LIFECYCLE COST ANALYSIS OF A NEW REVERSE OSMOSIS CONCENTRATE MANAGEMENT SYSTEM USING BRACKISH DIATOMS FOR ENHANCED FRESHWATER RECOVERY

by

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ABSTRACT

World population increase and climate change call for an urgent need for an alternative water source. Brackish and recycled water (also known as reclaimed water) are considered possible alternative sources. Brackish groundwater desalination and potable reuse of recycled water often require reverse osmosis (RO) to remove undesirable impurities and produce freshwater. However, the challenges of the treatment process are high capital expenditure (CAPEX) and operation and maintenance expenditures (OPEX), along with the availability of brine disposal methods, especially for inland communities. To increase the freshwater recovery and reduce concentrate volume, incorporating an additional stage of RO (secondary RO) after the existing stages (primary RO) is desirable. However, a high concentration of silica, calcium and other inorganic scalants in the primary RO concentrate (ROC) may cause frequent scaling in the secondary RO. A novel diatom-based photobiological treatment of ROC can be introduced after the primary RO to treat the concentrate and solve the scaling problem for the secondary RO. Comprehensive bench-scale research works have been conducted in our laboratory to determine the conditions necessary to operate and maintain a photobioreactor (PBR). Although the technical feasibility of the photobiological treatment has been demonstrated along with bench-scale experiments, no research has been performed to propose this method for an industry-scale implementation. The goal of this research was to construct a detailed life cycle cost analysis (LCCA) model by exploring several parts, including designing a hypothetical industry-scale PBR and secondary RO, estimating the quantities of additional freshwater recovery, energy and chemical use, by-products production, and disposal cost reduction.

In this research, a hypothetical one million gallons per day (MGD) industry-scale PBR-secondary RO facility was proposed and designed to enhance freshwater recovery and reduce concentrate disposal costs. In this hypothetical facility, concentrate from a brackish groundwater treatment plant would be treated as part of the photobiological

treatment with a brackish water diatom *Gedaniella flavovirens* Psetr3 and the photobiologically treated water would be sent to the secondary RO. Two different light sources for the diatoms [namely, sunlight and light-emitting diode (LED)] could be used for the photobiological treatment of primary ROC. In the sunlight system, the photobioreactors would be inside greenhouses, whereas in the LED system, the photobioreactors would be inside a warehouse. A hydraulic retention time (HRT) of 1.5 days was selected, according to previous lab-scale experiments conducted in our laboratory. In addition, scenarios assuming 1.0 and 1.5 days of HRTs were also discussed in this study. Freshwater production was optimized by RO configuration and membrane selection. Energy recovery device installation was also considered for the secondary RO. Chemical dosages for antiscalant and cleaning solutions were calculated for the secondary RO facility. For the photobiological treatments, nutrient dosage was also calculated.

In the photobiological treatment, the diatoms precipitate calcium and produce cellular biomass made of silica and organics, which might be valuable by-products to offset the introduction of the new concentrate management process. Silica and calcite would generate revenue to offset the investment cost for the plant set-up, and biogas production from the diatom biomass could partially offset the power requirement of the proposed secondary RO facility. Bioresources production rate, along with the revenue from the bioresources was discussed in this research. Additional freshwater recovery would also be additional revenue of the system.

For the LCCA modeling, all the components of the PBR-secondary RO facility were listed along with their specifications. A net present value analysis was performed to consider the time value of money that would translate the future cash follows into today’s dollars. A break-even point analysis was also performed to determine the year when the project would start making revenue. Based on the LCCA, the sunlight system was more revenue generator than the LED system. CAPEX for the sunlight and LED systems for the 1.5-day HRT scenario were $17.1M and $30.8M, respectively, whereas the OPEX was $1.0M and $3.6M, respectively. HRT played a significant role in determining the most economically feasible scenario. CAPEX was reduced by 24% and 43% by the 1.0- and 0.5-days HRT scenarios in comparison to the 1.5-days HRT scenario for the sunlight system. OPEX was reduced by 6% and 12% by the 1.0- and 0.5-days HRT scenarios in comparison to the 1.5-days HRT scenario of the sunlight system. The significant difference between the sunlight and LED system in terms of CAPEX was caused by the construction of a warehouse, LED lighting installation as a light source, as well as the installation of a heating, ventilation and air conditioning system instead of an evaporative cooling system for the LED system. The high OPEX for the LED system compared to the sunlight system is caused mainly by the high electricity cost to run the LED lights.

Freshwater production costs for all the scenarios of sunlight and LED systems were determined to understand how the cost of producing fresh water from the proposed PBR-secondary RO facility would compare with the existing conventional water treatment methods and alternative water sources. Freshwater production costs for the 1.5 days HRT scenario of the sunlight system would be $5.33 without any grant, and with a 30% grant on the CAPEX the production cost would be $2.04. For the 0.5 days HRT scenario of the sunlight system, the production costs reduced to $2.49 and $0.02 for without and with a 30% grant on the CAPEX, respectively. Freshwater production costs for the 1.5 days HRT scenario of the LED system with 1.5 days HRT scenario $31.12 and $22.59 for without grant and with considering a 30% grant on the CAPEX, respectively. For the 0.5 days HRT scenario of the LED system, the production costs reduced to $13.90 and $9.77 for without and with a 30% grant on the CAPEX, respectively. Freshwater production cost comparison indicates the economic advantage of the sunlight system over the LED system. Freshwater production costs from brackish water typically ranges between $1.49–$2.49, and for seawater, the cost ranges between $3.00–$9.00. Direct potable reuse costs $1.7–$2.84 to produce freshwater. Comparing freshwater production costs of the sunlight and LED systems with alternative sources, it can be said that the sunlight system could be a promising ROC treatment system if the HRT could be reduced, whereas the LED would not be a feasible solution. Due to high CAPEX and OPEX, the LED system did not show any break-even point for any of the scenarios within the project lifetime of 20 years. However, there was break-even points for the sunlight system after 18, 15, and 7 years for 1.5-, 1.0- and 0.5-days HRT scenarios when a 30% grant was considered on the CAPEX. Additionally, the sunlight system also showed break-even point after 13 years with the 0.5 days HRT scenario with no grant consideration. Further research is needed to propose the shortened HRTs to an industry-scale ROC treatment system.

1. INTRODUCTION

1.1 BACKGROUND

The intensification of fresh water scarcity has become a global issue affecting many countries' economic and social development [1]. The global effects of water shortages are worsening in the face of climate change and population growth and migration, further straining the delicate politics of water rights within and among countries [2]. The challenge of providing access to clean water is visible in Texas, where chronic drought coincides with increasing water demand, and policymakers are evaluating new sources, including brackish groundwater of total dissolved solids (TDS) ranging from 1,000–10,000 mg/L as a source of water supply after desalination [3, 4]. Brackish water desalination is becoming increasingly important in many regions of the world as traditional freshwater supply options are becoming more limited. It is estimated that Texas aquifers contain more than 8×10^8 million gallons of brackish groundwater, which if converted to freshwater by desalination, could meet current consumption needs for 150 years, albeit at a greater cost [3].

Water reclamation and reuse have become a global phenomenon in recent years due to the increasing pressure on freshwater supplies [5]. The TDS concentration in municipal recycled water can be higher than 1,000 mg/L, indicating this as a source of brackish water [6]. In addition to long-practiced non-potable water reuse, such as urban landscape irrigation, agricultural irrigation, cooling towers, and industrial reuse, as well as indirect potable reuse (IPR) and direct potable reuse (DPR) have gained much popularity in the southwestern United States, such as California, Arizona, New Mexico, and Texas, as well as eastern states such as Florida, Georgia and Virginia [7, 8]. According to the Texas Commission on Environmental Quality (TCEQ), water from DPR projects must meet all existing drinking water quality requirements, such as maximum contaminant levels [9].

There are two principal methods by which desalination is performed, including the membrane process (*i.e.,* forcing water through a selectively permeable membrane) and the non-membrane process (*i.e.*, evaporating and condensing water away from brine)

[10]. Low-pressure membrane systems (*e.g.*, microfiltration and ultrafiltration) do not remove TDS, hence, cannot be used for desalination, whereas high-pressure systems [*e.g.*, reverse osmosis (RO)] are capable of removing TDS, as RO facilities are designed for nanosized particles' dissolved constituents [1].

The performance of the RO facility is affected by several factors, including salinity, silt, inorganic scaling, organics, and biological fouling of the RO membranes [11, 12]. The RO technology generates a concentrated stream of 15%–25% brine when it is used to produce permeate from non-potable water sources, such as brackish groundwater and recycled water [13]. Concentrate (brine) management and minimization has become a critical issue in RO-based water reuse and desalination projects, especially in inland areas where the means of concentrate disposal are limited. By introducing an additional stage of RO (secondary RO) in advanced water treatment facilities and brackish water desalination facilities, the volume of RO concentrate (ROC) can be reduced [14]. However, the presence of inorganic scalants, including silica, calcium, and phosphate in the primary ROC will cause severe scaling to the secondary RO membrane and reduce the permeate flow [12].

To solve this challenge, a unique photobiological process utilizing selectively cultured diatoms has been proposed to efficiently remove the inorganic scalants from ROC so that secondary RO can be employed to achieve additional freshwater recovery [14]. Diatoms are a group of unicellular microalgae (Bacillariophyta) that can be found in both freshwater and seawater and are one of the most important sources of biomass in oceans for oxygen (O_2) production [15]. They have a hard and porous cell wall (frustule), and it is also known that up to 70% of the cell's dry weight is silica [13]. Decades-old biological facts indicate that cultured diatoms may be used to remove aqueous silica from water and wastewater [12]. In addition to aqueous silica and macronutrients (*e.g.*, orthophosphate, ammonia, and nitrate), calcium, bicarbonate, iron, and manganese can also be removed effectively by photobiological treatment [13].

Diatom cultivation is an important area of research to produce energy from biomass as they accumulate larger amounts of total lipids than cyanobacteria and filamentous green algae [16]. The average lipid content in diatoms is 22.7% of dry cell weight under normal growth conditions, whereas, under stress, it can reach up to 44.6%, and there is a high demand for lipids in the industry for producing bio-oil and bio-crude [16, 17]. By-products from diatom biomass have significant applications in the pharmaceutical, nutraceuticals (nutritional supplements), and cosmetic industries as they contain valuable chlorophylls, antioxidants, carotenoids, blue pigments, amino acids and fatty acids [16, 18].

Lifecycle assessment (LCA) and lifecycle cost analysis (LCCA) are used for environmental and economic assessment, respectively [19]. Evaluating the ecological performance of new water treatment technologies is not enough; the study of financial aspects must also be considered because high costs can make a project unfeasible [20], and LCCA is a valuable tool to elucidate the broader economic impact of design, construction, and operation decisions. Lifecycle cost (LCC) considers the costs incurred throughout the lifecycle of the system, including costs related to energy consumption, chemicals, maintenance, repairs, equipment replacement, and waste disposal [21]. LCCA is a helpful tool for assessing the cost and benefits of several alternatives to help decide which one has the lowest LCC [22].

1.2 PROBLEM STATEMENT

The proposed scheme of installing an industry-scale photobioreactor (PBR) followed by a secondary RO is a technically feasible solution to treat the ROC to enhance water recovery from a brackish groundwater treatment facility. To make this proposed scheme viable for an industrial-scale application, it is essential understand the energy requirement, facility set-up cost, freshwater recovery rate, and revenues from by-products of the proposed enhanced freshwater recovery system of the PBR-secondary RO facility. Moreover, diatom biomasses are needed to be characterized to understand the composition and quantify different potentially useful bioresources along with the production rate and commercial value of the potential by-products.

1.3 OBJECTIVES

The goal of this research was to determine the economic feasibility of designing a hypothetical 1.0 million gallons per day (MGD), which is 3,786 cubic meters per day, industry-scale PBR and secondary RO by creating an LCCA model where different possible scenarios like light source options (*e.g.*, sunlight and LED), chemicals, usage of renewable energy (*e.g.*, biogas) to offset the power requirement of secondary RO, and various operational conditions for the PBR and secondary RO was analyzed. All the energy and chemical uses of the PBR-secondary RO systems were considered while maximizing the economic feasibility. Biomass characterization was performed in this study to evaluate the commercially valuable by-products and their production rates. The commercial value of the valuable bioresources was assessed as well. The revenue from the bioresources was incorporated in the LCCA and analyzed to offset the cost of introducing a PBR. By considering all the costs incurred during construction, as well as OPEX, the LCCA would help the economic decision-makers to select the most cost-effective options while securing maximum freshwater recovery and minimizing the ROC disposal cost. Moreover, optimization of the proposed scenarios (*e.g.*, light sources and different HRTs) productivity by maximizing the freshwater productivity and beneficial bioresources generation from diatom biomass while minimizing the overall cost was a critical analysis of this study. In addition, a laboratory photobiological treatment experiment was conducted using silica-rich water samples with a wide range of TDS concentrations as a side, preliminary experiment.

2. LITERATURE REVIEW

2.1 DESALINATION FACILITY WITH REVERSE OSMOSIS

Despite the enormous volume of water on earth, only around 10% of the 1,400 million cubic meters of water is low in salt and appropriate for use after conventional water treatment alone [23]. Increasing demand, climate change, and recurrent drought continue to constrain freshwater resources in many of the most populated areas around the globe [24]. Water-scarce countries and communities now require a rethink of water resource planning and management, which includes the innovative research of an expanding set of viable but unconventional water resources for sector water uses, livelihoods, ecosystems, climate change adaptation, and sustainable development [25]. A possible solution is to adapt the desalination technology to treat brackish groundwater and wastewater.

Several technologies are available for water desalination [26]. Processes based on evaporation (*e.g*., multi-effect distillation, multi-stage flash distillation, and vapor compression), along with processes based on membranes [*e.g*., RO, nanofiltration (NF), electrodialysis] are the two main process groups of the available technologies [27]. RO desalination systems have energy efficiency, as well as process and plant compactness, among other advantages in comparison to thermal desalination technologies [28]. Consequently, 88% of the desalinated water in the United States is produced by RO [29]. Over 15,000 RO-based desalination facilities are currently operating in more than 120 countries worldwide, producing over 3,500 MGD of potable water [23].

Membrane filtration systems such as RO and NF serve as a selective barrier that will only allow the entrance and exit of specific constituents of specific size while the other large-sized constituents will get retained and flow as concentrate through the other side of the feed [30]. The efficiency of RO depends on several factors, including the operational parameters, the employed membrane, and the feed water characteristics [28]. Although most seawater sources contain 30,000–45,000 mg/L of TDS, seawater RO membranes are used to treat waters within a TDS range of 10,000–60,000 mg/L, while brackish water RO membranes are used to treat water sources within a TDS range of 1,000–10,000 mg/L [11]. The specific energy consumption typically ranges from 2.5–4 kilo-Watt-hour/cubic meter (kWh/m^3), and 1.0–1.5 kWh/m^3 in seawater RO (SWRO) and brackish water RO (BWRO) desalination plants, respectively [31]. Due to the lower energy requirement and lower operating pressure of BWRO plants compared with SWRO plants, BWRO is gaining its popularity as a cost-effective solution to water scarcity [26, 32].

2.1.1 BRACKISH GROUNDWATER DESALINATION AND REVERSE OSMOSIS

All natural waters contain some TDS, a measure of the concentration of all inorganic and organic dissolved substances, including salts, minerals, and metals. Groundwaters with a higher concentration of TDS are often drawn from a greater depth below the land surface [33]. Fortunately, Texas is ideally suited for brackish groundwater desalination, with more than 30 aquifers spreading across the state, each containing an ample supply of brackish groundwater [34]. Figure 1 shows a brackish groundwater RO system in San Antonio, Texas.

Figure 1: RO Facility at San Antonio Water System H2Oaks Center, San Antonio, Texas (Photo Credit: Author)

San Antonio Water System (SAWS) H2Oaks Center employs a three-stage RO system with 89% feedwater recovery and found that the third stage of the RO system fouled more frequently than the first two stages [35]. As a pretreatment of the brackish groundwater, the SAWS uses chemical addition (*e.g.*, sulfuric acid and antiscalant) and a physical barrier (*e.g.*, cartridge filter) to protect against RO membrane scaling and fouling. Moreover, brackish groundwater is readily available in Texas and across much of the United States, particularly in California and Florida. Thirty-four municipal plants with a combined capacity of 276,000 m^3/day are operating across Texas as of 2015 [36]. Groundwater desalination facilities are all-over Texas, as shown in Figure 2 [37].

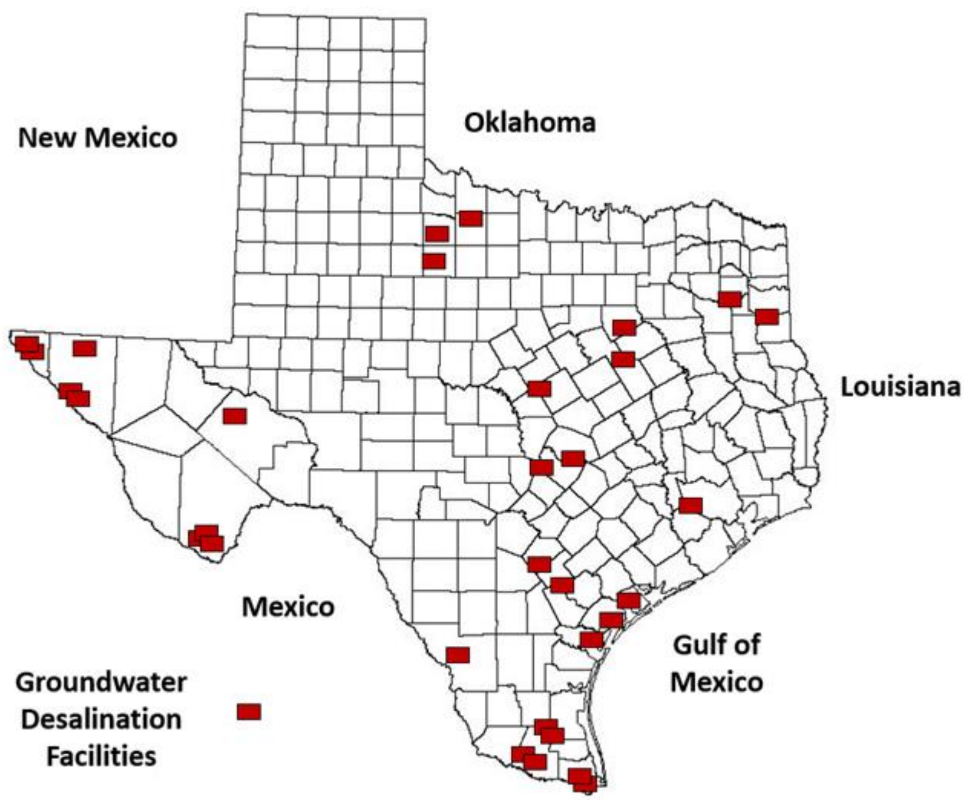


Figure 2: Groundwater Desalination Facilities in Texas [37]

The City of El Paso blends brackish groundwater RO permeate with brackish water to produce approximately 30 MGD of potable water, which could supply 35% of the city’s water supply [3]. Figure 3 shows the RO facility of the Kay Bailey Hutchison Desalination Plant at El Paso, Texas.

Figure 3: Kay Bailey Hutchison Desalination Plant, El Paso, Texas (Credit: Author)

2.1.2 ADVANCED WATER PURIFICATION AND REVERSE OSMOSIS

Wastewater reclamation is an essential part of the water reuse cycle [38, 39], and it is an effective way to improve the utilization rate of water resources. The two major types of water reuse are potable and non-potable water reuse. For several decades, most reuse projects were limited to non-potable applications, such as municipal, agricultural, and industrial reuse. Still, diminishing water supplies, dramatic population growth, historic drought conditions, the high cost of parallel infrastructure, and a greater acceptance and understanding of reuse have led to potable applications [40]. Several categories of potable reuse can be defined, including DPR, IPR, and de facto reuse [9]. The logic of potable water reuse is growing as it offers renewable, drought-proof supplies, bolsters independence, and provides more excellent dependability [2]. Utilities are considering water reuse because it can be affordable and environmentally friendly for augmenting water supplies [41]. By installing RO, the Orange County Water District (OCWD) (Fountain Valley, CA) Groundwater Replenishment System (GWRS) is currently designed to produce up to 100 MGD of purified recycled water based on a recovery rate of 85% from RO [42]. An image of the OCWD GWRS of Fountain Valley, California is shown in Figure 4.

Figure 4: OCWD GWRS Advanced Water Purification Facility, Fountain Valley, California (Credit: Author)

For additional water supplies in many parts of the state, the TCEQ has been approving DPR projects case-by-case basis in Texas [9]. By incorporating advanced treatment technologies, including microfiltration, RO, and ultraviolet disinfection, the water treatment plant at Big Spring, Texas, is treating approximately 2.5 MGD of biologically treated wastewater and recovering 1.78 MGD of fresh water [43]. The water reclamation plant in Scottsdale, Arizona, uses advanced water treatment with ozonation, membrane ultrafiltration, RO, and ultraviolet photolysis to treat up to 20 MGD of water a day [44].

Recycling wastewater within a community relieves stress on water sources by decreasing withdrawals. Membrane processes are currently being widely studied for industrial water treatment in many contexts, such as mining, agriculture, food and beverage industries, textile industry, leachate treatment plants, power plants, refineries, and various types of plants in the oil and gas sectors [45]. Certain treatment technologies have experienced cycles of popularity over the past few decades (*e.g.*, ozone), and other technologies have become more technologically or economically feasible in recent years (*e.g.*, RO) [40]. To produce process water for reuse purposes, RO membranes are necessary to remove organic and inorganic components [46-48]. There are tight rules for water quality, but high-efficiency membrane treatments, such as RO, have a good chance of producing good quality water for reuse [49]. The method of using membrane filtration for wastewater reclamation has received significant attention in removing dissolved organic matter because of its advantages, such as high rejection and small footprint [38]. RO membranes remove more than 98% salt in wastewater, and the removal of organic matter is more than 80% [50].

Moreover, recent activity in the IPR and DPR reuse initiatives will include membrane processes designed to provide pathogen removal. The most critical water quality risk that must be managed in potable water recycling is related to pathogens contaminated by bacteria, viruses, and protozoa [51, 52]. High-pressure membranes (*e.g.*, RO, NF) can remove particles (*e.g.*, inorganics, bacteria, viruses) and dissolved compounds (*e.g.*, salts and natural organic matter compounds of emerging concern) very effectively [53].

2.1.3 BARRIERS OF REVERSE OSMOSIS CONCENTRATE MANAGEMENT

Although the RO technology has been proven to be very useful and reliable to produce very high quality, nearly drinkable permeate from non-potable water resources, such as brackish groundwater and recycled water [11, 54], it generates a concentrated stream of 15–25% needing disposal. A fundamental question of how to properly handle

ROC produced in brackish groundwater desalination facility and advanced water purification facility is naturally on the agenda of the water authority of many countries [55].

The untreated or improperly managed concentrate can result in adverse environmental effects due to high salinity, nutrients (phosphorus, nitrogen), organic contaminants including emerging contaminants, and trace amounts of inorganics [56]. Direct discharge to the ocean and municipal sewer disposal of ROC are widely used disposal options for wastewater reclamation plants using high-pressure membranes [42]. TDS concentration in typical municipal wastewater may vary between 500–1,500 mg/L, where TDS concentration in the ROC could be as high as 7,000 (*e.g.,* wastewater ROC) to 18,000 mg/L (*e.g.,* brackish water ROC). In addition, ROC may also contain a certain level of ammonium depending on the performance of upstream biological nutrient removal processes [55]. For these reasons, concentrate generation and management have been major challenges for utilities that own and operate RO-based water treatment facilities [54, 57].

