Preliminary Report

Techno-Economic Analysis (TEA) of a Duke Reinvent the Toilet System

Ultrafiltration, Granular Activated Carbon, and Electrolysis
Liquid Treatment System (The Reclaimer)

By John T. Trimmer, Hannah A.C. Lohman, Diana M Byrne, Jeremy S. Guest

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Executive Summary

This techno-economic analysis (TEA) estimates the user costs associated with a Reinvent the Toilet (RTT) system that integrates ultrafiltration (UF), granular activated carbon (GAC), and electrochemical (EC) disinfection. This report summarizes preliminary results and suggests possible strategies for improving economic outcomes and priorities for further exploration of the system. In what we consider to be the most probable scenario (the base case), the expected system cost is $0.17 per user per day, with the UF component system representing the largest fraction (61%) of this total. Pumping energy demands account for nearly half (47%) of the UF system cost. The GAC system cost is controlled by operational expenses related to GAC media replacement (75%), although the GAC replacement period is highly uncertain. While the EC system requires energy for the EC cell and stirrer, initial capital is its main cost driver (54%).

Based on the results of scenario analyses, several measures may reduce costs. These include minimizing general operating and maintenance (O&M) requirements, working with local suppliers to ensure low electricity and GAC media prices, securing low- or no-interest loans, adding a second UF membrane unit, scaling-up production to minimize construction costs, and taking measures to increase UF membrane flow rate or GAC media longevity. Under conditions incorporating these changes (the best case), the cost of the overall system may drop to approximately $0.08 per user per day.

Broadly, the uncertainties associated with this preliminary analysis are considerable, and we do not yet have sufficient information to rigorously model treatment performance of the system. Moving forward, we propose treating these preliminary recommendations as suggestions for future experimentation and testing. Key factors related to system design include the following:

- Increasing the number of UF membrane units to reduce pumping energy requirements;
- Testing whether permeate flux can be increased without sacrificing permeate quality;
- Characterizing GAC media life and the factors governing longevity;
- Understanding the drivers of EC cell treatment performance, and comparing the performance and pretreatment needs of alternative disinfection approaches;
- Characterizing treatment performance of each individual component and what factors drive performance.

Further experimentation and field testing focused on these specific topic areas will enable more rigorous model development, and these efforts may lead to a more robust and cost-effective system.

Introduction

This report presents the preliminary findings from a techno-economic analysis (TEA) of a Reinvent the Toilet (RTT) system that combines ultrafiltration (UF), granular activated carbon (GAC), and electrochemical (EC) disinfection for treatment of liquids (urine and flushing/cleansing water). Broadly, these findings provide estimates of the likely costs per user per day associated with the system and identify possible strategies and focus areas for improving the existing system's financial feasibility. However, as this system has not yet been field-tested, our estimates are associated with a large degree of uncertainty. Several uncertain parameters may be affected by influent concentrations and desired levels of treatment, but we do not yet have sufficient performance data to reliably relate these factors to cost. At this point, we cannot state that recommended cost reduction strategies will definitely maintain comparable levels of performance as those expected from the current design. Rather, we hope these recommendations can provide opportunities for ongoing collaboration to better understand and advance the system together.

Techno-economic analysis (TEA) methodology and scope

Generally, TEA provides a framework for assessing the economic viability of one or more technologies (Short et al., 1995). The centerpiece of a TEA is often a discounted cash flow analysis, which tracks expenses and incomes throughout a technology's life cycle. It includes initial capital costs (for example, construction materials and labor), ongoing operating costs (for example, electricity consumption or periodic maintenance), end-of-life costs (for example, disposal of spent materials), and revenue streams (for example, user fees or recovered resources). As these cash flows may occur over many years, a discount rate (determined by the interest rate on a loan, for example) adjusts the value of each cost or income stream to account for the diminishing value of money over time. For the current system, the objective is to estimate the daily user fee necessary to account for the entire system cost, and to compare this user fee with the goal of $0.05 per user per day.

Data collection and assumptions. This analysis was based primarily on documentation regarding system design and preliminary testing, information on construction materials in a preliminary bill of materials (BOM), and discussions with the Duke team. However, several assumptions were required to undertake a complete TEA. While many of the major materials needed to construct the system were listed in the BOM, detailed cost information on other items (e.g., piping, fittings) was not available. In some cases, preliminary estimates for prototype assemblies (electrodes, stirrer) were provided, but final prices (with markups) had not yet been set. Conversely, costs for prototypes are likely to be far higher than the costs of similar items produced and purchased at scale for widespread implementation. Accordingly, we used available prices from the BOM whenever possible, incorporated other items from the RTT system assessed in our previous report (August 31, 2018), found our own cost estimates for some additional items (all specific materials included in our capital cost estimate are listed in **Appendix I**), and assumed any remaining material or manufacturing costs would be incorporated into a labor markup (**Table 1**). Similarly, regarding ongoing operation and maintenance (O&M), we were able to develop detailed estimates for certain aspects of the system, such as electricity needs and the likely cost of granular activated carbon (GAC) filter media, based on information from the Duke team and additional research. However, estimating how often certain components of the system may require maintenance or how much a caretaker might be paid to perform this maintenance is more difficult. Therefore, in addition to specific costs associated with ongoing operation (e.g., electricity, GAC replacement), we also applied an annual cost for general O&M, estimated as a small percentage of initial capital cost (**Table 1**). Our analysis of the overall system was based on the individual analysis of each component system (UF, GAC, EC; specific assumptions and calculations associated with each component system can be found in **Appendices II-IV**).

