PRIORITIZING OPPORTUNITIES TO ADVANCE SUSTAINABILITY OF NON-SEWERED SANITATION SYSTEMS THROUGH FINANCING MECHANISMS AND QUANTITATIVE SUSTAINABLE DESIGN

BY

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THESIS

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ABSTRACT

Safe sanitation is crucial to prevent the spread of diarrheal diseases and to reduce gender-related health disparities. Although it has been recognized as a universal right, the world is not on track to achieve universal coverage of safe sanitation. Lack of sanitation coverage in rural, geographically challenged, and rapidly increasing population density areas is particularly challenging due to cost and feasibility barriers to sewered connections. Non-sewered sanitation (NSS) systems are a potential solution to provide safely managed sanitation services according to strict wastewater treatment standards. The NEWgenerator, a NSS technology which uses an anaerobic membrane bioreactor, ion exchange, and electrochlorination, was simulated in QSDsan to determine the economic and environmental feasibility in different deployment contexts and to prioritize targeted improvements to advance the system sustainability. The configuration of the NEWgenerator using direct photovoltaic electricity had 1.2 cents higher cost at 0.113 [0.105 – 0.124] USD·cap^{-1}·day^{-1} but 8.7 kg CO_2-eq·cap^{-1}·year^{-1} lower GHG emissions at 67.7 [38.5 – 113.6] kg CO_2eq·cap^{-1}·year^{-1} compared to the configuration using electricity from the grid. The use of location-specific parameters in a country-specific analysis for five countries (China, India, Senegal, South Africa, and Uganda) resulted in variation in photovoltaic user cost and GHG emissions from 0.055 USD·cap^{-1}·day^{-1} and 65.3 kg CO_2eq·cap^{-1}·year^{-1} in Uganda to 0.091 USD·cap^{-1}·day^{-1} and 76.6 kg CO_2eq·cap^{-1}·year^{-1} in China. This research provides evidence of the NEWgenerator as a low-cost, low-emission, NSS backend technology with potential for resource recovery to increase access to safe sanitation globally. The financing of NSS technologies, such as the NEWgenerator, has not been readily explored due to its more recent development. Therefore, understanding of financing mechanisms such as subsidies, results-based, microfinance, blended finance, and market-based models and their characteristics to quantify their impact on life cycle costs is vital to efficiently allocate resources.

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CHAPTER 1: INTRODUCTION

Diarrheal diseases account for 1.6 million deaths globally in 2017 caused by the spread of excreted enteric pathogens.[1] Unsafe drinking water and poor sanitation are among the highest risk factors which lead to the spread of diarrheal diseases. Therefore, the access to sanitation, the maintenance of hygienic conditions by proper treatment and disposal of excreta, is a necessity to reduce this risk. Lack of safe sanitation also disproportionally affects women and individuals who have internal reproductive organs and experience menstruation, where they may experience poor mental health outcomes, gender-related non-partner violence, adverse pregnancy outcomes, and absenteeism from workplace and educational facilities.[2–5] The United Nations has recognized safe sanitation as a universal right and, through the Sustainable Development Goal (SDG) 6.2, aims to achieve access to adequate and equitable sanitation and hygiene for all and end open defecation by 2030.[6] However, at current rates of progress, the world is not on track to achieve and will leave 2.8 billion people (33% of the global population) without safe sanitation by 2030.[7] Rural areas, geographically challenged areas, and regions with increasing urban density[8] often struggle with lower sanitation coverage and face difficulties when increasing sanitation services. Rural areas account for 92% of open defecation practices and two-thirds of limited and unimproved sanitation of the total population.[7]

On-site sanitation technologies, such as septic systems, leaching pits, pit latrines, and advanced non-sewered sanitation (NSS) systems, are a solution when sewered connections are infeasible and account for 43% of global sanitation coverage as of 2020.[7] Despite its importance to communities, on-site sanitation is often constructed and operated with limited regulatory oversight and can experience high loadings (i.e., usage) which can overwhelm the system capacity – posing a risk to water sources and public health.[7,9] Therefore, NSS systems, which are prefabricated, integrated treatment units designed to treat wastewater and meet strict effluent requirements, can be a solution to provide safe sanitation. One such NSS technology is the NEWgenerator, a backend technology has demonstrated robust treatment of real wastewater from 100+ users with a 25-year system lifetime and has been tested in eThekwini Municipality, KwaZulu-Natal

Province, South Africa; Thiruvananthapuram, Kerala, India; and Tampa, Florida, United States of America.[10,11]

The financial viability and environmental sustainability of the NEWgenerator, as well as contextual considerations for deployment, have yet to be quantified. This work utilizes QSDsan, an open-source, community-led platform for the quantitative sustainable design (QSD) of sanitation and resource recovery systems which enables design, simulation, techno-economic analysis (TEA), and life cycle assessment (LCA) under uncertainty.[12] In addition to the baseline life cycle system costs and GHG emissions, further simulation using location-specific parameters considering deployment were characterized using contextual analysis for China, India, Senegal, South Africa, and Uganda. Full understanding of the financial and environmental implications of NSS technologies to simulate location-specific considerations is vital to advance global sanitation coverage and sanitation investments (discussed in Chapter 3).

Economics and financing are central to the sustained supply of safely managed sanitation services in low-income settings. To bridge the sanitation gap towards universal sanitation coverage by 2030 significant financial investment is required. There are multiple mechanisms for financing sanitation development, and efficient allocation of resources is critical to build momentum. To date, there have been minimal studies incorporating multiple financing mechanisms in life cycle economic models to understand the impact on proportional costs and expenses for financial stakeholders and the relative economic sustainability of sanitation technologies. A literature review on the traditional and innovative financing mechanisms such as subsidies, output-based aid, grants, microfinance, and market-based models from the public and private sectors utilized to fund sanitation systems globally is explored in Chapter 2. In addition, to quantifying the financial viability of a sanitation technology, characterizing the financial implications of specific financing mechanisms on system cost will provide insight on how public and private sectors can most effectively deploy funding to deliver technologies for sustained sanitation globally.

The objective of the work presented in this thesis is to assess the financial viability and environmental sustainability of the NEWgenerator to inform technology improvements and deployment decisions: (i) by elucidating key drivers to the NEWgenerator's sustainability, (ii) by simulating technology, design, and input improvements, and (iii) by using location-specific values to simulate country-specific deployment. Future work on how to incorporate financial mechanisms in the cost analysis, as an additional layer to the financial viability analysis of sanitation technologies (as discussed Chapter 3), is discussed in Chapter 4.

CHAPTER 2: BACKGROUND

2.1 Why Safe Sanitation Matters

2.1.1 Diarrheal diseases

Diarrheal diseases resulted in 1.53 million deaths globally in 2017, of which one-third were children under the age of 5 years.[1,13] It is the third-leading cause of childhood mortality and eighth-leading cause among adults 70 years and older.[14] Bacterial and viral pathogens are spread via feces-contaminated water, foods, or person-to-person due to poor hygiene. Exposure generally results in diarrhea, defined as the passage of three or more loose or liquid stools per day.[15] The most common bacteria, viruses, and protists responsible for mortality for all age groups are Rotavirus (3.1 deaths per 100,000), by Shigella (2.9 deaths per 100,000), *Vibrio cholerae* (1.5 deaths per 100,000), Adenovirus (1.3 deaths per 100,000), and Non-typhoidal *Salmonella* spp. (1.1 deaths per 100,000).[14,16] Severe dehydration and fluid loss from diarrhea are the main causes of diarrheal-related deaths. Two significant reasons for diarrhea being a leading cause of death specifically for young children and older, vulnerable people is due to the prevalence of diarrhea-related risk factors such as unsafe or complete lack of sanitation, contamination of drinking water, malnutrition, and lack of access to essential treatment such as oral rehydration therapy, vaccine availability, and healthcare facilities.[1]

2.1.2 Gender-related health disparities

Sanitation insecurity is defined as the "insufficient and uncertain access to a socio-cultural and social environment that respect and respond to the sanitation needs of individuals, and to adequate physical spaces and resources for independently, comfortably, safely, hygienically, and privately urinating, defecating, and managing menses with dignity at any time of day or year as needs arise in a manner that prevents fecal contamination of the environment and promotes health."[2] 526 million of the total global population of 739 million people who practice open defecation were women in 2015.[7] Beyond direct health effects from diarrheal diseases from unsafe sanitation, women and individuals who have internal reproductive organs and experience menstruation often face disproportionate gender-related disparities due to sanitation insecurity. Open defecation practices and sanitation insecurity can result in higher occurrence of the following: poor mental health outcomes, gender-related non-partner violence, adverse pregnancy outcomes, and absenteeism from workplace and educational facilities.[2–5] Individuals at risk are from age of first menstruation to menopause which is the time range where safe sanitation is necessary for menstrual hygiene management.[5,17] It is reported that one in three women worldwide reported risk of shame, disease, harassment, and even physical attacks because they do not have a safe location to defecate.[18] They also experience an additional time-burden of 97 billion hours per year finding a place to defecate safely when living without access to a toilet.[4,18]

Without access to safe sanitation there are physical dangers such as increased risk of insect and snake bites, especially when crouching, while openly defecating. In addition to potential physical and sexual assault, even if they do not occur can create a large emotional toll on the individual every time they defecate.[19] Instances of absenteeism from the workplace and educational facilities are much more likely in girls, women, and individuals compared to their male peers due to the lack of a clean, safe toilet, especially during menstruation. The World Bank has reported that school-aged girls are 6 to 10 percentage points more likely to miss a day from school than male peers in a 6-month period.[20] A study on women working in a Bangladesh factory reported that 73% of women were absent 6 days per month due to the lack of safe sanitation at the workplace.[18] Cross-sectional studies have been conducted in South Asia that women experience increased negative mental health outcomes such as anxiety, depression, or distress when lacking safe sanitation. Findings have also found that functional household latrine access was associated with higher well-being scores.[19] Many women and individuals have adopted unhealthy coping strategies to suppress defecation such as reducing intake of foods and liquids which may cause toilet-avoidance dehydration, urinary tract infection, chronic constipation, and other gastric disorders.[5,17]

2.1.3 Disproportionally affected regions

Diarrheal death rates are highest in sub-Saharan Africa, and Central, Southern, Eastern and South-Eastern Asia ranging from approximately 50 to 225 deaths per 100,000 people as of 2019.[13] These regions also account for much of the total global population without safely managed sanitation, with Central and Southern Asia accounting for 1.08 billion people (Rural: 635 million, Urban: 441 million), Eastern and South-Eastern Asia accounting for 934 million people (Rural: 530 million, Urban: 404 million), and Sub-Saharan Africa accounting for 864 million people (Rural: 516 million, Urban: 348 million).[7] There is a correlation between diarrheal-related deaths and a country's gross domestic product (GDP) or average income, with lower GDP countries having higher death rates while higher GDP countries (such as the United States and many European countries) having less than 1 death per 100,00 people.[1,13] However, there is wide sub-national variation of sanitation coverage within many countries between urban, rural, geographically challenged, and rapidly urbanized areas where sewered connections or other safe sanitation is not available. This may be due to geographical challenges such as flood-prone, high altitude, and high-water table areas, regions with rapid urbanization such as peri-urban, urban fringe areas, and informal settlements which experience increase in population density, and rural areas with population dispersion over large and isolated areas. Informal settlements are most prevalent in these regions, with 370 million people reported from Eastern and South-Eastern Asia, 238 million from sub-Saharan Africa (238 million), and 226 million from Central and Southern Asia (226 million).[8]

2.2 Existing and Novel Technologies to Bridge the Sanitation Gap

On-site sanitation are facilities that store and treat excreta on-site, such as septic tanks, improved latrines, decentralized treatment systems. Currently on-site sanitation accounts for 43% of global sanitation, roughly equal to the prevalence of sewered sanitation.[7] However, on-site sanitation is often constructed and operated with limited regulatory oversight which may result in lack of operation and maintenance and result in high loadings (i.e., usage) which can overwhelm the system capacity or cause system failures.[7,9] A global household survey from 2017 to 2020 determined that a high proportion of septic tanks and improved latrines have never been emptied and waste has never been removed off-site.[7] Pit latrines or septic tanks that leach, overflow, or have effluent lines which discharge into the surface environment are unsafe and pose a risk to water sources and public health with the spread of human enteric pathogens.[7,9]

NSS systems are a “sanitation system that is not connected to a networked sewer system and collects, conveys, and fully treats the specific input, to allow for safe reuse or disposal of the generated output.”[21] The International Organization for Standardization (ISO) and National Sanitation Foundation International have established strict testing and performance requirements for NSS systems in ISO 30500.[21] Requirements for liquid effluent for different usage are also specified; Category A is unrestricted urban use and Category B is discharge into surface water of other restricted urban use. The ISO 30500 requirements are: (i) an *Escherichia coli* maximum concentration and removal threshold of 100 count$\cdot$L^{-1} or 6-log reduction values (LRV), (ii) pH range 6 to 9, (iii) chemical oxygen demand (COD) of 50 mg$\cdot$L^{-1} and 150 mg$\cdot$L^{-1} for Category A and B, respectively, (iv) total suspended solids (TSS) of 10 mg$\cdot$L^{-1} and 30 mg$\cdot$L^{-1} for Category A and B, respectively, (v) 70% total nitrogen (TN) removal, and (vi) 80% total phosphorus (TP) removal.[21] The Bill & Melinda Gates Foundation’s Reinvent the Toilet initiative, which has spurred the development of many NSS technologies, has the target to develop sanitation technologies that perform reliably, affordably, and with low environmental impact.[22] A range of technologies, categorized by user capacity, have been developed to bridge the sanitation gap.[11,23–32] Single-unit reinvented toilets (SURTs) are designed to treat wastewater from individual households, multi-unit reinvented toilets (MURTs) are designed to treat wastewater from small schools or communities, and Omni Processors (OPs) are designed for fecal sludge management for larger communities up to 12,000 people. The NEWgenerator is a MURT technology which has achieved reliable treatment performance of real wastewater streams (97.6 ± 3.1% TSS removal, 94.5 ± 5.0% COD removal, 7.4 ± 1.5 LRV, 82.1 ± 24.0% TN removal).[11]

2.3 Review of Global Sanitation Financing Mechanisms

2.3.1 Financing Mechanisms

It is estimated that to meet the goals of SDG 6.2 of universal sanitation coverage by 2030 it will require $114 billion annually in capital investments.[33] The benefits of safe sanitation are invaluable and sanitation investment is necessary to achieve SDG 6.2. Therefore, there is an increased need for research on efficient allocation of sanitation funding and targeted use of financing mechanisms.[33,34] Papers with case studies of an individual technology implemented in a specific location using a single financing mechanism are available. However, comprehensive reviews of those case studies have yet to be conducted, particularly on the quantitative assumptions of each financing mechanism and their impact on the life cycle costs (via TEA) of the sanitation technology. Financing mechanisms used in water, sanitation, and hygiene (WASH) are generally funded by public and private sectors such as local, state, and national-level government, finance institutions, non-governmental organizations, and users.