TDS removal efficiency of RO membranes is reduced by scaling, biofouling, and chemical degradation [58]. Fouling of RO membranes can be reduced by adjusting the operating characteristics (*e.g*., flux, recovery rate, feed channel pressure drop), by using appropriate pre-treatment methods selected based on the characteristics of the feedwater (*e.g.*, antiscalant, sand filtration, coagulation, and flocculation) [59]. The addition of antiscalants is one of the most used methods for inhibiting scaling in the RO process. However, recovery over the recommended level of the used RO feed water antiscalant can lead to mineral salt concentrations that are both above the limits of their solubility and the antiscalant's ability to prevent precipitation onto the membrane surface and feed spacer (*i.e.*, mineral scaling) [17, 60, 61].

In arid & semi-arid climate regions such as California with stricter environmental laws, many disposal options, like evaporation ponds and discharge to the surface and seawater, are deemed to fail or to be rejected by regulators. Deep well injection into a more saline, confined aquifer is one of the possible solutions to the concentrate management problem though there are several situations to be considered including: (I) water quality comparison of the injected water to the ambient groundwater in the target aquifer; (II) reactions that may be occurring in the mixing zone between the native groundwater and injected concentrate; and (III) how well the clogging issue may be prevented while injecting a supersaturated solution [62]. Figure 5 shows typical ROC management by evaporation pond and seawater discharge [63].

Figure 5: ROC Management by (a) Evaporation Pond; (b) Seawater Discharge [63]
(Credit: Dr. Keisuke Ikehata)

Although regulatory issues appear to represent the most limiting barriers to deep well injection, obstacles go beyond regulatory concerns. They include impediments in hydrogeology, water quality, water quantity, cost, environment, technology, and public/political issues. Moreover, conventional chemical and physical treatment methods for ROC present certain limitations, such as relatively low nitrogen and phosphorous removal efficiencies and the requirement for an extra hardness removal process [64].

2.2 PHOTOBIOLOGICAL TREATMENT OF REVERSE OSMOSIS CONCENTRATE

The advanced water purification facilities and brackish desalination plants require many chemicals and high energy-demanding operation and maintenance technologies that reduce their environmental and energy sustainability [65]. Addition of a photobiological treatment by brackish water diatom could be an energy-efficient process to treat ROCs from brackish water desalination facility. Diatoms are photosynthetic, eukaryotic microalgae, and there are more than 200 genera of extant diatoms with approximately 100,000 living species [17, 66, 67]. Usage of diatoms in ROC treatment might bring some remarkable advantages, including: (I) the sunlight needed for the growth of the diatoms reduces the energy demand; (II) reduction in greenhouse gas (*e.g.*, CO_2) emission and (III) production of valuable algal biomass. This unique photobiological treatment of ROCs utilizes the natural biology of diatoms, a class of photosynthetic microalgae whose cells are surrounded by a stiff silicon dioxide-based structure called frustule [68]. The unique photosynthetic, cellular, and metabolic characteristics of diatoms enable them to utilize constituents in ROC like nitrate, iron, phosphate, molybdenum and silica which make diatoms a viable addition to wastewater and brackish water ROC treatment.

One of the potential benefits of this algal process is that it can be used to treat ROC, which may contain up to 120 mg/L of silica, to recover more water in the secondary RO process [12]. A mixture of brackish water diatoms was obtained from agricultural drainage water to treat silica-rich RO concentrate samples from advanced water reclamation plants in Southern California. More than 75% of silica and 90% of orthophosphate removal was observed in 5 days, along with other inorganic cations, such as calcium (49%), iron (>96%), and manganese (81%) removal by the photobiological process [12]. After a microscopic analysis of isolated and digested cells, Ikehata et al. have confirmed the presence of several diatom species, including *Pseudostaurosira* sp., *Nitzschia* sp., and *Halamphora* sp. [12]. RO concentrate samples from different full-scale RO facilities in Southern California were treated using two diatom strains, *Gedaniella flavovirens* (formerly known as *Pseudostaurosira trainorii*) and *N. amphibia* in a later study where the researchers noticed 95% of 78 mg/L reactive silica removal within 72 hours [69, 70]. Nutrient addition was not necessary while testing concentrate samples from advanced water treatment facilities; however, while treating the ROC from brackish groundwater desalination facilities [14], which did not contain enough nutrients to complete silica removal, supplementation was required.

Using the diatom strain *P. trainorii* to treat ROCs, 95% of reactive silica removal along with 64% of calcium removal from the PBR was observed [13], and after introducing a secondary RO to treat the photobiologically treated water to enhance freshwater recovery, a 66% recovery rate was noticed which indicated a total of 95% overall recovery, including 85% recovery in the primary RO unit [13]. In addition to the scaling constituents, the photobiological treatment removed 12 pharmaceuticals, personal care products, and *N*-nitrosodimethylamine from the RO concentrate samples [13].

More details on the photobiological treatment are observed in research where 11 ROC samples from six full-scale potable reuse facilities in the southwestern United States were treated by the photobiological treatment process using *P. trainorii*, where eight out of the 11 samples were successfully treated. The other three samples were obtained from the facilities where non-nitrified effluent was used as source water which was unsuitable for the treatment due to high levels of ammonia-N [5]. While treating ROC from a brackish groundwater desalination facility, addition of 4 mg/L orthophosphate (1.28 mg/L as P) and nitrate dose of 12 mg/L as N was found to be adequate for the growth of the diatom to achieve maximum silica uptake due to lack of nutrient in the feed water [4]. An experimental study on the performance of silica removal by diatoms under direct sunlight and under shaded condition indicated that the diatoms preferentially removed the reactive silica when incubated outdoors under the shade versus under direct sunlight, which implies that in the larger scale PBRs, direct penetration of the sunlight may be avoided utilizing the suitable cover material restricting harmful UV radiations but making enough light available for the photosynthesis [4].

Besides diatoms, other strains of algae have been used in previous research to understand the possibility of treating ROC to remove nutrient and scalant materials. Among green algae, *Scenedesmus quadricauda* was used in a study to treat highly saline ROC under continuous illumination, which resulted in a notable increase in the biodegradability of dissolved organic matter, subsequent removal of biodegradable fractions, and simultaneous removal of nutrients (N and P) [71]. Other green algae *Chlorella* sp. and *Scenedesmus* sp. grew well in ROC with nitrogen and phosphorus removal efficiencies of up to 89.8% and 92.7%, respectively [64]. This study also reported 55.9%–83.7% of Ca^{2+} removal, where Mg^{2+} removal began when Ca^{2+} precipitation ceased [64].

2.3 ALGAL BIOMASS AND BENEFICIAL BY-PRODUCTS

Microalgae are a promising sustainable feedstock for food and feed products, materials, chemicals, fuels, and high-value products [72]. The diatom biomass is very useful because of: (I) their ubiquitous presence and competitive advantage up against other microalgae under suitable, controllable conditions will allow for continuously varying the species that are cultivated to follow seasonal variations in the available optimal organisms; (II) their rapid growth rate; and (III) almost all their biomass can be put to profitable use [17]. The frustule of the diatom cell wall comprises overlapping valves called epitheca and hypotheca joined by silica girdle bands, like a petri dish [73]. During the formation of cell walls, the silicon is absorbed from the environment in very low concentrations and transported as silicic acid via silica acid transporters across the membrane [16, 68]. The siliceous structures of their cell wall create unique morphologies which are used as taxonomic keys [74]. The frustules are a significant component of diatoms besides lipids. Their consent could reach up to 50%–60% of the dry weight of diatom biomass [75].

Diatoms also contain a wide variety of lipids, including membrane-bound polar lipids, triglycerides, and free fatty acids [17, 76, 77]. Lipid accumulation in diatoms is influenced by physiochemical factors such as light, temperature and nutrients. Notably, lipid fractions as high as 70%–85% have been reported in some diatoms [78]; however, 15%–25% is more typical. Given their positive response to artificial CO_2 supplementation, an opportunity for industrial ecology is emerging that sees microalgae cultivation co-located with emissions-intensive stationary power generators and heavy industry [79]. Bio-crude from diatoms contains active ingredients which are not fully explored, such as phytol, neophytadiene, alkanes, terpenes, and sterols. Diatoms produce a variety of secondary metabolites with antifungal, antiviral, anti-obesity, antioxidant, antibiotic, and other activities [80]. In the following subsections, beneficial by-products production from biomass (*e.g.*, biogas, silica, calcite, pigments, biofuel) are discussed in detail.

2.3.1 BIOGAS

Anaerobic digestion has long been used to produce biogas from organic residues, such as sewage sludge, and agricultural and industrial by-products. Both freshwater and marine microalgae species have drawn attention as anaerobic digestion substrates for biogas production [81]. The anaerobic processing of organic waste and its utilization for energy production is encouraged by stringent environmental regulations, growing waste disposal costs, and rising prices of energy resources [82]. Biogas production through anaerobic digestion is a simple and low-cost method to convert biomass feedstocks into a renewable energy source [83]. For example, biogas' efficient production and use in a WWTP is a source of heat and power [84].

The idea of coupling such a process with algal production was mentioned and positively commented on in previous research works since the possibility of using micro-algae for biogas, biodiesel, and bioethanol production was analyzed by Uggetti et al. [86,87]. The (bio)methane produced through the anaerobic digestion of microalgae, which accounts for about 60%–70% of the biogas, can be used as fuel gas to generate heat in a boiler or to cogenerate electricity and heat in a combined heat and power unit [8]. Cultivating sustainable sources of high-volume biomass to produce fossil fuel substitutes is a key to the growth of the biofuel industry and the mainstream commercial use of its derivatives [79]. Researchers argue that it is most beneficial to process algae for biogas and biodiesel production because most of the energy is produced when doing so. Although numerous studies have paid attention to the anaerobic digestion of raw microalgae for biogas production, limited research investigated the utilization of microalgae residue resulting from the oil extraction process or *in situ* transesterification reaction for biodiesel production [83]. Results of previous studies demonstrate that the biogas production rate is from 0.28 to 0.65 m^3/kg of dry biomass weight, where the methane concentrations range from 54% to 67% [85]. Operational [*i.e.*, bioreactor design, hydraulic retention time (HRT), and temperature] and cultivation conditions, which are responsible for variations in cellular proteins, carbohydrates, and lipids contents, may lead to a wide variation in methane conversion [86]. An LCA study of biogas production from microalgae *Chlorella vulgaris* suggested that the impacts generated by methane production from microalgae are strongly correlated with the electric consumption, and further progress can be achieved by improving the efficiency of the anaerobic process under controlled condition [87].

2.3.2 SILICA

Silica in diatoms can be introduced to the market to produce some high and low-value products (*e.g.*, silica sand). Silica obtained by processing low-valued silica sand and quartzite is generally classified based on their properties and production methods. They include fumed silica, precipitated silica, silica gels, sols and micro-silica [88]. Precipitated silica, which is produced by precipitation from a solution containing silicate salts, are expected to enjoy the most rapid growth and remain the largest segment of the specialty silica market over the next decade [89]. The global silica sand market reached a value of $17.4 billion in 2020, and the market is expected to grow at a compound annual growth rate (CAGR) of 5.2% during 2021-2026 [90]. Silica sand, generally known as industrial sand, is one of the most common varieties of sand found across the world. Nowadays, silica sand has been used for well-diversified applications including paving roads, glass making, foundries, and coal burning boilers, oil, and water filtration, industrial casting, and sandblasting. Rising demand for the product from the rubber industry is the primary factor driving the market [91].

Recently, commercialized core-silica phases have attracted great interest, where core-shell particles are composed of a nonporous silica core and porous silica shell, and they are also called superficially porous particles [92].

Another competitive industry of commercial silica market is paints, and coating sector. Silica is utilized in this industry to control rheological characteristics and to deter rust and corrosion. Silica is also used as an anti-setting agent and thixotropic agent in this sector. Silica fumes are majorly used in the concrete industry to impart strength and durability in concrete. Carbon black is one of the major substitutes of silica and acts as a restraint for market growth regarding green tire manufacturing industry. However, green tire manufacturers are replacing carbon black with silica on account of its eco-friendly benefits and stronger performance as opposed to carbon black [91].

2.3.3 CALCIUM CARBONATE

The photobiological treatment of ROC by diatoms precipitates calcium and bicarbonates as calcium carbonate which can be utilized as high-value products (*e.g.*, paint and coatings) for the market. The produced calcium carbonate from the photobiological treatments can be transformed into commercially valuable compounds (*e.g.*, paper and construction materials) after the biomass collection and harvesting process. The global market size of calcium carbonate (calcite) is expected to reach $60.7 billion, registering a CAGR of 5.6% [93]. Calcite is extensively used in various applications, including paper, paints and coatings, food, health-related products, and building and construction materials. The paper application segment accounted for the largest market share of over 50% in 2019 and is expected to grow steadily [93]. Increasing concerns regarding sustainability and hygiene are the major growth drivers for the paper industry. For instance, initiatives to ban single-use plastic products have propelled paper consumption in packaging applications. Calcium carbonate is not just considered as a resin extender in plastics anymore, but its addition has contributed to increasing performance, processing, and sustainability in the finished parts. Calcite is also extensively used as a stomach antacid and in the production of lime and Portland cement. Calcite is mostly used in road construction as an element in cement, or the starting material to produce builders' lime by kiln burning [94].

2.3.4 OTHER VALUABLE BIORESOURCES

2.3.4.1 BIOFUEL

High growth rates of diatoms combined with significant lipid productivities make diatoms a leading candidate as a source of either bio-crude or bio-oil. Bio-oil refers to the oil extracted from diatom lipid that can be upgraded using processes such as transesterification, and biocrude refers to the natural crude-like oil converted from the diatom biomass via thermochemical means [17]. Presently, research is focused on microalgae that are particularly rich in oils for biodiesel production and whose yield is considerably higher than that of conventional sources like sunflower or rapeseed [95, 96].

Diatom biomass contains monounsaturated fatty acids, saturated fatty acids, and polyunsaturated fatty acids, all of which are useful for biofuel production. The oils from

Navicula cincta and *Skeletonema costatum* produced via transterification have a heat of combustion of 40.7 MJ/g with low sulfur content (0.0056% w/w). Characteristics of these biodiesel are similar to those of biodiesel from soybean, which offers the possibility of using diatom biomass as a raw material for the production of biofuels [16]. Mass cultivation of microalgae for biodiesel and high-value products needs an enormous supply of growth medium. Meeting this need with clean water fertilizers is not environmentally sustainable, as using fertilizer to supply nitrogen and phosphorous produces greenhouse gas emissions [97]. Diatom, when grown in wastewater, will consume excess nutrients and release oxygen from photosynthesis. Cultivating diatoms in ROC where sufficient nutrient is readily available is an attractive solution to produce biofuel while limiting the cost and solving the ROC management barriers.

2.3.4.2 PIGMENTS

Researchers acknowledge microalgae to be a very diverse source of bioactive molecules, and among these compounds, natural pigments comprise one of the most exciting components produced in microalgae-based systems [106]. Besides their coloring potential, natural pigments from microalgae have health benefits and can replace artificial colorants with advantages [98, 99]. Three classes of pigments are found in microalgae: phycobiliproteins [usually 8% of dry cell weight (DCW)], carotenoids (usually 0.1% to 0.2% of DCW, but achieving up to 14% in some species), and chlorophylls (0.5%–1.0% of DCW) [99].

Recently, carotenoid pigments from algae have received more attention in health food applications. Oxygenated carotenoids are referred to as xanthophyll, while other carotenoids are hydrocarbon carotenoids or are referred to as carotenoids. Carotenoids are fat-soluble pigments and are tetraterpenoids (C_{40}). C_{40} carbon atoms are considered the backbone of the carotenoid molecule, and the composition of carotenoid pigments produced by microalgae species varies and is influenced by the culture condition [18]. Microalgae rich in carotenoids are used as food colorants, additives and vitamin supplements. Various cultivation systems (tubular glass photobioreactor, raceway ponds and Christmas tree reactor) are used for the mass cultivation of algae to obtain higher biomass yield and carotenoids for commercial applications [18]. Diatoms are well known to produce β-carotene, lutein, canthaxanthin, astaxanthin, diatoxanthin, diadinoxanthin, zeaxanthin, violaxanthin, and fucoxanthin [18]. Besides, among green algae, *Dunaliella salina* and *Haematococcus pluvialis* are cultivated at the industrial level to obtain carotenoids, especially β-carotene (vitamin A precursor) and astaxanthin (a potent antioxidant), respectively [99, 100]. Fucoxanthin is a major carotenoid in diatoms and a major component of the chlorophyll *a/c* complex as a primary light-harvesting pigment responsible for diatom photosynthesis [101].

2.3.4.3 AQUACULTURE APPLICATIONS

Diatom lipids and sterols are essential in aquaculture as natural feed and high-quality food supplements for feeding bivalve mollusks' larvae, post-larvae, and shrimp [102, 103]. Diatom biomass contains active compounds with known antibacterial and antiviral activity, especially against aquaculture pathogens. Extracts from the marine diatom *Skeletonema costratum* inhibit the growth of *Vibrio,* a pathogen of fish and shellfish [104]. *S. costratum* produces ascorbic acid during the stationary phase, whereas *Chetoceros gracilis* produces it during the exponential phase.

2.4 LIFECYCLE COST ANALYSIS

Decision-making problems in the field of environmental science are multidimensional and require the participation of multiple stakeholders. In most cases, the decision-maker cannot make rational decisions considering the difficulty in collating and analyzing all the relevant data [105]. The lifecycle approach represents tools for economic and environmental decision-makers of products, services, or processes. LCA and LCCA are used for environmental and economic assessment, respectively. Both of these techniques are used to measure and quantify the impacts (environmental and economic) associated with all stages of the product, process, or service from the cradle to the grave [19]. However, lifecycle cost (LCC) is used to evaluate the environmental performance of alternative products or service systems for providing the same function. Despite the similarity of their names, there are some significant methodological differences (*e.g.,* the activities and flows considered, time treatment, and scope) between LCA and LCCA [106]. Current practices in the field of LCC of WWTP use a hybrid approach of combining LCA with LCC with more focus on LCCA, compromising critical elements of LCCA like methodological depth and scale, making LCC a secondary tool with little efficacy. Key findings behind the possible reason for this practice reflect that more focus is given to the environmental aspect compared to the economic element [22]. Other economic evaluation methods apart from LCCA, like benefit-cost analysis, net present value (NPV), and profitability index, each of which has its applicable conditions and limitations.

In water treatment, LCCA was first applied in the late nineteens. Since then, in the last two decades, there has been an increasing volume of literature exploring the environmental and economic analysis of wastewater treatment technologies, facilities, and unit processes. According to previous research on cost categories, it is evident that the operation and maintenance cost far exceed the capital cost. Furthermore, the operation cost depends on the technology used, as different treatment technologies have additional operational and capital expenses. Previous cost comparison studies of different stages of a WWTP indicate that lifetime operational and maintenance costs far exceed the capital cost [19], where energy cost contributes 40% to the total operation cost of the WWTPs [107]. Initial construction is the second significant cost, 4.6% of the total LCC [19]. Since LCCA considers future costs, the time value of money needs to be accounted for in the calculations. Therefore, future cash flows need to be discounted to present value, especially if the asset's life is long [108]. Defining articles in the field of LCC also suggest that sensitivity analysis is needed to cope with the uncertainty [108].

2.4.1 CASH FLOW ANALYSIS

A cash flow analysis determines a company's working capital – the amount of available money to complete transactions and run business operations. Cash flow analysis helps to understand how much cash is generated or used by a business during a specific accounting period. Cash flow is an essential parameter for a project as it enables the owner to meet existing financial obligations and plan for the future [109]. By balancing the inflows and outflows of the cash, the owner can ensure the smooth day-to-day running of a business. It also allows for building sufficient reserves to weather peaks and troughs in sales, late invoice payments, or unexpected expenses.

2.4.2 NET PRESENT VALUE ANALYSIS

NPV is one of the best financial tools to establish the value of a project or investment. NPV is used for capital budgeting and is widely used throughout economics, where it measures the excess or shortfall of cash flows in present value terms once financing charges are met [110]. NPV is usually defined as the total sum of capital expenditure (CAPEX), operational expenditure (OPEX), and income generated by the service. For monopolistic water businesses, it can be argued that the income is directly defined by cost, *i.e.*, the income is not independent and is commonly regulated to be proportional to the costs [111]. The system's total cost in its whole life cycle is the sum of the construction, operation, maintenance, and energy costs [112]. However, since the changes in the time value of money, the project costs occurring at different points in the asset life cycle cannot be compared or simply added together. They are needed to be discounted to their present value.

2.4.3 BREAK-EVEN POINT ANALYSIS

The break-even point defines the total revenue from a system, and the total investment costs are uniform. Amounts before and after meeting the break-even point interpret loss and gain for the project, respectively [113]. Most importantly, the break-even point and the payback period are different. While the break-even point is the price or value that an investment or project must rise to cover the initial costs or outlay, the payback period refers to how long it takes to reach that breakdown.

2.4.4 RENEWABLE ENERGY SCENARIO

To stabilize the global climate, the world's governments must commit to drastically reducing greenhouse gas emissions. Switching from fossil fuels to renewable energy sources is one of the most promising methods of curbing greenhouse gas emissions [114]. In 2021, renewable energy provided about 12.16 quadrillion British thermal units, 12% of total U.S. energy consumption [115]. The electric power sector accounted for about 59% of total U.S. renewable energy consumption in 2021, and about 20% of the entire U.S. electricity generation was from renewable sources [115]. Solar photovoltaic (PV) cells possibly offer a technically sustainable solution to the projected enormous future energy demands which convert sunlight into direct electricity and offer a technically feasible and environmentally sustainable solution to our massive future energy needs. Some researchers utilized RETScreen Clean Energy Management Software and other related software packages to work on solar PV to assess the viability and government regulatory structures involved in implementing both off the grid and on grid electrification [116]. RETScreen allows for the comprehensive identification, assessment and optimization of the technical and financial viability of potential renewable energy, energy efficiency and cogeneration projects, the measurement and verification of the actual performance of facilities, the identification of energy savings/production opportunities, and portfolio management of multiple facilities [117].

3. MATERIALS AND METHODS

3.1 MATERIALS

3.1.1 DIATOMS

In this study, a unialgal culture of brackish diatom *G. flavovirens* Psetr3 (Figure 6) was obtained from Dr. Shinya Sato, Fukui Prefectural University (Obama, Japan) for the photobiological process. The culture was transferred to larger tubes (15 and 50-mL sterile VWR SuperClear polypropylene centrifuge tubes, VWR International, Radnor, PA) with filter-sterilized wastewater ROC from OCWD GWRS and maintained until use. Acrodisc 32 mm syringe filters with 0.8 µm/0.2 µm hydrophilic polyethersulfone membrane (Pall Newquay, Cornwall, UK) were used to filter ROCs. After confirming the active biomass growth, ROC was replaced weekly to ensure an appropriate amount of biomass for photobiological treatment experiments. Subcultures were created by transferring 0.5 or 1.0 mL of biomass suspension using sterile pipet tips to new culture tubes containing filter sterilized OCWD ROC. The ROC was replaced every week to ensure sufficient nutrient supply. After the photobiological treatments of ROC, diatom biomasses were used for characterization and fractionation.

