, 2	10
Equipment-Cooling Fan, Guard with Filter, for 3.62" High Square Fan	1	2.72	0.027	12, 5	15
Plastic Fan Guard for 3.62" (92 mm) Fan	1	1.1	0.014	12, 5	15
316 Stainless Steel Nylon-Insert Locknut, Super-Corrosion-Resistant, 8-32 Thread Size	4	0.31	0.007	1, 2	10
316 Stainless Steel Washer for Number 8 Screw Size, 0.174" ID, 0.375" OD	4	0.14	0.002	1, 2	10
316 Stainless Steel Hex Drive Flat Head Screw, 82 Degree Countersink Angle, 8-32 Thread Size, 1" Long	4	1.48	0.024	1, 2	10
Socomec handle, round, S01 type, black/blue, external front or right side mount, 2-position, lockable in OFF only, defeatable. For use with NEMA 4/4X enclosures.	1	33	0.192	24, 5	15

Table 14 cont

Description	Qty	Total Cost	Total Mass (kg)	Unit Impacts	LCA Uncertainty
Socomec shaft, 200mm length, 5 x 5mm. For use with S01 type handles.	1	7.25	0.091	13, 14	25
DINnector fuse terminal block, with indicator for 220 V, accepts wire size 20-6 AWG, gray, 30A, 600V rated (UL), 35mm DIN rail mount. Package of 10. For use with ABC, AGC, MDA and MDL series fuses, For Use with Small Dimension Fuses 1/4" x 1-1/4"	10	54	0.327, 0.6	24, 21*(0.6kg/0.03kg)	15, 25
Edison fuse, MDA series, small dimension, 1/4" x 1-1/4", time-delay, 15A, 250 VAC, ceramic tube. Package of 5. Supplemental, electronic protection applications. Manufacturer part number: MDA-15-R.	1	2	0.004	28	25
Edison fuse, MDA series, small dimension, 1/4" x 1-1/4", time-delay, 3A, 250 VAC, ceramic tube. Package of 5. Supplemental, electronic protection applications. Manufacturer part number: MDA-3-R.	1	2	0.007	28	25
Edison fuse, MDA series, small dimension, 1/4" x 1-1/4", time-delay, 3A, 250 VAC, ceramic tube. Package of 5. Supplemental, electronic protection applications. Manufacturer part number: MDA-3-R.	1	2	0.007	28	25
Edison fuse, MDA series, small dimension, 1/4" x 1-1/4", time-delay, 5A, 250 VAC, ceramic tube. Package of 5. Supplemental, electronic protection applications. Manufacturer part number: MDA-5-R.	1	2	0.007	28	25
Edison fuse, MDA series, small dimension, 1/4" x 1-1/4", time-delay, 1A, 250 VAC, ceramic tube. Package of 5. Supplemental, electronic protection applications. Manufacturer part number: MDA-1-R.	1	2	0.004	28	25
Edison fuse, MDA series, small dimension, 1/4" x 1-1/4", time-delay, 8A, 250 VAC, ceramic tube. Package of 5. Supplemental, electronic protection applications. Manufacturer part number: MDA-8-R.	1	2	0.004	28	25

Table 14 cont

Description	Qty	Total Cost	Total Mass (kg)	Unit Impacts	LCA Uncertainty
Edison fuse, MDA series, small dimension, 1/4" x 1-1/4", time-delay, 5A, 250 VAC, ceramic tube. Package of 5. Supplemental, electronic protection applications. Manufacturer part number: MDA-5-R.	1	2	0.007	28	25
DINnector fuse terminal block, with indicator FOR 24 VDC, accepts wire size 20-6 AWG, gray, 30A, 600V rated (UL), 35mm DIN rail mount. Package of 10. For use with ABC, AGC, MDA and MDL series fuses, 1/4" x 1-1/4"	11	59.4	0.409	24	15
Edison fuse, MDA series, small dimension, 1/4" x 1-1/4", time-delay, 10A, 250 VAC, ceramic tube. Package of 5. Supplemental, electronic protection applications. Manufacturer part number: MDA-10-R.	1	2	0.007	28	25
Edison fuse, MDA series, small dimension, 1/4" x 1-1/4", time-delay, 10A, 250 VAC, ceramic tube. Package of 5. Supplemental, electronic protection applications. Manufacturer part number: MDA-10-R.	1	2	0.007	28	25
Edison fuse, MDA series, small dimension, 1/4" x 1-1/4", time-delay, 15A, 250 VAC, ceramic tube. Package of 5. Supplemental, electronic protection applications. Manufacturer part number: MDA-15-R.	1	2	0.004	28	25
Low-Voltage Equipment-Cooling Fan, 24V DC with Wire Leads, 3.62" Square x 1" Deep Overall, 60 CFM	1	30.81	0.105	6, 5	15
Equipment-Cooling Fan, Guard with Filter, for 3.62" High Square Fan	1	2.72	0.027	12, 5	15
Plastic Fan Guard for 3.62" (92 mm) Fan	1	1.1	0.014	12, 5	15
316 Stainless Steel Washer for Number 8 Screw Size, 0.174" ID, 0.375" OD	4	0.14	0.002	1, 2	10
316 Stainless Steel Nylon-Insert Locknut, Super-Corrosion-Resistant, 8-32 Thread Size	4	0.31	0.007	1, 2	10
316 Stainless Steel Hex Drive Flat Head Screw, 82 Degree Countersink Angle, 8-32 Thread Size, 2" Long	4	3.3	0.019	1, 2	10
Relay socket, 35mm DIN rail or panel mount. For use with 781 series cube relays.	1	4	0.045	17	25