Subsidies are a more traditional financing mechanism where funds are publicly or externally sourced to an individual, service provider, or business to pay the upfront cost of the facility.[35] However, there are many kinds of subsidies such as hardware, software, and cross-subsidies which can also offset all or part of the incurred costs. Hardware subsidies offset upfront or capital costs for the sanitation infrastructure. Software subsidies offset the operational costs of running the system or the supply of the sanitation service, and are usually paid to the service provider.[35,36] Cross-subsidies are contributed by a group of households or users to offset the cost of service to others, often in the form of a surcharge or tariff (this is more common for water service delivery and sewered sanitation connections).[35,37] Subsidies help remove the upfront capital funding needed for sanitation, which is a major barrier to lower-income households. However, if poorly designed and lacking specific objectives it may result in failure through lack of O&M, harm to other potential financial sources, unsustainable use, and creation of dependency.[35,38,39] Results-based financing (or output-based aid) is when funds are delivered only after the sanitation infrastructure is successively delivered, or in some cases after demonstration of effective sanitation (e.g., open defecation free achieved).[40,41] There is higher level of accountability to the user and service provider as the funds aren’t provided until the specific objective is achieved and is also a solution to prevent funding used for unsuccessful sanitation being delivered.[35,40,41]

Microfinance loans are a short-term, small loan provided by a microfinance institution with minimal collateral requirements and reduced interest rates than traditional loans from banks or other finance institutions.[42,43] Microfinance loans or subsidized credits that can be used to fund sanitation services allowing households and users to finance high upfront capital costs and make investments into the sanitation market. The user or household is the active decision maker in the financing aspect and type of sanitation technology which promotes user accountability and sustained use.[44,45] Self-finance from where households or users invest their own funds to pay for the sanitation facility and any associated fees outright (usually from their own savings).[35,46] Blended finance is defined as the strategic use of development finance for the mobilization of additional finance towards sustainable development in least developed countries.[56,57] Some methods of blended finance mechanisms include guarantees, credit enhancement, investment funds or collective investment vehicles, credit lines, and technical assistance.[56,57]

Marketing-based financing relies on selling sanitation via commercial marketing to encourage households to buy and build sanitation facilities.[47–51] These products and services can be subsidized by the public sector to be more affordable, or also work complementary with traditional and microfinance loans. It heavily relies on social marketing and behavior change approaches to promote moving up the sanitation ladder to more advanced sanitation technologies.[47–51] Without an existing sanitation market, additional funding is needed to conduct market assessment, interventions to stimulate the market, training of workers, advertising, and research and development. However, this may be subsidized by the government in order to deliver benefits that users desire so they adopt behaviors that will profit the community.[48] Cost recovery is a viable method for financing sanitation, either as a business model from selling recovered resources or as a collection of user fees on a timely basis. However, this may not fully cover entire life cycle costs and thus it could be feasible in combination with another financing mechanism.[52–54] Recycled nutrients or resources that are recovered from wastewater and fecal matter can be sold and generate income as fertilizers or compost.[53,54] Timely funds collected by an entity such as a community leader, service provider, or the government in the form of user fees, tariffs, or surcharges can provide a steady stream of income that may cover O&M costs.[52,55]

2.3.2 Methods

To better understand the financing mechanisms used to fund water and sanitation services globally, the Scopus citation database was used to identify papers which included specific search terms found in the title, abstract, and keywords of literature. The Scopus input search categories for sanitation were TITLE-ABS-KEY(sanitation OR open defecation OR household sanitation), financing were TITLE-ABS-KEY(financ* OR subsid* OR subsidies OR funding OR payments OR aid OR funded OR business OR investment OR donor OR incentive), low-income or resource-limited were TITLE-ABS-KEY(marginalized OR poverty OR trib* OR indigenous OR resource-limited OR resource limited OR native OR peri-urban OR rural OR slum* OR low income, and exclusion terms were TITLE-ABS-KEY(covid OR industr* OR meat*). The literature search was limited to research articles published between January 1990 through February 2021. The Scopus search according to the search terms yielded 1,065 papers, where each paper was screened individually for relevance to the research topic. The first manual literature screening involved a review of the title and abstract, of which 208 papers were identified as potentially relevant to the objective of the study. The second manual screening involved a review of the body of the literature for specific information such as location, sanitation technology, financing mechanism, and funding source to be clearly identified. Concluding the Scopus search and two manual literature screenings, a total of 79 papers were selected for further analysis. The papers were then analyzed and sorted for the country, financing mechanism, and technology type.

2.3.3 Literature Review

Literature review results for assessing global water and sanitation financing mechanisms from the 79 papers resulted in 204 reported case studies which reported information on the country, technology type, and financing mechanism (**Figure 2.1**). The geographical regions which had the highest reported case studies with financing of water and sanitation services were in Sub-Saharan Africa, South and South-East Asia, which have been identified as regions disproportionately affected by lack of safe sanitation services. The countries which had the highest contributions included India (15%), Kenya (9%), Bangladesh (7%), Ghana (6%), Indonesia (4%), and South Africa (4%) (**Figure A.1**). The technologies financed in the case studies covered a broad range of water and sanitation services, which included water service delivery (24%), latrines (19%), other onsite sanitation (12%), fecal sludge management services (12%), improved latrines (8%), urine-diverting dry toilets (4%), sewage connections (4%), and septic tanks (2%) (**Figure A.2**). Notably, there was minimal inclusion of advanced onsite sanitation such as NSS technologies. There was representation of numerous financing mechanisms reported in the case studies with each having at least 5 case studies. More traditional financing mechanisms such as subsidies, loans/credits, and grants were highly reported accounting for 19%, 12%, and 8% of the case studies, respectively. Microfinance (11%), blended finance (11%), results-based (9%), and cost recovery (8%) funding mechanisms were also well represented and accounted for a large portion of the reported financing mechanisms (**Figure A.3**). Further review and additional analysis addressing details such as user scale, beneficiary conditions, funding source, distribution of costs if multiple financing mechanisms, duration, repayment scheme, interest rate, and assessment on success would be needed to characterize these assumptions for incorporation in economic sustainability analysis.

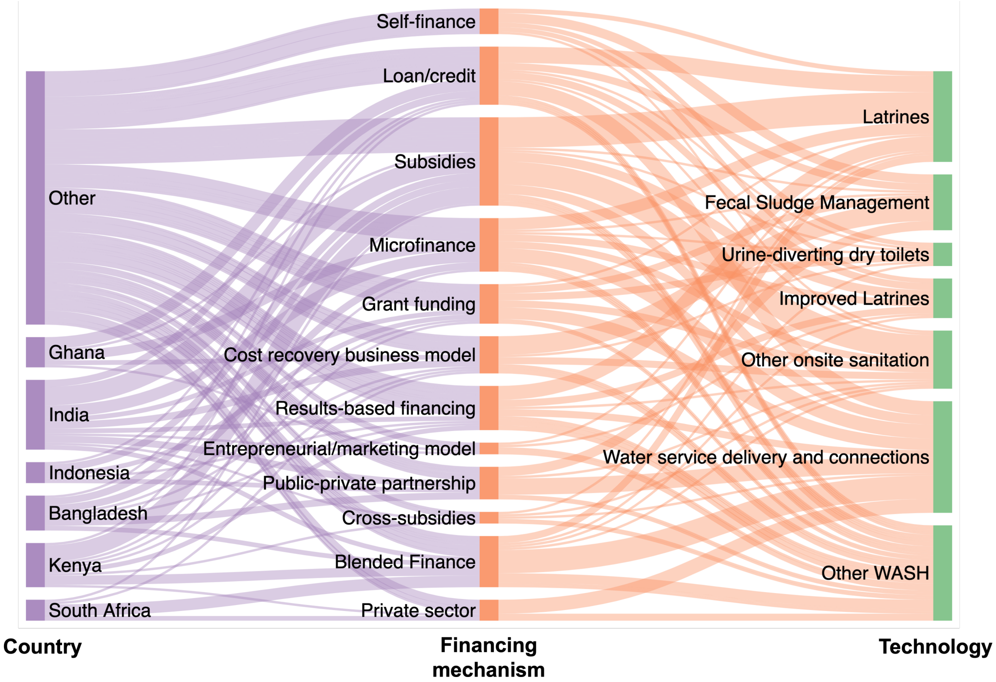

Figure 2.1 The Sankey diagram depicting the literature review of 79 papers on global sanitation financing mechanisms sorted by country, financing mechanism, and technology type. The thickness of the flow lines is indicative of the number of papers, therefore thicker lines depicted a higher number of papers for each category.

CHAPTER 3: ADVANCING ECONOMIC AND ENVIRONMENTAL SUSTAINABILITY OF THE NEWGENERATOR NON-SEWERED SANITATION SYSTEM[*]

Abstract

Coverage of safely managed sanitation and resource recovery using centralized facilities in rural, geographically challenged, and rapidly increasing population density areas may not be feasible due to spatial needs, site-specific concerns, and high costs associated with installation of sewered and grid-tied electricity connections. Non-sewered sanitation (NSS) systems have the potential to provide safely managed sanitation services according to strict wastewater treatment standards. One such NSS backend technology is the NEWgenerator which uses anaerobic membrane bioreactor (AnMBR) technology, nutrient recovery via ion exchange, and electrochlorination to achieve robust treatment of real waste streams for over 100 users. This study characterizes the financial viability and

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[*] *The following section contains a manuscript that was in preparation at the time of the submittal of this thesis. It is included in its entirety below.*

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Keywords

Non-sewered sanitation system (NSSS), multi-unit reinvented toilet (MURT), techno-economic analysis (TEA), life cycle assessment (LCA), decentralized sanitation, on-site sanitation

environmental implications for the NEWgenerator to elucidate key drivers of sustainability and prioritize opportunities to advance system sustainability through targeted improvements and intentional deployment. QSDsan (an open-source python package) was used to conduct uncertainty and sensitivity analysis on the NEWgenerator. The photovoltaic configuration NEWgenerator had 1.2 cents higher cost at 0.113 [0.105 – 0.124] USD·cap^{-1}·day^{-1} but 8.7 kg CO$_2$-eq·cap^{-1}·year^{-1} lower GHG emissions at 67.7 [38.5 – 113.6] kg CO$_2$eq·cap^{-1}·year^{-1} compared to the grid-tied energy alternative. The use of location-specific parameters in country-specific analysis for five countries (China, India, Senegal, South Africa, and Uganda) resulted in significant variation in photovoltaic user cost and GHG emissions from 0.055 USD·cap^{-1}·day^{-1} and 65.3 kg CO$_2$eq·cap^{-1}·year^{-1} in Uganda to 0.091 USD·cap^{-1}·day^{-1} in China and 76.6 kg CO$_2$eq·cap^{-1}·year^{-1}. A combination of improvements such as sustainable photovoltaic battery alternative, low-cost housing, reduced frontend operation assumptions, and sludge pasteurization service have the potential to cumulatively reduce daily user cost by 1.4 cents with negligible change in emissions. Doubling user capacity, if treatment performance can be maintained, can reduce daily user cost by approximately 2.4 cents. This research provides evidence of the NEWgenerator as a low-cost, low-emission, and renewable energy powered NSS backend technology with potential for resource recovery to increase access to safe sanitation globally.

3.1 Introduction

The United Nations has recognized safe sanitation as a universal right[58,59] with the goal to attain universal coverage of safe sanitation services by 2030,[6] however the world is not on track to achieve this target.[7] One driving force influencing sanitation coverage is the rapid global urbanization[8] coupled with the increasing population density in peri-urban, urban fringe areas, and informal settlements that lack conventional or safe sanitation infrastructure. There are significant challenges in extending infrastructure services such as sewer, water, and grid electricity to these areas, which leaves poor and vulnerable populations at the risk of unsafe sanitation. In 2020 it was reported that the use of on-site sanitation (e.g., septic tanks, improved latrines, decentralized wastewater systems) was just as common as sewered sanitation in these settings (43% population coverage by each).[7] Despite its importance to communities, on-site sanitation is often constructed and operated with limited regulatory oversight and can experience high loadings (i.e., usage) which can overwhelm the system capacity – posing a risk to water sources and public health.[9] Non-sewered sanitation (NSS) systems are prefabricated, integrated treatment units required to meet strict wastewater treatment standards. NSS systems can be used to extend safe sanitation to rural areas where sewered connections are not feasible, in temporary or permanent settlements, and in locations with geographical challenges (e.g., flood-prone, high-water table, isolated areas).

The development of NSS systems has been accelerated in recent years, in part due to the Bill & Melinda Gates Foundation's Reinvent the Toilet initiative targeting reliable performance, affordable costs, and low greenhouse gas (GHG) emissions.[22] A range of technologies – serving individual households up to communities of 12,000 people (single and multi-unit reinvented toilets to Omni Processors) – have emerged to tackle the universal sanitation challenge.[11,23–32] In recognition of the potential of NSS to contribute to safe sanitation coverage, the International Organization for Standardization (ISO) and National Sanitation Foundation International established testing and performance requirements (ISO 30500, NSF 40, NSF 245) for NSS systems. The stringent testing and performance requirements ensure human health protection in solids output and liquid effluent via log reduction values (LRV) of human enteric bacterial pathogens, thresholds for COD, total suspended solids, pH, and nutrient load reduction percentage of total nitrogen and total phosphorus.[21]

One such NSS technology that has been demonstrated to achieve robust treatment of real waste streams (97.6 ± 3.1% TSS removal, 94.5 ± 5.0% COD removal, 7.4 ± 1.5% LRV, 82.1 ± 24.0% total nitrogen removal)[11] is the NEWgenerator. The NEWgenerator is an NSS backend technology that can be integrated with various frontends (i.e., user interfaces such as urinal, squatting or seating pan, and associated plumbing) to serve 100+ users. The technology consists of an anaerobic membrane bioreactor (AnMBR), a nutrient capture system (NCS) with ion exchange and carbon sorption, and an electrochlorination (EC) unit.[11] All NEWgenerator units are fully-integrated and housed in a mini-shipping container (40 ft^2 footprint) for compact and portable design. To date, however, the financial viability and GHG implications of this technology, as well as their sensitivities to site-specific considerations (i.e., contextual parameters such as the electricity mix),[12] are yet to be quantified. As we seek to advance the sustained supply of safe sanitation via deployment of NSS, a deeper understanding of the economic cost and environmental impacts for location-specific deployment is vital to provide evidence to support and increase sanitation investment.

The objectives of this study were (i) to elucidate the drivers governing the environmental and economic viability of the NEWgenerator, and (ii) to prioritize opportunities to advance system sustainability through targeted improvements and intentional deployment of the technology. To this end, we used a quantitative sustainable design (QSD)[12] approach to characterize the technological, economic, and environmental sustainability of the NEWgenerator technology. Our analysis leveraged detailed design and performance data from a field trial in an informal settlement in South Africa over a 530 day period (October 2018 to March 2020), treating high strength blackwater and yellow water from a community toilet facility.[11] In addition to the NEWgenerator, the analysis included a frontend (user interface such as urinal, squatting or seat pan and associated plumbing), pretreatment, a foundation, and on-site sludge treatment to simulate fully operational NSS system. We evaluated the system using QSDsan,[12] an open-source, community-led platform for the QSD of sanitation and resource recovery systems. QSDsan enables an integrated workflow of design, simulation, techno-economic analysis (TEA), and life cycle assessment (LCA) under uncertainty.[60] The implications of deployment location on costs and life cycle GHG emissions were characterized via a contextual analysis considering country-specific factors (including average wages, grid electricity price and makeup, and waste characteristics) for China, India, Senegal, South Africa, and Uganda. The results from this study provide insight into opportunities to advance the sustainability of the NEWgenerator and, more broadly, NSS through targeted research, development, and deployment of treatment and resource recovery technologies.