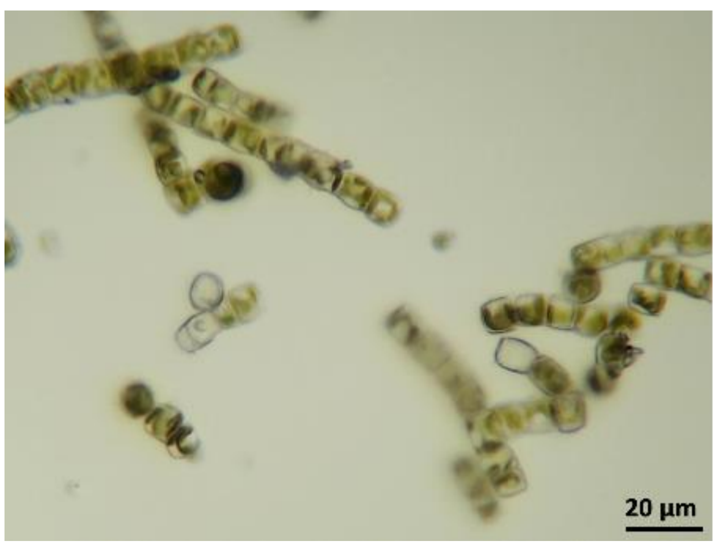


Figure 6: Photomicrograph of *G. flavovirens* Psetr3 (Credit: Author)

3.1.2 PRE-CULTURED DIATOM BIOMASS

The *G. flavovirens* biomass samples used in this study were collected by Ms. Han Gao [118]. These diatom biomasses were used for biomass fractionation and characterization in this study. In her photobiological treatment experiments, *G. flavovirens* was grown in ROC samples from SAWS and OCWD in 100 mL polystyrene bottles with LED bulbs as a light source. The diatoms were collected from the 100 mL photobioreactors as soon as the experiments ended and kept in a 1.7 mL microcentrifuge tube (Figure 7) [118]. Biomass from a clear polystyrene coliform bottle as a bioreactor was transferred to 1.7 mL microcentrifuge tubes using bamboo stick to scrape the biomass off the bottom of the bottle and thoroughly washed using ultra-pure water until almost all the biomass was transferred. After the final wash and supernatant removal, the microcentrifuge tube was kept in a desiccator to let the biomass dry. Daily mass data of the sample in a 1.7 mL microcentrifuge tube was recorded to determine when the samples were dry [118]. As soon as the sample was completely dry (*i.e.*, no mass change in the daily mass change graph), it was kept in a rack (Figure 7) [118].

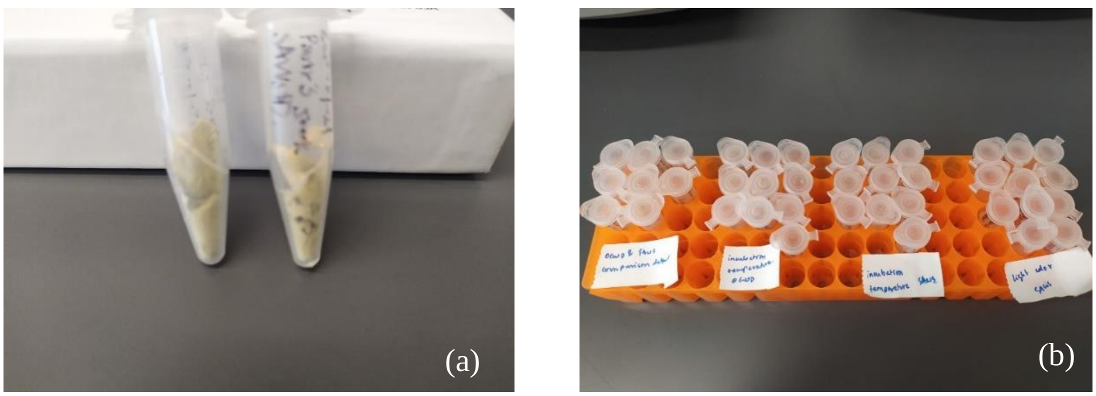


Figure 7: Biomass (a) in 1.7 mL Microcentrifuge Tubes; (b) Storage of Biomass

3.1.3 CHEMICALS

A commercial bleach containing sodium hypochlorite solution (The Clorox Company, Oakland, CA) with an active chlorine concentration of 48.2 g/L (as determined on April 11th, 2021) was used for organics destruction as part of the biomass characterization. A 2.34 M citric acid solution was prepared by mixing 91.392 grams of citric acid monohydrate (VWR Chemicals, Solon, OH) with ultra-pure water to prepare 250 mL of solution. The solution was prepared by mixing the powdered citric acid with ultra-pure water in a 250-mL volumetric flask and stored in a 250-mL high-density polyethylene (HDPE) bottle. To dry the treated biomass after the experiment, Drierite (W.A. Hammond Drierite Company, Xenia, OH) was used as a desiccant. A GenPure Pro system (Thermo Scientific Barnstead, Sweden) was used to produce ultra-pure water for research use.

F/2 medium concentrate (Part B; Fritz Aquatics, Mesquite, TX) containing 6% nitrogen and 2% phosphate was used as a nutrient source. A 2.7% F/2-part B solution containing 1.0 g/L of orthophosphate and 10 g/L of nitrate-N was prepared by adding 2.7 mL of algae food solution to a 100-mL volumetric flask and diluting it with ultrapure water. Then, the solution was filtered with 0.8/0.2-µm sterile syringe filters and stored in a fridge. Fluval Hagen Sea Marine Salt for Aquarium (Rolf C. Hagen Corp.) enriched in magnesium (1,200 mg/L) and calcium (460 mg/L) was added in Fiji Water to adjust TDS concentrations for photobiological treatment experiments.

3.1.4 SAMPLE FOR THE PHOTOBIOLOGICAL TREATMENT

In this study Fiji Water, a brand of bottled water, was used as a silica-rich water medium for photobiological treatment. This experiment was performed to understand the impact of salt concentrations on the photobiological treatment of ROC. The brackish groundwater ROC used by Han Gao for photobiological experiments had 130 mg/L of reactive silica [118], whereas Fiji Water used in this study contained 89 mg/L of reactive silica, which is comparable to the ROC. Samples were prepared with a wide range of TDS using the Fluval Hagen Sea Marine Salt and Fiji Water to understand the impact of salt concentration on silica uptake rate by diatoms in the photobiological treatment of ROC under controlled conditions. Using sterile pipette tips 0.4 mL of 1 g/L diluted F/2 algae food Part B solutions was added to the photobioreactors, and the pipette was rinsed up to add 4 mg/L of orthophosphate and 10 mg/L of nitrate-N.

3.1.5 SOFTWARE

To design the photobioreactors, AutoCAD 2021 software (Autodesk, San Francisco, CA) was used [119]. Complete 2D design of photobioreactors in sunlight and LED systems including the pump layouts were designed using this software. 3D rendering of the photobioreactors in the sunlight system was designed using Fusion 360 software (Autodesk, San Francisco, CA) [120]. Integrated Membrane System (IMS) Design (Hydranautics, Oceanside, CA) was used to design the secondary RO facility [121]. RETScreen Clean Energy Management Software (Government of Canada) was used to design and analyze the feasibility of introducing PV system as a renewable energy source for the proposed PBR-secondary RO facility [122].

3.2 EQUIPMENT

3.2.1 ANALYTICAL

The concentrations of water quality parameters were tested by Hach DR1900 spectrophotometers (Loveland, CO) with corresponding Hach Methods and listed in Table 1. Samples were tested for water quality analysis before and after the photobiological experiments.

Table 1: Water Quality Parameters and Corresponding Analytical Methods

Parameters	Method	Method #
Reactive silica (mg/L)	Silicomolybdate Method	Hach 8185
Orthophosphate (mg/L)	USEPA PhosVer 3 Method	Hach 8084
Nitrate-N - HR (mg/L)	Chromotropic Acid Method	Hach 10020
Sulfate (mg/L)	USEPA SulfaVer 4 Method	Hach 8051
Chloride (mg/L)	Silver Nitrate Method	Hach 8207
Sodium (mg/L)	Direct ISE Method	Hach 8233
Potassium (mg/L)	Tetraphenylborate Method	Hach 8049
Conductivity (mS/cm)	USEPA Direct Measurement Method	Hach 8160
Alkalinity (mg/L)	Phenolphthalein and Total Alkalinity	Hach 8203
Calcium hardness (mg/L)	Titration Method with EDTA	Hach 8204
Total hardness (mg/L)	Titration Method with EDTA	Hach 8213
Color at 455 nm (PtCo unit)	Platinum-Cobalt Standard Method	Hach 8025
Chemical oxygen demand (mg/L)	USEPA Reactor Digestion Method	Hach 8000

A Hach 2100Q turbidimeter was used to test turbidity. Conductivity and pH were tested by Hach Pocket Pro Testers. A Hach DRB 200 was used for total and dissolved chemical oxygen demand. UV_{254} was measured with an Evolution 201 UV-Visible Spectrophotometer from Thermal Fisher Scientific (Waltham, MA). Photosynthetically active radiation (PAR) was measured with an MQ-500 full-spectrum quantum meter (Apogee Instruments, Logan, UT). A VWR analog vortex mixer was used to vortex the samples during the biomass fractionation experiment. Hach Digital Titrators were used for measuring calcium and total hardness. Photomicrography of the samples was done before and after each treatment using a compound microscope with a camera (AF205

1080p 60 fps HDMI microscope camera, AmScope, Irvine, CA). A scanning electron microscope (SEM, Model JEOL SEM-6010 PLUS/LA, Peabody, MA) was used to characterize the elements present in the diatom biomass using energy dispersive spectroscopy (EDS) mapping.

3.2.2 PHOTOBIOLOGICAL TREATMENT EXPERIMENT

Several plastic 5-gallon buckets [Lowe's, Dimensions: 14.25 inches (height), 12.5 inches (diameter)] with a reflective bubble wrap roll (ULINE, Product # S-11476) were used as incubators for the photobiological treatment experiments. The reflecting bubble wrap was used to cover the bottom and indie wall of the buckets (Figures 8a and 8b).

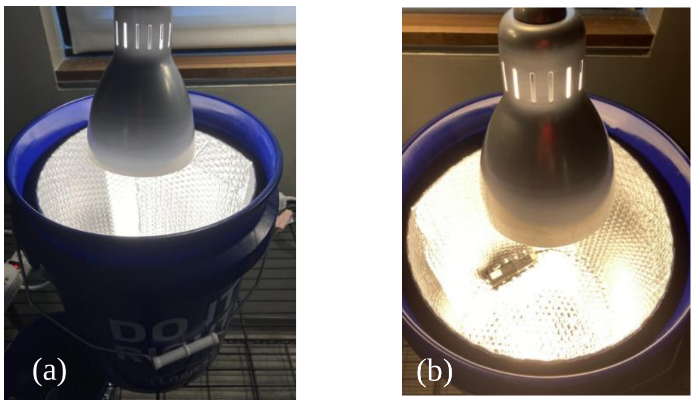


Figure 8: (a) Incubator; (b) Incubator Inside

100-mL polystyrene sterile coliform bottles were used as photobioreactors. USB Temperature Data Loggers (EasyLog, EL-USB-1; Lascar Electronics, Erie, PA) were used to continuously measure the temperature in the incubators. Clip lamps and LED bulbs (2,700 k, 800 Lm, 10 W) (Product #LED10DA19/827, GE, Louisville, KY) were used as a light source for the diatoms.

3.2.3 OTHER EQUIPMENT

A shaker attachment was attached to the vortex mixer to hold the 15-mL centrifuge tubes. To centrifuge the 15-mL tubes for the biomass experiment, a VWR centrifuge (Radnor, PA) was used. Desiccators (Bel-Art, SP Scienceware, South Wayne, NJ, USA) were used to dry the biomass samples. A gravity oven from Thermo Fisher Scientific (Waltham, MA) was used for temperature control purpose to dry the biomass samples.

3.3 METHODS

3.3.1 PHOTOBIOLOGICAL TREATMENT

Series of bench-scale experiments were conducted to investigate the impact of salt concentrations on the photobiological treatment of ROCs using TDS adjusted Fiji Water. Silica uptake by *G. flavovirens* Psetr3 in the prepared sample was noticed in this study. The experiment was conducted with an LED light bulb (temperature: 2,700 K) with a light intensity of 200 µmol m^{-2} s^{-1}. Table 2 shows the water quality parameters of Fiji Water before TDS adjustment.

Table 2: Water Quality Data of Fiji Water Before TDS Adjustment

Parameters	Measurement
Reactive silica (mg/L)	89
Orthophosphate (mg/L)	0.70
Nitrate-N - HR (mg/L)	0.48
Sulfate (mg/L)	< 2
Chloride (mg/L)	14
Sodium (mg/L)	37.2
Potassium (mg/L)	5.4
Conductivity (mS/cm)	0.133
Alkalinity (mg/L as $CaCO_3$)	121
Calcium hardness (mg/L as $CaCO_3$)	49
Total hardness (mg/L as $CaCO_3$)	105
Color at 455 nm (PtCo unit)	< 5
pH	8.2

Fluval Hagen Sea Marine Salt for Aquarium was added to the Fiji Water to prepare solutions of a wide range (222, 1,000, 2,000, 4,000, 8,000, 16,000. 32,000 and 64,000 mg/L). These silica rich Fiji Water with low TDS, brackish water TDS and seawater TDS samples were prepared to understand the impact of salt concentration on silica uptake by brackish water diatom.

3.3.2 BIOMASS FRACTIONATION AND CHARACTERIZATION

Biomass fractionation was performed in this study to determine the percentage and production rate of the valuable components like organics, silica, calcium carbonate present in the biomass during the photobiological treatment of ROC. As part of the biomass fractionation, bleach treatment was performed first to remove the organics from the cultivated diatom biomass. Subsequently, citric acid treatment was conducted to draw out calcium carbonate (calcite) from the bleached biomass. A detailed, step-by-step procedure of the biomass fractionation process is shown in Figure 9 as well as the subsections are explained afterward.

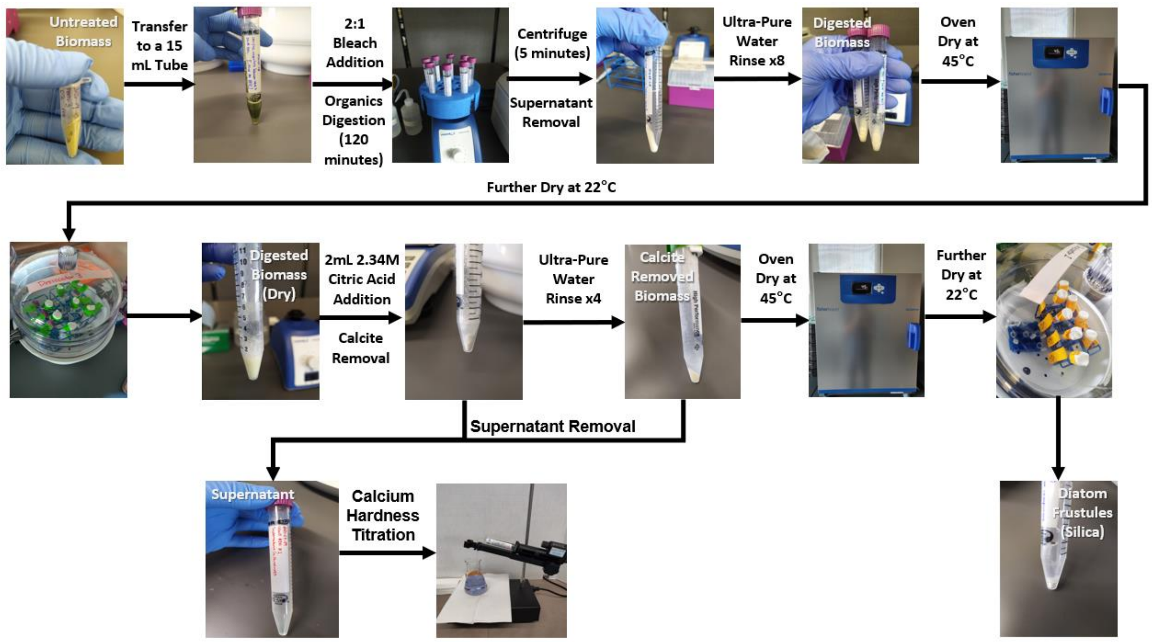


Figure 9: Biomass Fractionation Experimental Procedure

3.3.2.1 BLEACH TREATMENT

At first, biomass from a 1.7-mL microcentrifuge tube was transferred to a 15-mL sterile centrifuge tube using a weighing paper. Later, the 1.7-mL microcentrifuge tube was rinsed with ultra-pure water to ensure all the biomasses were transferred. After that, a bleach solution of 48.2 g/L as Cl_2 was added at a 2:1 ratio to make sure that all the organics were destroyed from the biomass samples. As soon as the bleach was added to the 15-mL tube, the biomass samples had a rapid color change as they turned grey from green. The 15-mL tube was then kept on an analog vortex mixer with a shaker attachment for two hours to let the reaction between the organics and bleach complete. After 15 minutes intervals, the cap of the 15-mL tube was loosened to let the gas out, and after one hour of shaking, an additional 1-mL of bleach solution was added. After two hours of reaction time, the 15-mL tube was centrifuged, and the supernatant was pipetted out. The sample was rinsed 8 times with 1-mL ultrapure water each time to remove all the bleach (chlorine). In the end, the tube was kept in an oven to dry at 40° C and the mass was noted daily. When there was no significant mass change, the tube was transferred to a desiccator, and mass was noted again till there was no significant change.

3.3.2.2 CITRIC ACID TREATMENT

Once there was no significant mass change in the sample tubes after the bleach treatment, the citric acid treatment took place. A 2.34 M citric acid solution was added dropwise (~0.200 ml) to the sample to dissolve calcium carbonate which took place according to the following equation:

$$2C_6H_8O_7 + 3CaCO_3 \rightleftharpoons Ca_3(C_6H_5O_7) + 3CO_2 + 3H_2O$$

As soon as the citric acid solution was added to the diatom biomass, bubble formation was noticed at the bottom of the tube, indicating the generation of carbon dioxide. The presence of carbon dioxide confirmed the existence of calcium carbonate in the biomass. After adding citric acid, the 15-mL tube was vortexed for ten minutes to make the reaction happen completely. After that, the tube was centrifuged again. However, this time the supernatant was stored for further calcium hardness titration. The sample was rinsed four times with 2-mL of ultra-pure water each time. Finally, the tube was kept in an oven to dry and later transferred to a desiccator. After the organics destruction and calcite extraction, only diatoms frustules (silica) remained. By detailed analysis of the biomass fractionation experiment and comparing the data with the mass balance from the photobiological treatment data, by-product quantification, their percentage, and production rate were evaluated.

3.3.2.3 NITROGEN AND PHOSPHORUS QUANTIFICATION

In the photobiological experiment, nitrogen and phosphorus were added to the ROC as a nutrient source in the form of F/2 algae food Part B solution. After the diatoms completed the silica removal from the ROCs, there should be remaining nitrogen and phosphorus in the diatoms. To completely understand the elemental composition of biomass, nitrogen and phosphorus quantification was performed. Table 3 represents the corresponding analytical methods for nitrogen and phosphorus. Samples used for the nitrogen and phosphorus quantification were from the incubation temperature photobiological treatment experiment conducted by Han Gao [118]. To prepare samples for the nitrogen and phosphorus quantification experiment, a biomass solution of 1 g/L was prepared. The biomass was mixed thoroughly (*i.e.*, until there was a suspension of biomass at the top), and biomass was spiked from the solution to perform the experiment. Then the methods listed below were followed to complete nitrogen and phosphorus quantification.

Table 3: Nitrogen and Phosphorus Quantification from Biomass

Parameters	**Method**	**Method #**
Total Nitrogen (mg/L)	Persulfate Digestion Method	Hach 10072
Total Phosphorus (mg/L)	Molybdovanadate with Acid Persulfate Digestion Method	Hach 10127

3.3.2.4 CHEMICAL OXYGEN DEMAND AND CARBON ANALYSIS

Chemical oxygen demand (COD) and carbon analysis were performed on the biomass samples from the incubation temperature photobiological treatment experiment. The COD and carbon analysis experiment samples were the same samples used for nitrogen and phosphorus quantification. After the photobiological treatment experiment, this experiment was performed to understand the quantification of organic and inorganic carbon in biomass. The theoretical oxygen demand (ThOD) was calculated using the chemical oxygen demand. Percentages of organic carbon in the biomass sample were calculated from the ThOD.

3.3.3 CHLORAMINE DOSAGE EXPERIMENT

A lab experiment was performed on photobiologically treated ROC to determine the ammonium sulfate and bleach dosages. According to previous studies, chloramination of wastewater in the feed solution at 3-8 mg/L residual monochloramine significantly reduces membrane biofouling [123]. For this study, 1.0 g/L NH_3-N and 650 mg/L chlorine solutions were prepared. Later six different chlorine dosages (1, 2, 3, 4, 5 and 6 mg/L) were added to the stock ammonia solution of 1.0 g/L and tested for monochloramine, free ammonia, total chlorine and free chlorine.

3.3.3.1 SEM-EDS IMAGING AND ANALYSIS

SEM-EDS imaging and mapping were performed on three stages of the biomass characterization and fractional experiment: untreated samples, bleached samples, and bleached and citric acid-treated samples. SEM imaging was conducted to provide a clear image of the diatom samples and their corresponding structures. The SEM imaging and EDS mapping was primarily done by an undergraduate research assistant Mr. Mason S. Underwood. After the imaging was performed, elemental mapping and spectroscopy point analysis was performed to have additional details on the precise location of elements on various structures along with relative abundances of elements throughout the samples.

3.3.4 PBR-SECONDARY RO FACILITY DESIGN

3.3.4.1 PROPOSED PBR-SECONDARY RO FACILITY

The LCCA of this study focused on a full-scale PBR-secondary RO that would treat ROC from a brackish groundwater desalination facility. The feed flow for the existing facility was assumed to be 10 MGD and it would be working at 90% freshwater recovery from the primary RO generating 1 MGD of ROC. This 1 MGD of primary ROC would be the feed for the proposed PBR, and 1 MGD of photobiologically treated ROC from the PBR would be the feed for the secondary RO (Figure 10). The secondary RO would operate at a 70% permeate recovery generating 0.7 MGD of permeate. Combining the permeate from the primary RO and the proposed scheme, the entire facility could recover 9.7 MGD of permeate or 97% overall freshwater recovery. The recovery rate was a variable in the LCCA study to optimize the freshwater recovery with cost minimization or according to the project goal.

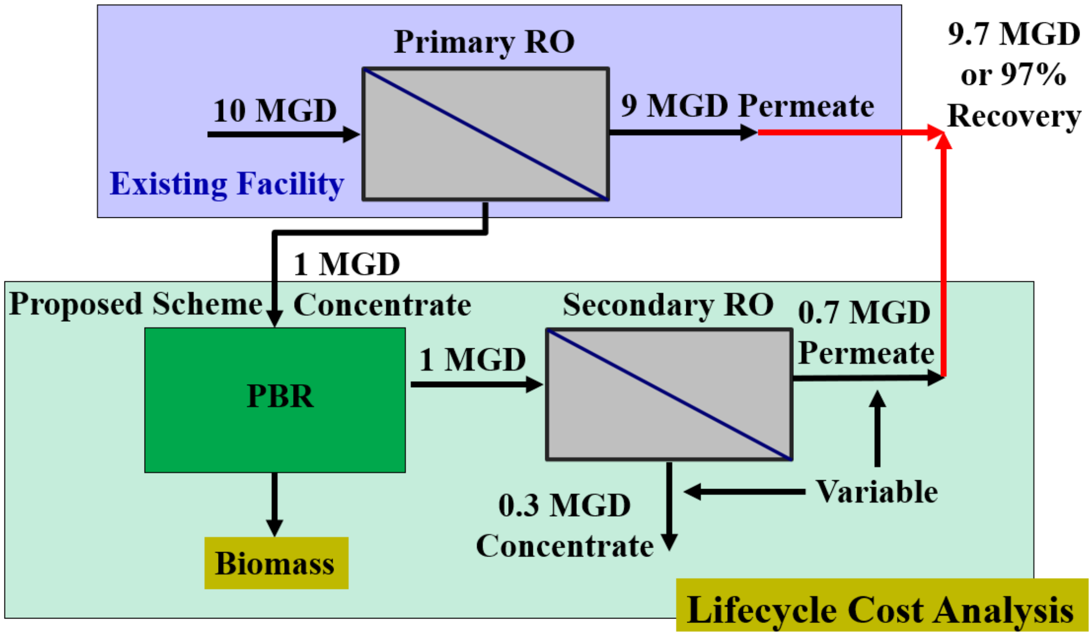


Figure 10: Simplified RO-PBR-Secondary RO Scheme

Figure 11 shows the more detailed process scheme diagram, including the cartridge filters, chemicals, pumps and tanks. Nutrients would be added to the ROC before entering the PBR. Sunlight and LED were considered as light sources in this study. It was obvious that sunlight would be more cost-effective than LED due to having no cost for the light source. However, the sunlight system was compared to the LED system to understand the degree of cost-effectiveness. After the treatment, treated water was assumed to be stored in a one million-gallon holding tank which would supply water to a cartridge filtration system before the photobiologically treated water reaches the secondary RO membranes. Antiscalant and sulfuric acid (H_2SO_4) solutions would be added to prevent scaling and fouling issues in the secondary RO membranes.