Table 14 cont

Description	Qty	Total Cost	Total Mass (kg)	Unit Impacts	LCA Uncertainty
Ice cube control relay, socket mount, 24 VDC coil voltage, SPDT, 15A contact rating, 5-pin configuration, LED indicator, push-to-test. Purchase 781-1C-SKT mounting socket separately.	1	4	0.045	17	25
Fuji Electric selector switch, 22mm, 2-position, maintained, LED illuminated, (1) N.O. contact(s), plastic base, metal bezel, Operator: blue, knob, 30mm, round, plastic, 24 VAC/VDC, full voltage, 7/8" Panel Cutout	1	29	0.0454	18	25
DINnector triple-level terminal block, accepts wire size 26-14 AWG, gray, 10A, 300V rated (UL), 35mm DIN rail mount. Package of 25.	16	26.24	0.319	17	25
DIN Rail Mounting Clip, Black, 35mm width, RoHS, M4 Countersink Mounting Holes	1	1.8	0.017	27	10
EC Control Board	1	10	0.0003	15	50
EC Display Board Assy	1	5	0.017	15	50
EC Board Mount	1	20	0.001	15	50
316 Stainless Steel Hex Drive Flat Head Screw, 82 Degree Countersink Angle, 6-32 Thread Size, 1/2" Long	3	0.77	0.008	1, 2	10
Super-Corrosion-Resistant 316 Stainless Steel Socket Head Screw, 4-40 Thread Size, 1/4" Long	4	0.42	0.003	1, 2	10
316 Stainless Steel Button Head Hex Drive Screw, Super-Corrosion-Resistant, 1/4"-20 Thread Size, 1/2" Long	4	1.33	0.016	1, 2	10
316 Stainless Steel Thin Hex Nut, Super-Corrosion-Resistant, 1/4"-20 Thread Size	8	0.66	0.019	1, 2	10
DINnector grounding terminal block, accepts wire size 24-10 AWG, green and yellow, 35mm DIN rail mount. Package of 10. Use to mechanically and electrically connect wires to 35mm DIN rail through the clamping foot.	4	9.8	0.073	17	25
DINnector triple-level terminal block end cover, gray. Package of 25. For use with DN-TL14 series terminal blocks.	1	0.4	0.004	17	25
Super-Corrosion-Resistant 316 Stainless Steel Socket Head Screw, 8-32 Thread Size, 1/4" Long	4	0.53	0.005	1, 2	10