3.2 Methods

3.2.1 NEWgenerator Overview and Process Model

The NEWgenerator consists of three main treatment processes: (i) an AnMBR for solids separation breakdown and methane production, (ii) an NCS consisting of ion exchange (with zeolite) and granular activated carbon for nitrogen (and incidental phosphorus) removal and recovery, and (iii) an EC system for disinfection (**Figure 3.1**). Other ancillary units include process controls, a mini-shipping container as housing, and a photovoltaic power unit (including photovoltaic panels, battery, DC distribution box, etc.) or grid-tied power unit (including AC conversion, DC distribution box, etc.) as the energy source. All treatment data used for this work is from a 534-day field trial of the NEWgenerator 100 from October 2018 to March 2020 at an informal settlement community in eThekwini Municipality, KwaZulu-Natal Province, South Africa.[11] The system treated high-strength wastewater from a community ablution block (which operated as the frontend), where wastewater from approximately 100 users was fed into a valve chamber, a bar screen, and an underground equalization tank before entering the NEWgenerator system. Temporal data were analyzed to determine the percentage of time that the liquid effluent and solid output met ISO 30500 requirements,[11] specifically chemical oxygen demand (COD) concentration, total suspended solids (TSS) concentration, *Escherichia coli* (*E. coli*) maximum concentration and LRV, pH range, total nitrogen (TN) removal, and total phosphorus (TP) removal (**Table 3.1**). The two different usage categories for the effluent were assessed for COD and TSS are Category A threshold for unrestricted urban usage and Category B threshold for discharge into surface water of other restricted urban use. Additional details about the performance of the NEWgenerator system were reported by Shyu et al.[11] and Castro et al.[61]

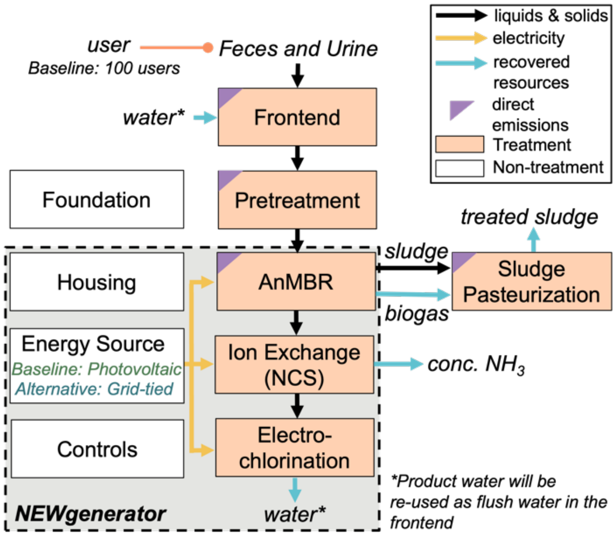

Figure 3.1 Process flow diagram summarizing the prefabricated NEWgenerator units (within black dashed line boundary), and additional units added for this analysis (outside of boundary). The color of the boxes represents ancillary units (white) and all treatment processes included both in the design of the NEWgenerator and the on-site pre-treatment (orange). The boxes with purple tags on the upper left corner represent unit processes from which fugitive emissions (e.g., N_2O) are released. There are two different energy configurations for the NEWgenerator: photovoltaic (blue) and grid-tied (green). The inputs and outputs for the system and between units are categorized as liquids and solids, electricity, and recovered resources. Outputs across the baseline scenarios include four recovered resources: biogas from the AnMBR, treated sludge from the sludge pasteurization, liquid NH_3-N from the ion exchange, and water from the EC to be recycled for flush water use in the frontend.

Table 3.1 The ISO 30500 requirements for liquid effluent and solid output parameters of NSS systems and the percentage of time that the NEWgenerator met those requirements based on temporal data from the 534-day South Africa field trial are summarized. This also includes the Category A (A) and Category B (B) requirements for COD and TSS dependent on effluent usage.

Parameter	ISO 30500 requirements		Percentage of time NEWgenerator met ISO 30500 requirements	
COD	A: <50 mg/L	B: <150 mg/L	A: 29%	B: 64%
TSS	A: <10 mg/L	B: <30 mg/L	A: 63%	B: 98%
TN	70% minimum load reduction		77%	
TP	80% minimum load reduction		2%	
E.coli	> 6 LRV		84%	
pH	6-9		98%	

We modeled the construction and performance of the NEWgenerator using QSDsan[12] python package.[62] The baseline NEWgenerator was designed to treat bodily waste from 100 users over a 25-year system lifetime. Since the NEWgenerator is a backend system only, the frontend, pretreatment, foundation, and sludge pasteurization units were also included to evaluate the complete NSS system's costs and environmental impacts. The frontend was based on an existing frontend toilet unit in QSDsan, assuming 1 seated toilet and 1 urinal per 25 people (4 seated toilets and 4 urinals for 100 users). Wastewater collected from the frontend (containing feces, urine, flush water, toilet paper, etc.) will firstly enter the pretreatment unit, which was designed using the on-site specifications for the equalization tank and bar screen, and concrete foundation based on the South Africa field trial (**Section B.2**).[11] The wastewater will then be treated by the AnMBR, where the liquid effluent will be subsequently processed by the ion exchange and EC units, and the sludge from AnMBR will be processed by a pasteurization unit. Spatial treatment performance from the South Africa field trial were simulated in the process model using mean removal values for the AnMBR (COD: 82%; TN: 20%; TP: 19%), ion exchange (COD: 63%; TN: 79%; TP: 36%), and EC units (COD: 18%; TN: 22%; TP: 11%).[11] Although the system in the South Africa field trial did not include a sludge treatment unit, a sludge pasteurization unit was modeled for on-site solids treatment to comply with ISO 30500 solids output requirements.[21] The pasteurization process was designed to be at 70°C for 30 minutes,[63] and energy needed for this process was provided by biogas from the AnMBR with LPG as a supplement. Input streams of the system include consumables such as zeolite, granular activated carbon (GAC), sodium chloride (NaCl), sodium hydroxide (NaOH) in the ion exchange unit, and liquefied petroleum gas (LPG) in the sludge pasteurization unit. Output streams include biogas from the AnMBR unit, treated sludge from the sludge pasteurization unit, wasted zeolite, wasted GAC, and concentrated liquid NH_3-N from the ion exchange unit. TEA and LCA of the NEWgenerator over the system lifetime were simulated to generate total user daily costs and annual GHG emissions from capital, operation and maintenance (O&M) (e.g., replacements, consumables), electricity, and direct sources. Two alternatives were considered for the energy sources – photovoltaic power and grid-tied electricity in the process model. The general case assumptions for cost include the capital and replacement components, materials, and consumables according to USA-build (used in South Africa field trial) excluding electricity which used global average cost. For GHG emissions assumptions, global average values were used for electricity GHG emissions, materials, components, and consumables.

3.2.2 Techno-economic Analysis (TEA)

We performed a TEA[64] of the full NSS system to determine user costs using a discounted cash flow analysis. Capital costs for all components, units, and materials were estimated using the bill of materials (BOM) from the construction of the NEWgenerator in Tampa, Florida (USA) for the general case. For the contextual analysis, we estimated capital costs across locations using country-specific price level ratios for BOM components which can potentially be manufactured or purchased locally (**Table B.4**).[65] Capital costs of NEWgenerator components were scaled using a learning curve and a production volume of 100,000 units (**Table B.2**).[66–68] We assumed shipping costs associated with transportation of raw materials was embedded in the material price, and shipping costs for prefabricated components (for large-scale deployment) could be minimized (to be a small fraction of capital costs) with large-scale deployment (~100,000 units) of the technology. Operation and maintenance (O&M) costs consisted of component replacements, consumables, energy (i.e., electricity and LPG), and labor expenses incurred over the lifetime of the system. We excluded the cost of land from the TEA due to its high variability and sensitivity to contextual factors, including the potential for the site to be publicly owned. Component replacement costs were annualized according to their respective lifetime if it is less than the system's 25-year lifetime, and any replaced components with a useful life beyond the system's 25-year lifetime was considered salvageable. Electricity requirements were based on the reported energy consumption from the Tampa, Florida (USA) field trial provided by the design team. Labor expenses were based on the detailed maintenance and replacement labor time requirements provided from the design team and labor wage price.[69] Finally, we applied a discount rate of 5% to determine the final user cost per day in United States Dollars (USD·cap^{-1}·d^{-1}). Additional details are provided in **Section B.3** of Appendix B.

3.2.3 Life Cycle Assessment (LCA)

To characterize the life cycle GHG emissions of the NSS system, we performed a LCA across the construction and operational stages. All sources of GHG emissions were normalized to global warming potential (GWP) with a functional unit of kg CO_2-eq·cap^{-1}·y^{-1}. Material requirements for construction and replacement parts were acquired from the BOM, and consumables and energy consumption were determined from field trial operational data. Inventory data for all materials and processes were acquired from the ecoinvent v3.2 database[70] and translated to GWP using the U.S. EPA's Tool for the Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI 2.1 v1.03).[71] For the general and country-specific cases, rest of world or global emission factors were used when available to consider global deployment . When material masses were not available in the BOM, masses were calculated using material density and volume, or by identifying surrogates (similar items with masses available). Direct emissions (i.e., fugitive methane, CH_4; and nitrous oxide, N_2O) from the degradation of bodily waste during storage and treatment were estimated using COD and nitrogen quantities in the bodily waste.[72–76] A 90% biogas combustion efficiency was assumed for the sludge pasteurization unit (i.e., 10% of methane was released as a fugitive emission), and a 10% heat loss was assumed in the sludge heating process.[77] The final effluent from the NSS system has the potential to be recycled for use as flush water, but would require Category A treatment per ISO 30500.[21] Ultimately, however, local regulations and conditions are likely to govern the reuse of recycled water. Additional details are provided in **Section B.6** of Appendix B.

3.2.4 Uncertainty and Sensitivity Analyses

To characterize the uncertainty in TEA and LCA results, probability distributions of 154 input parameters, for both photovoltaic and grid-tied configurations, were used in Monte Carlo simulation. Latin Hypercube Sampling[78] was used to generate 10,000 sets of input parameters for each configuration (photovoltaic vs. grid-tied electricity) and improvement scenarios. Input values for parameters were determined from the BOM, vendors, manufacturers, and literature; the distribution (e.g., 15 – 35%) of these values and type (e.g., uniform, triangular) were determined based on the accuracy and quality of data source. We utilized a lower range of uncertainty (15%) for values provided directly from the BOM, and higher ranges of uncertainty (25% – 35%) for costs and weights that were calculated, found externally on vendor or manufacturer websites, or when similar alternative values were used (e.g., tank specifications, GWP characterization factors). A 20% uncertainty was applied to energy and labor requirement values provided from the design team. Uniform distribution was used for all uncertainty ranges except for values from literature with data to support triangular distribution. To better understand the relative sensitivity of TEA and LCA results to each uncertain input parameter, Spearman's rank order correlation coefficients were calculated. Additional details are provided in **Section B.7** of Appendix B.

3.2.5 Contextual analysis

Consistent with a recent study on Omni Processors (a NSS technology designed to serve 12,000 users),[32] contextual analysis was performed to account for location-specific parameter impacts on costs and environmental sustainability in comparison with the general case. The countries included in this analysis were China, India, Senegal, South Africa, and Uganda, of which the NEWgenerator has been piloted in India and South Africa. [10,11] These counties were selected based on where NSS systems would have greatest impact; informal settlements are most prevalent in Eastern and South-Eastern Asia (370 million), sub-Saharan Africa (238 million), and Central and Southern Asia (226 million), additionally each of these regions also account for approximately 1 billion people lacking safe sanitation.[7,8] 11 location-specific parameters we considered included the unit grid electricity cost,[79] the GHG intensity of local grid electricity,[80] price level ratio,[65] tax rate,[81] labor wages,[69] local diets (consumption of vegetal protein, animal protein, total caloric intake),[82] food waste ratio,[83] LPG price,[84] and NaCl price (**Table B.4**). Location-specific price level ratio was applied to the general case BOM costs to account for differing costs of materials, consumables, and components if sourced locally.

The trade-off between photovoltaic versus grid-tied power on the relative sustainability of NSS technologies is crucial when informing deployment decisions, particularly of energy source, across various contexts. The driving contextual parameters which impact this decision are the unit cost and the unit GHG intensity of the local grid electricity, therefore the NEWgenerator was simulated across a range of unit grid electricity costs (\$0.0-\$0.6 USD·kWh^{-1}) and unit grid GHG emissions (0-1 kg CO_2eq·kWh^{-1}). These value ranges consist of the lowest and highest unit grid electricity costs[79] and emissions[80] across the globe and can inform discussions about the implications of local electricity sources on the relative sustainability of grid-tied NEWgenerator. It is important to note that due to being limited by 11 location-specific parameters, the selected parameters do not directly result in significant changes for the photovoltaic GHG emissions, except for diet-related parameters affecting excretion. Rest of world or global emission factors were used across the contextual analysis for consistency due to data insufficiencies regarding location-specific manufacturing emission factors for components or consumables (e.g., photovoltaic panels).

3.2.6 Simulation of Targeted Improvements

Five potential improvement scenarios were simulated separately: (Scenario 1) increase system capacity from a user capacity from 100 (baseline) up to 600 users; (Scenario 2) alternative sustainable components and assumptions, such as lithium photovoltaic battery, low-cost housing, sludge pasteurization service, and reduced frontend O&M assumption; (Scenario 3) alternative zeolite configurations in ion exchange such as only replacing zeolite for ion exchange instead of regenerating it and increasing the zeolite capacity for ion exchange to reduce O&M requirements; (Scenario 4) dissolved methane reduction via hollow fiber membrane contactor (HFMC) installed post-AnMBR to reduce direct GHG emissions; and (Scenario 5) potential sales and offset emissions from resource recovery of recovered concentrated NH_3 as liquid fertilizer. Notably, the NEWgenerator has only been tested at 100 users in the South Africa field trial, but we simulated underutilization and hypothetical increases in system loading in Scenario 1 to evaluate the implications of such cases, and further study is necessary to realize this improvement and determine the feasibility. Additionally, nutrient recovery, sales, and emission offsets were not considered in the baseline scenario as the current design would require additional treatment units to achieve commercial quality nutrients, however the potential of recovered nutrients to reduce cost and GHG emissions were calculated in Scenario 5 to provide insight for recovered resources at current design.

3.3 Results and Discussion

3.3.1 Financial viability and environmental performance of the NEWgenerator

The economics and environmental impacts of the baseline NEWgenerator were characterized under general case assumptions (**Figure 3.2A**) and across five countries of interest (**Figure 3.2B**). Under the general case assumptions, the use photovoltaic energy as the electricity source for the NEWgenerator resulted in lower GHG emissions but at a higher user cost when compared to the grid-tied energy configuration (**Figure 3.2A**). The photovoltaic energy configuration median user cost was 0.113 USD·cap^{-1}·day^{-1}, with a 5th and 95th percentile range of 0.105 – 0.124 USD·cap^{-1}·day^{-1} [hereafter, the 5th and 95th percentile range will be shown in brackets following the median value]. The grid-tied energy configuration user cost was approximately 1.2 cents cheaper compared to the photovoltaic configuration, at 0.101 [0.092 – 0.113] USD·cap^{-1}·day^{-1}. The user GHG emissions when using photovoltaic energy were lower than grid-tied, with impacts estimated at 67.7 [38.5 – 113.6] kg CO_2-eq·cap^{-1}·year^{-1} and 76.4 [46.4 – 123.1] kg CO_2-eq·cap^{-1}·year^{-1}, respectively. The increase in general case user cost for the photovoltaic configuration (as compared to grid-tied) can be attributed to the capital and O&M replacement costs of the photovoltaic panels and battery which incurred greater costs than those imposed by the grid-tied electrical components and consumptive cost of grid electricity over the 25-year lifetime. The grid-electricity consumption of treatment units accounted for approximately 8.7 kg CO_2-eq·cap^{-1}·year^{-1} of user GHG emissions. Ultimately, the transition from grid electricity to photovoltaics reduced GHG emissions is quite high at a cost of 501.9 [581.4 – 428.1] USD·tonne CO_2-eq^{-1} in the general case scenario, due to the minimal 1.2 cent daily user cost and 8.7 kg CO_2-eq·cap^{-1}·year^{-1} emission differences.