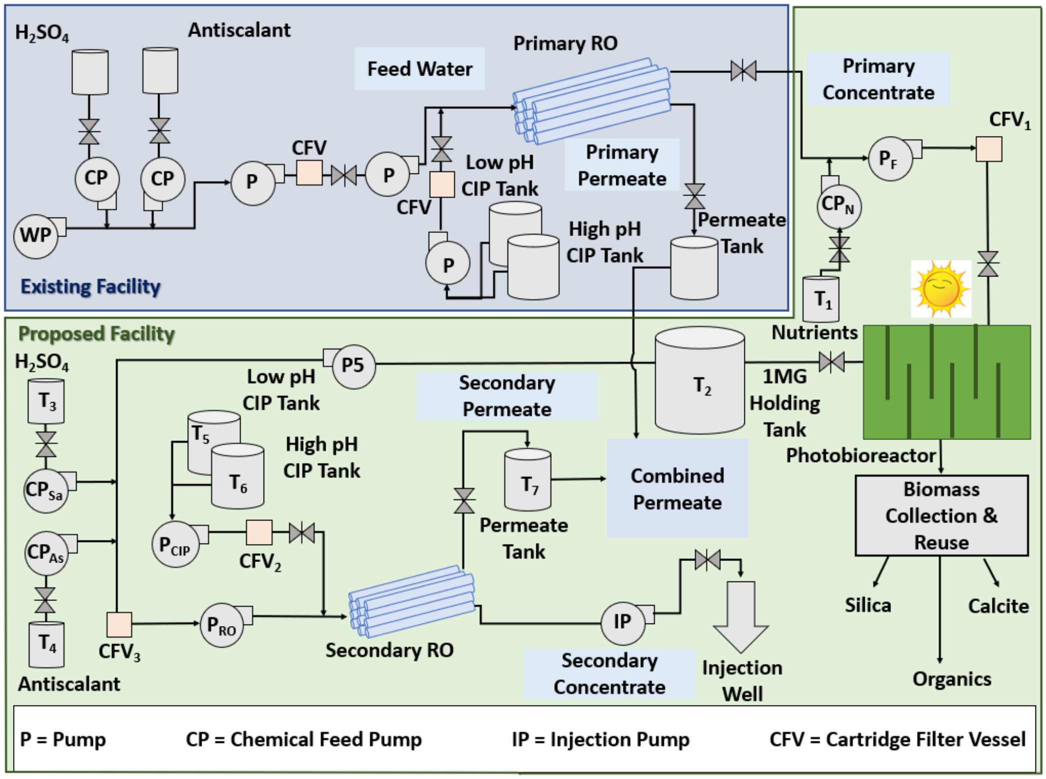


Figure 11: Detailed RO-PBR-Secondary RO Scheme for LCCA Study

Permeate from the secondary RO would be blended with the primary RO permeate to achieve enhanced freshwater recovery. The concentrated stream would be held in an injection tank, and later, it would be disposed of using the deep well injection. Biomass from the PBR would be collected and taken for separating and commercializing the bioresources. The diatom biomass contains silica, organics, and calcite, from which many high-value products might be achieved. The biomass would need to be processed to the desired valuable bioresources.

To clean the RO elements, a cleaning solution prepared with RO permeate and cleaning agents would be recirculated to and from the membranes by a clean-in-place (CIP) system. CIP is a cleaning method for cleaning equipment without changing the position of the equipment. The CIP systems would perform regular cleaning (*i.e.*, once a month) and sanitize RO membranes to remove fouling and restore membrane system performance. The cleaning agent dosage would be 2%/wt. (*i.e.*, 17 lb./100 gallon of permeate) to prepare the cleaning solution. Through acid (*i.e.*, low pH CIP) and alkali cleaning (*i.e.*, high pH CIP), microorganisms, organic matter, inorganic substances, and other fouling materials would also be removed. After recirculating the chemical agents, the membranes would be rinsed with RO permeate.

3.3.4.2 PHOTOBIOREACTOR DESIGN

Two different light source options were considered for this study. In one system, the diatom photobioreactors were designed in a warehouse, and the light source would be LED. In the other system, the photobioreactors were considered in greenhouses with sunlight as a light source. A design comparison between the sunlight and LED system is listed in Table 4. The previous research inspired the design of the PBRs. In an earlier study, a 1,500-gallon pilot-scale photobioreactor was built to continuously treat a simulated brackish groundwater ROC stream at a flow rate of up to two gallons per minute [135]. In another pilot study, a continuous-flow 45-gallon photobioreactor with a 100 gallons per day secondary RO system was built to operate with an HRT between 8 to 24 hours, corresponding to 135 to 45 gallons per day of ROC [131]. The reactors in both systems (*e.g.*, sunlight and LED) were designed with three different HRTs: 1.5 days, 1.0 days, and 0.5 days with 1.0 MGD feed flow. The 1.5-MGD HRT was derived following the previous bench-scale studies by Ms. Han Gao and Mr. Jacob A. Palmer [118, 124], and assuming the HRT could be shortened through further research in the future, other two HRTs were considered to compare the economic feasibility of the proposed scheme. Reason behind designing with two different light sources were to compare the economic feasibility with different lighting options. The sunlight system had the advantage of less cost as this system did not need LED as light source or a large warehouse construction. However, the LED system would provide better control on ambience according to previous research [118]. Critical part of this study was to figure out the difference between costs associated in both the systems for the discussed HRTs to propose the optimal system between these two light source options.

In both systems, there would be additional space for an underground storage tank, a storage tank, a RO facility, an office room and an industrial electrical control room. Additionally, the LED system would include an educational room and a conference room. PBRs in both systems would be made of concrete with 3.33 feet of height where the water depth would be 2 feet. The height and depth were also derived following the bench scale experiments by Ms. Han Gao (100 mL scale) and Mr. Jacob A. Palmer (4 liter and 40-gallon scale) [118, 124]. Assuming the opening of the baffles and the spacing between the baffles to be same, the number of baffles were designed in this study. There would be 10 baffles in each of the PBRs. Twin-wall polycarbonate sheets were considered as clear covers for the PBRs to avoid direct sunlight in both systems. Heating, ventilation and air-conditioning systems (HVAC) and evaporative coolers were designed for the LED and sunlight systems for temperature control and ventilation purposes, respectively.

Table 4: Design Comparison Between Sunlight and LED System

Parameters	Sunlight System	LED System
Light source	Sunlight	LED
Building type	Greenhouse	Warehouse
Ventilation system	HVAC	Evaporative cooler

A cartridge filtration would be installed before the PBRs, which would act as pre-filtration to reduce the chance of contamination from other algal species. The pore size of the filtration media would be 5 and 1 µm. A tank for the nutrient solution and a feed pump were also designed to supply nutrient to the PBRs.

3.3.4.3 SECONDARY RO FACILITY DESIGN

A secondary RO facility was designed to treat 1.0 MGD photobiologically treated ROC using the IMS Design software. The water type was selected as ‘Brackish Well High-Fouling’ as the feed TDS of the photobiologically treated ROC was between 1,100 mg/L to 15,000 mg/L with COD >9 mg/L [121]. For the design purpose, water quality analysis data of the photobiologically treated ROC was collected from Mr. Jacob A. Palmer’s previous study on photobiological treatment of a brackish groundwater ROC [124]. Assuming 60% removal of silica and 60% removal of calcium by the diatoms, the water quality analysis was adjusted for the RO design purpose. Table 5 includes the water quality data before and after adjustment for ion balance. Then the membrane selection part was taken care of by trying different membranes for the collected water quality data.

By the analysis, the membrane that provided the maximum recovery while satisfying all other design criteria (*e.g.*, Langelier saturation index, design flux, calcium carbonate precipitation potential) was selected. There were several built-in membrane types at the software with different nominal production (gallons per day), rejection percentage, size (in^2), area (ft^2), test pressure (psi) and spacer specifications. By the trial-and-error method, different membrane types were tested with the software, and the optimal membrane type was selected. According to the membrane type, membranes/vessels and the number of vessels were selected.

Table 5: Water Quality Data Before and After Adjustment for Secondary RO Design

Parameter	Before Adjustment	After Adjustment
Cations		
Sodium (mg/L)	3,485	3,485
Potassium (mg/L)	55	55.04
Calcium (mg/L)	67	123.25
Magnesium (mg/L)	75	75.00
Barium (mg/L)	0.03	0.04
Strontium (mg/L)	11.14	13.38
Anions		
Chloride (mg/L)	2,033	2,033
Sulfate (mg/L)	4,882	4,882
Bicarbonate (mg/L)	550	550
Reactive silica (mg/L)	20	54
Fluoride (mg/L)	1.63	1.63
Orthophosphate (mg/L)	0.26	0.15

Then the configuration of the secondary RO was designed. Two-stage RO was chosen with the selected membrane type to achieve up to 70% freshwater recovery. In a two-stage RO system, the concentrate from the first stage becomes the feed water for second stage. The permeate collected from the first stage would be combined with the permeate from the second stage. After the membrane selection and RO configuration, the installation of an energy recovery device (ERD) was evaluated to reduce the power requirement. An ERD takes concentrate from the last stage and then boosts the pressure to the first stage. It would not only reduce the electricity cost, but also would reduce the energy demand of the high-pressure pump. There would be a very little pressure drop in the concentrate which would be used to recover the energy for the RO. For the two-stage RO design, two turbochargers would be installed as ERD devices for this study using IMS Design. With this design, the software confirmed that 70% freshwater recovery could be achievable after the photobiological treatment of the ROC. Remaining 30% of primary ROC would be disposed by deep well injection. To determine the CAPEX of the injection well, literature information [125] was used and extrapolated by using a discount rate. There would be monitoring wells around the deep well to observe the groundwater levels and flow conditions, obtaining samples for determining the water quality, and for evaluating hydraulic properties of water-bearing strata.

3.3.5 LIFECYCLE COST ANALYSIS

LCCA was performed here in the design process to have room to make changes and refinements that would ensure that the life cycle cost would be reduced. The LCCA of this study was performed to estimate the overall costs of project alternatives and to select the optimal scenario (*i.e.,* light source, HRT) that would ensure that the proposed facility would provide the lowest overall cost of ownership consistent with its quality and function. LCCA for the PBR-secondary RO considered all the costs associated with obtaining, owning, constructing the facilities for all the discussed scenarios, and disposal of the ROC. Here, the LCCA considered multiple alternatives for both the RO and the PBR designs, and all the alternatives were checked regarding their ability to meet the performance necessities. The alternatives were compared later to find one that could maximize the revenue.

3.3.5.1 PHOTOBIOREACTOR DESIGN SCENARIOS FOR DIFFERENT HRT

A complete design of the photobioreactor was performed for the cost analysis. For the greenhouse system, it was assumed that there would be one PBR in a greenhouse. To treat 1.0 MGD of ROC in the 1.5 days HRT scenario, the proposed system would need 36 PBRs in 36 greenhouses. From this 36 PBRs, 30 would be operational, and 6 would be backup. During the biomass harvesting and cleaning processes of the operational PBRs, the backup PBRs would become functional to treat 1.0 MGD ROC continuously. For the LED system, it was assumed that all the PBRs would be situated in a warehouse and there would be a need of 24 PBRs. From these 24 PBRs, 20 PBR would be operational and 4 PBR would be the backup PBRs. Specifications of the PBRs along with the greenhouse and warehouses for both sunlight and LED systems with 1.5 days HRT are listed in Table 6. When the HRT was assumed to be shortened, the number of PBRs reduced as ROC would be treated quicker than 1.5 days HRT. With the shortened treatment time, the required volume of the photobioreactor reduced in comparison to the 1.5 days HRT scenario.

Table 6: Dimensions and Specifications of PBRs with a HRT 1.5 Days

Specification	LED	Sunlight
Length (ft)	116	136
Width (ft)	56	32
Area (ft^2)/ PBR	6,496	4,352
Water depth (ft)	2	2
Volume (ft^3)/PBR	12,992	8,704
No. of PBR in use	20	30
No. of PBR offline	4	6
No. of PBRs in total for greenhouse/ warehouse	23.77	35.51
Total PBR area (ft^2)	154,420	154,548
Total water volume (ft^3)	256,872	256,872
Total volume (million gallons)	1.6	1.6
Warehouse/ greenhouse length (ft)	567	144
Warehouse/ greenhouse width (ft)	566	40
Warehouse/ greenhouse height (ft)	35	27
Area of concrete wall (ft^2)	27,230.79	39,733.61
No. of baffles/PBR	10	10
Total no. of baffles	237.72	355.12
Opening and intermediate space between baffles (ft)	11.6	13.6
Total baffle area (ft^2)	35,146.71	21,758.88
Total wall (ft^2)	62,377.50	61,492.49

For 1.0 days HRT, there would be a total of 22 PBRs in the sunlight system from which 18 would be operational and 4 would be offline or backup. For the LED system, there would be a total of 16 PBRs from which 12 PBR would be operational and 4 would be the backup PBRs. Dimensions and specifications of the PBRs in both LED and sunlight system for 1.0 days HRT are listed in Table 7.

For HRT 0.5 days, there would be a total of 12 PBRs in the sunlight system from which 9 would be operational and 3 would be offline or backup. For the LED system, there would be a total of 8 PBRs from which 6 PBR would be operational and 2 would be the backup PBRs. Dimensions and specifications of the PBRs in both LED and sunlight system for 0.5 days HRT are listed in Table 8.

Table 7: Dimensions and Specifications of PBRs with a HRT 1.0 Days

Specification	LED	Sunlight
Length (ft)	116	136
Width (ft)	56	32
Area (ft^2)/ PBR	6,496	4352
Water depth (ft)	2	2
Volume (ft^3)/PBR	12,992	8.704
No. of PBR in use	12	18
No. of PBR offline	4	4
No. of PBRs in total for greenhouse/ warehouse	16	22
Total PBR area (ft^2)	106,257	97,681
Total water volume (ft^3)	160,545	160,545
Total volume (million gallons)	1.0	1.0
Warehouse/ greenhouse length (ft)	412	144
Warehouse/ greenhouse width (ft)	573	40
Warehouse/ greenhouse height (ft)	35	27
Area of concrete wall (ft^2)	18,738	25,113
No. of baffles/PBR	10	10
Total no. of baffles	164	224
Opening and intermediate space between baffles (ft)	11.6	13.6
Total baffle area (ft^2)	24,184	13,752
Total wall (ft^2)	42,992	38,866

Table 8: Dimensions and Specifications of PBRs with a HRT 0.5 Days

Specification	**LED**	**Sunlight**
Length (ft)	116	136
Width (ft)	56	32
Area (ft^2)/ PBR	6,496	4,352
Water depth (ft)	2	2
Volume (ft^3)/PBR	12,992	8,704
No. of PBR in use	6	9
No. of PBR offline	2	3
No. of PBRs in total for greenhouse/ warehouse	8	12
Total PBR area (ft^2)	53,128	53,192
Total water volume (ft^3)	80,273	80,273
Total volume (million gallons)	0.50	0.50
Warehouse/ greenhouse length (ft)	573	144
Warehouse/ greenhouse width (ft)	251	40
Warehouse/ greenhouse height (ft)	35	27
Area of concrete wall (ft^2)	9,369	13,675
No. of baffles/PBR	10	10
Total no. of baffles	82	122
Opening and intermediate space between baffles (ft)	11.6	13.6
Total baffle area (ft^2)	12,092	7,489
Total wall (ft^2)	21,461	21,164

3.3.5.2 ASSOCIATED ITEMS

Three main groups for cost analysis were used in this study: PBR, secondary RO, and biomass processing. The components for PBR included the pretreatment (*e.g.*, nutrient addition and cartridge filter) of the primary ROC, and PBR construction costs. Associated items for the PBR included the prefiltration system (*e.g.*, cartridge filters), nutrient dosing pump, chemicals (*e.g.*, nutrients), light source (*e.g.*, LED or sunlight), tanks (*e.g.*, primary ROC holding, nutrient holding, treated ROC holding), and PBR construction costs. Items associated with the secondary RO were pretreatment of photobiologically treated ROC (*e.g.*, cartridge filters), secondary RO set-up tanks (*e.g.*, H_2SO_4 holding, antiscalant holding, low pH CIP holding, high pH CIP holding, commercial bleach holding, ammonium sulfate holding), chemicals (*e.g.*, H_2SO_4, low pH CIP, high pH CIP, commercial bleach, ammonium sulfate), pumps (*e.g.*, chemical feed pumps, RO booster pump, deep well injection pump), RO facility setup. Additionally, the installation cost of deep well injection and monitoring wells was considered in this study. Table 9 represents the discussed items categorized into CAPEX and OPEX form.

Table 9: CAPEX and OPEX Categorization of the Associated Items

Unit process	**CAPEX**	**OPEX**
PBR	Construction	Chemicals
	Engineering and permitting	LED operation
	Tanks	Pump operation
	Lighting installation	
	Pumps and piping installation	
Warehouse	Construction	HVAC operational
	Warehouse lighting installation	Warehouse lighting operation
	HVAC installation	
Greenhouse	Greenhouse construction	Evaporative cooler operation
	Evaporative cooler installation	Greenhouse lighting operation
	Greenhouse lighting installation	
Secondary RO	Cartridge filters	Chemicals
	Tanks	Pump operation
	Pumps	
	RO elements and vessels	
	Monitoring well installation	

3.3.5.3 COST ANALYSIS

The LCCA of this study was based on a total expenditure approach [126]. Total expenditure would combine both OPEX and CAPEX which is presented in the NPV analysis. The lifecycle of the proposed facility was assumed as 20 years. The analysis also accounted for bioresource recovery from diatom biomass and possible integration with LCCA to offset the cost of setting up the PBR, and the power requirement for running the secondary RO. LCCA was performed for sunlight and LED systems along with considering the discussed HRT scenarios. The HRT scenarios were further divided into two categories, including: HRT scenario without any grant and HRT scenario considering a 30% grant from local, federal, national agencies on the CAPEX.

To calculate the NPV for year n, the following equation was used [126]:

$$NPV_n = \frac{C_n}{(1+i)^n} \tag{1}$$

where NPV_n is the NPV for year n; C_n is the project net cash flow at year n; i is the discount rate, generally within 6–12% range. Based on an LCCA study on the desalination process [126], a discount rate of 6% was used in this study to calculate the NPV_n, and n is the year of service for the proposed facility (from year 1 to year 20). C_n was calculated using the equation below [113]:

$$C_n = Cash\ inflow_n - Cash\ outflow_n \tag{2}$$

where $Cash\ outflow_n$ is the total expenditure at year n that includes the OPEX and amortized CAPEX at year n. The following equation was used to determine the cash outflow at year n:

$$Cash\ outflow_n = CAPEX_n + OPEX_n \tag{3}$$

The $OPEX_n$ was calculated using the following equation [126]:

$$OPEX_n = OPEX_1 \times (1 + f_a)^n \tag{4}$$

where $OPEX_1$ is operational expenditure at year 1; and f_a is the annual inflation factor. The inflation rate for consumer prices in the United States moved over the past 61 years between -0.4% and 13.5%, and for the year 2021, an inflation rate of 4.7% was calculated [127]. For this study, the same inflation rate of 4.7% was used. To calculate the annual $CAPEX_n$, the total capital investment was amortized over the service life of the PBR-secondary RO facility (20 years), and the following equation was used, taking the depreciation into consideration [126]:

$$CAPEX_n = CAPEX_0 \times \frac{i \times (1+i)^n}{(1+i)^n - 1} \tag{5}$$

where $CAPEX_0$ is the capital investment made at year 0, and n is the service life of the proposed plant (20 years). Tax was applied to all the purchased items and a sales tax of

8.25% was used in this study [128]. *Cash* $inflow_n$ is the revenue made from the bioresources sales and the account and the following equation was used:

$$Cash\ inflow_n = (C_{in})_1 \times (1 + f_a)^n \quad (6)$$

Break-even analysis amounts were calculated for each year using each year's cash inflows and outflows.

3.3.5.4 GRANT POSSIBILITIES ON CAPEX

In this study, possible grants on the CAPEX were considered to understand the overall cost reduction by applying for grants on the CAPEX. The Water Infrastructure Improvements for the Nation Act provides new authorities to the US Bureau of Reclamation to develop a desalination construction program to provide a path for ocean or brackish water desalination projects to receive Federal funding [129]. Assuming a 25% grant on the CAPEX from the US Bureau of Reclamation and an additional 5% grant raised from other Federal and State agencies, a total of 30% grant was applied on the CAPEX for all three HRT scenarios (1.5-, 1.0- and 0.5-days HRT) for both LED and sunlight systems. The LCCA section of the results and discussion chapter discusses the impact of the grant on the unit cost of freshwater production.

3.3.6 PV ANALYSIS

The RETScreen Expert software was used to analyze the feasibility of installing a PV system to run the proposed PBR-secondary RO facility. Using the software, the installation cost, OPEX, profit generation, and greenhouse gas reduction of the PV system for the sunlight system with all three HRT scenarios (*i.e.*, 1.5-, 1.0- and 0.5-days HRT) were calculated. To install the PV system, the total power requirement of the system was calculated in kW. Then, assuming the facility location to be central Texas, the discount rate and inflation factor were adjusted in the software to perform the cost analysis.

4. RESULTS AND DISCUSSIONS

4.1 PHOTOBIOLOGICAL TREATMENT

A photobiological treatment experiment with *G. flavovirens* Psetr3 was conducted on water samples containing dissolved silica (> 80 mg/L) prepared with different salt concentrations. The objective of this experiment was to understand the impact of salt concentration on photobiological treatment of ROCs. The prepared samples had TDS concentrations of 222, 1,000, 2,000, 4,000, 8,000, 16,000, 32,000 and 64,000 mg/L, and the samples were termed Fiji, Fiji 1k, Fiji 2k, Fiji 4k, Fiji 8k, Fiji 16k, Fiji 32k, and Fiji 64k, respectively. Figure 12 shows the trend of silica concentration in the photobiological treatment of a wide range of salt concentration samples by the brackish water diatom. Photobiological treatment with low (*e.g.,* 222 and 1,000 mg/L) to moderate TDS samples (*e.g.*, 2,000 and 4,000 mg/L) would explain the behavior of the diatoms in terms of silica uptake in samples containing very low to moderate salt concentration. Photobiological treatment with the brackish water ranged TDS samples (*e.g.*, 8,000 and 16,000 mg/L) samples explained the trend of silica uptake rate in brackish water ROC samples. Photobiological treatment with the sea water ranged (*e.g.,* 32,000 mg/L) and above (*e.g.,* 64,000 mg/L) TDS samples would indicate if using a photobiological treatment of the ROCs with sea water TDS concentrations would be a feasible option or not. Tables 10, 11, 12, 13 and 14 shows the experimental results for different salt concentration's impact on the photobiological treatment by brackish water diatom.

Diatoms in the prepared sample with no TDS addition (*e.g.*, Fiji) and with 1k TDS (*e.g.,* Fiji 1k) started removing silica initially, however, after 48 and 64 hours for Fiji and Fiji 1k, respectively., the diatoms stopped removing silica and the concentration of silica in the samples started to increase (Figure 12). This indicated that low TDS concentrations might not be the ideal environment for the diatoms. The photomicrographs of the biomass collected after the first cycle in these two water samples had dead diatom cells confirming this observation.