Table 14 cont

Description	Qty	Total Cost	Total Mass (kg)	Unit Impacts	LCA Uncertainty
18-8 Stainless Steel Socket Head Screw, 1/4"-20 Thread Size, 1" Long	4	1.19	0.033	1, 2	10
80mm x 20mm x 90mm Straight Mounting Adapters for DIN Rail, DIN Rail Mounting Fasteners Included	2	10.46	0.168	1, 2	10
Male-Female Threaded Hex Standoff, Aluminum, 3/8" Hex Size, 3" Long, 8-32 Thread Size	5	11.6	0.085	13, 14	10
DINnector terminal block jumper, push-in type, 12-pole, blue. Package of 10. For use with DN-TL14-A, DN-TL14S-A, DN-TL14SLP or DN-14SLN-A series terminal block.	1	1.5	0.003	17	25
DINnector screw-down end bracket, 9mm wide. Package of 20. For use with 35mm DIN rail.	1	0.9	0.016	12, 5	25
DINnector double-level terminal block, with diode, connected between levels, accepts wire size 24-10 AWG, gray, 30A, 600V rated (UL), 35mm DIN rail mount. Package of 50. For use with jumpers DN-24J4Y, DN-2J4Y and DN-3J4Y.	6	14.28	0.12	17	25
Relay socket, 35mm DIN rail or panel mount. For use with 781 series cube relays.	2	8	0.045	17	25
Ice cube control relay, socket mount, 12 VDC coil voltage, SPDT, 15A contact rating, 5-pin configuration, LED indicator, push-to-test. Purchase 781-1C-SKT mounting socket separately.	2	8.9	0.091	17	25
Multi-Cord Grip, Liquid-Tight, Black Nylon, for 3 Cords, 0.24"-0.28" OD, 3/4" Trade Size (1.109") Knockout	2	12.48	0.059	24, 5	15
Multi-Cord Grip, Liquid-Tight, Black Nylon, for 4 Cords, 0.31"-0.35" OD	1	9.65	0.045	24, 5	15
Multi-Cord Grip, Liquid-Tight, Black Nylon, for 6 Cords, 1 Knockout Size (1.375"), For Cord OD 0.22"-0.26"	1	9.2	0.052	24, 5	15
Compact Plastic Submersible Cord Grip, NPT Threads, for 0.24"-0.47" Cord OD, 1/2 Knockout Size (.875")	2	6.68	0.145	24, 5	15

Table 14 cont

Description	Qty	Total Cost	Total Mass (kg)	Unit Impacts	LCA Uncertainty
316 Stainless Steel Pan Head Phillips Screw, Super-Corrosion-Resistant, 1/4"-20 Thread Size, 1/4" Long	4	1.59	0.017	1, 2	10
316 Stainless Steel Pan Head Phillips Screw, Super-Corrosion-Resistant, 10-32 Thread Size, 1/4" Long	20	4.2	0.042	1, 2	10
Enclusure Fan Vent Duct	2	70	0.98	1,2	10
Vent Sealing Foam Assy, Make from MCM #8694K136 Light Duty Blended EPDM Foam Strip with Adhesive Back, 6" Wide, 1/4" Thick, 50 Feet Long	2	2.52	0.077	29	50
18-8 Stainless Steel Press-Fit Nut for Sheet Metal, 10-32 Thread Size, for 0.09 Minimum Panel Thickness, 1/4" Drill Bit Size	2	1.45	0.005	1, 2	10
18-8 Stainless Steel Socket Head Screw, 10-32 Thread Size, 3/8" Long	2	0.16	0.0024	1, 2	10
Cable, SJOOW, Black Outer Insulation, 14 Gauge, 2 Wires	2	50	0.282	11	25
Cable, SJOOW, Black Outer Insulation, 14 Gauge, 3 Wires, .37" OD	2	52.8	4. 54	11	25
Control Cable, Two 18-Gauge Wires	2	69.6	16.52	11	25
MISCELLANEOUS		**3,657.65**			
Robust Single Diaphragm Design Sink & Shower Drain Pump, 12V Flow rate: Nominal 16 Liters/min (4.2 US gallons/min)	1	186.71	2.98	23*(72 W/40W)	25
Vibration- and Corrosion-Resistant Pressure Gauge, 1/4 NPT Male Center Back Connection, 2-1/2" Dial, 0-60 PSI	1	50.58	0.238	1, 2	15
Power Entry Connector Receptacle, Male Blades IEC 320 (S16 Variant) Panel Mount, Bulkhead, IP67/69K - Dust Tight, Water Resistant, Waterproof, UL 15A 250 VAC, Termination - Quick Connect - 0.250" (6.3mm), Digi-Key #486-4361-ND	2	74.2	0.14	10	25
Fuji Electric indicating light, IP65, 22mm, LED illuminated, blue, round, plastic base, metal bezel, 24 VAC/VDC, full voltage, 22.3mm Mounting Hole, 1-6mm Panel Thickness	4	88	0.0452	9	15