Uncertainty and sensitivity analyses. Given that the exact future costs of all individual components cannot be guaranteed, a key aspect of our TEA methodology (and our general design philosophy) involves the incorporation of uncertainty and sensitivity analyses. While we first analyzed a "base case" in which we assumed a single value for each uncertain parameter that we believed to be most likely, the uncertainty analysis enabled us to go beyond this one scenario. We defined distributions that are likely to contain most or all possible values of uncertain parameters (**Table 1**), and then we ran numerous simulations in which random values for all uncertain parameters are pulled from the distributions we have defined. For this project, we ran 10,000 simulations with parameter values generated through Latin hypercube sampling (McKay et al., 1979). This process produced a distribution of costs defining the range in which system costs are likely to fall.

Table 1. Parameters varied in the uncertainty analysis. For each parameter, the assumed value reflects the base case assumption. The expected range and distribution type define the distribution of values used in the uncertainty analysis. For triangular distributions, the peak occurs at the assumed value.

Parameter	Unit	Assumed value	Expected range	Distribution type	Reference(s)
Discount rate	%	2%	1-5%	Triangular	African Development Bank
Income tax rate	%	28%	20-35%	Triangular	http://taxsummaries.pwc.com
Construction labor	% of construction materials	25%	15-35%	Uniform	assumption
General O&M	% of initial capital cost	5%	2-8%	Uniform	Hutton & Varughese, 2016
Electricity cost	USD per kWh	$0.06	$0.04-0.10	Triangular	http://eskom.co.za; https://data.gov.in
Membrane pressure	bar	2.25	0.5 – 3.5	Uniform	Hawkins et al., 2018
Membrane cross flow velocity	m/s	3.8	3.5 – 5.6	Uniform	Hawkins et al., 2018; Porex membrane specifications
Permeate flow rate per membrane	L/hr	7.5	7.5 – 10	Triangular	Duke team, assumption
GAC cost	USD per kg	$3.00	$0.29-5.00	Triangular	Duke team
GAC replacement period	L treated	10,000	2,000-20,000	Uniform	Duke team, assumption
GAC bulk density	kg per m^3	450	400-500	Uniform	https://tigg.com
Fraction of GAC column filled	%	80%	75-85%	Uniform	Duke team, assumption
EC cell energy per liter treated	Wh/L	6.0	5.6-6.4	Uniform	Duke team, assumption
Electric current in liquid influent	A	4	4-8	Triangular	Duke team
Stirrer power requirement	W	24	18-30	Uniform	assumption
Discharge pump flow rate	L/min	15	8-16	Uniform	Pump specs, assumption
Electrode assembly cost	USD	$54	$45-$200	Triangular	Duke team, multiple vendors
Stirrer assembly cost	USD	$150	$125-$150	Triangular	Duke team, multiple vendors

We also considered several unique sensitivity scenarios to investigate the impact of altering a single parameter in the model. Many of the most important uncertain parameters were included in these additional sensitivity scenarios. Some scenarios also examined a few key assumptions that were not incorporated into the uncertainty analysis (20-year system lifetime, 180-liter influent flow rate per day, wiping or washing culture). Additional scenarios considered possible alterations to the design of certain components systems (increasing the number of UF units, changing the geometry of the GAC column). The base case, uncertainty analysis, and all sensitivity scenarios incorporated a discounted cash flow analysis that used a 20-year analysis period and linear depreciation of the system over its lifetime. End-of-life disposal costs were excluded.

Scenario analysis. Finally, by combining various beneficial modifications identified through the sensitivity analyses, we estimated an idealized best-case economic scenario for the system. Essentially, this scenario explores the general economic environment, system design and construction, and operating conditions that would be most conducive to reducing system cost.

Existing system estimates

Base case. Under the scenario in which all parameters are assigned their assumed values, the overall system cost is estimated to be $0.17 per user per day (**Figure 1a**). Notably, this cost is based on pump sizing calculations suggesting a smaller pump (0.5 hp) may be able to replace the pump that is currently specified within the UF system (0.75 hp). With the larger pump, the total cost would be $0.20 per user per day. Separately, the UF system costs $0.11 ($0.13 with the larger 0.75 hp pump), the GAC system costs $0.03, and the EC system is $0.04 (discrepancies between the overall cost and the sum of individual components are due to rounding and items not classified under a single component). Different types of expenses drive the cost of each component system. Energy needed for pumping accounts for nearly half (47%) of the UF system cost, even when using the smaller pump size. In contrast, the GAC system requires no operational energy. Its cost is controlled by operational expenses related to GAC media replacement (75%), although our assumption regarding the GAC replacement period (**Table 1**) is highly uncertain. The EC system does require some energy for the EC cell and stirrer, but initial capital is the main cost driver (54%).