Silica uptake rate by the brackish water diatoms showed better results for the samples Fiji 2k and Fiji 4k compared to the previous two samples regarding silica removal for both cycles 1 and 2. The diatoms removed more than 85% silica in the first and second cycles, while the removal rate was relatively slow in the 3rd cycle.

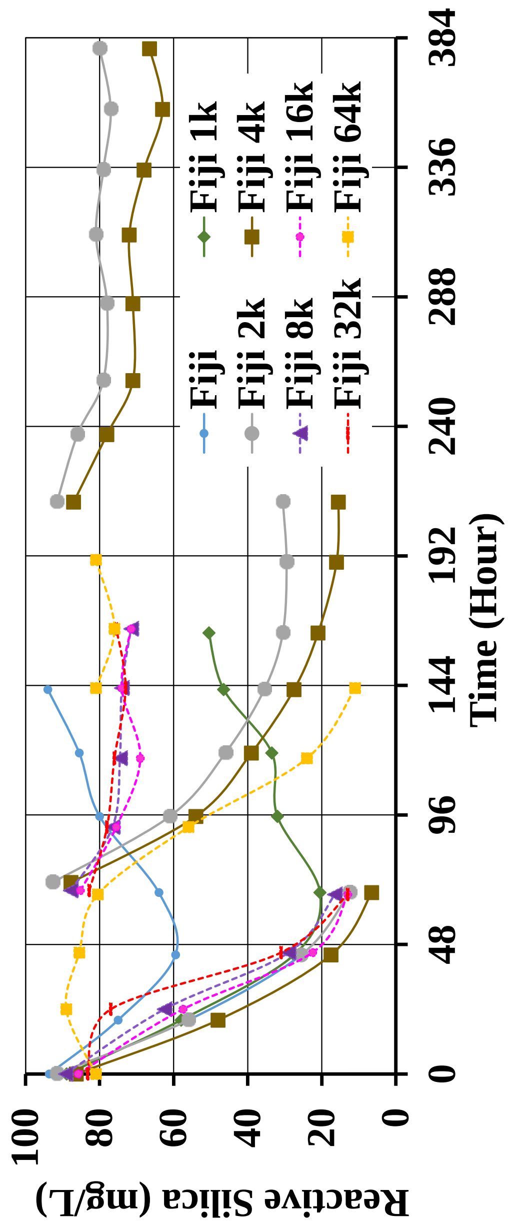


Figure 12: Silica Uptake by *G. flavovirens* Psetr3 in Water Samples with Various TDS Concentrations

Table 10: Water Quality Before and After the Photobiological Treatment (Low to Moderate TDS, First Cycle)

Cycle no.	**First cycle**							
Parameter	Initial samples				Final samples			
	Fiji	Fiji 1k	Fiji 2k	Fiji 4k	Fiji	Fiji 1k	Fiji 2k	Fiji 4k
Silica (mg/L as SiO_2)	93.6	88.9	91.6	86.3	94	50.5	12.5	6.5
Nitrate (mg/L as N)	12.00	11.70	12.10	10.80	4.20	4.20	7.40	4.90
Ammonia (mg/L as N)	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4
Orthophosphate (mg/L as PO_4^{3-})	4.40	4.80	5.20	5.40	0.15	0.07	0.10	0.21
Total chemical oxygen demand (mg/L)	<3	5	12	24	23	27	24	35
pH	8.1	8.2	8.3	8.5	10.3	9.5	8.7	9.0
Color at 455 nm (PtCo unit)	0	8	3	1	89	70	56	54
Calcium hardness (mg/L as $CaCO_3$)	52	80	112	152	35	121	134	198
Alkalinity (mg/L as $CaCO_3$)	143	148	152	156	99	75	51	48
Biomass (g/L)	0.8810	0.8810	0.8810	0.8810	0.9680	0.9789	N/A	N/A

Table 11: Water Quality Before and After the Photobiological Treatment (Low to Moderate TDS, Second Cycle)

Cycle no.	**Second cycle**			
Parameter	Initial samples		Final samples	
	Fiji 2k	Fiji 4k	Fiji 2k	Fiji 4k
Silica (mg/L as SiO_2)	92.7	87.7	30.5	15.5
Nitrate (mg/L as N)	11.60	7.45	8.80	6.85
Orthophosphate (mg/L as PO_4^{3-})	4.41	4.20	0.13	0.14
Total chemical oxygen demand (mg/L)	16	33	22	34
pH	8.4	8.3	9.2	8.8
Color at 455 nm (PtCo unit)	0	5	26	29
Calcium hardness (mg/L as $CaCO_3$)	106	167	118	172
Alkalinity (mg/L as $CaCO_3$)	153	152	32	28

Table 12: Water Quality Before and After the Photobiological Treatment (Low to Moderate TDS, Third Cycle)

Cycle no.	**Third cycle**			
Parameter	Initial samples		Final samples	
	Fiji 2k	Fiji 4k	Fiji 2k	Fiji 4k
Silica (mg/L as SiO_2)	91.5	87	80	66.5
Nitrate (mg/L as N)	11.30	10.15	10.95	8.7
Orthophosphate (mg/L as PO_4^{3-})	4.33	4.52	1.06	1.17
Total chemical oxygen demand (mg/L)	15	23.5	16	29
pH	8.4	8.3	9.2	9.2
Color at 455 nm (PtCo unit)	0	18	12	30
Calcium hardness (mg/L as $CaCO_3$)	105	155	98	142
Alkalinity (mg/L as $CaCO_3$)	149	147	108	109
Biomass (g/L)	N/A	N/A	1.104	1.729

Table 13: Water Quality Before and After the Photobiological Treatment (Brackish Water, Seawater and Above Seawater TDS, First Cycle)

Cycle no.	**First cycle**							
Parameter	Initial samples				Final samples			
	Fiji 8k	Fiji 16k	Fiji 32k	Fiji 64k	Fiji 8k	Fiji 16k	Fiji 32k	Fiji 64k
Silica (mg/L as SiO_2)	89.2	85.8	83.2	81.0	16.5	13.0	13.0	11.0
Orthophosphate (mg/L as PO_4^{3-})	4.58	4.68	4.58	4.68	0.22	0.12	0.06	0.04
Total chemical oxygen demand (mg/L)	45	80	160	400	35	95	190	650
pH	8.2	8.0	8.0	8.0	10.1	9.9	9.8	9.3
Color at 455 nm (PtCo unit)	0	0	0	0	34	32	38	34
Calcium hardness (mg/L as $CaCO_3$)	240	425	925	1,720	239	412	745	1,453
Alkalinity (mg/L as $CaCO_3$)	194	216	274	400	72	76	98	94
Biomass (g/L)	0.2370	0.2370	0.2370	0.2370	N/A	N/A	N/A	N/A

Table 14: Water Quality Before and After the Photobiological Treatment (Brackish Water, Seawater and Above Seawater TDS, Second Cycle)

Cycle no.	**Second cycle**							
Parameter	Initial samples				Final samples			
	Fiji 8k	Fiji 16k	Fiji 32k	Fiji 64k	Fiji 8k	Fiji 16k	Fiji 32k	Fiji 64k
Silica (mg/L as SiO_2)	87.8	85.2	82.8	81.0	71.5	71.5	75.5	75
Orthophosphate (mg/L as PO_4^{3-})	4.66	4.54	4.76	4.56	2.68	1.92	2.68	0.90
Total chemical oxygen demand (mg/L)	50	85	140	370	45	90	210	450
pH	8.0	8.0	8.0	7.9	9.1	9.0	8.8	8.3
Color at 455 nm (PtCo unit)	0	0	0	3	16	24	8	14
Calcium hardness (mg/L as $CaCO_3$)	247	420	900	1,790	241	415	808	1,625
Alkalinity (mg/L as $CaCO_3$)	194	210	284	406	78	78	238	336
Biomass (g/L)	N/A	N/A	N/A	N/A	0.5150	0.5330	0.5870	0.4390

For Fiji 8k and Fiji 16k, the diatoms completed the 1st cycle by removing 85% silica, however they started removing silica at a slow rate in the second cycle. For the TDS range with Fiji 32k and Fiji 64k, the diatoms completed the 1st cycle at a very slow rate, and in the 2nd cycle the removal rate was even slower.

In previous works, Ikehata et al. and Palmer et al. found that the brackish water diatom *G. flavovirens* can remove silica from a wide range of TDS varying between 3,000 to 16,000 mg/L [124]. From Figure 12 and the tables (Tables 10,11, 12, 13 and 14), it could be concluded that the photobiological treatment worked well in all water samples except for Fiji Water without TDS addition and the one with a TDS of 1,000 mg/L in the first cycle. Results from this study were consistent in terms of silica removal in a controlled condition with a wide range of TDS samples. However, in the previous research, the diatoms completed three cycles of 85% silica removal from ROCs [130]. In this study, the photobiological treatment did not work well in the second cycle, and none of the water could go beyond that possibly due to lack of minerals in the prepared samples. The silica uptake was the slowest in the water, with the highest TDS concentration (64,000 mg/L). It might be concluded from this experiment that, to remove silica from ROCs, the diatoms favor a salty environment rather than a very low TDS environment.

The silica uptake rates for Fiji 4k, 8k and 16k were very close in the first cycle, which became different from the subsequent cycles. Based on the silica uptake rates of the first cycle, the silica uptake rate by the brackish water diatom *G. flavovirens* Psetr3 was 30 mg/L/day. According to previous photobiological treatment on brackish groundwater ROCs by the brackish water diatoms, the silica uptake rate is 44 mg/L/day [118]. Results from this study of silica uptake was close to previous research work; however, the diatoms would favor an environment of ROC instead of a prepared solution.

4.2 BIOMASS CHARACTERIZATION

4.2.1 MICROSCOPIC IMAGES OF UNTREATED, BLEACHED AND CITRIC ACID-TREATED SAMPLES

In this section, the characterization of the biomass samples by bleach and citric acid treatment will be discussed using the photomicrographs taken before and after the treatments. Biomass samples were collected from the photobiological treatment on ROC from a brackish groundwater desalination facility (SAWS H2Oaks, San Antonio, TX) and an advanced water purification facility (OCWD GWRS AWPF, Fountain Valley, CA). The actual photobiological treatment experiments were done by Ms. Han Gao in 2020-2021 [118]. Figure 13 shows the appearance of biomass before, during and after the treatments. Figures 14, 15 and 16 include the images of the biomass characterization stages (*i.e*., untreated biomass, bleached biomass and bleached and citric acid treated biomass). SEM imaging was conducted to provide a clear image of the diatom samples along with their corresponding structures.

Figures 14a (microscopic) and 14b (SEM) represent the untreated biomass images before the bleach and citric acid treatment where the frustules are green which indicates the presence of organics in them, and there is the presence of precipitates which were assumed to be calcite based on the water quality analysis before and after the photobiological treatment. Figures 15a (photomicrograph) and 15b (SEM) are the biomass images after bleach treatment where almost no green organics were present in the frustules. This might explain the impact of the bleach treatment that ensured two major results: one was the volume of bleach addition, which was twice the volume of biomass present, the other was the digestion time, which was two hours. Still, there was the presence of precipitates, indicating the presence of calcite after the bleach treatment. Figures 16a (photomicrograph) and 16b (SEM) are the images that explain the impact of the citric acid treatment by removing the precipitates. In these images (*e.g.*, 16a and 16b) there was almost no presence of precipitates observed (*e.g.*, calcium carbonate), and the remaining should be silica frustules.

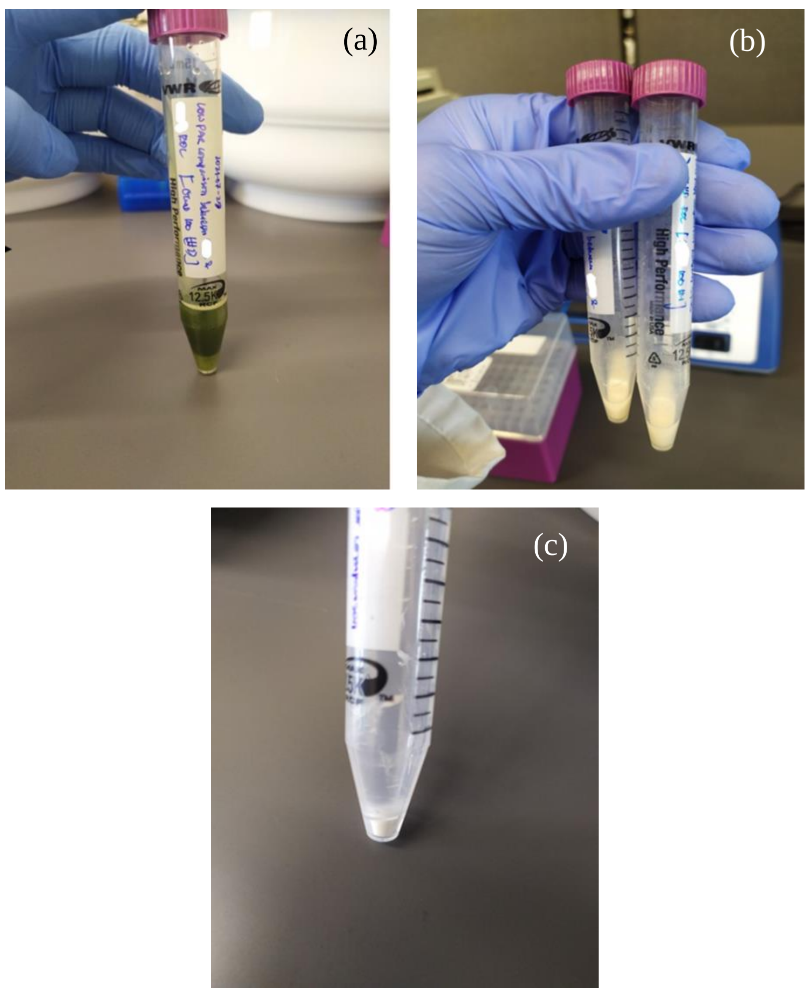


Figure 13: Appearances of Diatom Samples During Biomass Fractionation (a) Untreated Biomass; (b) Bleached biomass; (c) Bleached and Citric Acid Treated Biomass

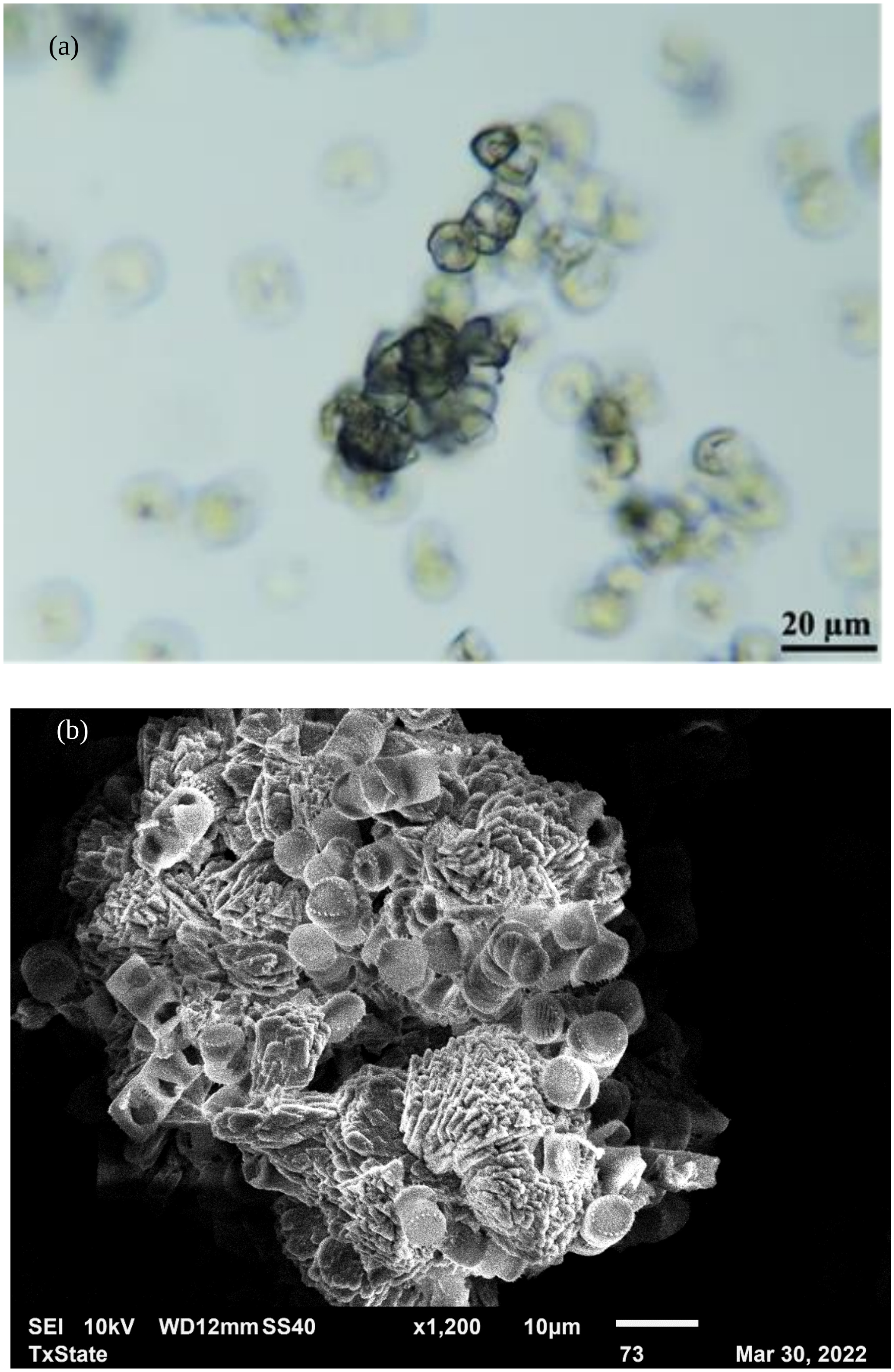


Figure 14: (a) Photomicrograph (Credit: Author); (b) SEM (Credit: Mr. Mason S. Underwood) Image of Untreated Biomass

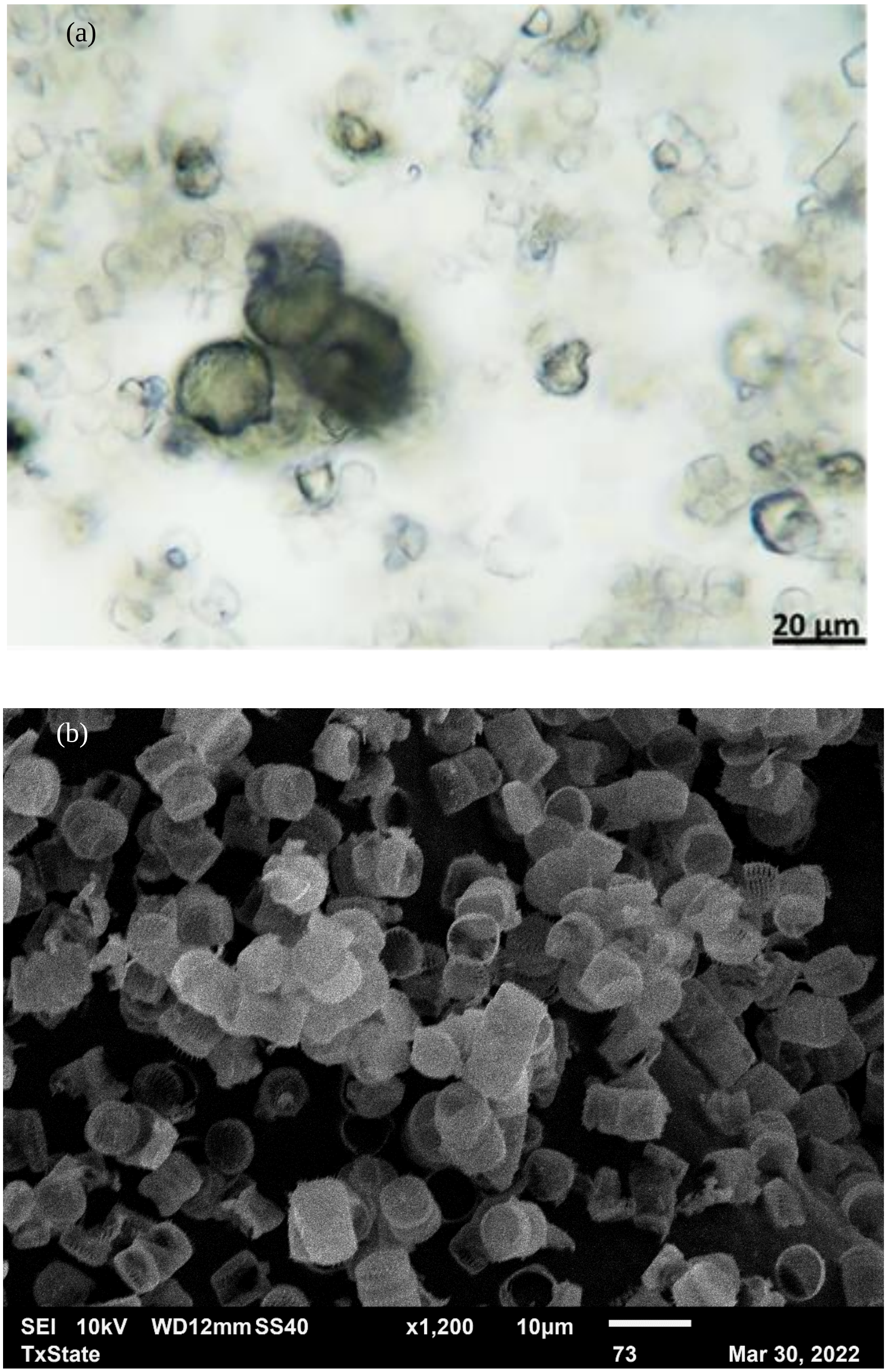


Figure 15: (a) Photomicrograph (Credit: Author); (b) SEM (Credit: Mr. Mason S. Underwood) Image of Bleached Biomass

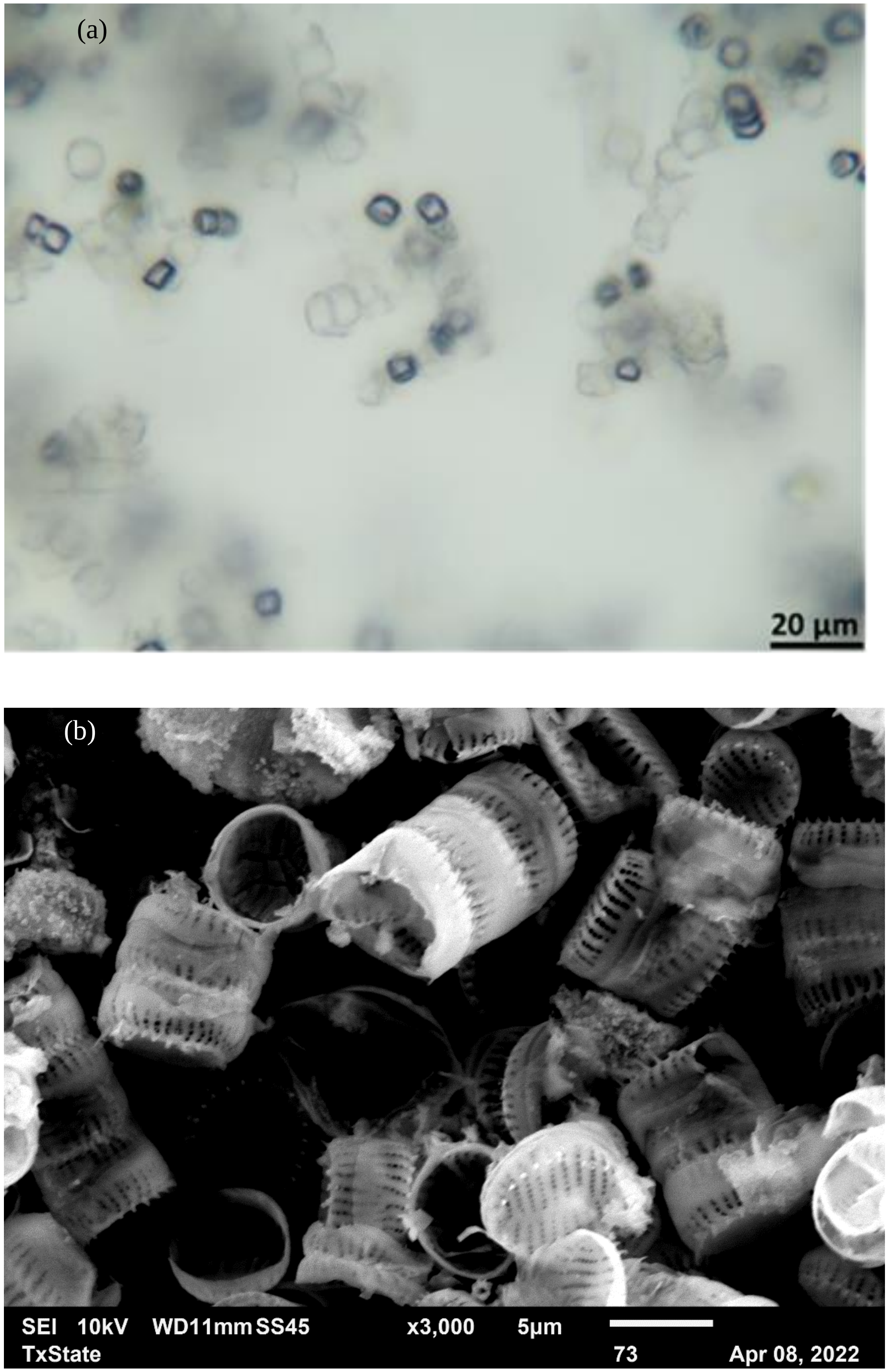


Figure 16: (a) Photomicrograph (Credit: Author); (b) SEM (Credit: Mr. Mason S. Underwood) Image of Bleached and Citric Acid Treated Biomass

4.2.2 BIORESOURCES IN DIATOM BIOMASS

4.2.2.1 DIATOM BIOMASS FRACTIONATION FROM SAWS ROC

Biomass fractionation results provided the percent composition of organics, calcite, and silica present in the biomass samples. Figure 17 shows the biomass fractionation results for biomass samples collected from one of Ms. Han Gao's experiments. Results from her other experiments are listed in the appendix section (Section A, Figures 1, 2 and 3).