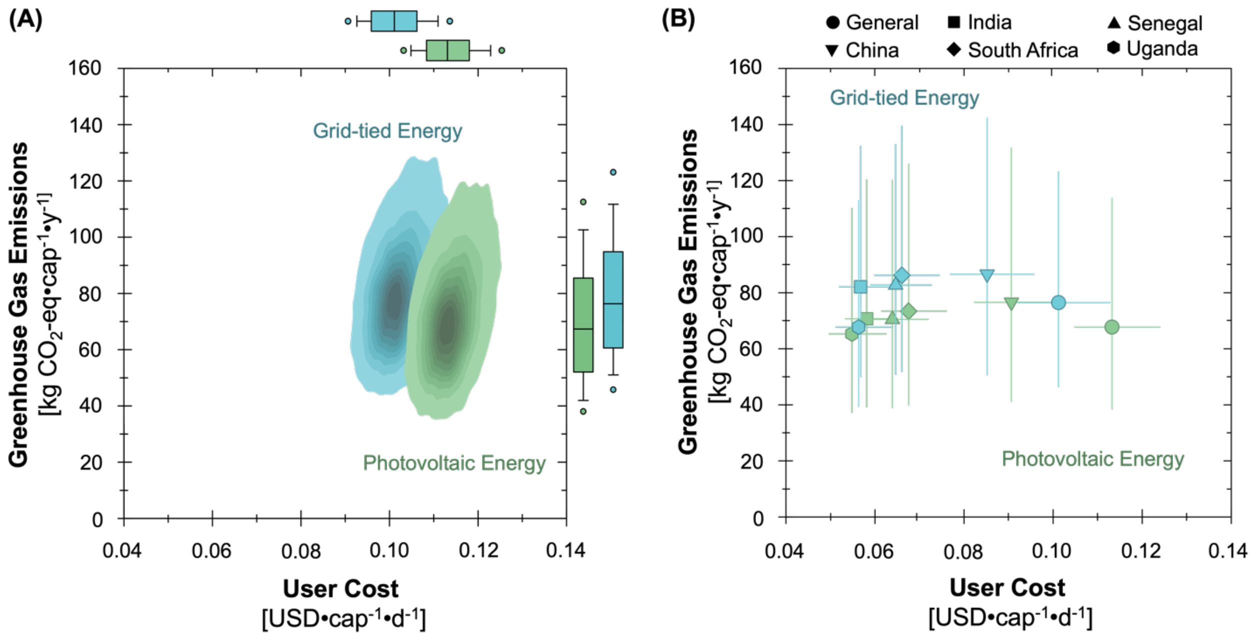

Figure 3.2 Estimates of economic and environmental outcomes associated with the NEWgenerator under (A) two different energy configurations (photovoltaic in green and grid-tied in blue) and (B) different deployment contexts (the general case and the five countries of interest). In A, the kernel density maps represent 10,000 Monte Carlo simulations. The horizontal position corresponds to user cost, and the vertical position corresponds to GHG emissions. In the box and whisker plots along the axes, median, 25th/75th, 10th/90th, and 5th/95th percentiles are represented by the center line, bottom and top of the box, lower and upper whiskers, and points on either end of the whiskers, respectively. In B, the points represent the baseline values and the error bars represent 5th/95th percentiles, respectively.

While the general case user cost and GHG emissions help characterize the sustainability of the NEWgenerator using USA-build BOM costs and global average emissions factors, understanding how contextual factors impact the economics and environmental impact of the NEWgenerator is necessary to inform intentional deployment decisions. Across the five countries, an overarching trend of grid-tied configurations having lower cost but higher emissions than photovoltaic configurations were observed with the exception of Senegal and Uganda (**Figure 3.2B**). The photovoltaic daily user cost for all countries fell below 9.1 cents, with similar but lower costs produced for the grid-tied configuration except for Senegal and Uganda where the photovoltaic daily user costs were slightly lower (<0.2 cents) than the grid-tied configuration. The photovoltaic user cost for Uganda was lowest of the five countries at 0.055 USD·cap^{-1}·day^{-1}, followed by India, Senegal, South Africa, and then highest for China at 0.091 USD·cap^{-1}·day^{-1}. All five countries had lower user costs for both energy sources than the general case due to the country-specific price level ratio applied to general case BOM costs (USA-build), in addition to the country-specific consumables and grid-electricity prices being lower than the global average values used in the general case. For all countries, the grid-tied configurations ranged from 10.0 – 12.8 kg CO_2-eq·cap^{-1}·year^{-1} higher than their photovoltaic counterparts, except for Uganda which was only 2.4 kg CO_2-eq·cap^{-1}·year^{-1} (**Figure 3.2B**). All countries had higher GHG emissions for both energy sources than the general case, except for Uganda which was 2.4 and 8.7 kg CO_2eq·cap^{-1}·year^{-1} lower for photovoltaic and grid-tied sources, respectively. There was greater variation across countries in the grid-tied configuration GHG emissions due to the country-specific grid electricity mix. China, India, Senegal, and South Africa had relatively high median GHG emissions ranging from 82.1 – 86.6 kg CO_2eq·cap^{-1}·year^{-1}, while Uganda had significantly lower GHG emissions at 67.7 kg CO_2eq·cap^{-1}·year^{-1} due to Uganda's primarily hydroelectric grid electricity mix in Uganda being as opposed to coal or oil energy source for the other countries (**Table B.5**).

The inclusion of 11 location-specific parameters help account and assist deployment decisions based on characteristics and economics, they alter the user cost for both energy sources significantly with a quantifiable impact on grid-tied GHG emissions due to the grid-tied electricity carbon intensity [kg CO_2eq·kWh^{-1}]. Beyond the diet-related parameters affecting excretion, the selected parameters do not directly result in significant changes for the photovoltaic GHG emissions, especially as global average GHG emissions factors were used for components and consumables (except NaCl and LPG) which may not be an accurate reflection of manufacturing locations and these assumptions may need to be revisited. For example, using global average emissions factors may not be accurate for photovoltaic panels as China accounts for 62% of total photovoltaic panel production worldwide.[85] Therefore, further inclusion and addition of detailed location-specific parameters, especially related to the emissions factors associated with local manufacturing or production of components and consumables, can provide more accurate contextual costs and GHG emissions. Evaluating the country-specific user costs and GHG emissions for transparent feasibility of NSS technologies is beneficial when making informed feasibility deployment decisions on system sustainability, given the likelihood of variation in results for target deployment countries compared to the general case.

3.3.2 Elucidating key drivers of cost and GHG emissions

The key drivers of user cost and GHG emissions were elucidated via detailed breakdown of each unit by the respective contributions of capital, O&M, electricity, labor, and direct emissions (**Figure 3.3**). Both energy source configurations were analyzed to identify the respective key contributors to the economic and environmental impact outputs. The major drivers of user cost were spread relatively evenly among the ion exchange, EC, and AnMBR treatment units, power unit, and controls. The unit contributions of to the total daily user cost for photovoltaic/grid-tied configurations are as follows: ion exchange 23%/24%, EC 18%/21%, AnMBR 15%/16%, photovoltaic or grid power unit 13%/1%, and controls 11%/13%, respectively (**Figure 3.3**). For both energy source configurations, the user cost was from the capital costs of the key components (e.g., pumps, reactors, tanks, electrochlorinator, photovoltaic panel, and membrane module), O&M replacement costs of those components, and consumables in the treatment units (e.g., zeolite, GAC, NaCl, and NaOH), as well as the labor associated with maintenance and replacement. The cost contribution of grid-tied power consumption was minimal to the overall cost, and the grid-tied unit had lower capital and O&M costs than the photovoltaic unit which consisted of photovoltaic panels, and battery. For all units the O&M costs were the main drivers of user cost, followed by capital costs except for ion exchange due to the higher labor requirements for zeolite regeneration.

In both energy source configurations, the GHG emissions were primarily driven by the sludge pasteurization, effluent, ion exchange, and EC units. The unit contributions to the total GHG emissions for photovoltaic/grid-tied configurations are as follows: sludge pasteurization 36%/32%, effluent 27%/24%, ion exchange 26%/23%, and EC 2%/12%, respectively (**Figure 3.3**). The direct emissions can be attributed to the dissolved methane in the effluent from the anaerobic treatment and the biogas lost as methane during biogas combustion in the sludge pasteurization unit. The O&M emissions is primarily attributed to the production of the consumables in the sludge pasteurization (e.g., LPG) and the chemically driven ion exchange unit (e.g., zeolite, NaCl, NaOH). In the grid-tied configuration, the emissions from the grid-tied electricity consumption are solely from the EC unit (7.5 kg CO_2-eq·cap^{-1}·year^{-1}). There are tangible GHG emissions benefits of selecting electrically driven treatment processes in photovoltaic-powered NSS technologies. For the NEWgenerator, the benefit of electrified treatment such as EC is not realized if the grid-tied configuration is used, and if nutrient removal can be electrified the user cost and GHG emissions for the photovoltaic configuration could be reduced further. It is also important to note that the frontend, pretreatment, sludge pasteurization, and foundation had negligible impact on the overall costs or emissions of the NEWgenerator, with most of the cost and emissions stemming from the backend treatment units. The sludge pasteurization emissions stem from the AnMBR biogas production, and if without biogas combustion the methane, which will be directly emitted into the atmosphere.

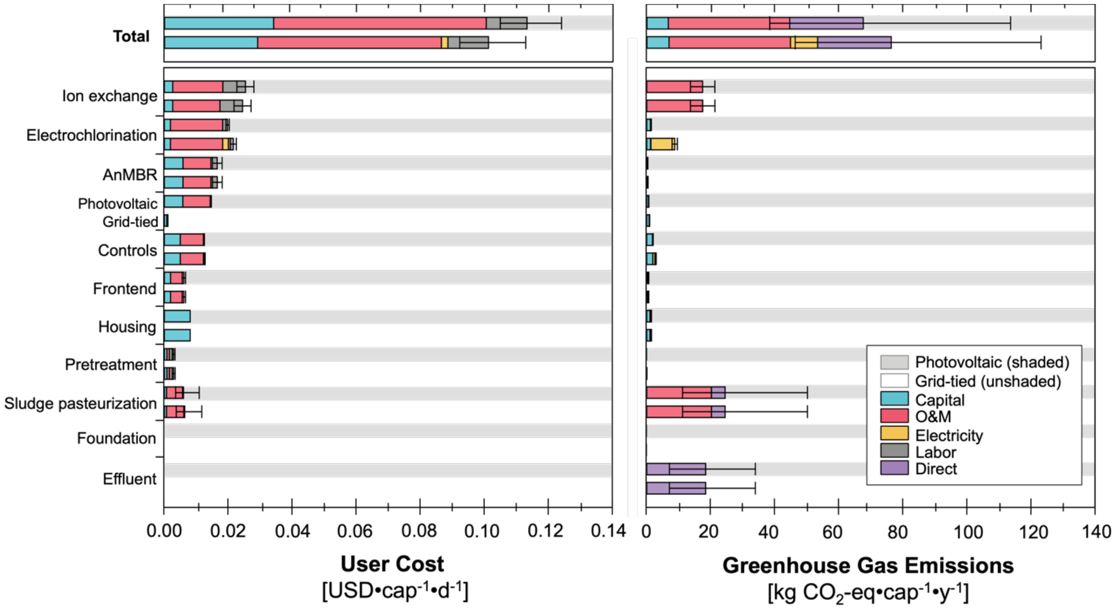

Figure 3.3 Daily user cost estimates and annual user GHG emissions for the NEWgenerator technology assuming 100 users, a 25-year lifetime, and 100,000 units produced at scale for two different energy configurations. The shaded bars depict the photovoltaic energy configuration (gray), and the unshaded bars depict the grid-tied energy configuration. The top panel shows the total breakdown of user costs and GHG emissions by relative contributions from capital, O&M, electricity, labor, and direct (for GHG emissions only) to the median user cost. Further breakdown of user cost and GHG emissions by each unit process with stacked bars to show relative contributions from each source of cost and emissions. Error bars extend to 5th and 95th percentile values from the uncertainty analysis.

Sensitivity analysis was used to determine the absolute Spearman's rank correlation coefficient (with 1 indicating the highest correlation) of assumptions and parameters in the analysis which had the greatest influence on the cost and GHG emissions of the NEWgenerator (**Figures B.1 and B.2**). The user cost was highly sensitive to the AnMBR sludge moisture content[86] with a Spearman's rank coefficient of 0.67 and 0.66, for photovoltaic and grid-tied configurations, respectively. This was followed by the photovoltaic/grid-tied Spearman's rank coefficient of LPG price 0.39/0.38, urine excretion 0.35/0.35, and fecal excretion 0.32/0.32. The labor wage price was used to determine the total labor cost required for the NEWgenerator based on the hourly maintenance requirements, therefore a change in the labor wage price parameter can significantly influence changes in the user cost. The sludge moisture content and LPG price directly relate to the amount of heat, and therefore volume and cost of fuel, needed to dry and pasteurization the sludge due to its water content. The user GHG emissions was most sensitive to the energy excretion (fraction of intake) with a Spearman's rank coefficient of 0.86 and 0.86, for photovoltaic and grid-tied configurations, respectively, which influences the amount of COD in the waste stream and in turn how much which will degrade to form fugitive methane. This was followed by the photovoltaic/grid-tied Spearman's rank coefficient of AnMBR methane yield/production fraction[87] 0.21/0.21, sludge moisture content 0.19/0.19, and AnMBR COD removal 0.17/0.17. All the above parameters directly relate to the COD and its degradation to methane in the waste stream and AnMBR, as well as the sludge characteristics which corresponds to the amount of fuel needed for sludge pasteurization.

The NEWgenerator has met the ISO 30500[21] treatment performance requirements except for total phosphorus (TP) removal as the current design only passively removes TP, therefore additional treatment unit would be necessary. Future work in incorporation of phosphorus treatment would be insightful, such as phosphorus precipitation via Magnesium Hydroxide addition. The phosphorus precipitation can be implemented in the current mixed excreta design within the AnMBR unit or for a source-separated excreta design using urine diverting dry toilet within a separate tank where urine is collected.[88,89]

3.3.3 Simulating improvements to advance relative sustainability

Increase user capacity

Increasing hydraulic throughput and loading rate into the NEWgenerator was modeled by altering the number of users and the corresponding influent flowrate and waste stream characteristics. The South Africa field trial demonstrated robust treatment performance of high-strength black and yellow water at 100 users and may have the potential to serve more. Thus, increasing the user capacity is plausible for the NEWgenerator and was simulated for potential cost (**Figure 3.4A**) and environmental impact reductions (**Figure 3.4B**). For this analysis, the user cost and user GHG emissions from 100 to 600 users were simulated at scale, and an underutilization scenario at 50 users was also simulated. These increases were simulated using the NEWgenerator general case at a baseline design of 100 users, while scaling the costs and GHG emissions associated with the following: capital components, O&M replacement of components (e.g., pumps,

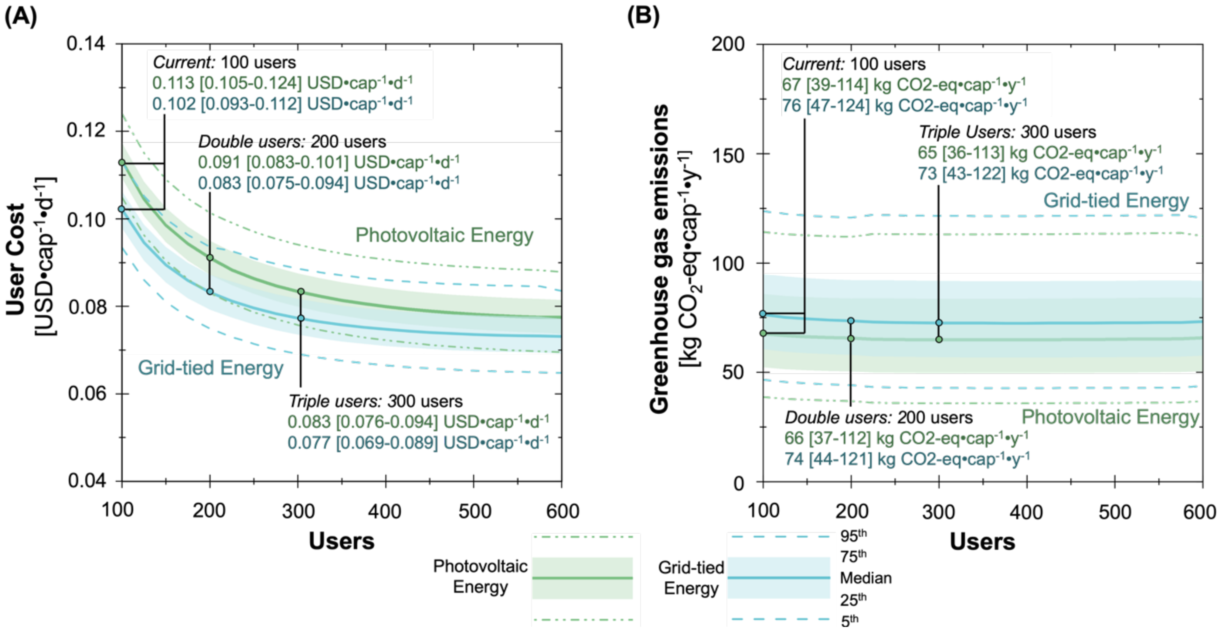

Figure 3.4 The daily user cost and annual user GHG emissions were simulated based on the impact of increasing users (increasing hydraulic throughput and loading rate) at NEWgenerator general case. Two different energy configurations were simulated: photovoltaic (green), and grid-tied (blue). The user capacity was simulated from 100 users (baseline or current) to 600 users, with user cost and emissions for current, double, and triple users shown in callout. The median, $25^{th}/75^{th}$, and $5^{th}/95^{th}$ are depicted by the solid line, shaded region, and dashed line, respectively, to represent the range of results from uncertainty analysis.

electrochlorinator, biogas storage, photovoltaic panel and batteries, grid-tied power box), O&M streams (e.g., consumables such as zeolite, GAC, NaCl, NaOH), O&M labor (e.g., for pump replacements, battery replacements, zeolite regeneration and replacement, GAC replacement), and electricity demand (e.g., pump, electrochlorinator). Capital costs, O&M replacements costs, and respective weights of components were scaled exponentially, while O&M streams, labor, electricity demand, and frontend were scaled linearly.