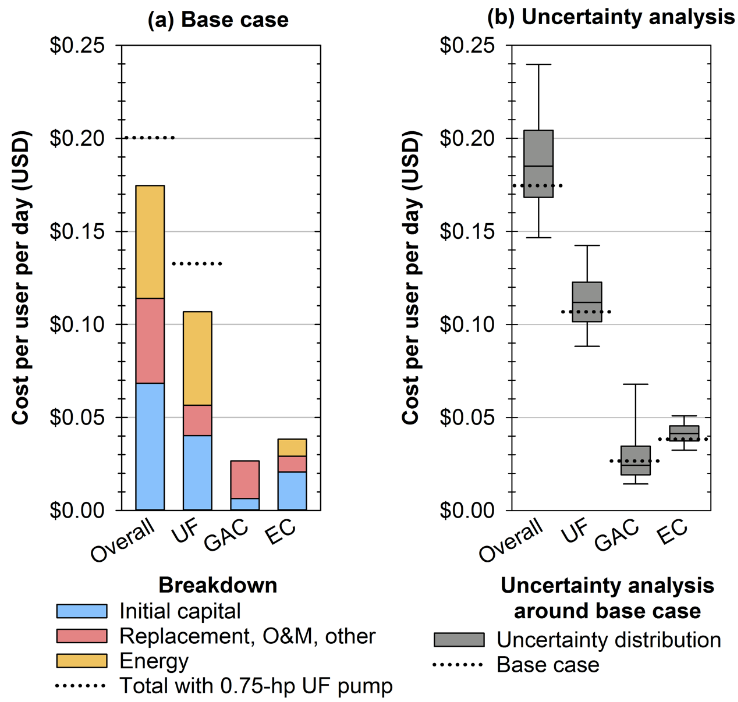

Figure 1. Estimated costs per user per day for the overall system and its three major component systems (UF, GAC, EC). The base case **(a)** reflects the scenario in which all parameters are set to their assumed values (**Table 1**). Total cost is broken down to show the portions coming from initial construction, operating energy needs, and replacement, general O&M, and other miscellaneous items. In this scenario, our estimates suggest the UF system's 0.75 hp pump can be replaced with a smaller 0.5 hp pump. The bars reflect use of the smaller pump, while dotted lines show the cost with the larger pump for comparison. From this point forward, we assume the base case employs the 0.5 hp pump. The uncertainty analysis **(b)** provides a probable range of total system costs relative to the base case (dotted line), generated by a set of 10,000 simulations pulling input values from each uncertain parameter's distribution (**Table 1**). Boxplots show 5th, 25th, 50th, 75th, and 95th percentile values in each cost distribution.

Uncertainty analysis. Going beyond one case and integrating possible variations in input values (**Table 1**), the uncertainty analysis generates a distribution of system costs, with the base case falling in the distribution's lower half (**Figure 1b**). With regard to the UF system's pump, a different size (0.5, 0.75, or 1.0 hp) was selected in each scenario depending on the required pump capacity. The likely range (5th-95th percentile) of overall system costs is $0.15-0.24 per user per day. The UF system is always the most expensive of the three component systems, and the EC system is typically more costly than the GAC system. However, the long upper tail of the GAC system's distribution (related to GAC media replacement) exceeds the EC system's likely range.

Estimating how much each uncertain parameter contributes to variations in the results enables us to identify which aspects of the system or its broader environment may be most critical for improving economic feasibility (**Figure 2**). In the overall system, general O&M requirements are the largest contributor, while the price of electricity and GAC replacement also play key roles. Electricity cost is particularly important for the UF system, because pumping energy represents a large portion of its total cost. General O&M is also a substantial factor in the UF system, but this parameter is most critical within the EC system. The general O&M assumption is based on capital expenses, which make up the largest part of the EC system's total cost. The GAC system is highly dependent on how often media must be replaced and the media price. A number of other parameters also contribute to cost variance, and these include the discount rate, the construction labor markup, and certain UF-specific parameters (membrane pressure, permeate flow rate). In contrast, several parameters have little impact on the variance of system costs. In some cases, the assumed uncertainty range is small (e.g., EC cell energy per liter), while other parameters with larger uncertainty ranges simply do not have a meaningful impact on overall cost (e.g., stirrer power requirement). To some degree, the UF cross-flow velocity has a minimal impact on cost because our UF pump options were confined to a discrete set of three sizes within the specified pump series. Under the existing design (incorporating only one UF membrane unit), changing the cross-flow velocity does not change the required pump capacity enough to necessitate a different pump size. Employing other pump models that offer a greater number of intermediate sizes might increase the effect of UF-specific parameters.

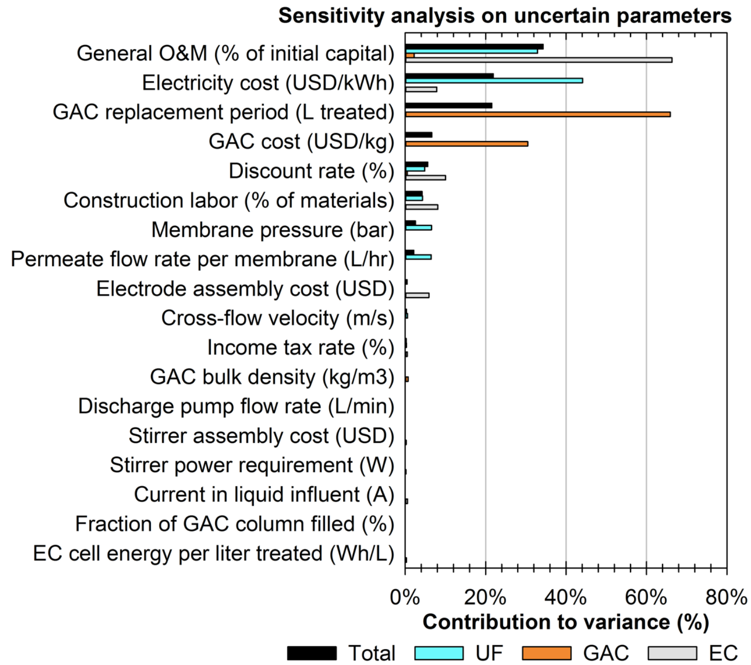

Figure 2. The relative importance of each uncertain parameter to the overall system and its three component systems (UF, GAC, EC). An input parameter's contribution to variance estimates the degree to which it alone explains the variation of the output values. A higher contribution to variance signifies a parameter having more of an effect on the final output, suggesting that it should receive greater attention when deciding where to focus cost reduction efforts.

Sensitivity scenarios. While a parameter's contribution to variance provides an indication of its importance to the system's overall economics, investigating additional scenarios where a single parameter value is altered with respect to the base case allows us to estimate a potential change in cost associated with that individual parameter (**Figure 3**). For many of the uncertain parameters (particularly those identified as most critical in **Figure 2**), we developed individual scenarios to assess the beneficial or adverse economic effect caused by increasing or decreasing each parameter. For example, a rising electricity price could substantially increase the UF system cost, while minimizing general O&M costs could generate relatively large improvements for the UF and EC systems. Similarly, the discount rate, which may be determined by the type of capital investment funding the system, could alter economic feasibility. A relatively high-interest loan from a venture capitalist (e.g., 10% discount rate) would markedly raise the user cost, while a no-interest loan from a development agency (0% discount rate) would reduce user costs.