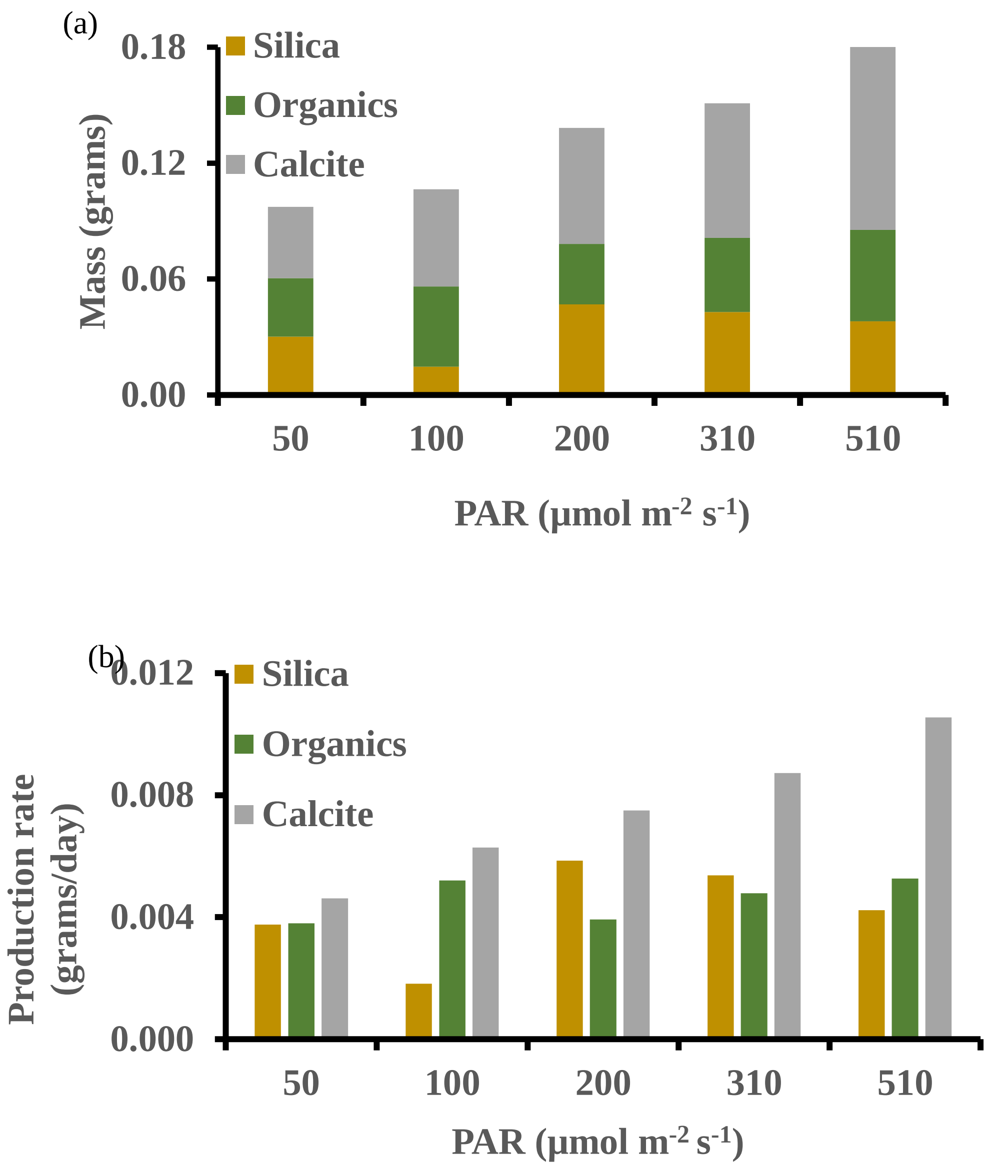


Figure 17: Silica, Calcite and Organics (a) Percentages in Biomass from SAWS ROC; (b) Production Rate in Biomass from SAWS ROC

Figure 17a explains the percentages of silica, calcite, and organics present in the biomass. The average percentages are 27%, 35% and 38% for silica, calcite and organics, respectively. The experimental results from Figure 17b indicated that the average biomass production rate of silica, organics and calcite would be 0.0046, 0.0048 and 0.0083 grams/day. These experimental results are from the 100 mL-lab scale experiments. The results were extrapolated to the 1 MGD scale proposed facility to determine the bioresources production rates and revenue from the bioresources. For the 1 MGD scale proposed facility, the production rates for silica and calcite would be 70 and 125 metric tons per year, respectively, assuming a 15% loss during the biomass collection and harvesting process for silica and a 25% loss for calcite. Similarly, organics production would be 112 tons per year from biomass.

4.2.2.2 DIATOM BIOMASS FRACTIONATION FROM OCWD ROC

Figure 18 shows the biomass fractionation results for the biomass samples collected from one of Ms. Han Gao's experiments with OCWD ROC. Figure 18a explains the mass percentages of silica, calcite and organics present in the biomass sample collected from OCWD ROC. The average percentages are 20%, 25% and 55% for silica, organics, and calcite, respectively.

Figure 18b indicates the average production rates of silica, organics, and calcite in the biomass, which are 0.0047, 0.0060 and 0.0134 grams/day, respectively. A higher production rate of bioresources indicates that the revenue from by-products could be higher for the photobiological treatment of ROC samples from advanced water purification facilities compared to the photobiological treatment of ROC samples from the brackish groundwater treatment facility.

Excluding the percent of calcite from the biomass compositing, the silica content would be 55%, and the organics content would be 45% in the biomass. The calcite was excluded as it was not a part of the biomass as it was precipitated during the photobiological treatment process. According to previous studies, diatoms typically have 15%–25% lipid content which can reach up to 85% in them, which is the organics content [17]. Findings from the biomass fractionation experiment of this research indicate that the diatom strain *G. flavovirens* would have organics content after the photobiological treatment of ROCs that is consistent with the organics content of previous research. Additionally, researchers have found that diatom frustules are supposed to be made of silica which can reach up to 60% of the dry weight of the biomass [75], whereas, in this study, it was found that the silica content in the diatom biomass is 55% of the dry weight, which is also very consistent with the previous research works.

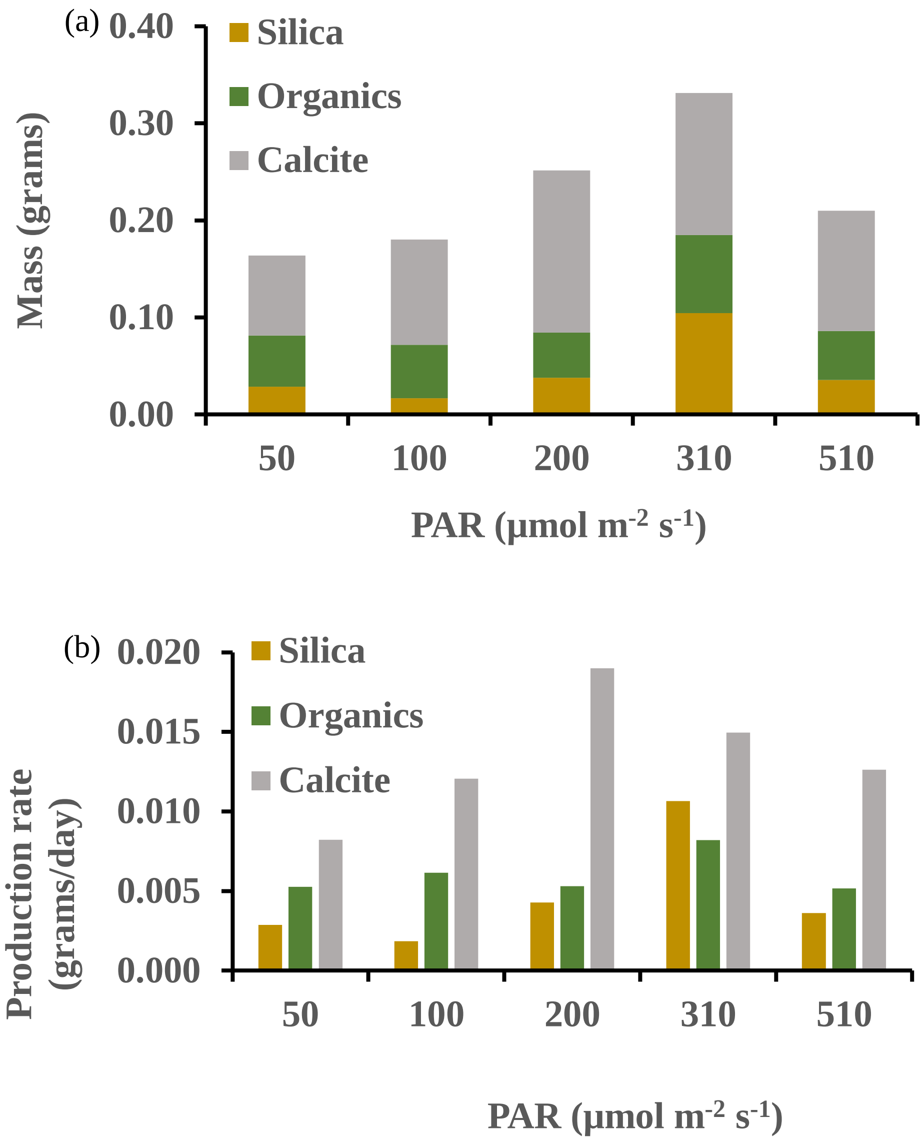


Figure 18: Silica, Calcite and Organics (a) Proportions in Biomass from OCWD ROC; (b) Production Rate in Biomass from OCWD ROC

4.2.3 ELEMENTAL COMPOSITION OF DIATOM BIOMASS

Organic carbon was measured by COD analysis on the biomass samples from SAWS ROC. Nitrogen and phosphorus quantification was performed using the total nitrogen and total phosphorus analysis on untreated biomass samples. Experimental results are shown in Table 15.

Table 15: Nitrogen, Phosphorus and Organic Carbon Quantification in Untreated Biomass

Sample	Total nitrogen (%)	Total phosphorus (%)	Organic carbon (%)
SAWS 23°C #1	1.8	0.6	0.9
SAWS 23°C #2	1.9	0.9	0.5
SAWS 30°C #1	2.2	1.2	0.5
SAWS 30°C #2	1.6	1.1	0.5
OCWD 23°C #1	2.6	1.1	0.9
OCWD 23°C #2	2.0	1.2	1.0
OCWD 30°C #1	1.6	1.2	0.7
OCWD 30°C #2	1.7	1.2	0.8

From the experimental results, the average percentages of total nitrogen, total phosphorus and organic carbon in the biomass would be 2%, 1.0% and 0.90%, respectively. EDS analysis of these samples was performed, and among the results, EDS analyses of SAWS 23°C and OCWD 23°C are presented in Table 16, and 17, respectively.

Table 16: Elemental Composition of Biomass from SAWS 23°C Sample

Element	SAWS 23°C #1	SAWS 23°C #2	Average
Carbon	30.1%	32.2%	31.2%
Oxygen	48.4%	48.3%	48.4%
Magnesium	4.2%	1.9%	3.0%
Silicon	5.5%	8.5%	7.0%
Potassium	0.0%	0.5%	0.2%
Calcium	11.0%	8.0%	9.5%

Later, experimental results from the total nitrogen, total phosphorus, and COD were incorporated with the EDS analysis, and corrected mass percentages of the elements were calculated. Mass percentages for the SAWS 23°C, and OCWD 23°C are listed in Table 18 and 19, respectively.

Table 18 and 19 indicate that the percentage of organic carbon was extremely low (0.90%), whereas the inorganic carbon percentage was 31.2%, and39.3% in SAWS and OCWD samples, respectively. Several COD analysis was performed to double-check the organic carbon percentages. However, the results were always the same. Future research works are needed to confirm the organic carbon percentage present in the diatom biomass.

Table 17: Elemental Composition of Biomass from OCWD 23°C Sample

Element	**OCWD 23°C #1**	**OCWD 23°C #2**	**Average**
Carbon	51.2%	30.8%	41.0%
Oxygen	36.7%	48.2%	42.5%
Magnesium	1.9%	4.2%	3.0%
Silicon	2.8%	5.8%	4.3%
Potassium	0.0%	0.0%	0.0%
Calcium	7.1%	10.4%	8.7%
Sulfur	0.2%	0.2%	0.2%

Table 18: Estimated Elemental Composition in Mass Percentages from SAWS 23°C Sample

Element	**Mass percentage of SAWS 23°C**	**Corrected mass percentage of SAWS 23°C**
Inorganic carbon	31.2%	29.5%
Organic carbon	0.7%	0.6%
Oxygen	48.4%	46.8%
Magnesium	3.0%	2.9%
Silicon	7.0%	6.8%
Potassium	0.2%	0.1%
Calcium	9.5%	9.2%
Nitrogen	2.0%	2.0%
Phosphorus	1.0%	1.0%

Table 19: Estimated Elemental Composition in Mass Percentages of OCWD 23°C Sample

Element	Mass percentage of OCWD 23°C	Corrected mass percentage of OCWD 23°C
Inorganic carbon	41.0%	39.3%
Organic carbon	0.9%	0.9%
Oxygen	42.5%	41.5%
Magnesium	3.0%	2.9%
Silicon	4.3%	4.2%
Sulfur	0.2%	0.2%
Calcium	8.7%	8.5%
Nitrogen	2.0%	2.0%
Phosphorus	1.0%	1.0%

4.3 PHOTOBIOREACTOR ANALYSIS

4.3.1 PHOTOBIOREACTOR DESIGN

Following the calculations from Tables 6, 7 and 8 for the dimensions of the PBRs, the PBRs were designed using AutoCAD. PBR and baffle wall thickness were assumed to be 6", whereas the PBR and baffle height were considered 3'4". Costs for building the PBRs included the foundation and construction costs, including the PBR walls and baffles. The cost also included the multiwall polycarbonate sheets for the PBRs to reduce the contamination and create a controlled condition. Engineering and delivery costs of the construction items were also included in the cost analysis for the PBR construction, and the quote was provided by Texas Aquastore Inc. (Sherman, TX). Table 20 contains the PBR construction cost breakdown for the 1.5 days HRT systems. The construction costs are for all the PBRs in the LED (*e.g.*, 24 PBRs) and sunlight (*e.g.*, 36 PBRs) systems. PBR construction costs for the 1.0- and 0.5-days HRT scenarios are included in the appendix section (Section B, Tables 1 and 2).

Table 21 includes the total cost of PBR setup for both the sunlight and LED system for all three scenarios. Figures 19 and 20 are the two-dimensional drawings of a PBR in the LED, and sunlight system, respectively. Taking the previous studies into consideration, the PBRs for this study was designed for both the sunlight and LED systems with different HRTs to compare the break-even points of the project and the freshwater production costs.

Table 20: PBR Cost Breakdown for the 1.5 Days HRT System

PBR Cost Breakdown		
Costs	LED System ($)	Sunlight System ($)
Foundation cost	2,019,200	1,924,000
Construction cost	1,961,000	1,852,000
Engineering	1,405,000	1,638,000
Delivery	70,261	81,900
Clear cover	150,000	116,000
Total	5,606,000	5,612,000

To treat 1.1 MGD brackish groundwater ROC, Gao et al. [118] suggested a 600’ × 200’ × 2’ photobioreactor for a brackish groundwater desalination facility. However, operating a photobioreactor of that size would be difficult. To build a photobioreactor of 600’ × 200’ for the sunlight system, a large greenhouse would be needed which could make the construction cost higher and impossible. Additionally, for the LED system, a photobioreactor of 600’ × 200’ would be impossible as the PBR was assumed to be installed in a warehouse. Construction of a 600’ × 200’ warehouse without internal columns would be a structurally impossible task. Moreover, biomass collection and cleaning system for the 600’ × 200’ size photobioreactor would be very difficult. For this reason, this study proposed having multiple PBRs to treat 1.0 MGD ROC in a brackish groundwater desalination facility.

Table 21: PBR Installation Cost in Sunlight and LED Systems

System	**Scenario**	**PBR installation cost ($)**
Sunlight	0.5 days HRT	1,931,000
	1.0 days HRT	3,546,000
	1.5 days HRT	5,612,000
LED	0.5 days HRT	1,929,000
	1.0 days HRT	3,857,000
	1.5 days HRT	5,606,000

(a)

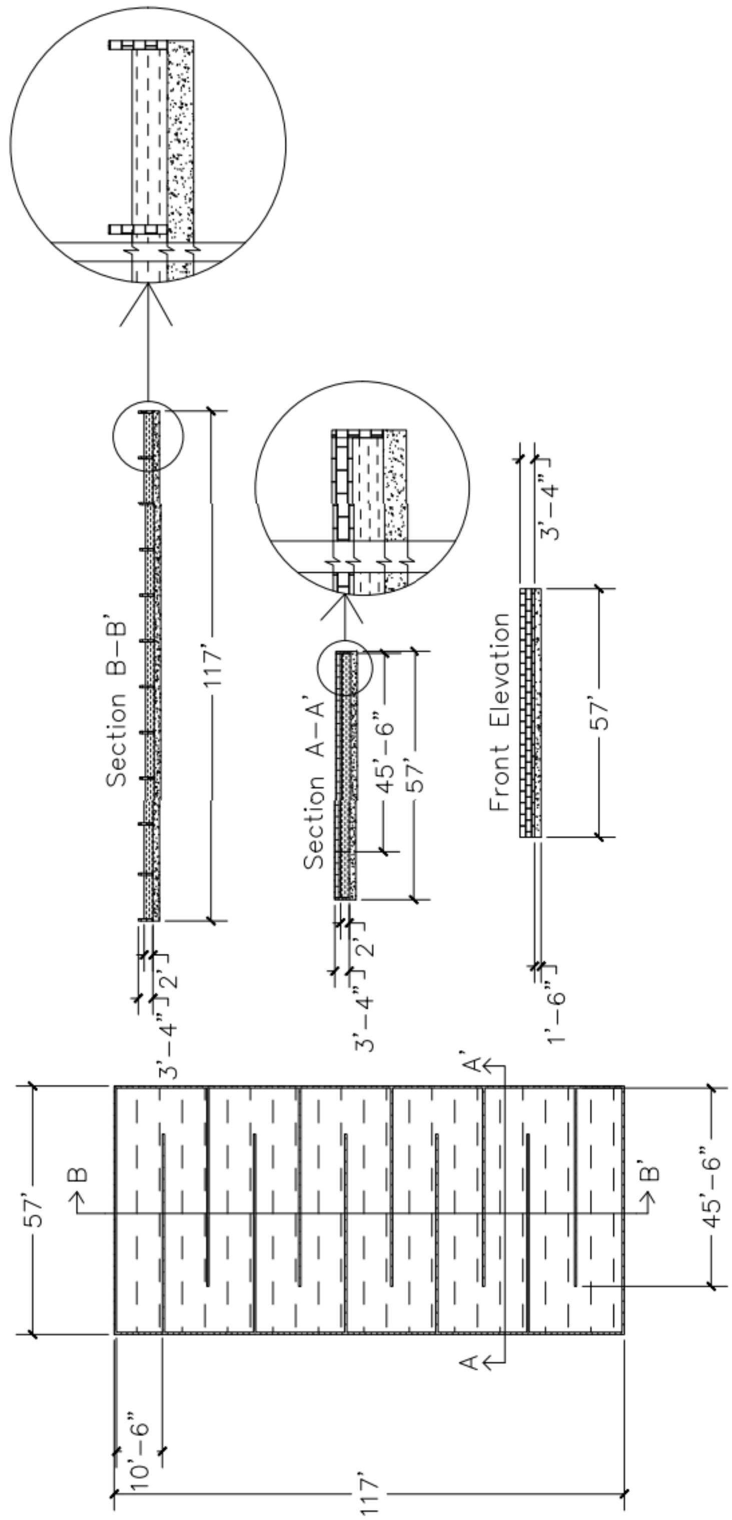


Figure 19: PBR Detail Drawing for the LED System

(b)

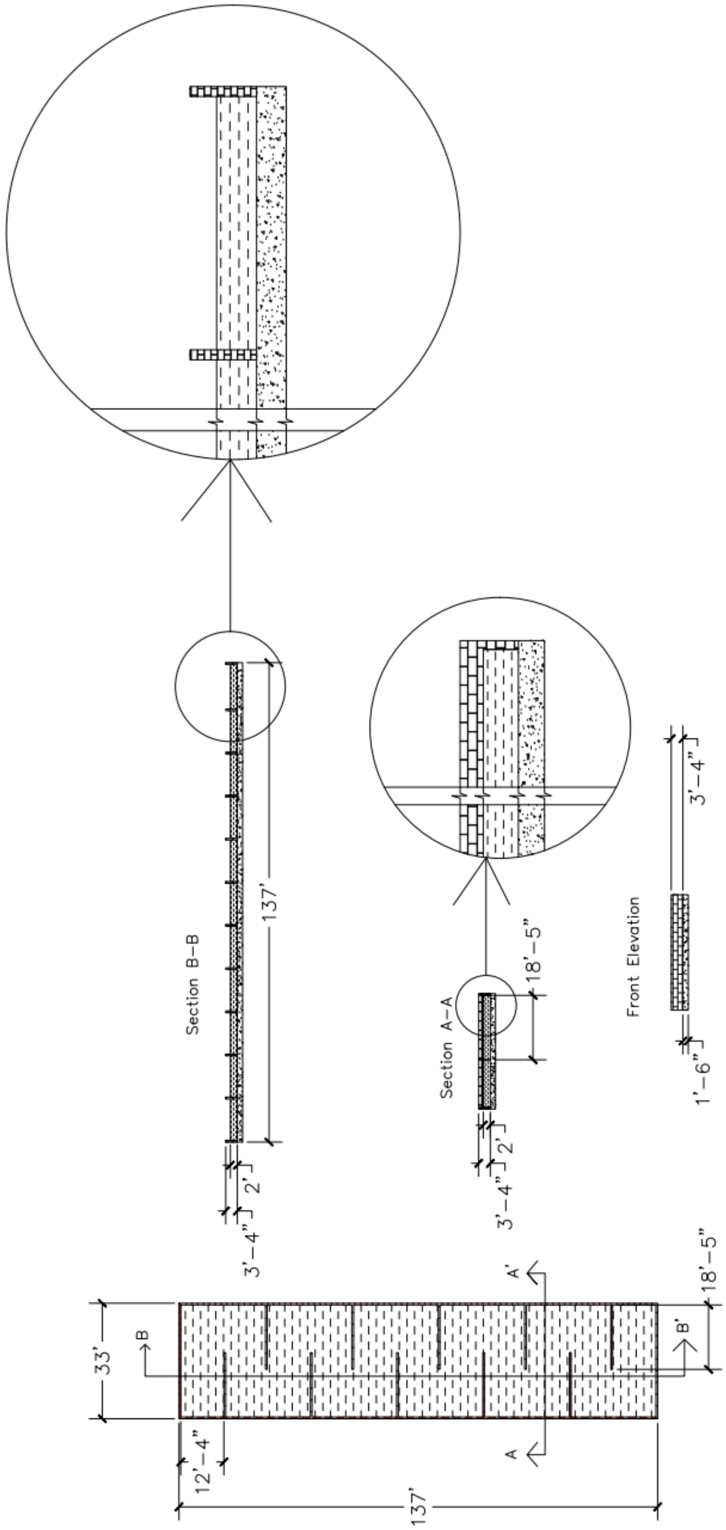


Figure 20: PBR Detail Drawing for the Sunlight System

4.3.2 SUNLIGHT SYSTEM DESIGN

The PBRs designed for the sunlight system would be built inside greenhouses for all the three scenarios: 1.5-, 1.0- and 0.5-days HRT. Figure 21 is the three-dimensional PBR drawing in the sunlight system designed using the Fusion 360 software.