Increasing the number of users reduces the user cost significantly; however, there is a minimal impact on user GHG emissions (**Figure 3.4B**). Doubling the number of users from the baseline of 100 users to 200 users reduces the median daily user cost by 2.2 cents (from 0.113 USD·cap^{-1}·day^{-1} to 0.091 USD·cap^{-1}·day^{-1}) for the photovoltaic energy configuration and 2.4 cents (from 0.102 USD·cap^{-1}·day^{-1} to 0.083 USD·cap^{-1}·day^{-1}) for grid-tied energy configuration (**Figure 3.4A**). Further increase in users has diminishing improvement on cost, with a plateau in photovoltaic and grid-tied configuration user cost at approximately 7.8 and 7.3 cents per user per day, respectively. O&M, electricity, and direct emissions are the main sources of the NEWgenerator GHG emissions (**Figure 3.3**) and are scaled linearly as users increase, therefore when normalized to GHG emissions per user there is minimal improvement. It is unlikely that increases beyond doubled and tripled users while maintaining the system design (e.g., hydraulic retention time, contact time) and treatment performance are possible without additional scaling of capital, O&M, labor costs, and respective emissions. If the NEWgenerator is underutilized at 50 users (half of its design capacity), the photovoltaic configuration median user cost and GHG emissions approximately doubles to 0.221 USD·cap^{-1}·day^{-1}, and 92.0 kg CO_2eq·cap^{-1}·year^{-1}, respectively. However, the NEWgenerator has only been tested at 100 users in the field trial, so further study is necessary to determine the influence of increased users on treatment performance. If maintaining treatment performance is possible when increasing the number of users while at the baseline design of 100 users, the NEWgenerator user cost will improve significantly and maintain similar amount GHG emissions.

Alternative sustainable components and assumptions

Improvements to capital and replacement components using sustainable alternative and improved assumptions were simulated in this scenario (**Figures B.3 and B.4**). The alternative components include using a lithium photovoltaic battery with longer lifetime and a 75% lower-cost standard shipping container for housing. Assumptions improvements include a 5% reduction in frontend OPEX over CAPEX ratio to 2.5%, and sludge pasteurization as a service to treat sludge from 10 NEWgenerators. All improvements reduced user cost, the component changes (lithium photovoltaic battery and low-cost housing) each reduced cost by approximately 0.005 USD·cap^{-1}·day^{-1} with no increase in GHG emissions. The assumptions improvements which included the reduced frontend O&M ratio and sludge pasteurization service reduced user cost by 0.003 and 0.001 USD·cap^{-1}·day^{-1}, respectively, and had negligible increase in GHG emissions. If all the above improvements are applied (assuming no negative interactions), there is potential for the median daily user cost to be reduced by 1.4 cents to 0.099 USD·cap^{-1}·day^{-1} with negligible change in GHG emissions.

Alternative zeolite configurations in ion exchange

One of the key drivers to cost and GHG emissions is the ion exchange unit using zeolite to remove total nitrogen (TN). The baseline design consists of the 3 zeolite regeneration events per year to extend the zeolite lifetime and replacements every 3-years.[61] Different design scenarios for the zeolite in the ion exchange unit were evaluated including a zeolite replacement only scenario where zeolite is not regenerated and replaced annually, and an increased zeolite capacity scenario where the zeolite capacity is increased 3-fold and replaced annually (**Figures B.3 and B.4**). The zeolite replacement only scenario increased user cost by 0.006 USD·cap^{-1}·day^{-1} and GHG emissions by 50.2 kg CO_2eq·cap^{-1}·year^{-1}. The increased zeolite capacity scenario increased user cost by 0.004 USD·cap^{-1}·day^{-1} and GHG emissions by 50.4 kg CO_2eq·cap^{-1}·year^{-1}. Although in both scenarios, the cost and emissions associated with regeneration labor and consumed NaCl (in regenerant solution) is reduced, the increase of zeolite consumed from annual replacements exceed those reductions. Therefore, the baseline design using zeolite regeneration would be preferable over these zeolite configuration scenarios as reductions in labor and consumables do not outweigh the increase in zeolite required for the alternative ion exchange designs.

Dissolved methane reduction via hollow fiber membrane contactor (HFMC)

Dissolved methane remaining in the liquid effluent is a major source of direct GHG emissions due to anaerobic processes in wastewater treatment and it has been reported that approximately 30-50% of methane produced (converted from COD) will remain in dissolved form.[90,91] For the NEWgenerator, this accounts for 18.6 kg CO_2eq·cap^{-1}·year^{-1} (28%) of total photovoltaic GHG emissions in the liquid effluent (**Figure 3.3**). To reduce the dissolved methane leaving the system, a scenario involving the installation of a HFMC post-AnMBR was simulated (**Figures B.3 and B.4**). The micro-porous HFMC was selected for high liquid-gas separation where dissolved gas will diffuse through the membrane pores and is appropriate for AnMBR permeate due to its low organic solute concentration which will limit scaling issues.[92,93] For the simulation, the HFMC was assumed to remove 63.3-98.9% (uniform uncertainty range) of dissolved methane via process boundary conditions for separation which has been demonstrated for analogue and real anaerobic effluents.[92,93] The recovered dissolved methane was assumed to be converted to methane gas in biogas for the sludge pasteurization to account for GHG emissions. The addition of a HFMC comes at a tradeoff; a 14.5 kg CO_2eq·cap^{-1}·year^{-1} reduction in GHG emission to 53.2 [32.0 – 92.0] kg CO_2-eq·cap^{-1}·year^{-1}, at the expense of 1.4 cents increase in user cost to 0.127 [0.114 – 0.151] USD·cap^{-1}·day^{-1}.

Potential sales and offset emissions from resource recovery

Resource recovery of the NH_3-N recovered from the ion exchange unit via zeolite adsorption and desorption has the potential to further offset cost and emissions. At baseline operation at 100 users and photovoltaic energy configuration, approximately 79.5 kg NH_3-N·year^{-1} is recovered in liquid form in the wasted brine regenerant solution. If the NH_3-N recovered can be sold at market N fertilizer value, the potential median daily user cost offset via sales is less than 0.1 cents (0.0016 USD·cap^{-1}·day^{-1}), which will have very minimal impact on the user cost. In contrast, the median offset GHG emissions will be 3.5 kg CO_2eq·cap^{-1}·year^{-1}, or an approximately 12.5% reduction from baseline GHG emissions. However, it should be noted that further treatment of the liquid NH_3-N in the regenerant solution is needed to reach market fertilizer quality, and the current design does not account for costs associated with the additional treatment units needed.

3.3.4 Evaluating the impact of contextual parameters on the relative sustainability

To further identify the contextual landscape of the photovoltaic versus grid-tied energy source on NEWgenerator user cost and GHG emissions, the impact of grid electricity unit cost (**Figure 3.5A)** and GHG emissions (**Figure 3.5B)** were simulated. A pair-wise comparison was conducted of the photovoltaic and grid-tied configurations across a range of grid electricity unit cost (0.00 – 0.60 $USD \cdot kWh^{-1}$) and grid electricity unit emissions (0 – 1 kg $CO_2eq \cdot kWh^{-1}$). User cost of the grid-tied energy configuration is lower than the photovoltaic configuration if the grid electricity unit cost is below 0.42 $USD \cdot kWh^{-1}$ (**Figure 3.5A)**. Currently, the highest global household electricity price is 0.37 $USD \cdot kWh^{-1}$ in Bermuda[79] which is lower than the 0.42 $USD \cdot kWh^{-1}$ threshold point, therefore it will be assumed that the grid-tied configuration is the more cost-effective alternative to the photovoltaic configuration at all global electricity prices. The photovoltaic configuration has lower GHG emissions than the grid-tied configuration across all grid electricity unit GHG emissions values and equivalent emissions to the photovoltaic configuration can only be achieved at grid electricity unit emissions of 0 kg $CO_2eq \cdot kWh^{-1}$. The five countries (China, India, Senegal, South Africa, and Uganda) all have country-specific household grid electricity price below the intersection point ranging from 0.081 – 0.186 $USD \cdot kWh^{-1}$, and all had high grid unit GHG emissions due to energy mix apart from Uganda. Therefore, when solely considering the location-specific grid electricity unit price and unit GHG emissions, all five countries have lower user costs with the grid-tied configuration but at the expense of higher GHG emissions.

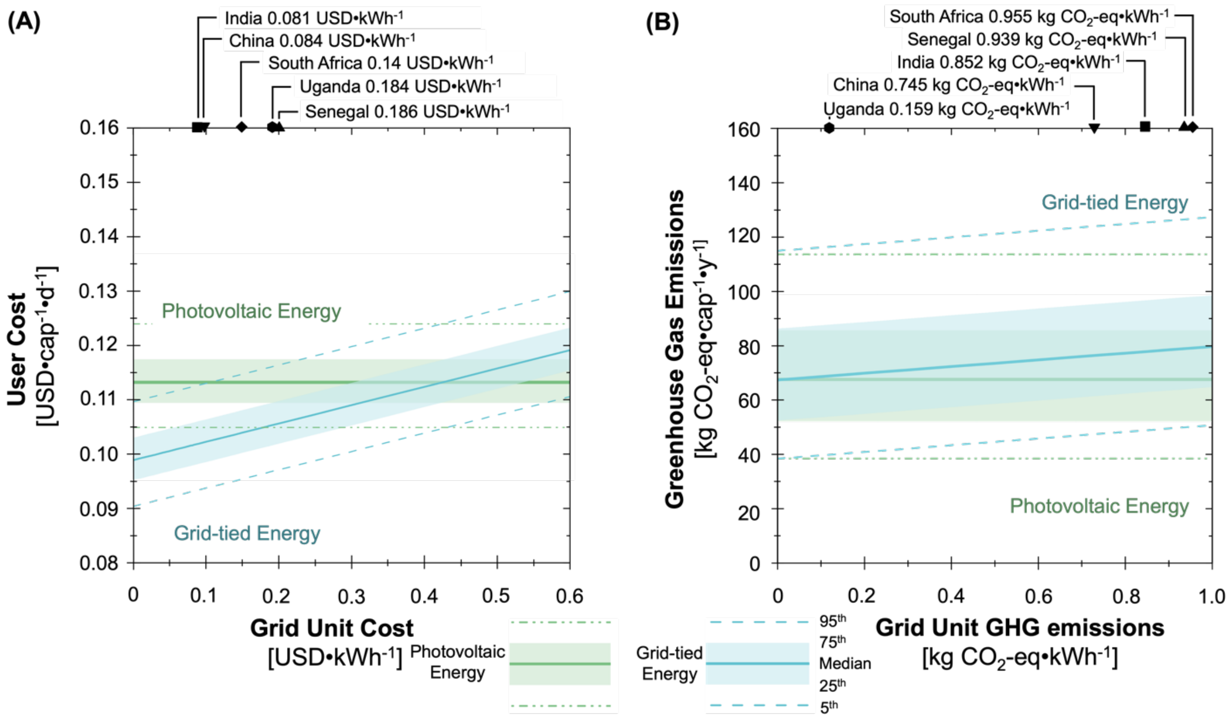

Figure 3.5 The impact of grid unit electricity cost (0.00 – 0.60 USD·kWh^{-1}) and grid electricity unit emissions (0 – 1 kg CO$_2$eq·kWh^{-1}) on the NEWgenerator for two energy configurations were simulated. The photovoltaic configuration (green) user cost and GHG emissions are constant across all values, however the grid-tied configuration (blue) changes as the inputs are varied. The country-specific values of grid unit electricity cost and emissions for the five countries of interest (China, India, Senegal, South Africa, and Uganda) are depicted on the upper horizontal axes. The median, 25th/75th, and 5th/95th are depicted by the solid line, shaded region, and dashed line, respectively, to represent the range of results from uncertainty analysis.

To navigate the tradeoffs between cost and GHG emissions for decision-making between photovoltaic or grid-tied energy configuration, the dollars per metric tonne of GHG emissions (USD·tonne CO$_2$eq^{-1}) were quantified to determine the economic equivalent of global warming impact for the countries of interest. The social cost of carbon is an estimated metric of the marginal damages incurred with an additional metric tonne of CO$_2$ emissions. The expected current carbon market for a net-zero CO$_2$ emission target is 34 – 64 USD·tonne CO$_2$$^{-1}$ in 2025 and 77 – 124 USD·tonne CO$_2$$^{-1}$ in 2030.[94] The dollars per metric tonne of GHG emissions capture the increase in cost to reduce GHG emissions when comparing the photovoltaic and grid-tied energy sources. For the NEWgenerator these values are approximately 414 USD·tonne CO$_2$eq^{-1} for India, 471 USD·tonne CO$_2$eq^{-1} for China, 260 USD·tonne CO$_2$eq^{-1} for Senegal, 305 USD·tonne CO$_2$eq^{-1} for South

Africa, and 1766 USD·tonne CO_2eq^{-1} for Uganda. All five countries fall above the 2025 and 2030 net-zero emission target, this indicates that there would not be value in mitigating GHG emissions at a higher cost via selection of photovoltaic energy configuration due to the NEWgenerator's value of dollars per metric tonne of GHG emissions being much higher than the off-set carbon emissions in the current market.

3.4 Prioritizing paths forward for technology and deployment improvements

This research assessed the financial viability and environmental implications of the NEWgenerator, a non-sewered sanitation system (NSSS), providing insight on the sustainability of implementing targeted improvements and informing intentional deployment decisions. Under general case assumptions, the photovoltaic energy configuration daily user cost was approximately 1.2 cents higher than the grid-tied configuration but had lower GHG emissions by 8.7 kg CO_2-eq·cap^{-1}·$year^{-1}$. The treatment units (AnMBR, ion exchange, EC), controls and photovoltaic power unit were the main drivers of the NEWgenerator cost for both energy sources, particularly from the O&M such as component replacements and consumables. The NEWgenerator GHG emissions were primarily driven by the sludge pasteurization, effluent, and ion exchange units. Direct emissions from dissolved methane and biogas loss during combustion and O&M emissions from production of consumables such as fuels and chemicals were the main contributors to emissions. The treatment performance data, technical, O&M, and BOM are based on field-trial deployment and laboratory-based experiments which may vary based on geographical, contextual, and site-specific factors when considering deployment. The assumptions made based on the 534-day South Africa field trial may not be accurate for different contexts and could further benefit from additional long-term field trials to be more robust. The sustainability metrics considered in this study are economic cost and environmental impact which does not consider social aspects such as stakeholder involvement, user acceptance, and technology uptake, therefore further studies on these aspects would be critical for sustained use of NSS technologies.