Parameters related to individual component systems could also lead to meaningful changes. If the permeate flow rate per UF membrane module could be increased from 7.5 to 10 liters per minute, the UF pump could treat the same volume of liquid in a shorter time, reducing electricity costs. Increasing the UF membrane pressure may increase cost because a larger pump is required, but reducing the pressure does not generate a similar decrease in cost, since using the smallest pump size (0.5 hp) is already possible at the assumed baseline pressure (2.25 bar). Within the GAC system, buying media in bulk (at $0.29 per kilogram) could substantially reduce media replacement expenses, while doubling the assumed replacement period would lead to a smaller cost reduction. However, a shorter replacement period may raise costs considerably, although purchasing media in bulk would offset some of this increase. The GAC replacement period remains highly uncertain, because its long-term performance under field conditions remains unknown. In the future, field data regarding extended GAC performance may be particularly useful for optimizing the GAC component of the system.

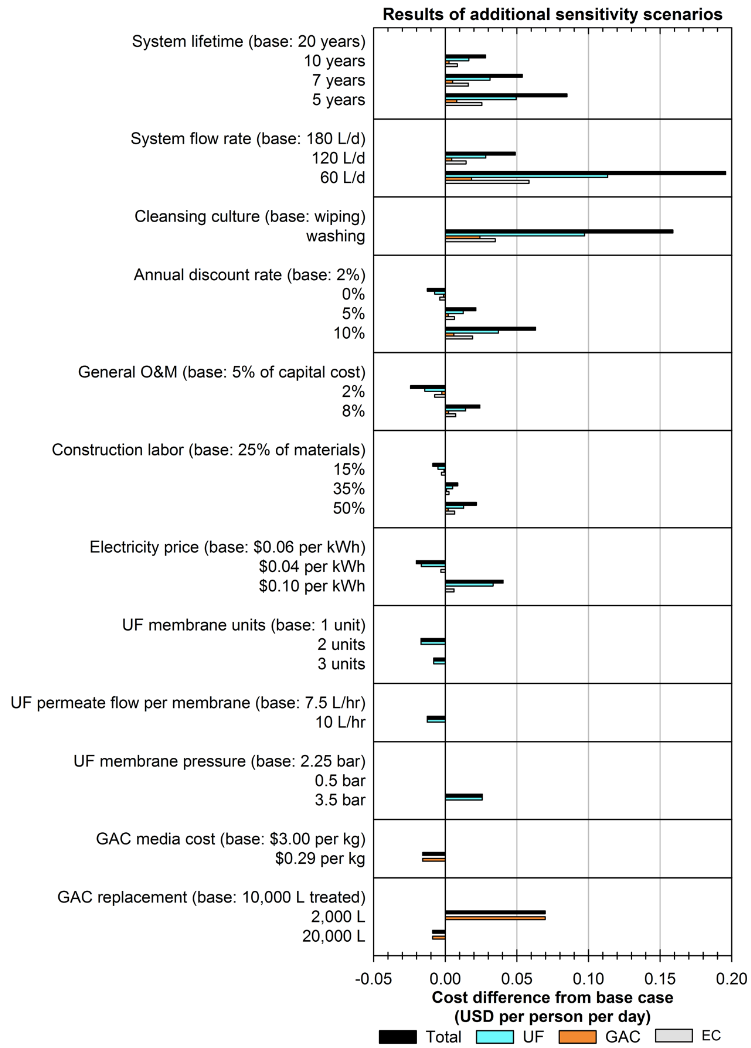

Figure 3. Sensitivity of total costs to changes in individual parameter values. Beyond the uncertainty analysis, where all uncertain parameters were varied simultaneously across 10,000 simulations, we conducted several additional sensitivity scenarios to estimate the individual impacts of changes to 12 specific parameters. The figure is divided into sections, with each section showing how costs change relative to the base case when a given parameter is altered. If changing a parameter results in a large reduction from the base case, then creating conditions that optimize that parameter could lead to significant cost improvements.

In these sensitivity scenarios, we also examined key parameters that were not varied in the uncertainty analysis (**Figure 3**). The system's longevity and daily flow rate will be critical factors in ensuring economic viability. In the base case, we assumed an optimistic system lifetime of 20 years, meaning the system did not need to be replaced during our 20-year analysis window. A reduced lifetime would result in significant replacement costs in the future, making the system less affordable. Ensuring a long lifetime is particularly important for the UF and EC systems, as their capital costs are relatively large.

Regarding daily influent flow rate, the base case assumed 180 liters per day, reflecting the system's design capacity. However, this flow rate may be lower in practice (due to fewer users), raising the cost per user. While electricity and GAC replacement costs per user are constant (or nearly so), capital and general O&M costs per user increase as the flow rate drops. Accordingly, operating the system at or close to its capacity may help to prevent increases in user costs.

The maximum number of users the system can accommodate also relates to the “cleansing culture” that is prominent where the system is installed. Based on reported flush volumes and expected urine excretion (Rose et al., 2015), a daily flow rate of 180 liters in a wiping culture equates to 10-11 users per day. In a washing culture, a system serving 5-6 users may need to handle the same daily flow rate. Optimistically, our base case assumed a wiping culture, but the system’s cost per user will be much larger in a washing culture.