Table 14 cont

Description	Qty	Total Cost	Total Mass (kg)	Unit Impacts	LCA Uncertainty
1" SCH 40 Standard-Wall PVC Pipe Fitting for Water, Tee Connector, White, 1 Size Socket-Connect Female	1	0.81	0.211	3, 5	15
1" Pipe Male to 1/4" NPT Female SCH 40 Standard-Wall PVC Pipe Fitting for Water, Bushing Adapter with Hex, 1 Socket Male x 1/4 NPT Female	1	1.04	0.059	3, 5	15
Tube Routing	1	20	1.58	3, 5	15
Flexible Tubing Assy	1	10	0.04	3, 5	50
Discharge Pump Tube, Make from Trident Marine Hose & Propane #147-0340 (Series 147 Extra Heavy-Duty Bilge and Livewell Hose), Available at Fischeries Supply #HOS 147-0340	1	2.2	0.198	3, 5	50
Polycarbonate Washdown Enclosure with Gray Lift-Off Cover, 3-7/8" x 3-7/8" x 3"	1	23.37	0.22	6, 5	10, 15
18-8 Stainless Steel Unthreaded Spacer, 1/2" OD, 1-3/4" Long, for Number 8 Screw Size	4	35.8	1.56	1, 2	15
Super-Corrosion-Resistant 316 Stainless Steel Socket Head Screw, 8-32 Thread Size, 2-1/2" Long	4	3.08	0.031	1, 2	10
Compact Plastic Submersible Cord Grip, NPT Threads, for 0.24"-0.47" Cord OD, 1/2 Knockout Size (.875")	1	3.34	0.145	24, 5	15
Redi-Vent with PVC Adapter Valve, 1-1/2" NPT Male Thread, Available from Home Depot	1	18.52	0.273	3, 5	15
Thick-Wall PVC Pipe Fitting for Water, Connector with Hex Body, 1-1/2 NPT Female	1	9.37	0.122	3, 5	15
Chemical-Resistant Barbed Tube Fitting for 3/4" Tube ID x 3/4 NPT Male, 150°F Maximum	1	1.16	0.017	12, 5	15
Thick-Wall PVC Pipe Fitting for Water, Bushing Reducing Adapter, 1-1/2 x 3/4 NPT	1	4.62	0.054	3, 5	15
Adjustable Plastic Clamping Hanger, 2-1/8" to 2-1/2" ID	1	3.65	0.036	24, 5	15
Vibration-Resistant Pinch Clamps for Firm Hose/Tube, Tight-Seal, 15/16" to 1-1/16" ID	1	0.48	0.017	1, 2	10
316 Stainless Steel Flanged Button Head Screw, 1/4"-20 Thread, 5/8" Long	1	0.78	0.006	1, 2	10

Table 14 cont

Description	Qty	Total Cost	Total Mass (kg)	Unit Impacts	LCA Uncertainty
18-8 Stainless Steel Press-Fit Nut for Sheet Metal, 1/4"-20 Thread Size, for 0.125" Minimum Panel Thickness, 11/32 Drill Bit Size	1	1.4	0.006	1, 2	10
Chemical-Resistant Barbed Tube Fitting, Tee Connector, for 3/4" Tube ID, 150°F Maximum Temperature	1	1.05	0.013	12, 5	15
Vibration-Resistant Pinch Clamps for Firm Hose/Tube, Tight-Seal, 15/16" to 1-1/16" ID	3	1.45	0.017	1, 2	10
Adjustable Plastic Clamping Hanger, 1" to 1-1/16" ID	1	1.1	0.009	24, 5	15
316 Stainless Steel Flanged Button Head Screw, 8-32 Thread, 1/2" Long	1	0.45	0.002	1, 2	10
Blackwater Housing Master	1	2859.5	67	13, 14	10
Leveling Foot, Make from MCM #2531K340 (Bolt-Down Swivel Leveling Mount with Cushion, 4" Long 3/8"-16 Threaded Stud and 2" Base Diameter)	4	47.8	0.435	1, 2	15
Housing Hinge, Make from MCM #1581A560 (Surface-Mount Piano Hinge, 5052 Aluminum, 2" Overall Width, 0.430" Knuckle Diameter, 5052 Aluminum)	1	50	0.91	13, 14	10
Handle Pocket	1	20	0.333	13, 14	10
Window, Make from MCM #8574K263 (Clear Polycarbonate Sheet, 12" x 36" x 1/8") or similar	1	20.57	1.09	6, 5	10, 15
Drawer Wear Strip, Make from MCM #7701T211 (UHMW Strip, Adhesive-Back, 1" Wide, 1/16" Thick)	4	9.92	0.117	12	50
18-8 Stainless Steel Hex Drive Flat Head Screw, 8-32 Thread Size, 3/8" Long	2	0.1	0.003	1, 2	10
18-8 Stainless Steel Press-Fit Nut for Sheet Metal, 3/8"-16 Thread Size, for 0.125" Minimum Panel Thickness, 1/2" Drill Bit Size	4	9.44	0.024	1, 2	10
Aluminum Blind Rivets with Aluminum Mandrel, Flush-Mount, 1/8" Diameter, for 0.1880"-0.25" Material Thickness, for #30 Drill, .129-.133" Hole Size, 120 Deg Countersink Angle, .22" Head Diameter, 120 lb Shear Strength, 150 lb Tensile Strength	24	2.53	0.013	12, 14	10