There are significant reductions in user cost which can be achieved with increased user capacities, but it is heavily dependent on whether the system can maintain treatment performance at these higher loadings and would require further lab and field testing. Targeted improvements to components and assumptions can provide some improvements to cost cumulatively but would have minimal impact individually. The alternative zeolite configurations in the ion exchange unit were not feasible considering the cost and emissions associated with the increase in zeolite consumption exceeding the reductions in regeneration labor and NaCl consumed. The addition of a HFMC is theoretically promising, with potential to significantly reduce GHG emissions from dissolved methane in the effluent at a slight increase in cost, it would benefit from further testing when combined with the NEWgenerator. Although at the current scale of 100 users resource recovery is not economically feasible, it may be insightful to determine the minimum number of users or clustered NEWgenerators that would result in a profitable business. Further analysis on the detailed cost and GHG emissions associated with additional treatment units to achieve commercial market quality fertilizers would also need to be explored. It is important to note that the recovered resources may not have significant economic benefit but may provide intangible benefits to the local community such as close proximity to and lower costs of locally sourced fertilizers as opposed to commercialized fertilizer products.

Contextual analysis through five country-specific simulations determined that the quantitative sustainability of the NEWgenerator was highly dependent on the country that it will be deployed in. The NEWgenerator user cost for the five countries with photovoltaic energy was as low as 0.055 $USD \cdot cap^{-1} \cdot day^{-1}$ in Uganda and highest in China at 0.091 $USD \cdot cap^{-1} \cdot day^{-1}$, with very similar results for the grid-tied configuration. The wide variation in user costs from the general case when including the 11 location-specific parameters indicates how important it is to include and consider contextual parameters when considering the financial viability of a NSS technology. The use of global average values or build in higher-income countries may overestimate the costs when simulating deployment costs of locally manufactured or produced technologies. Additionally, further inclusion of location-specific parameters beyond the 11 selected in the analysis and updated country-specific BOM costs, materials, and location-specific GHG emissions factors based on local manufacturing would be extremely beneficial. This analysis does not account for sub-national variation in location-specific values used and relies on country-wide averages which does not capture variations that may occur in regions within these countries.

When navigating the tradeoffs between photovoltaic and grid-tied energy source for the NEWgenerator, all five countries had very high dollars per metric tonne of GHG emissions ranging from 260 – 1766 USD·tonne CO_2eq^{-1} which are significantly above the current and 2050 carbon market cost. These values can be attributed to the minimal change in cost between the two alternatives because of the relatively low electricity demand of the NEWgenerator due to the EC being the only electrically driven treatment process. Therefore, for the NEWgenerator there would be minimal value in pursuing photovoltaic energy configuration over grid-tied as the cost of mitigating GHG emissions is lower than the current carbon market cost. However, if an NSS technology has several electrically driven treatment processes or high electricity demand, this tradeoff would alter drastically.

Overall, the NEWgenerator has significant potential as a low-cost, low-GHG emission, and contextually flexible non-sewered sanitation system that can serve communities and informal settlements without sewered connections and regions where alternative on-site sanitation may not be feasible. Although the NEWgenerator is quantitatively sustainable in economic feasibility and environmental impact, qualitative aspects such as user perception, social acceptance, and technology uptake have not been assessed in this study and would be extremely beneficial to the sustained use of NSSS technologies. The NEWgenerator shows promise as a NSSS technology to bridge global sanitation gaps by providing accessible safe sanitation in many contexts.

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[†] *This concludes the research publication.*

CHAPTER 4: CONCLUSIONS AND ENGINEERING SIGNIFICANCE

In conclusion, NSS technologies such as the NEWgenerator have the potential to bridge the sanitation coverage gap in regions where sewered connections are not feasible. Additionally due to the limited regulatory oversight for other onsite sanitation, the strict effluent requirements and prefabrication ensures consistent and robust wastewater treatment of NSS technologies make it a potentially suitable solution. The NEWgenerator has significant potential as a low-cost and low-GHG emission NSS technology that can serve communities and informal settlements in five countries where alternative on-site sanitation may not be feasible. Relatively similar low user costs and emissions were achieved for both energy configurations, where the photovoltaic configuration NEWgenerator had 1.2 cents higher cost at 0.113 [0.105 – 0.124] USD$\cdot$cap$^{-1}\cdot$day^{-1} but 8.7 kg CO_2-eq$\cdot$cap$^{-1}\cdot$year^{-1} lower GHG emissions at 67.7 [38.5 – 113.6] kg CO_2eq$\cdot$cap$^{-1}\cdot$year^{-1} compared to the grid-tied energy alternative. The use of location-specific parameters in country-specific analysis for five countries (China, India, Senegal, South Africa, and Uganda) resulted in variation in photovoltaic user cost and GHG emissions from 0.055 USD$\cdot$cap$^{-1}\cdot$day^{-1} and 65.3 kg CO_2eq$\cdot$cap$^{-1}\cdot$year^{-1} in Uganda to 0.091 USD$\cdot$cap$^{-1}\cdot$day^{-1} and 76.6 kg CO_2eq$\cdot$cap$^{-1}\cdot$year^{-1} in China. Future work to improve country-specific simulations such as inclusion of additional location-specific parameters, location-specific BOM cost and emissions rather than price ratio assumptions or global average emissions values, and additional countries would create more accurate simulation of NEWgenerator deployment.

Moving forward, the targeted scenarios on increased user capacity and hollow fiber membrane contactor (HFMC) are theoretically promising but would require further laboratory and field testing to assess treatment performance. Resource recovery may be feasible at a larger scale such as several clustered NEWgenerators, therefore it would be advisable to explore this further. However, to generate income stream from selling recovered resources, additional treatment units would be necessary to achieve a commercial-quality product. The tradeoff between the photovoltaic (renewable) energy and a grid-tied energy source was assessed using the dollars per metric tonne of GHG emissions which was above the expected carbon market cost for all countries.

Therefore, the grid-tied alternative would appear to be more favorable when only considering contextual electricity cost and GHG emissions (and weighting them equally). However, for an NSS technology with several electrically driven treatment processes or high electricity demands, it is likely that the benefits to cost and emissions would be realized in the photovoltaic configuration due to its renewable energy source. However, regardless of the cost and GHG emissions, it is important to note that safe sanitation provides intangible benefits to the users and recovered resources can provide proximity to and lower costs of locally sourced fertilizers despite not being economically profitable. Social sustainability such as user perception, community involvement, social acceptance, and technology uptake are of equal importance to ensure the sustained use of the NSS technologies. However, these characteristics were beyond the scope of this work.

Full transparency and understanding of the costs of sanitation is critical to efficiently allocate resources to ensure that the sanitation will be maintained for its full lifetime. Financing mechanisms reported in water, sanitation, and hygiene (WASH) case studies include, but are not limited to subsidies, results-based financing, microfinance, blended finance, cost recovery models, and self-finance. Quantitative characteristics of each financing mechanism such as collateral, beneficiary conditions, funding source, distribution of costs if multiple financing mechanisms, duration, repayment scheme, interest rate, and assessment on success would provide an additional layer to the analysis sanitation life cycle cost. Further review and additional analysis of the incorporation of financing mechanisms in TEA is needed. This would allow specific allocation of capital and O&M costs to certain financial stakeholders using a single or multiple financing mechanisms. For example, a results-based hardware subsidy combined with user fees from the community to cover O&M costs could be considered in the calculation of the location-specific daily user cost.

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APPENDIX A: SUPPLEMENTARY MATERIALS FOR FINANCING MECHANISMS LITERATURE REVIEW

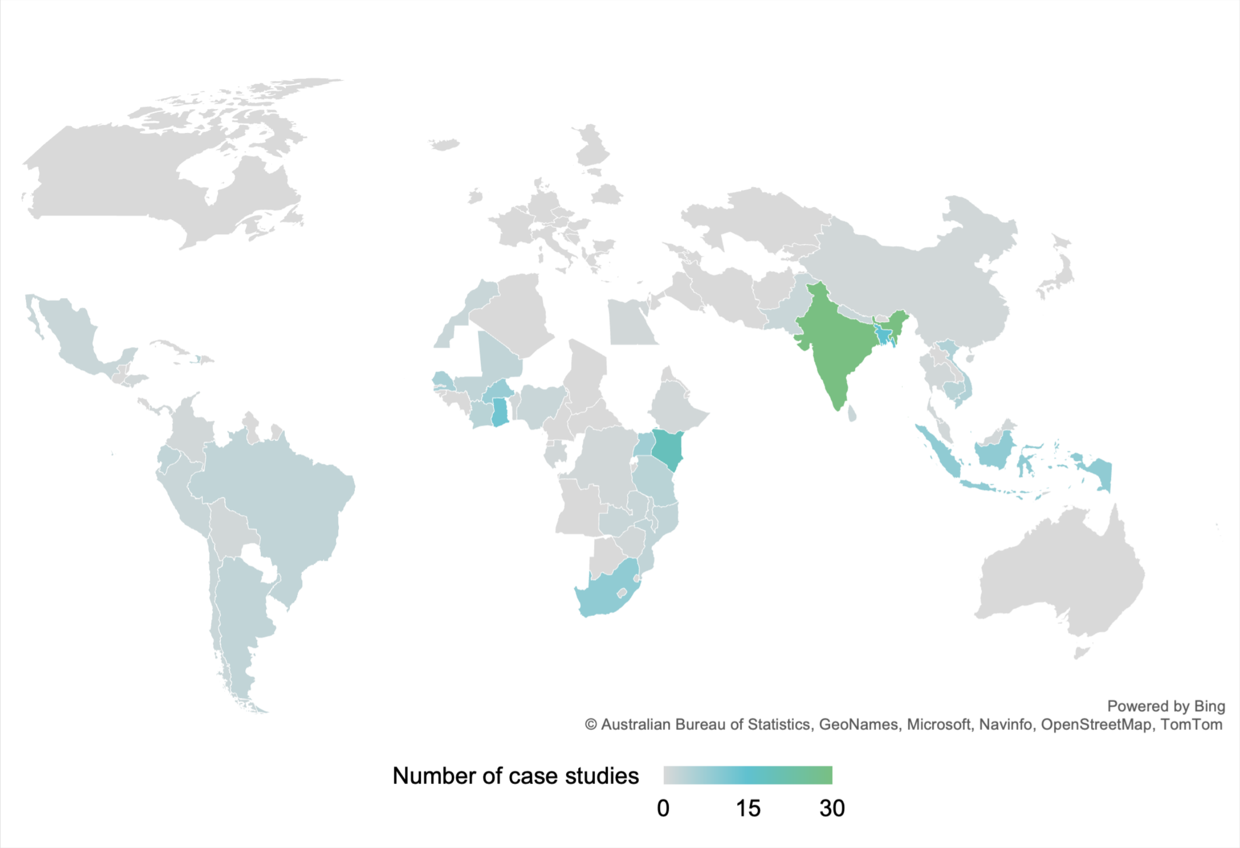

Figure A.1 World map depicting the number of case studies from the literature review of 79 papers on global sanitation financing mechanisms by country. The color in the legend indicates the higher number of studies in a particular country.

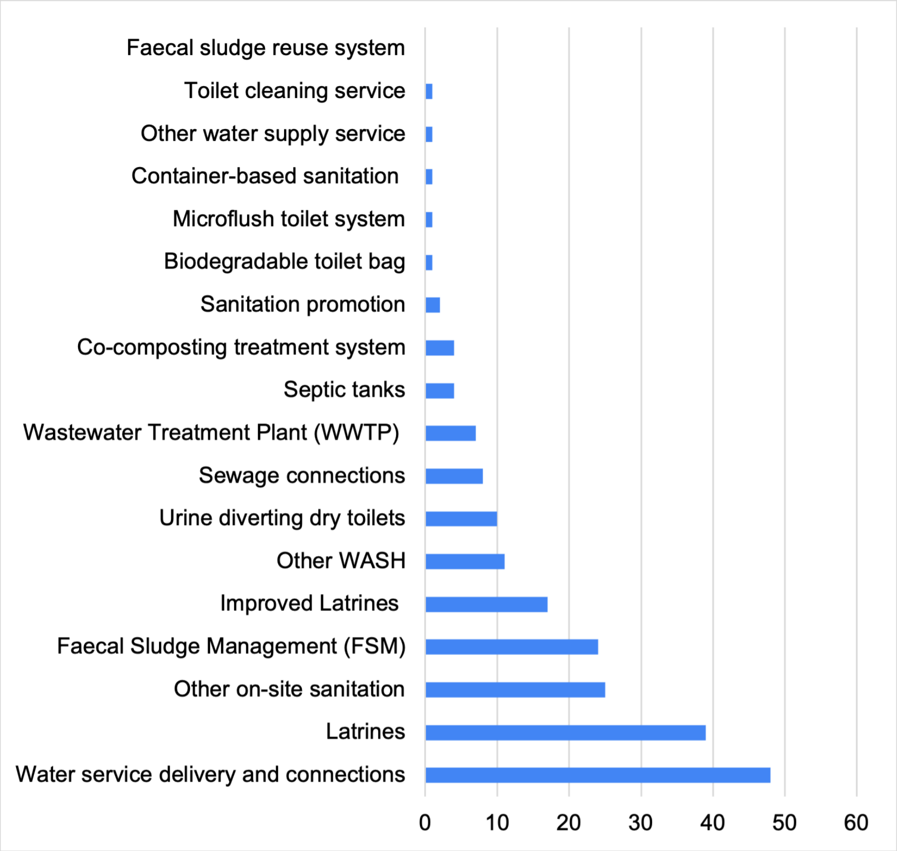

Figure A.2 Column graph showing the frequency of water and sanitation technologies in the case studies from the literature review of 79 papers on global sanitation financing mechanisms.

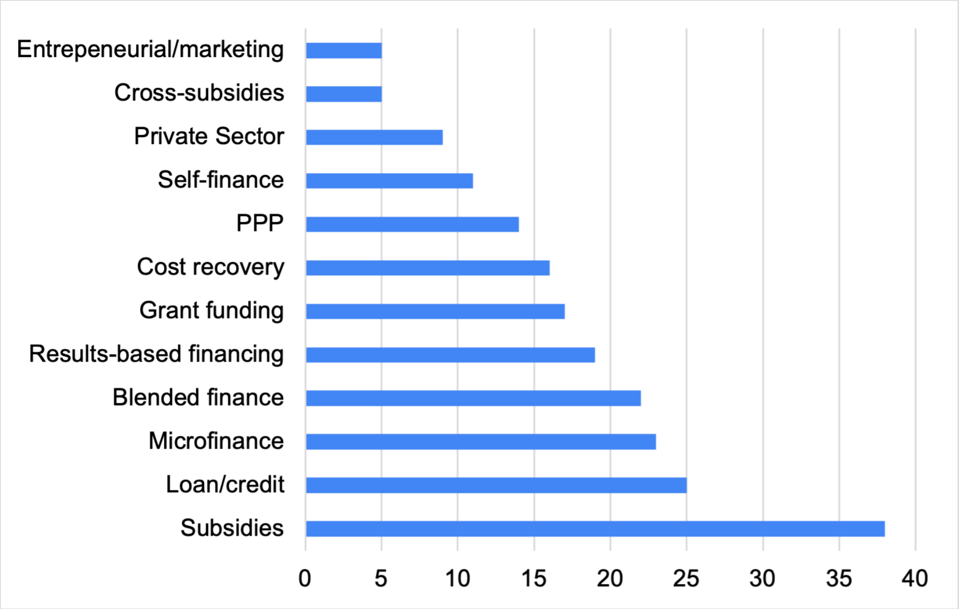

Figure A.3 Column graph showing the frequency of financing mechanisms used in the case studies from the literature review of 79 papers on global sanitation financing mechanisms.