Discrete design alternatives. A final set of scenarios examined discrete design choices related to the UF and GAC systems (as this preliminary analysis did not assess alternative disinfection approaches, the EC system did not contain any discrete choices). In the UF system, we considered the possibility of incorporating one or two additional membrane units to increase the total permeate flow rate and reduce the operating time of the pump. Increasing the number of UF membrane units raises the capital cost of the system, but the reduction in pump energy demand outweighs the capital increase. Adding a second UF unit results in a cost savings of approximately $0.02 per user per day, while adding a third leads to a cost that is lower than the base case but higher than the two-unit scenario (**Figure 3**). The third unit increases the pump capacity requirement enough to require a larger pump size (again, this finding may be constrained by our small set of discrete pump options). While pumping time is reduced, the larger pump requirement offsets some electricity cost savings. It is possible that the system could be further optimized by adjusting the membrane pressure and cross flow velocity, and certain combinations may improve the three-unit scenario. However, accurately optimizing this system will require more operational data to develop robust relationships between treatment performance and system configuration (e.g., linking cross-flow velocity, transmembrane pressure, and flux).

Within the GAC system, we examined the possibility of redesigning the geometry of GAC column while maintaining the same GAC media volume. Deviating from the current column diameter of four inches, we looked at a longer column with a three-inch diameter and a shorter column with a diameter of six inches. Both of these scenarios produced essentially no change in system cost (and are therefore not included in **Figure 3**). Optimistically, this result may suggest that the GAC column geometry could be altered substantially without changing costs, and perhaps different geometry may help create conditions that prolong the life of GAC media (e.g., achieve more even use across the column cross-section). Any improvements in media longevity (or at least conditions that minimize the possibility of a shorter lifetime) could create cost savings and avoid any logistical issues associated with frequent GAC replacement.

As a general point, it may be worth noting that the pretreatment requirements of the EC cell (low COD, low solids) place pressure on the UF and GAC systems to attain a certain level of treatment performance. It is possible that an alternative approach to disinfection (e.g., UV, ozone, chlorine dosing) could change these pretreatment needs, perhaps placing less of the treatment burden on upstream processes. At this point, we do not have sufficient data to rigorously model the performance and pretreatment requirements of disinfection alternatives within the given system, but we look forward to the opportunity to explore these possibilities in the future.

Best-case scenario. Based on the results of the scenarios described above, we developed a theoretical best-case scenario that improves numerous parameters simultaneously (**Figure 4a**). Essentially, this analysis suggests what general economic environment and what alterations might be needed to approach the most cost-effective scenario for the system. The single most impactful change comes from minimizing general O&M requirements, which may involve maximizing the longevity of GAC media and of any parts that might need to be replaced (e.g., pumps, valves, stirrer assembly). Working with local utilities to ensure low electricity prices and purchasing GAC media in bulk at lower unit costs may also generate considerable cost savings.

Securing low-interest (ideally no-interest) loans from entities such as international development banks will help to minimize the discount rate. Adding a second UF membrane unit reduces cost through energy savings from less pumping time. Minimizing labor and manufacturing costs may occur when scaling-up production. Any measures that can be taken to increase the permeate flow rate from each membrane (while maintaining a similar treatment level) may save energy by decreasing pumping time. Finally, extending the life of GAC media will reduce the total quantity that must be purchased each year. Other parameters could be optimized as well, but the previous scenarios suggest they would not generate substantial improvements to further reduce costs.