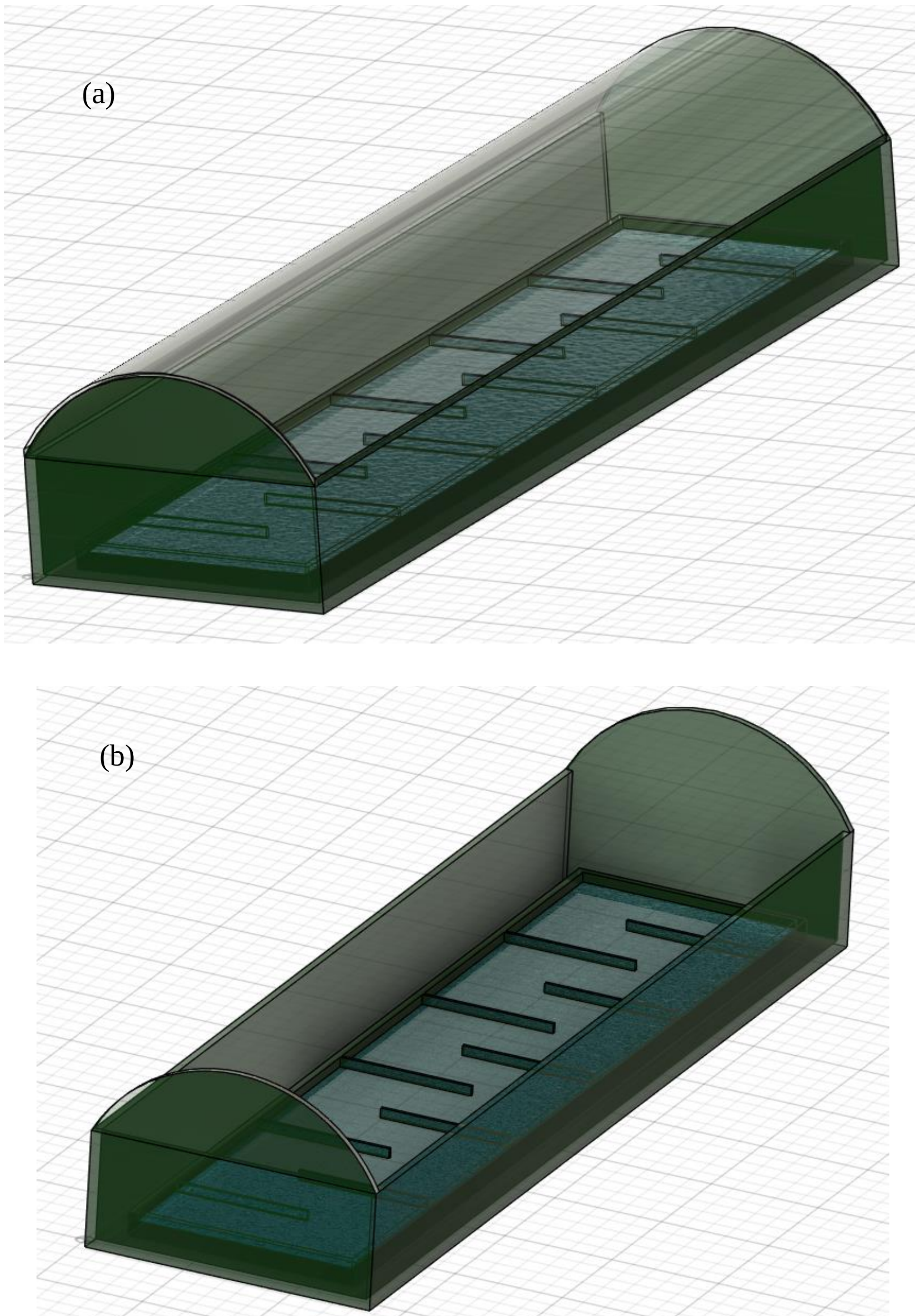


Figure 21: PBR in a Greenhouse (a) with Cover; (b) without Cover

The complete design would include an RO facility, water storage tanks, an electrical room, a control room, toilets, and a storage room. To make the sunlight system cost-effective, the RO facility was assumed to be situated in a vertical roof carport. Figure 22 shows a sample image of a 40’ × 40’ vertical roof carport. Pump layouts were designed, including the valves: T's and 90s. Figures 23, 24 and 25 presents the sunlight system layouts for 1.5-,1.0- and 0.5-days HRT, respectively.

Figure 22: 40’ × 40’ Vertical-Roof Carport [130]

4.3.3 LED SYSTEM DESIGN

The PBRs designed for the LED system were assumed to be built inside a warehouse for all the three scenarios: 1.5-, 1.0- and 0.5-days HRT. The complete design would include RO facility, water storage tanks, electrical room, control room, educational room, conference room, toilets, and storage room. Pump layouts were designed, including the valves’ T's and 90s. Figures 26, 27 and 28 include LED system layouts of 1.5-, 1.0-, and 0.5 days HRT, respectively.

4.3.4 HEATING VENTILATION AND AIR CONDITIONING AND EVAPORATIVE COOLER DESIGN

HVAC and evaporative cooler systems were designed for LED and sunlight system, respectively. Table 22 has the designed data for the HVAC system, and Table 23 has the designed data for the evaporative cooler system. The recommended HVAC system for the warehouse would be a roof type system. To supply the required refrigeration, 5 US metric tons of HVAC units were assumed to be installed in the warehouse. HVAC installation costs were the CAPEX, and the power requirement to run the HVAC system was the OPEX cost. Using the cost of one 5-tone HVAC system to be $7,000 [131], the total HVAC system installation cost was calculated in this study. During the fall and winter seasons, the warehouse system would not require HVAC because of moderate to cold weather, and the HVAC system would operate 6 months a year.

Table 22: HVAC Design Data for the LED System

Scenario	Tons of refrigerant required	HVAC installation cost
0.5 days HRT	1,433	$2,006,000
1.0 days HRT	2,056	$2,878,000
1.5 days HRT	2,605	$3,647,000

A ducted evaporative cooler with motor of 7,500 cfm (213 m^3/min) was used in this study, and the cost of one evaporative cooler would be $2,706 [132]. Using these numbers and calculating the air change required in cubic ft. per minute for the greenhouses, total number of evaporative coolers was estimated for each scenario listed in Table 23. Evaporative cooler installation cost was a part of the CAPEX and the power requirement to run the evaporative cooler was a part of OPEX of this study. During the fall and winter seasons, the sunlight system would not require the ventilation operation because of moderate to cold weather, and the evaporative cooler system would be operating 6 months a year. Complete calculation for the evaporative cooler design is provided in the appendix section (Section C, Table 3).

Table 23: Evaporative Cooler Design Data for the Sunlight System

Scenario	Number of evaporative coolers required	Evaporative cooler installation cost
0.5 days HRT	210	$548,000
1.0 days HRT	384	$960,000
1.5 days HRT	629	$1,560,000

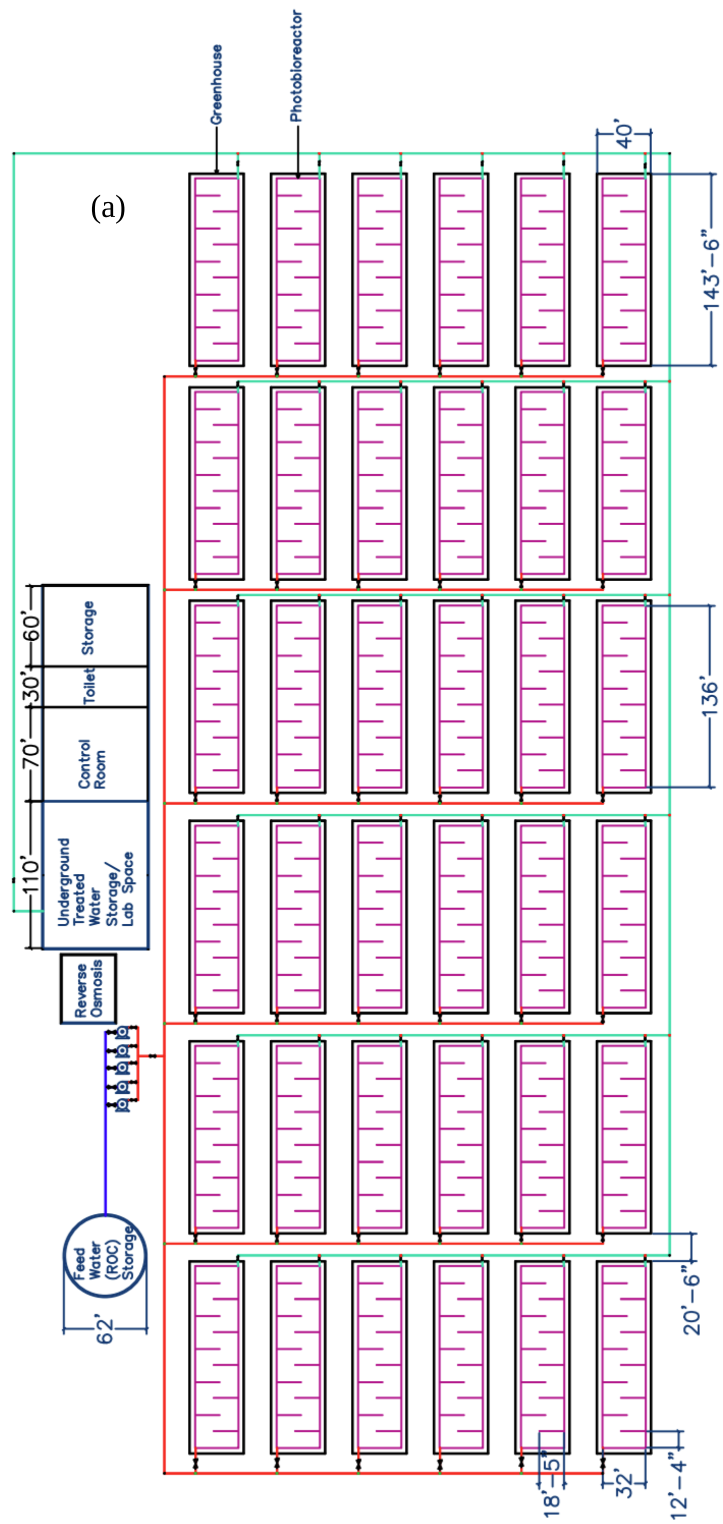


Figure 23: Sunlight System Layout of 1.5 Days HRT

(b)

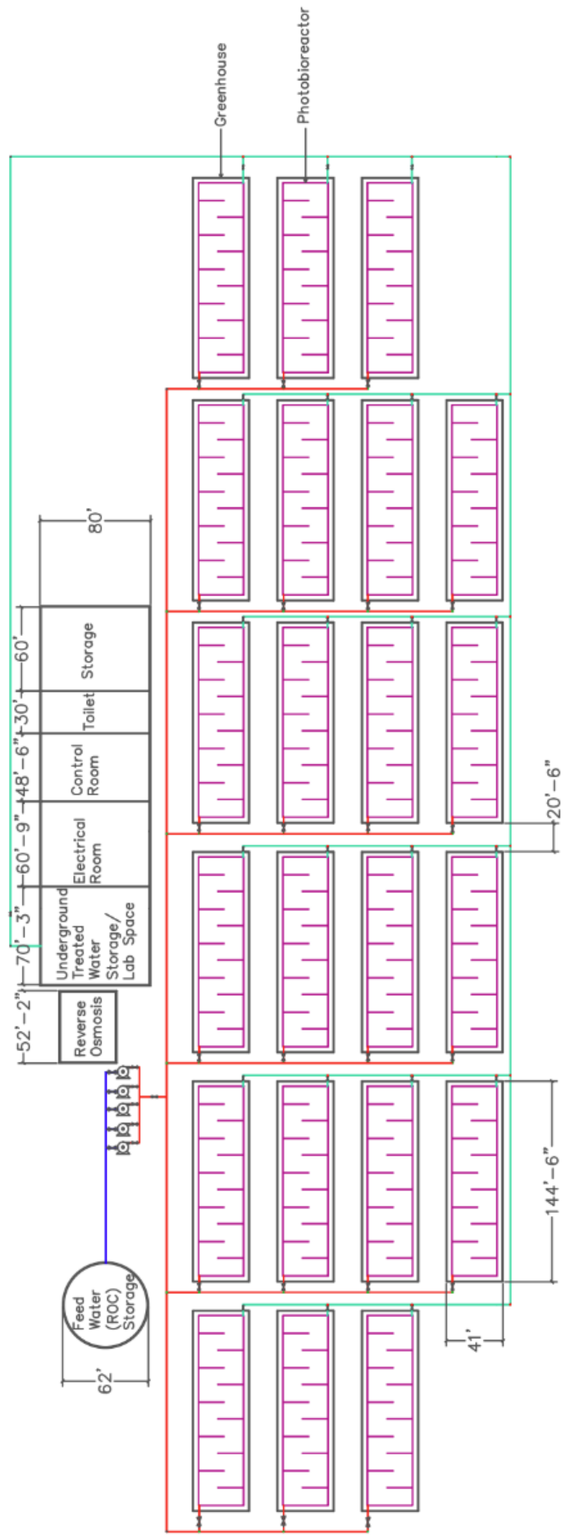


Figure 24: Sunlight System Layout of 1.0 Days HRT

(c)

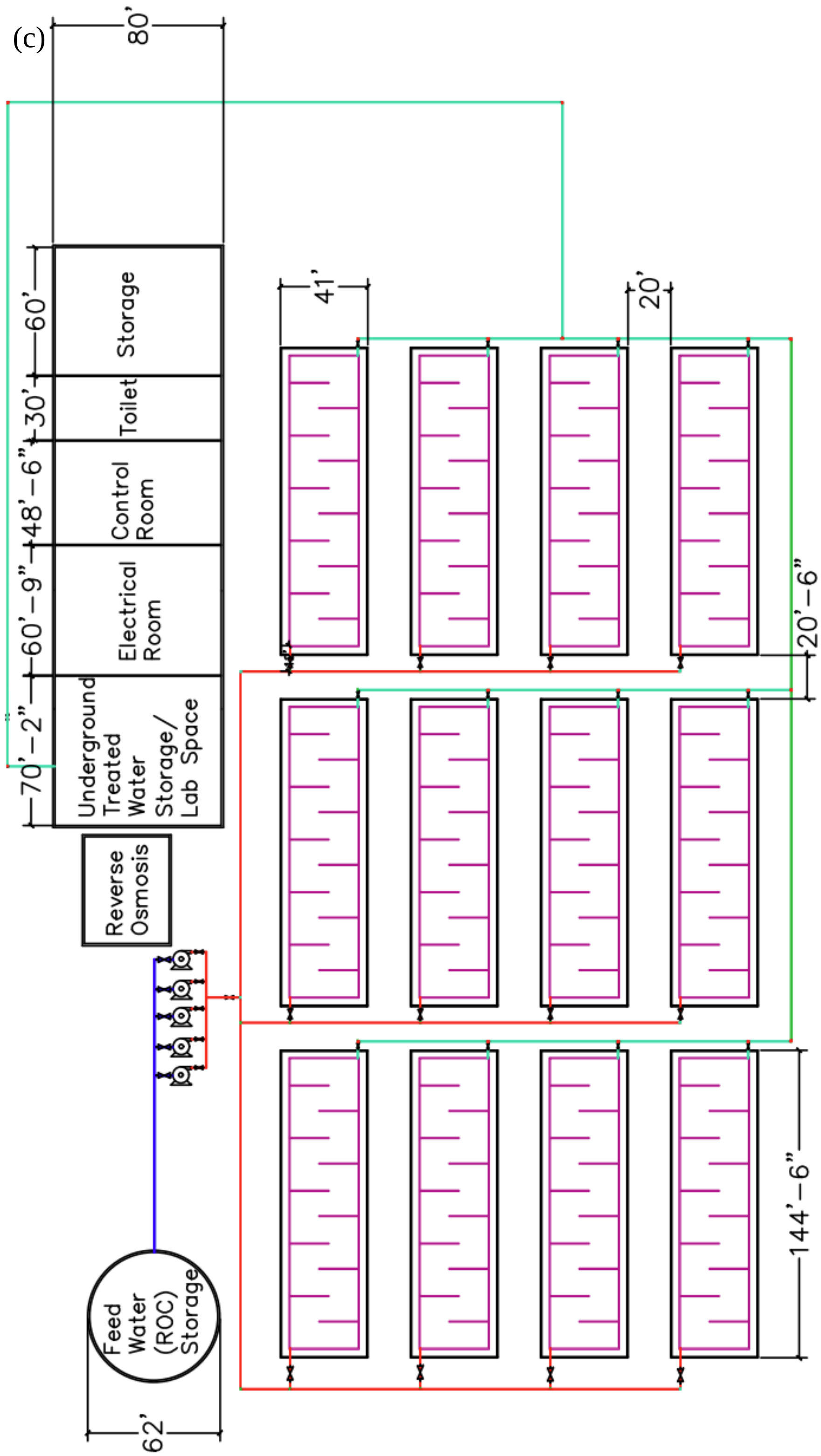


Figure 25: Sunlight System Layout of 0.5 Days HRT

(a)

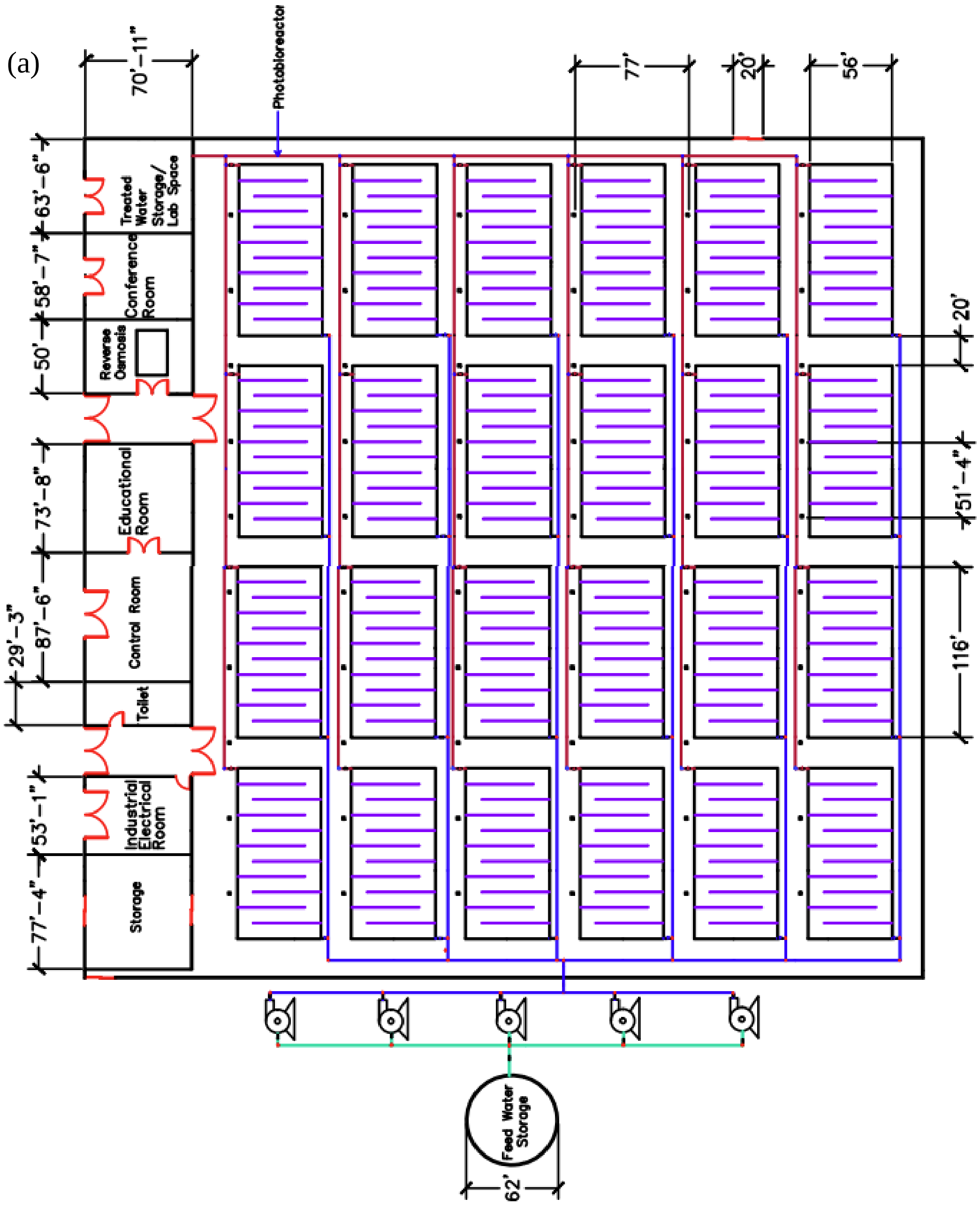


Figure 26: LED System Layout of 1.5 Days HRT

(b)