APPENDIX B: SUPPLEMENTARY INFORMATION FOR “ADVANCING THE ECONOMIC AND ENVIRONMENTAL SUSTAINABILITY OF THE NEWGENERATOR NON-SEWERED SANITATION SYSTEM”

B.1 QSDsan input assumptions for NEWgenerator simulation

Table B.1 Input waste characteristics based on relevant literature for process simulation of the NEWgenerator.[1–4]

Parameter	Expected Value (range)	Distribution
COD [$g \cdot cap^{-1} \cdot d^{-1}$]	71 (46-96)	Triangular
Nitrogen [$g \cdot cap^{-1} \cdot d^{-1}$]	12.8 (4.3-20.2)	Triangular
COD in feces [%]	81 (69-90)	Triangular
Nitrogen in urine [%]	88 (74-93)	Triangular
Total fecal mass [$g \cdot cap^{-1} \cdot d^{-1}$]	250 (75-520)	Triangular
Feces moisture content [%]	85 (76-88)	Triangular
Total urine volume [$L \cdot cap^{-1} \cdot d^{-1}$]	1.4 (0.8-2.5)	Triangular
Carbon:COD ratio [$g\ C \cdot g\ COD^{-1}$]	0.35 (0.25-0.4)	Triangular
Particulate COD [% of total]	66 (60-72)	Uniform

Table B.2 Techno-economic analysis (TEA) assumptions used for NEWgenerator cost simulation based on relevant literature.[5–9]

Parameter	Expected Value (range)	Distribution
Discount rate [%]	5	-
Number of units for scaled production estimates	100,000	-
Learning curve percentage for scaling production cost – materials [%]	92.5 (90-95)	Uniform
Minimum cost limit [% of prototype cost]	2 (0-4)	Uniform
Price level ratio	0.25 (0.1 - 0.4)	Uniform

Table B.3 NEWgenerator input parameters for consumables, labor, and electricity in general case.[10–13]

Parameter	Expected Value (range)	Distribution
Household electricity price [USD·kWh^{-1}]	0.06 (0.045-0.075)	Uniform
Electricity intensity [kg CO_2eq·kWh^{-1}]	0.69 (0.62-0.76)	Uniform
Maintenance labor wage [USD·h^{-1}]	3.64 (1.82-5.46)	Uniform
LPG price [USD·kg-LPG^{-1}]	1.523 (1.066-1.980)	Uniform
NaCl price [USD·kg-NaCl^{-1}]	0.276 (0.207-0.345)	Uniform
GAC price [USD·kg-GAC^{-1}]	1.10 (0.825-1.375)	Uniform
Zeolite price [USD·kg-Zeolite^{-1}]	0.23 (0.173-0.288)	Uniform

B.2 Additional non-NEWgenerator units

The frontend unit design consisted on an existing frontend toilet unit in QSDsan, assuming 1 seated toilet and 1 urinal per 25 people (4 seated toilets and 4 urinals for 100 users). In the increase system capacity scenario, the frontend was scaled up accordingly (**Section B.5**). The frontend consisted of housing, seated toilet, urinal, fan, and miscellaneous parts (e.g., pipe, lighting, floor, etc.). The annual O&M cost was calculated as 7.5% of the total capital costs which would consist of replacements, labor, and maintenance. Direct methane and N_2O were from the collection of waste were calculated accordingly (**Section B.6**).

The foundation unit was based off of the concrete foundation pad design used to support the NEWgenerator in the India and South Africa field trials. A foundation area of $4.8m^2$ and thickness of 0.1143m (4.5 in) was implemented. It was assumed to have the same duration as the 25-year system lifetime and would not require any O&M.

The pretreatment unit was based off of the pretreatment design in the South Africa field trial. It was consisted of the bar screen, pretreatment tank, piping, and feed pump. All components except the feed pump were assumed to have the same duration as the 25-year system lifetime, where feed pump had a 6-year lifetime according to the BOM. The O&M requirements consisted of pump replacements and labor associated with pump replacement and bar screen cleaning.

The sludge pasteurization unit was designed to utilize the biogas and sludge produced from the AnMBR unit as a fuel source to treat the sludge on-site according to ISO 30500 solids output requirements. The pasteurization method heats the sludge by biogas combustion at 70 degrees Celcius for 30 minutes to achieve the LRV and maximum concentration requirements.[14] The process was assumed to have 90% biogas combustion efficiency or 10% biogas loss during the where the methane in the lost portion would be directly emitted to the atmosphere.[15] A 10% heat loss from the combustion heat transferred to the sludge was also assumed.[16]

B.3 Learning curve for scaled production

A learning curve was used to conservatively estimate costs at scaled production. For the NEWgenerator, a production scale of 100,000 units was assumed. Each individual capital cost component or item, including Bill of Materials (BOM) specific items and additional items for the complete system, were assessed on its relevance to scaled serial production. The percentage of capital costs to be scaled from the total captail costs, was determined to be 65%. Indicating that 65% of the all capital cost items can be optimized with a learning curve as they could be mass-manufactured at a scaled production. The following generalized leaning curve function (Eq.1) was used to conservatively estimate the capital cost of the 100,000th unit produced and calculate a conservative estimate of user cost.

$$C_N = (C_1 - L)N^b + L \qquad \text{(Eq. 1)}$$

C_N is the cost of the Nth unit using the C_1, the first unit cost (which we assume to be the design team provided BOM or estimated cost at a single quantity), L the minimum cost limit, N the number of units, and b the learning curve exponent. assuming a certain rate of learning and efficiency improvement in the production process over time. Therefore, as the number of units increase the learning curve will approach the minimum cost limit asymptotically. A minimum cost limit of 1.5% of the first unit cost was assumed.[7,8] The learning curve exponent represents the rate of decrease in unit cost as additional units are manufactured (Eq. 2).

$$b = \frac{\log(learning\ curve\ percentage)}{\log(2)} \qquad \text{(Eq. 2)}$$

The learning curve percentage of 92.5% was assumed, which means that as the output doubles, the relative production cost is 92.5%. This means that the second unit costs 92.5% of the first unit, and then the fourth unit costs 92.5% of the second unit, which continues unit 100,00 units. This learning curve percentage of 92.5% for scaled material costs falls within the conservative range (typically 90-95%),[6] with lower values (e.g., 70%) is found to be aggressive. Learning curve percentages vary depending on the industry and type of production.

B.4 Country-specific analysis

Due to the variety of different contextual economic and environmental factors, the user costs and GHG emissions for the NEWgenerator is dependent on the country of deployment. To capture these location-specific differences in the five countries of interest (China, India, South Africa, Senegal, and Uganda) in our analysis, input parameters were changed to reflect the expected conditions in each country. These country-specific parameters include household electricity price, energy mix GHG, price level ratio, tax rate, maintenance labor wage, vegetal protein, animal protein, caloric intake, food waste ratio, Liquified Petroleum Gas (LPG) price, and Sodium Chloride (NaCl) price. For specific parameters where country-specific data could not be obtained (e.g., maintenance labor wage in India, South Africa, and Senegal), we calculated and used the average from the countries with available data. The analysis provides insight into how deployment in specific countries which have unique local conditions can affect economic and environmental impact outcomes. It is important to note, however, that these results only reflect the 11 parameters examined and does not encompass the full set of conditions that may affect economic and environmental outcomes. The use of expected or average values for these countries of interest, in addition to data gaps in some parameters, only provides a high-level average potential outcome and does not capture variations that may occur in regions within these countries.

Table B.4 Location-specific parameters used for contextual analysis for the NEWgenerator. When the specific value was not available, the general case value was used instead.[9–13,17]

Parameter	China	India	South Africa	Senegal	Uganda
Household electricity price [USD·kWh^{-1}]	0.084	0.081	0.14	0.186	0.184
Electricity intensity [kg CO_2eq·kWh^{-1}]	0.745	0.852	0.955	0.939	0.159
Price level ratio	0.610	0.300	0.460	0.408	0.348
Tax rate [%]	25	25	28	30	30
Maintenance labor wage [USD·h^{-1}]	6.26	-	2.95	-	1.33
Vegetal protein [g·cap^{-1}·d^{-1}]	60.63	48.35	48.33	48.67	34.69
Animal protein [g·cap^{-1}·d^{-1}]	40	15	36.03	13.69	12.25
Caloric intake [kcal·cap^{-1}·d^{-1}]	3191	2533	2899	2545	1981
Food waste ratio [%]	15	3	2	2	2
LPG price [USD·L^{-1}]	-	0.759	-	-	-
NaCl price [USD·kg-NaCl^{-1}]	0.35	0.47	0.225	0.05	0.284

Table B.5 The country-specific energy mixed used to determine the electricity GHG intensity for the contextual analysis.[10]

Energy source	China	India	South Africa	Senegal	Uganda
Coal	51%	48%	66%	10%	0%
Oil	14%	26%	21%	76%	6%
Gas	5%	6%	3%	1%	0%
Hydro	18%	9%	0%	7%	87%
Bio	1%	3%	0%	2%	6%
Geo	0%	0%	0%	0%	0%
Wind	5%	4%	2%	0%	0%
Solar	2%	2%	1%	3%	2%
Nuclear	4%	2%	6%	0%	0%

B.5 Increase System Capacity

Table B.6 User scaling method and equations used for the increased NEWgenerator capacity simulation by category and example items.[18]

Category	Example Items	Scaling	Equation
Capital Costs	Pumps, electrochlorinator	Exponential	$NEWCAPEX = CAPEX\left(\frac{New\ Users}{100\ Users}\right)^{0.6}$
O&M Streams (consumables)	Zeolite, GAC, NaCl, NaOH	Linear	$NEW\ streams\ =\ streams\ wt.\frac{New\ Users}{100\ Users}$
O&M Replacements	Pumps, electrochlorinator	Exponential	$NEW\ OPEX = OPEX\left(\frac{New\ Users}{100\ Users}\right)^{0.6}$
Labor	Pump replacement	Linear	$NEW\ labor\ =\ labor\ hrs\frac{New\ Users}{100\ Users}$
Frontend	-	Linear	$\#\ Toilets = \frac{New\ Users}{25\ users\ per\ toilet}$
Electricity demand	Pump electricity consumption	Linear	$NEW\ kWh =\ kWh\frac{New\ Users}{100\ Users}$

Table B.7 Items scaled for increased NEWgenerator capacity simulation in each unit and category.

Units	Capital Costs	O&M replacements	O&M Streams	Labor	Electricity Demand
Foundation	-	-	-	-	-
Ion exchange (NCS)	Pumps	Pumps	Zeolite, GAC, NaCl, NaOH	Pumps, Zeolite, GAC	Pumps
Housing	-	-	-	-	-
Pretreatment	Pump	Pump	-	Pump	Pump
AnMBR	Pumps, biogas storage	Pumps	-	Pump	Pumps
Sludge pasteurization	-	-	-	-	-
Photovoltaic	Photovoltaic panel, battery	Photovoltaic panel, battery	-	Battery	-
Grid	Power conversion, distribution box	-	-	-	-
Controls	-	-	-	-	-
Chlorination	Pumps, electrochlorinator	Pumps, electrochlorinator	NaCl	Pump	Pumps, electrochlorinator
Frontend (toilet)	Housing, toilets, urinals, piping, LED, floor, circuit change	-	-	-	-

B.6 Environmental impact assessment

Life-cycle assessment (LCA) was performed to characterize the life cycle GHG emissions of the NSS system across the construction and operational stages. All sources of GHG emissions were normalized to global warming potential (GWP) with a functional unit of kg CO_2-eq·cap^{-1}·y^{-1}. The ecoinvent v3.2 database[19] was used to acquire inventory data for all materials and processes and translated to GWP using the U.S. EPA's Tool for the Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI 2.1 v1.03).[20] The emission sources from direct impacts from excreta, construction, electricity, and O&M impacts were calculated.

Construction impacts were calculated for materials and processes of each component from the bill of materials (BOM), vendor websites, or manufacturers. If masses were not available from the BOM, vendors, or manufacturers the mass and materials for components were estimated and calculated using data or specifications available on dimensions, density, etc. Global or rest of world GHG emissions were used from the ecoinvent v3.2 database instead of country-specific for all analyses.

Electricity impacts were calculated using the energy demand from the NEWgenerator BOM for the grid-tied configuration and the unit grid-electricity environmental impacts. The country-specific local grid electricity intensity was used for the contextual analysis. The energy produced from the photovoltaic configuration exceeded the NEWgenerator energy demand, therefore no environmental impacts from grid electricity were considered as it was not necessary.

O&M impacts from consumables (production of) from the system processes and replacement components were calculated using the NEWgenerator maintenance schedule.

Direct GHG emissions from excreta using during collection and treatment (e.g., user interface/frontend, containment, conveyance, pretreatment) were estimated. Direct GHG emissions of biogenic methane and N_2O released from bodily waste degradation and dissolved methane were considered in the frontend, effluent, and sludge pasteurization unit. Methane accounts for 28 times greater at 28 and N_2O approximately 265 times greater global warming impact than carbon dioxide[21,22] and was considered that way in emissions calculations (**Table B.8**). For the process model, the direct methane and N_2O were calculated as a proportion of COD and nitrogen in the input waste stream. Dissolved methane remaining in the effluent after COD degradation in the anaerobic process was assumed to have direct GHG impact.

Table B.8 Assumptions used for the calculation of direct methane and N_2O impact from excreta for life cycle GHG emissions based on relevant literature.[22–25]

Parameter	Expected Value (range)	Distribution
Maximum CH_4 emission	0.25 (0.175-0.325)	Triangular
Full degradation time	2 (1-3)	Uniform
Log degradation	3 (2-4)	Uniform
Nitrogen volatilization [fraction of N input]	0.005 (0-0.1)	Uniform
MCF decay [fraction of anaerobic conversion of degraded COD]	0.1 (0.05-0.15)	Triangular
N2O EF decay [fraction of N emitted as N2O]	0.0005 (0.000-0.001)	Uniform
Methane yield [m^3-CH_4·kg-COD^{-1}]	0.28 (0.23-0.33)	Uniform
Soluble methane fraction	0.3 (0.234-0.36)	Uniform

B.7 Uncertainty and sensitivity analysis

The NEWgenerator QSDsan simulation involved 150 input parameters which values cannot be specified exactly (e.g., contextual differences, future change, data availability, numerous manufacturers). For each uncertain parameter a distribution (e.g., uniform, triangular) over a range was generated, where the range was defined using 15 – 35% variability based on accuracy and source of data or values. Latin Hypercube Sampling-based Monte Carlo simulation[27] was used for probabilistic generation of 10,000 sets of values for the uncertain parameters. A random seed of 5 was consistently used to generate the same number sequence and respective matching order of non-repeating 10,000 values for all input parameters in all simulations (e.g., photovoltaic configuration, grid-tied configuration). These input distributions were simulated to generate 10,000 output values which was used for the distributions of daily user cost and annual GHG emissions. Spearman's rank correlation coefficients were used to assess to the sensitivity of the results to the individual input parameters via the generated input and output distributions. The sensitivity was determined by how the functional output which is user cost or GHG emissions correlated to each individual input parameter by ranking the values in each input and their respective output distribution. Spearman's rank correlation coefficient determines the statistical dependence between the rankings of input parameter and output to assess the monotonic relationship. The correlation is high if the input parameter and output have a similar rank and low is dissimilar. The coefficient values range from -1 to 1, but for the purpose of this report absolute values of coefficients were used (0 to 1). The stronger the correlation between input parameter and output occurs with a larger the absolute value. The sensitivity analysis for input parameters by category (capital, O&M, direct) is detailed for daily user cost (**Figure B.1**) and annual GHG emissions (**Figure B.2**).