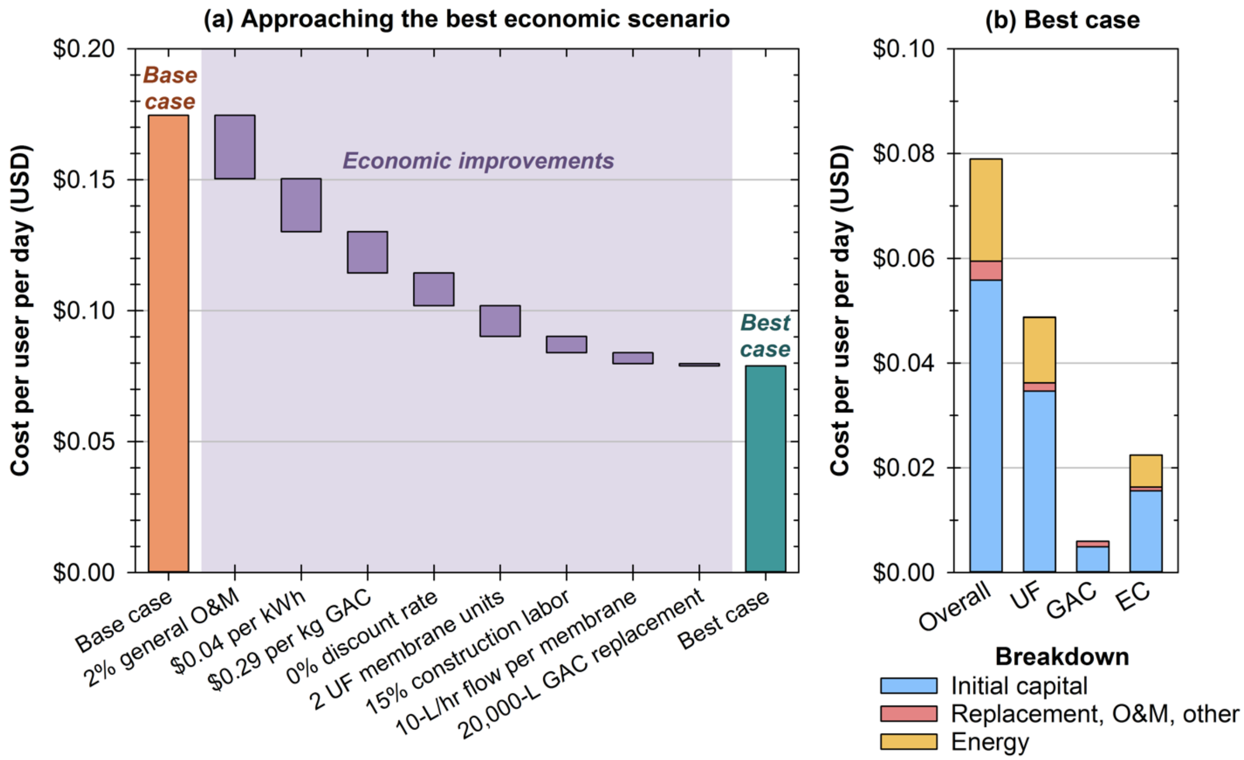

Figure 4. Estimating the best theoretical economic scenario for the system. As suggested by the sensitivity analyses (**Figure 3**), changing or enabling certain conditions could substantially improve economics. By combining several alterations to optimize the general economic environment, initial design and construction, and system use and operation **(a)**, it may be possible to move away from the base case and approach an idealized best case **(b)** of approximately $0.08 per user per day.

If all of these economic improvements can be achieved together, overall system costs may fall to $0.08 per user per day (**Figure 4b**), with much of the savings coming from reductions in electricity and other operating costs. As these improvements typically relate to different aspects of the system or its environment, many of the changes may be possible simultaneously. In some cases, making one improvement may contribute towards a second. For example, increasing GAC media longevity could help to reduce general O&M costs, as a technician would not need to replace the media as frequently. One possible exception involves an increase in the number of UF membrane units and a simultaneous increase in permeate flow rate through each membrane. At this point, we do not have sufficient information to model how adding a second membrane unit will impact permeate flow rate. Further experimentation and modeling would be required to determine whether increasing each membrane unit's permeate flow rate above 7.5 liters per hour is possible in a system with more than one membrane unit.

Additionally, achieving this user cost will also be dependent upon ensuring a long system lifetime and running at or close to capacity (thereby maximizing the number of users). The system is likely to be most cost-effective in wiping cultures. However, it may be possible to optimize or alter the treatment system to some extent in washing cultures to reduce costs, since contaminants in cleansing water may be less concentrated than in other liquid entering the system.

Conclusions

Overall, this preliminary TEA has provided first-order estimates of likely user costs that may be associated with this RTT system that integrates UF, GAC, and EC components, and the analysis suggests multiple strategies for improving its economic outcomes. In what we consider to be the most probable scenario (the base case), the expected system cost is $0.17 per user per day, with the UF component system representing the largest fraction (61%) of this total. However, substantial uncertainty is associated with this estimate, and several measures may reduce costs. These include minimizing general O&M requirements, working with local suppliers to ensure low electricity and GAC media prices, securing low-interest (or no-interest) loans, adding a second UF membrane unit, scaling up production to minimize labor and manufacturing costs, and taking measures that will increase the UF membrane permeate flow rate or increase GAC media longevity. Under conditions incorporating these changes (the best case), the cost of the overall system may drop to approximately $0.08 per user per day.

Broadly, this TEA and scenario analysis identifies potential aspects of the technology and its general environment that may have the greatest impact on economic feasibility and final user costs, and it suggests possible avenues for progress. However, the uncertainties associated with this preliminary analysis are considerable, and we do not yet have sufficient information to rigorously model treatment performance of the system. Moving forward, we propose treating the recommendations summarized in this report as suggestions for future experimentation and testing. Key factors related to system design include the following:

- Increasing the number of UF membrane units to reduce pumping energy requirements;
- Testing whether membrane permeate flow rate can be increased without sacrificing performance in terms of permeate quality;
- Characterizing GAC media life and operating conditions that are most conducive to increasing longevity;
- Understanding the drivers of EC cell treatment performance, and comparing the performance and pretreatment needs of alternative disinfection approaches;
- Generally, characterizing the treatment performance (removal of COD, solids, nutrients, and pathogens) of each component system and what factors drive performance.

In the future, further experimentation and field testing focused around these five areas will enable more precise and rigorous model development, and these efforts may lead to a more robust and cost-effective system. We look forward to the opportunity to continue collaborating and doing our part to advance sanitation technologies that efficiently meet the needs of diverse populations around the world.

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Appendix I. Breakdowns of individual materials and contribution to capital cost.

Table 2. Material costs included for construction of ultrafiltration (UF) system.

DESCRIPTION	QTY.	UNIT COST	TOTAL COST
UF SYSTEM			***$1,486.13***
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	$499.96	$499.96
10 Gallon Rinse Tank, White Polyethylene, 5/16-18 Inserts, This 10 gallon cone bottom tank is 13" L x 13" W x 21" H with a .220 nominal wall thickness. This tank has six 5/16-18 UNC inserts on one side and gallon graduations on the opposite side. Tank also comes with an 8" vented lid and a 1-1/4" FPT spinweld fitting in the bottom. This tank weighs 10 lbs., Maximum specific gravity: 1.7, Max. temperature: 120°F constant & spikes up to 140°F	1	$81.43	$81.43
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	$212.00	$212.00
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	$110.00	$220.00
THICK-WALL LIGHT GRAY CPVC THRD PIPE FITTING, HEX HOLLOW PLUG SCH80, 3/4 NPT MALE, McM 4589K112	2	$3.97	$7.94
HEX NUT PVC, 1/2-13	2	$1.76	$3.52
BARBED LIGHT-WEIGHT HOSE FITTING PP PLASTIC, FOR 3/4 IN HOSE ID, 3/4IN NPT MALE, McM 5218K460	1	$3.29	$3.29
BARBED PVC ADAPTER, STRAIGHT 3/4 NPT MALE X 3/4 ID TUBE BARB, McM 48315K92	2	$1.27	$2.54
90 DEG ELBOW BARBED CHEMICAL-RESISTANT PP PLASTIC FITTING, 3/8 IN ID TUBE X 1/2 IN NPT MALE, McM 53415K179	2	$0.97	$1.95
1" IPS Socket x Socket, 2-Way Diaphragm Valve, Cv 32.5 gpm, EPDM Diaphragm, PVC Body	2	$176.50	$353.00
Motorized Electric Ball Valve - 2-Way DC - 1", 2.5N.m, Stainless Steel, 12V - ON/OFF	1	$100.50	$100.50

Table 3. Material costs included for construction of granular activated carbon (GAC) system.