Table 14 cont

Description	Qty	Total Cost	Total Mass (kg)	Unit Impacts	LCA Uncertainty
18-8 Stainless Steel Press-Fit Nut for Sheet Metal, 1/4"-20 Thread Size, for 0.125" Minimum Panel Thickness, 11/32 Drill Bit Size	12	16.75	0.006	1, 2	10
18-8 Stainless Steel Press-Fit Nut for Sheet Metal, 10-32 Thread Size, for 0.09 Minimum Panel Thickness, 1/4" Drill Bit Size	7	5.06	0.005	1, 2	10
18-8 Stainless Steel Nylon-Insert Locknut, 4-40 Thread Size	2	0.08	0.001	1, 2	10
18-8 Stainless Steel Hex Drive Flat Head Screw, 4-40 Thread Size, 1/2" Long	2	0.07	0.001	1, 2	10
18-8 Stainless Steel Press-Fit Nut for Sheet Metal, 5/16"-18 Thread Size, for 0.09 Minimum Panel Thickness, Drill Bit Size Z .413"	8	15.9	0.062	1, 2	10
Surface Mount Magnetic Latch, 12 lbs. Maximum Pull, White Plastic	1	10.45	0.111	12, 5	15
18-8 Stainless Steel Hex Drive Flat Head Screw, 4-40 Thread Size, 1/4" Long	4	0.15	0.07	3, 5	15
18-8 Stainless Steel Press-Fit Nut for Sheet Metal, 5/16"-18 Thread Size, for 0.09 Minimum Panel Thickness, Drill Bit Size Z .413"	4	7.95	0.031	1, 2	10
Tree Leds Marine Led Utility Strip Light for Boats 12 Volts (Pack of 2), Waterproof, Blue	2	14	0.04	9	25
Cable Holders Adhesive Mount Cable Tie, 4-5/8" Lg, Pack of 10	5	3.18	0.016	24, 5	15
Draw Latch, Screw on, Powder-Coated Zinc, 3-5/16" Long x 1-3/8" Wide	1	19.6	0.13	26	15
316 Stainless Steel Hex Drive Flat Head Screw, 82 Degree Countersink Angle, 4-40 Thread Size, 1/4" Long	4	0.88	0.007	1, 2	10
316 Stainless Steel Hex Drive Flat Head Screw, 82 Degree Countersink Angle, 4-40 Thread Size, 5/16" Long	2	0.55	0.003	1, 2	10
TOTAL		**7,994.86**			

Table 15. *Cost reductions have been made from the original materials list (Table 14) where cheaper alternatives are available.*

DESCRIPTION	JUSTIFICATION	BOM COST ($)	REVISED COST ($)
UF SYSTEM		**1,821.49**	**1,476.81**
Goulds LB0712TE LB Series Booster Pump, 3/4 HP, 115-230 Volt, 60 Hz, Single Phase, 3500 RPM, Noryl 5" Impeller, TEFC - Totally Enclosed Fan Cooled Motor Enclosure, 1 1/4" NPT Suction, 1" NPT Discharge, Dual Rated 50/60 Hz	Value engineering efforts have been made to reduce the power of the current pump or use a different pump	519.68	175
CONTROLS SYSTEM	**PLCs will be replaced with embedded controls in production (reduce cost of controls system by 40%)**	**1,560.91**	**936.55**
MISCELLANEOUS		**3,657.65**	**2,216.19**
Robust Single Diaphragm Design Sink & Shower Drain Pump, 12V Flow rate: Nominal 16 Liters/min (4.2 US gallons/min)	Power demand is less than that for filtration pump	186.71	175
Blackwater Housing Master	Robust housing is unnecessary and may eventually be removed (reduce cost by 50%)	2859.5	1429.75
TOTAL		**7,994.86**	**5,584.34**

Table 16. *The table provides an explanation for the selection of LCA uncertainty intervals listed in Table 14.*