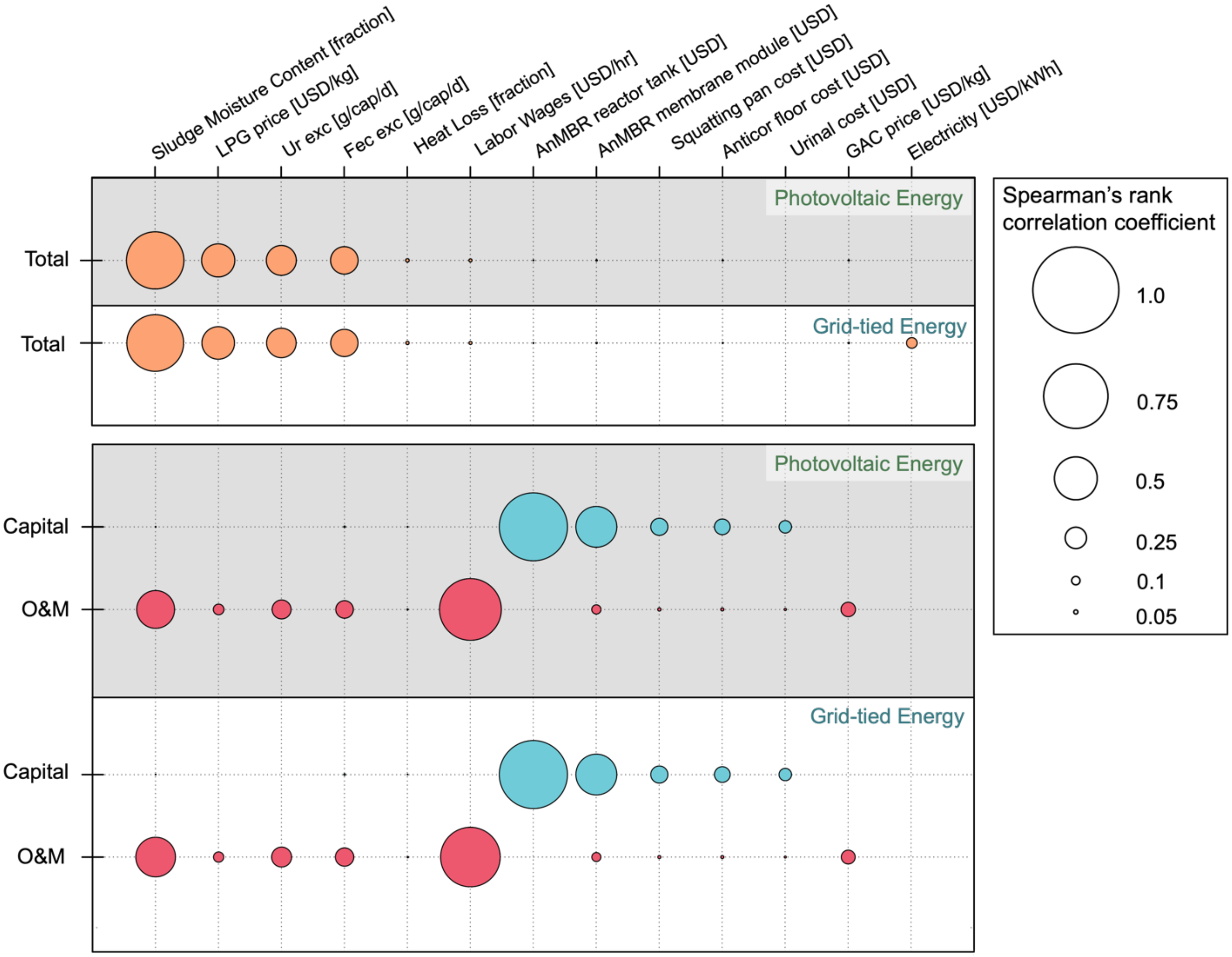

Figure B.1 The Spearman's rank correlation coefficient for total, capital, and O&M (including labor, electricity, consumables, and component replacements) daily user cost for photovoltaic and grid-tied energy configurations. The size of the bubble indicates value of the correlation, with the larger bubble indicating higher correlation between the parameter and daily user cost which indicates relative sensitivity that the daily user cost has to the uncertainty of specific input parameter.

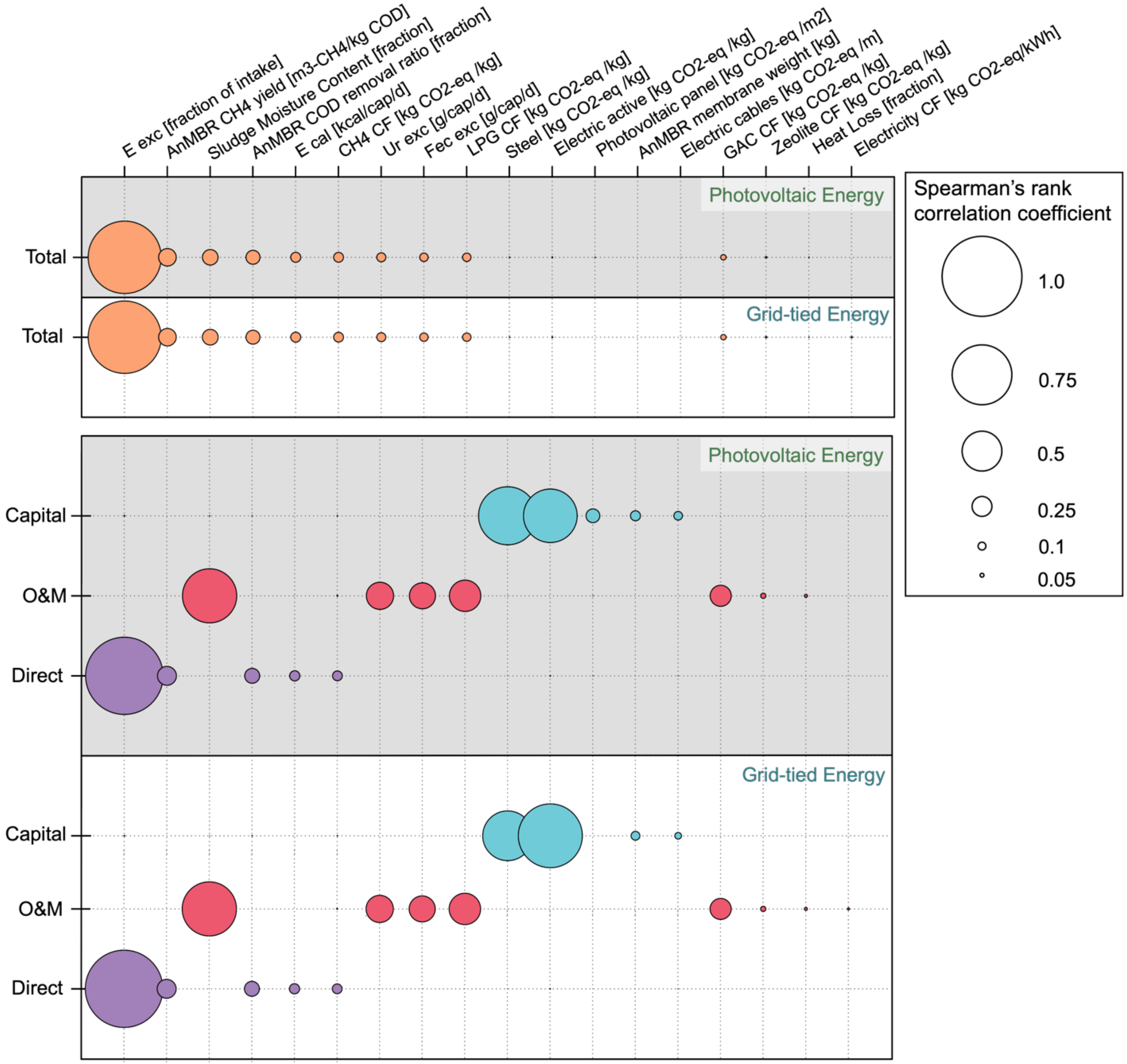

Figure B.2 The Spearman's rank correlation coefficient for total, capital, O&M (including electricity, consumables, and component replacements), and direct annual GHG emissions for photovoltaic and grid-tied energy configurations. The size of the bubble indicates value of the correlation, with the larger bubble indicating higher correlation between the parameter and annual GHG emissions which indicates relative sensitivity that the annual GHG emissions has to the uncertainty of the specific input parameter.

B.8 Targeted improvement scenarios

The targeted improvements (described in Scenario 2 through 4 of Methods) were simulated for the photovoltaic configuration NEWgenerator at general case for detailed breakdown (**Figure B.3**) and differences(**Figure B.4**). An additional scenario of LPG for sludge pasteurization only (no biogas) was explored, however resulted in negligible differences for user cost and GHG emissions from the baseline.

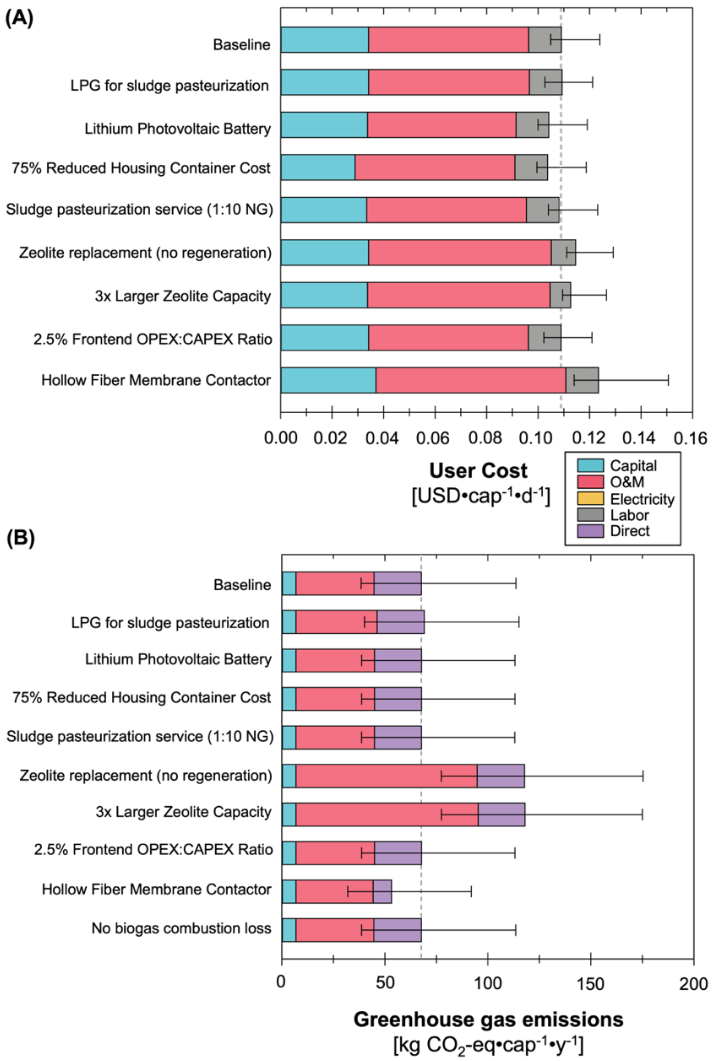

Figure B.3 Targeted improvement scenarios compared to baseline for median user cost (A) and GHG emissions (B) at general case photovoltaic configuration NEWgenerator. The cost and emissions are broken down into the respective contributions of capital, O&M, electricity, labor, and direct (for GHG emissions only). The dashed vertical line indicated the baseline user cost of GHG emissions, and the stacked bars show the relative contributions from each source of cost and emissions. Error bars extend to the 5th and 95th percentile values from uncertainty analysis.

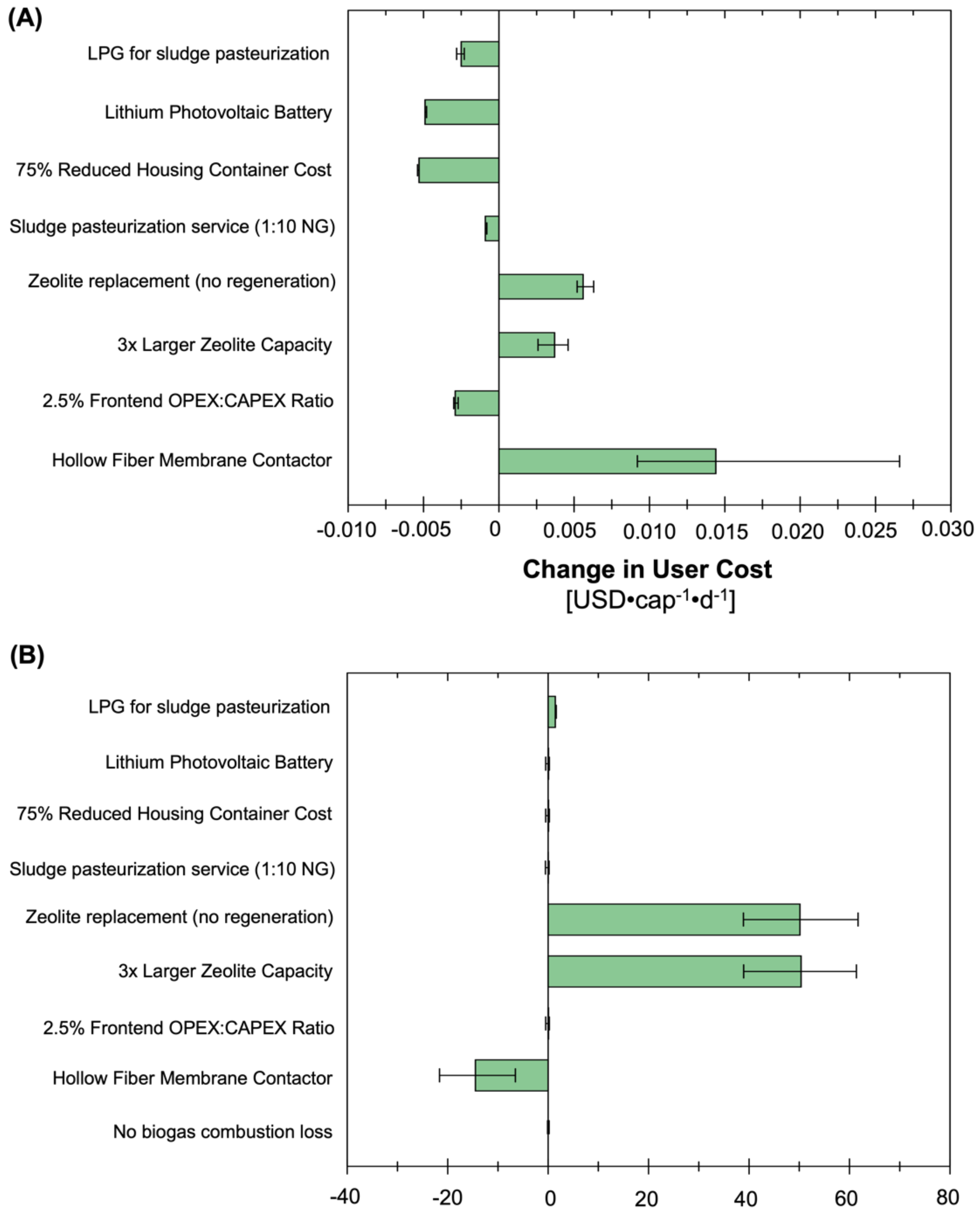

Figure B.4 Targeted improvement scenarios differences from the baseline for median user cost (A) and GHG emissions (B) at general case photovoltaic configuration NEWgenerator. The value of zero is representative of the baseline median user cost of GHG emissions. Error bars extend to the 5th and 95th percentile difference values from uncertainty analysis.

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