DESCRIPTION	QTY.	UNIT COST	TOTAL COST
GAC SYSTEM			***$240.80***
BULKHD FITTING 150PSI WATER, 3/8 NPT FEMALE X 3/8NPT FEMALE, THRU WALL CONN, McM 3773K117	2	$31.94	$63.88
BULK HD FITTING THRU' WALL THK 1IN NPT FEMALE X 2.875L, McM 36895K163	2	$23.46	$46.92
PVC PIPE (current design: 4IN DIA, 4 FT CUT TO LENGTH), 0.337 THK SCH40 WHITE	1	$17.78	$17.78
BALL VALVE BRASS, 1 IN NPT FEMALE,	1	$21.44	$21.44
UNION PVC THICKWALL, SCH80 3/8NPT FEMALE 2-5/32 IN LENGTH, McM 4596K84	1	$11.67	$11.67
SUCTION STRAINER SS MESH, NYLON CONN, 3/8 NPT MALE, MESH SIZE 40, DIA2.25 X 2.5L IN, McM 9806K611	1	$11.17	$11.17
PVC PIPE CAP FOR 4IN DIA SCH 40 PIPE WHITE, McM 4880K58	2	$5.83	$11.66
BALL VALVE BRASS, 0.375 NPT FEMALE, 150PSI, McM 47865K22	1	$8.27	$8.27
PVC UNION SCH40 1IN NPT FEMALE X 2.375L, McM 4880K373	1	$6.00	$6.00
NIPPLE PVC THICKWALL, SCH80, 3/8NPT 1IN LENGTH, McM 4882K12	3	$1.44	$4.32
HOSE ADAPTER BARBED ZING PL STEEL, 0.375 NPT MALE X 0.375 BARBED MALE, McM 5350K37	2	$2.14	$4.28
BARBED PVC HOSE FITTING, BLACK, FOR 1IN HOSE ID, 1IN NPT MALE 125 PSI, McM 5218K37	2	$1.97	$3.94
PIPE NIPPLE PVC THK WALL DARK GRAY ST, 3/8 NPT MALE ENDS, ID.0423 OD.0675 IN SCH80, McM 4882K720	1	$3.19	$3.19
ELBOW THICK WALL PVC, 3/8 NPT FEMALE SCH80, McM 4596K122	1	$2.86	$2.86
PVC PIPE NIPPLE SCH 80 1IN NPT MALE, .957IN ID X 2IN L, McM 4882K3	2	$1.22	$2.44
CAP PVC, 3/8 NPT FEMALE SCH 40, McM 4880K801	1	$1.34	$1.34
3201T260BLK-OXIDE STL U-BOLT, 1/2"-13 Thread Size, 4-1/2" ID, McM 3201T260	4	$4.91	$19.64

Table 4. Material costs included for construction of electrochemical (EC) system.

DESCRIPTION	QTY.	UNIT COST	TOTAL COST
EC SYSTEM			***$765.82***
ELECTRODE ASSY (cost from preliminary BOM with 20% markup)	1	$54.00	$54.00
STIRRER ASSY (cost from preliminary BOM with 20% markup)	1	$150.00	$150.00
SUCTION TUBE SS316, 3/8 OD .02 IN THK, SEAMLESS ASTM A213, 14 IN H	1	$27.40	$27.40
STRAIGHT SS 316 ADAPTER FOR 3/8 IN OD TUBE X 1/2 IN NPT MALE, McM 5182K126	1	$16.18	$16.18
SUCTION STRAINER SS MESH, NYLON CONN, 3/8 NPT FEMALE, MESH SIZE 40, McM 9877K731	1	$11.29	$11.29
THICK-WALL LIGHT GRAY CPVC THRD PIPE FITTING, PLUG HOLLOW HEX HD CPVC, 3/8 IN NPT MALE, McM 4589K152	1	$4.45	$4.45
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. Tank also comes with an 8" vented lid with a nylon lanyard and a 1-1/4" FPT spinweld fitting in the bottom. This tank weighs 6 lbs., 1-1/4" NPT Fitting, Maximum specific gravity: 1.7, Max. temperature: 120°F constant & spikes up to 140°F	1	$58.75	$58.75
BALL VALVE PVC WITH GARDEN HOSE THREAD, 3/4 NPTFEMALE X 3/4 NPT MALE 125PSI 140F, McM 9848K410	1	$13.68	$13.68
BARBED PVC PIPE ELBOW, 3/4NPT 3/4 PIPE DIA, 200PSI 140F, McM 48315K42	2	$3.62	$7.24
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	$110.00	$220.00
THICK-WALL LIGHT GRAY CPVC THRD PIPE FITTING, HEX HOLLOW PLUG SCH80, 3/4 NPT MALE, McM 4589K112	2	$3.97	$7.94
HEX NUT PVC, 1/2-13	2	$1.76	$3.52
THICK-WALL DARK GRAY PVC PIPE FITTING, PLUG HEX HD, PVC THICK WALL, 1-1/4 IN NPT SCH80, McM 4596K760	1	$3.69	$3.69
90 DEG ELBOW BARBED PP PLASTIC FITTING, 3/8 IN ID YOR-LOK TUBE FITTING X 1/2 IN NPT MALE	1	$0.97	$0.97
Robust Single Diaphragm Design Sink & Shower Drain Pump, 12V Flow rate: Nominal 16 Litres/min (4.2 US gallons/min), Connections: - for 19mm (¾") bore hose., Fuse Size: - 10(amp), Maximum Current: - 8(amps), Single diaphragm design allows extended dry running, Self-primes up to 3m (9.5ft) vertical lift, Rated for up to 30 minutes continuous running, Actual Weight: 2.98 Kg (Approx. 3.48 Kg packed)	1	$186.71	$186.71

Table 5. Miscellaneous material costs not classified under a single component system.