Uncertainty	Justification
10%	Mass and materials are known for item in BOM and eco-invent has an entry that matches
15%	Use extrusion rather than casting
	A surrogate material was used (e.g. nylon for polymide)
	Mass was aggregated to one material to simplify
	Created eco-invent entry from existing inventory
	Casting is ignored
25%	Eco-invent item is a general form of product listed in BOM (e.g. electronic for controls)
	Eco-invent item is scaled proportionate to product specifications (e.g. impacts of 40W eco-invent pump multiplied by 72/40 for 72W discharge pump)
50%	BOM description is too vague to accurately match with eco-invent item

Table 17. *The estimated lifetime of materials that have an expected lifetime less than that of the overall system (20 years) are listed.*

Description	Lifetime (yrs)
UF	
Goulds LB0712TE LB Series Booster Pump, 3/4 HP, 115-230 Volt, 60 Hz, Single Phase, 3500 RPM, Noryl 5" Impeller, TEFC - Totally Enclosed Fan Cooled Motor Enclosure, 1 1/4" NPT Suction, 1" NPT Discharge, Dual Rated 50/60 Hz	10 [±25%]
PE substrate/PVDF membrane/PVC housing/0.5" id/0.02 um/72"L/1 tube, Filtrate Port (Qty 1) 3/4” NPT Female, Retentate Ports 1 1/4” pipe stub, Housing Diameter 1 1/4” Sc80, Module Length 72” (1829 mm), Max Differential Pressure 120 psi (827 kPa) at 25°C	3 [±10%]
Motorized Electric Ball Valve - 2-Way DC - 1", 2.5N.m, Stainless Steel, 12V - ON/OFF	5 [±50%]
Gems CAP100 Non-Contact Capacitive Level Switch, L-type Non-Embeddable (no shielded for aqueous solution), 10-48 VDC Supply Voltage, 78" 3-wire Cable, Current Sourcing PNP, Max Load Current 300 ma	10 [±25%]
EC	
Gems CAP100 Non-Contact Capacitive Level Switch, L-type Non-Embeddable (no shielded for aqueous solution), 10-48 VDC Supply Voltage, 78" 3-wire Cable, Current Sourcing PNP, Max Load Current 300 ma	10 [±25%]
Stirrer Motor Mount	5 [±50%]
Ampflo Standard Series Motor, 150 Watt (.2 HP) Continuous Output, 79% Efficiency, No Load RPM at 24 VDC 3800, 3.0 lbs,12-24 VDC, with Pulley, 12 in Flying Leads	5 [±50%]
MIXER TROEMNER INC 5/16 IN WX12 IN L, 303/304 Stainless Steel, 2" Blade Diameter, (Vendor: Grainger)	5 [±50%]
303 Stainless Steel Set Screw Shaft Coupling for 5/16" Diameter Round Shaft	5 [±50%]
Thick-Wall PVC Pipe Fitting for Water, Plug with Hex Drive Style, 3/8 NPT Male	5 [±50%]
18-8 Stainless Steel Socket Head Screw, 10-32 Thread Size, 3/4" Long	5 [±50%]
18-8 Stainless Steel Socket Head Screw, 10-32 Thread Size, 2-1/2" Long	5 [±50%]
Washdown DC Connector Set, Crimp on, Male Plug and Female Socket, 2 Poles, 25 Amps	5 [±50%]
Titanium EC Electrode Plate	2 [±10%]
EC Plate Mounting Rod, Make from MCM #89145K11 (Ultra-Corrosion Resistant Grade 2 Titanium Rod, 1/8" Diameter x 6 Feet Long)	2 [±10%]
Titanium EC Rod Separator	2 [±10%]
Chemical-Resistant Polypropylene Socket Head Screws, 6-32 Thread Size, 1/2" Long	2 [±10%]
Electrical-Insulating Polypropylene Plastic Washer for Number 6 Screw Size, 0.14" ID, 0.312" OD	2 [±10%]
Non-insulated Screw-Down Butt Splices for 14-2 Wire Gauge, 1.19" Lg, 600V	2 [±10%]
Washdown DC Connector Set, Crimp on, Male Plug and Female Socket, 2 Poles, 25 Amps	2 [±10%]
Miscellaneous	

Table 17 cont

Description	Lifetime (yrs)
Robust Single Diaphragm Design Sink & Shower Drain Pump, 12V Flow rate: Nominal 16 Liters/min (4.2 US gallons/min)	10 [±10%]