DESCRIPTION	QTY.	UNIT COST	TOTAL COST
MISCELLANEOUS			***$30.24***
Custom Sheet Metal Counting Bracket--System Framing/Housing	1	$30.24	$30.24

Appendix II. Recirculation Pump and Ultrafiltration Membrane Calculations

Assumptions

The following parameters were assumed:

Parameter	Unit	Assumed Value (range)	Reference(s)
Permeate flow rate (per membrane unit)	L/hr	7.5 (7.5-10)	Duke team
Concentrate volume (per membrane unit)	L	0.23	Porex membrane specifications
Length of membrane unit	mm	1829	Porex membrane specifications
Daily volume to be processed	L	180	Duke team

Calculations

The internal cross-sectional area of the membrane unit was calculated from the concentrate volume and the membrane length:

$$A_{internal} = \frac{V_{concentrate}}{L_{membrane}}$$

The concentrate flow rate (per membrane unit) was calculated from the cross-flow velocity and the internal cross-sectional area:

$$Q_{concentrate} = V_{crossflow} * A_{internal}$$

The total feed flow rate for the membrane system was calculated from the concentrate flow rate, permeate flow rate, and number of membrane units:

$$Q_{feed} = (Q_{concentrate} + Q_{permeate}) * N_{membraneunits}$$

Using the calculated membrane feed flow rate and desired membrane pressure, the horsepower required by the recirculation pump was calculated using the pump curve provided by the manufacturer's pump specifications. This information was then used for pump selection.

The daily total time the pump must operate was calculated from the daily volume to be processed, permeate flow rate, and number of membrane units:

$$T_{pump} = \frac{V_{daily}}{Q_{permeate} * N_{membraneunits}}$$

The daily energy required for the pump was calculated from the pump horsepower and daily total time the pump must operate:

$$E_{pump} = HP_{pump} * T_{pump}$$

Appendix III. Granular Activated Carbon Calculations

Assumptions

<u>The following parameters were assumed:</u>

Parameter	Unit	Assumed Value (range)	Reference(s)
GAC replacement period	L treated	10,000 (2,000-20,000)	Duke team
GAC bulk density	kg per m^3	450 (400-500)	https://tigg.com
Fraction of GAC column filled	%	80 (75-85)	Duke team; assumption
Daily volume to be processed	L	180	Duke team
Column pipe diameter	in	4 (3, 6)	https://www.mcmaster.com
Previous GAC column length	ft	4	Duke team
Previous GAC column diameter	in	4	Duke team
Previous fraction of column filled	%	80	Duke team, assumption

Calculations

The GAC media volume was assumed to equal the GAC volume in one column of the previous liquid system design. The GAC media volume was calculated based on the column length, column diameter, and the fraction of GAC column filled with media:

$$V_{GAC} = f_{GAC,previous} * (\frac{\pi}{4} d_{column,previous}{}^2 * L_{column,previous})$$

The new design for GAC column length was calculated using the GAC volume, the filled fraction of the GAC column, and the discrete pipe diameter:

$$L_{column,new} = (\frac{V_{GAC}}{f_{GAC,new}}) \div (\frac{\pi}{4} d_{column,new}{}^2)$$

The mass of GAC required in the column was calculated with the volume of GAC and GAC bulk density with appropriate unit conversions:

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

The GAC replacement time was calculated with the GAC replacement period and the daily volume to be processed:

$$t_{GAC} = \frac{V_{replacement\ period}}{V_{daily}}$$

Appendix IV. Electrochemical System Calculations

Assumptions

The following parameters were assumed:

Parameter	Unit	Assumed Value (range)	Reference(s)
EC cell energy per liter treated	Wh/L	6 (5.6-6.4)	Duke team (energy may depend on desired pathogen removal and influent conditions; clarify with future testing)
Electrical current in liquid influent	A	4 (4-8)	Duke team
EC cell voltage	V	12	Duke team
Stirrer power requirement	W	24 (18-30)	Assumption based on previous system (power requirement is proportional to volume if assume same mixing velocity gradient)
Daily volume to be processed	L	180	Duke team
Discharge pump voltage	V	12	Pump specifications
Discharge pump current	A	6	Pump specifications; assume power consumption similar to baffle tank pumps in previous system
Discharge pump flow rate	L/min	15 (8-16)	Pump specifications; assume 1-2 minutes to drain 15-L tank

Calculations

The EC cell's daily operating time was calculated from the EC cell energy per liter, cell voltage, liquid current, and the daily volume to be processed:

$$t_{cell} = \frac{E_{liter} * Volume_{daily}}{Voltage_{cell} * I_{liquid}}$$

Parameter distributions were constrained to keep $t_{cell} \leq 24$ hours. The EC cell's daily energy demand was calculated from the daily operating time, cell voltage, and liquid current:

$$E_{cell} = Voltage_{cell} * I_{liquid} * t_{cell}$$

The daily energy required by the stirrer was calculated from the stirrer's power requirement and the daily operating time:

$$E_{stir} = P_{stir} * t_{cell}$$

The discharge pump's daily operating time was calculated using the pump flow rate and daily volume to be processed:

$$t_{discharge} = \frac{V_{daily}}{Q_{discharge}}$$

The daily energy required for the discharge pump was calculated from the pump voltage, current, and daily operating time:

$$E_{discharge} = Voltage_{discharge} * I_{discharge} * t_{discharge}$$