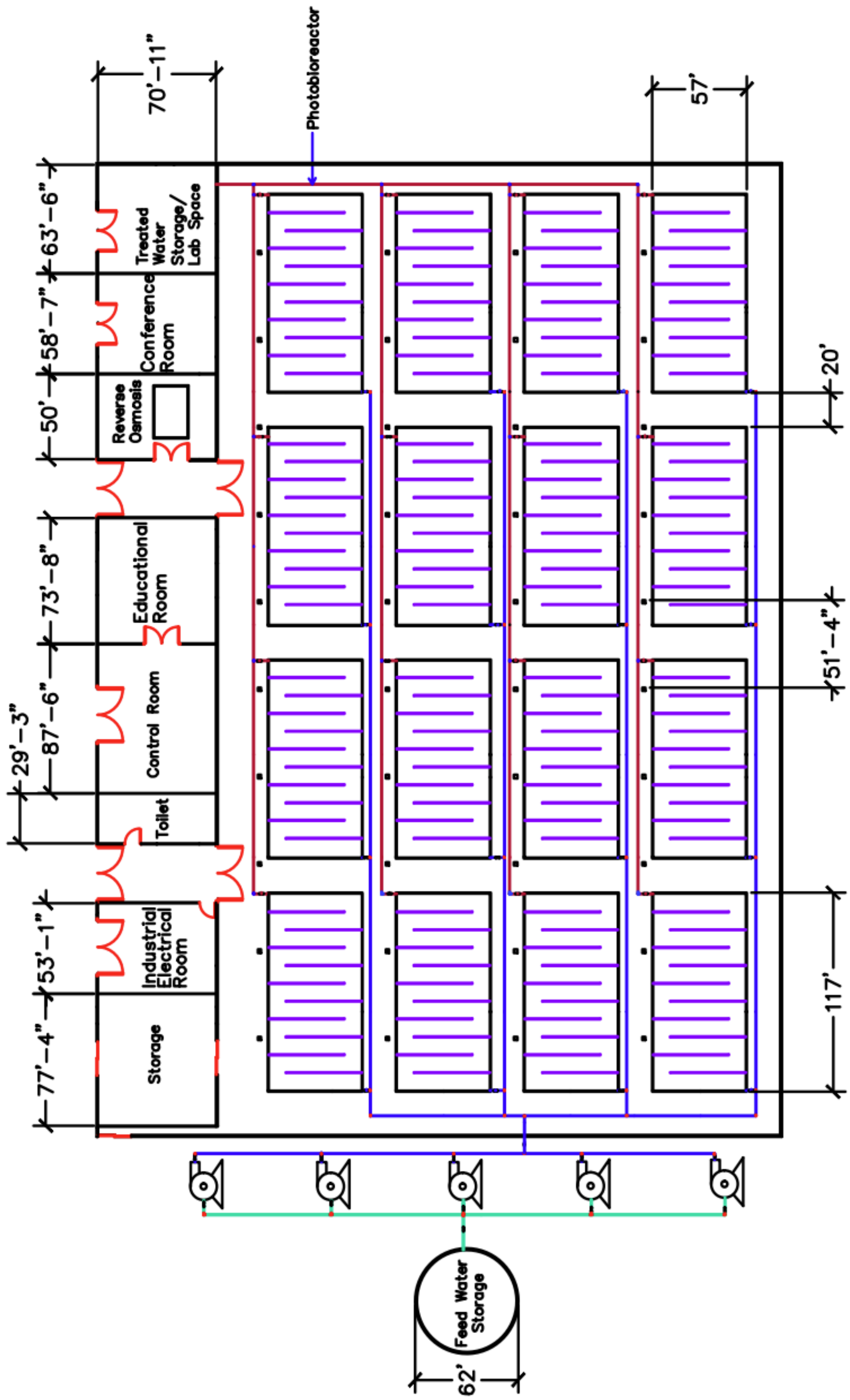


Figure 27: LED System Layout of 1.0 Days HRT

(c)

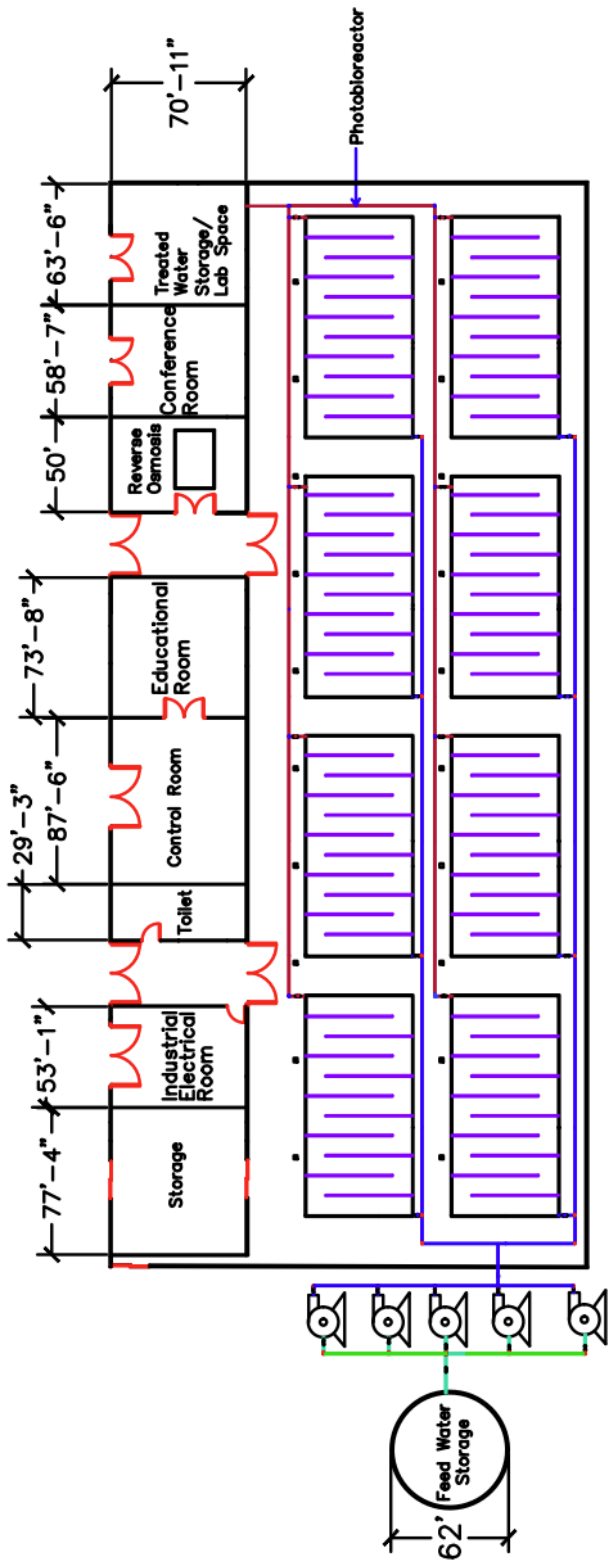


Figure 28: LED System Layout of 0.5 Days HRT

4.3.5 LIGHTING DESIGN

The types of lighting installation discussed in this section are LED lighting for the PBRs and ambient lighting for the warehouse and greenhouses. From the laboratory scale experiments by Han Gao, the diatoms would behave almost the same under intermittent and continuous light. To design a cost-effective system, intermittent lighting was considered in this cost analysis study. For the intermittent lighting system, the lighting was assumed to be in turned on for 12 hours a day. In the bench-scale experiments of brackish groundwater ROC by brackish water diatom, 2700 K, 800 Lm, 10 W by GE Lighting was used [118]. This study used 200-W full spectrum LED grow light for medical plants Chieko – 2000 [139] as lighting for the PBRs. The installation cost of the discussed 200-W LED grow light would be $11.79 per square foot. Table 24 has the LED installation cost for the LED system. Complete lighting calculations for all the scenarios are presented in the appendix section (Section D, Tables 4, 5 and 6).

Table 24: LED Lighting Installation Cost for the PBRs

Scenario	**Total LED installation cost**
0.5 days HRT	$626,000
1.0 days HRT	$1,253,000
1.5 days HRT	$1,821,000

The remaining two lightings are the ambiance illumination required for each scenario for the greenhouses and the warehouse. 25-W square natural white non-dimmable LED recessed ceiling panel down light bulb slim lamp [133] would be used as the lighting for this study. Table 25 has the lighting requirements for the systems including all three scenarios. To calculate the OPEX regarding greenhouse and warehouse illumination, the lights would be turned on for 6 hours a day.

Table 25: Ambience Lighting for the Greenhouse and Warehouse

System	**Scenario**	**Installation cost**
Sunlight	0.5 days HRT	$14,000
	1.0 days HRT	$26,000
	1.5 days HRT	$43,000
LED	0.5 days HRT	$53,000
	1.0 days HRT	$87,000
	1.5 days HRT	$103,000

4.3.6 PUMP DESIGN

Pumps were designed in this study to supply the 1.0 MGD flow to the PBRs for both sunlight and LED systems. There would be a total of 5 pumps for the supply purpose from which 4 pumps would be working and the other would be the backup pump for all the scenarios discussed. Flow rate for each pump was calculated to be 170 gallons/minute (660 liter/minute), and polyvinyl chloride pipes were assumed for the supply purpose. In this study, the minimum water velocity was considered 5 ft/sec (1.524 m/sec) to avoid settlement accumulation in the pipes. The pipe dimension for the supply from the storage tank to the pumps, and from the pumps to the PBRs was assumed to be 6 and 4 inches, respectively. Discharge pipes from the PBRs to the underground treated water storage were of the same dimension as the supply pipes from the pumps to the PBRs. Primary ROC was assumed to be kept in a storage tank of 30 feet height which would provide an elevation head of 20 feet. The total head loss for all the scenarios was calculated using this elevation head. The total head loss from the valves and fittings was accounted for while calculating the total head. Assuming the pump efficiency to be 60%, the pumps were designed using the total head loss data. 5 HP centrifugal pumps were assumed to be installed, costing $2,650 each [134]. Table 26 includes the information of the pump power requirements for all the discussed scenarios of this study.

Table 26: Pump Power Requirement for All the Discussed Scenarios

System	Scenario	Single pump power (kW)
Sunlight	0.5 days HRT	1.00
	1.0 days HRT	1.96
	1.5 days HRT	2.26
LED	0.5 days HRT	1.50
	1.0 days HRT	2.76
	1.5 days HRT	3.30

4.4 GREENHOUSE AND WAREHOUSE DESIGN

Greenhouses for the sunlight system and warehouses for the LED system were designed in this study. Commercial greenhouses were assumed to be bought and installed at the brackish groundwater desalination facility where the PBRs would be constructed.

Greenhouse costs would include the delivery cost and engineering cost. Cost for the greenhouse system would consist of the foundation cost, construction cost, window and door cost, toilet set-up cost, control room set-up cost, laboratory set-up cost, storage room cost, industrial electrical room cost, and office room cost. Cost for the warehouse system would include engineering cost, delivery cost, window and door costs, foundation cost, construction cost, toilet set-up cost, control room set-up cost, laboratory set-up cost, educational room cost, storage room cost, industrial electrical room cost, conference room cost and office room cost. Table 27 presents information on constructing the greenhouse, and warehouse systems for 1.5 days HRT scenario. Costs for 1.0- and 0.5-days HRT are presented in the appendix section (Section E, Tables 7 and 8).

Table 27: Greenhouse and Warehouse Costs for the Sunlight and LED Systems of 1.5 Days HRT, Respectively

Cost Item	Sunlight System ($)	LED System ($)
Engineering	198,000	3,111,000
Greenhouse	2,500,000	N/A
Foundation	174,000	2,735,000
Window and door	30,000	311,000
Toilet	14,000	14,000
Control room	30,000	30,000
Laboratory	200,000	200,000
Storage room	10,000	10,000
Industrial electrical room	100,000	100,000
Educational room	N/A	100,000
Conference room	N/A	50,000
Office room	50,000	50,000

4.5 RO FACILITY

Using the IMS Design by Hydranautics, a secondary RO facility was designed in this study. The modified water quality data as listed in Table 5, Section 3.3.4.3 for a photobiologically treated ROC were entered to the IMS Design's water quality analysis section. Feed water pH after the photobiological treatment was 9.0 which was assumed to be lowered to 8.3 by pretreatment with sulfuric acid dosage as shown in Figure 11 (Section 3.3.4.1). By evaluating different membranes, CPA6 MAX (high rejection

BWRO) was selected as the optimal type of membrane for this study to provide maximum freshwater recovery while satisfying all the design criteria (*e.g.*, Langelier saturation index, feed water flux, calcium carbonate precipitation potential). The CPA6 MAX has nominal production of 8,000 gallons/day with a rejection rate of 99.8%. Membrane size is 8 inches × 40 inches with spacer of 28 mil, and 225 psi test pressure. It was found that 2-stage RO could give the highest permeate recovery. There were 7 membranes per vessel, and the total number of vessels was 14 and 9 for stage 1 and stage 2, respectively. Turbochargers with 14.50 and 60.27 exhaust psi were used as energy recovery devices for stage 1 and stage 2, respectively.

Table 28: Feed, Permeate and Concentrate Water Quality of the Secondary RO from IMS Design

Parameters (mg/L)	Raw water	Feed water	Permeate	Stage 1 ROC	Stage 2 ROC
Hardness (as $CaCO_3$)	615.50	615.50	0.13	1,089.90	2,062.10
Ca	123.25	123.25	0.03	218.30	412.90
Mg	75.00	75.00	0.02	132.80	251.30
Na	3,485.00	3,485.00	39.80	6,149.30	11,584.10
K	55.04	55.04	0.71	97.10	182.80
Ba	0.04	0.04	0.00	0.10	0.10
Sr	13.38	13.38	0.00	23.70	44.80
H	0.00	0.00	0.00	0.00	0.00
CO_3	95.02	21.40	0.01	74.50	274.20
HCO_3	550.00	620.71	15.23	1,062.80	1,849.90
SO_4	4,882.00	4,943.26	14.16	8,746.20	16,530.50
Cl	2,033.00	2,033.00	23.21	3,587.20	6,757.70
F	1.62	1.62	0.04	2.90	5.40
NO_3	585.00	585.00	34.06	1,016.70	1,880.30
PO_4	0.15	0.15	0.00	0.30	0.50
OH	0.00	0.03	0.00	0.10	0.10
SiO_2	53.00	53.00	0.42	93.60	176.60
CO_2	0.64	3.62	3.62	3.62	3.62
NH_3	0.00	0.00	0.00	0.00	0.00
TDS	11,951.51	12,009.86	127.68	21,205.32	39,952.04
pH	9.00	8.30	6.81	8.51	8.72

The design parameters are shown in Figure 29, and the calculation results are shown in Figure 30. Figure 31 shows the flow diagram of the designed secondary RO. Table 28 has the feed, permeate, and concentrate water quality of the secondary RO facility. The designed secondary RO facility would operate at 70% freshwater recovery, where the feed water would be 1.0 MGD. By operating at 70% freshwater recovery, the secondary RO would generate 0.70 and 0.30 MGD of permeate and concentrate, respectively. After discussing with several vendors, the budget for setting up the secondary RO facility was estimated to be $1.5M. This budgetary cost would include the cartridge filters; high pressure RO feed pumps; epoxy-coating, fiberglass RO support frame; pressure vessels; membrane elements; skid piping and valving; RO instrumentation and controls; cleaning system and installation supervision. This would not include the building or roofing costs, the raw feed facilities, interconnecting piping, main supervisory control, and data acquisition (SCADA) system, pretreatment chemical systems, or finished water storage or pumping. Services that would be provided by the vendor within this budget would include preparation of engineering submittals, providing OPEX manuals, installation supervision and operator training. The chemical pretreatment of the feed water will be discussed further in the chemical requirement section 4.6.2.

The concentrate from the RO would be disposed of via a deep well injection system. The deep well injection pump was designed with a 75-kW power, and the cost of setting up the deep well injection system is detailed in Table 12. With the proposed system, there would be a disposal of 0.3 MGD secondary ROC; without the system, the disposal would be 1.0 MGD Primary ROC which would require a 180-kW pump. A comparison of the costs of both the proposed and existing system is also shown in Table 29.

Cost of setting up the deep well injection are $2.6M and $0.8 M for the existing and proposed system, respectively which accounts for a 67% reduction in the CAPEX of deep well injection system installation. In this study, the cost of setting up a deep well injection system was not included in the CAPEX. The proposed PBR-secondary RO facility was assumed to be an addition to an existing brackish groundwater desalination facility which would already have a deep well injection system operating at 1.0 MGD.

Similarly, the operating cost of the deep well injection for 0.3 MGD ROC was not included in the OPEX as well, whereas the cost of operating a 0.3 MGD ROC deep well injection system was considered as a revenue in the cost analysis section as this system would reduce the concentrate disposal cost of the existing facility. The deep well injection cost was not accounted while performing the cash-flow analysis, NPV analysis and break-even point analysis.

Table 29: Deep Well Injection Installation Costs with Comparison Between the Existing and Proposed System

System	Specifications	Cost ($)
Existing system (1.0 MGD concentrate disposal)	Pump cost	50,000
	Injection well cost	2,000,000
	Monitoring well cost	200,000
	Engineering cost	225,000
	Operational cost/ year	160,852
Proposed system (0.3 MGD concentrate disposal)	Pump cost	16,000
	Injection well cost	600,000
	Monitoring well cost	100,000
	Engineering cost	71,600
	Operational cost/ year	80,425

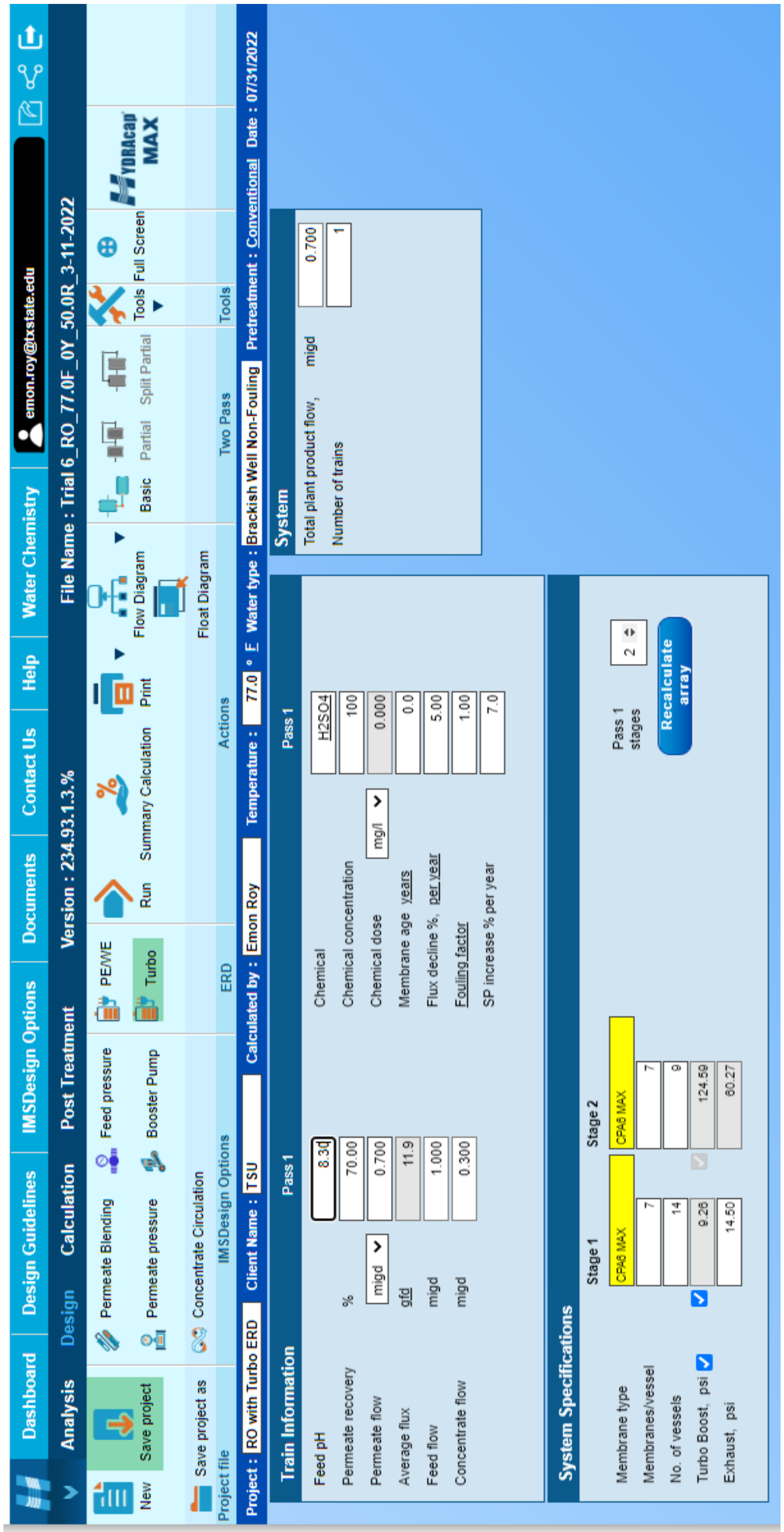


Figure 29: Design Parameters for RO by IMS Design

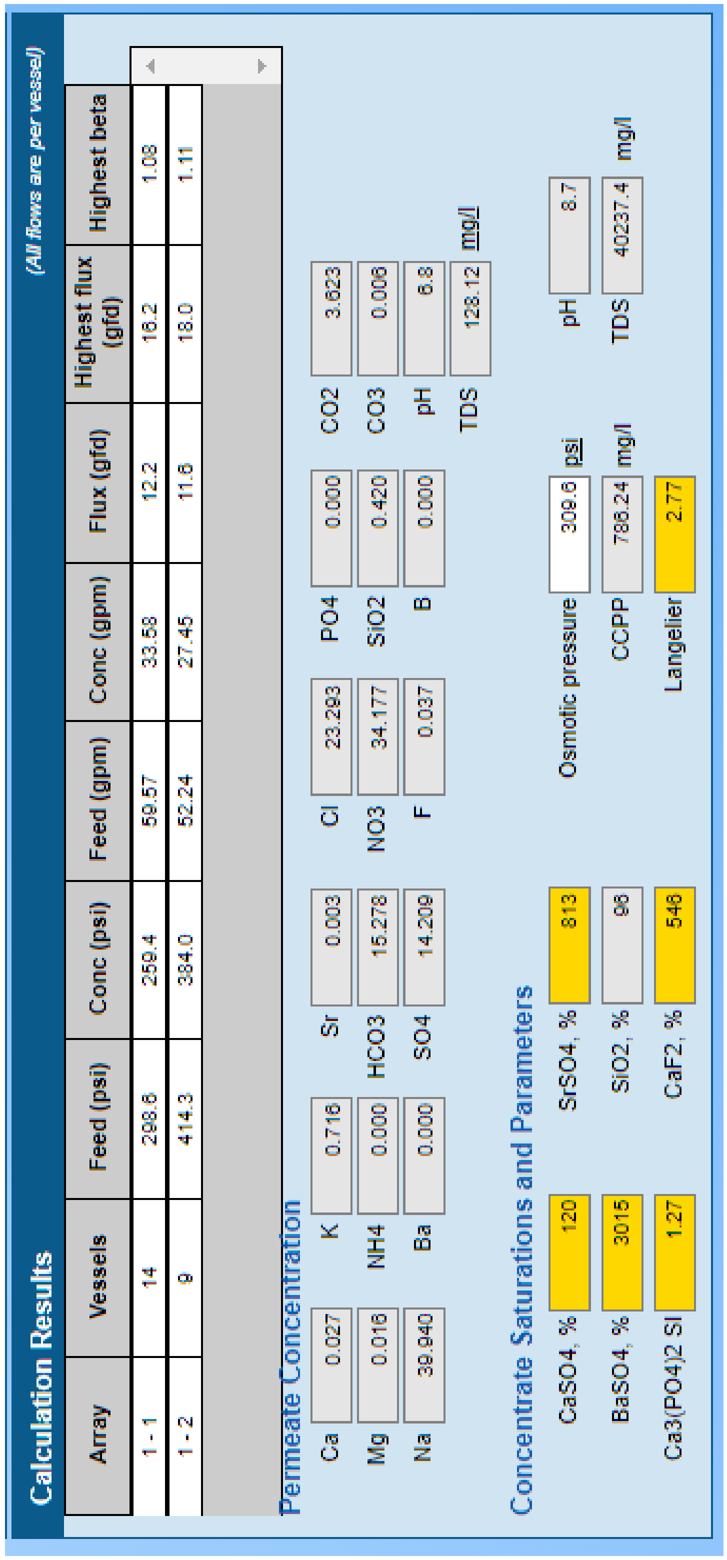


Figure 30: Calculation Results of the Designed System by IMS Design

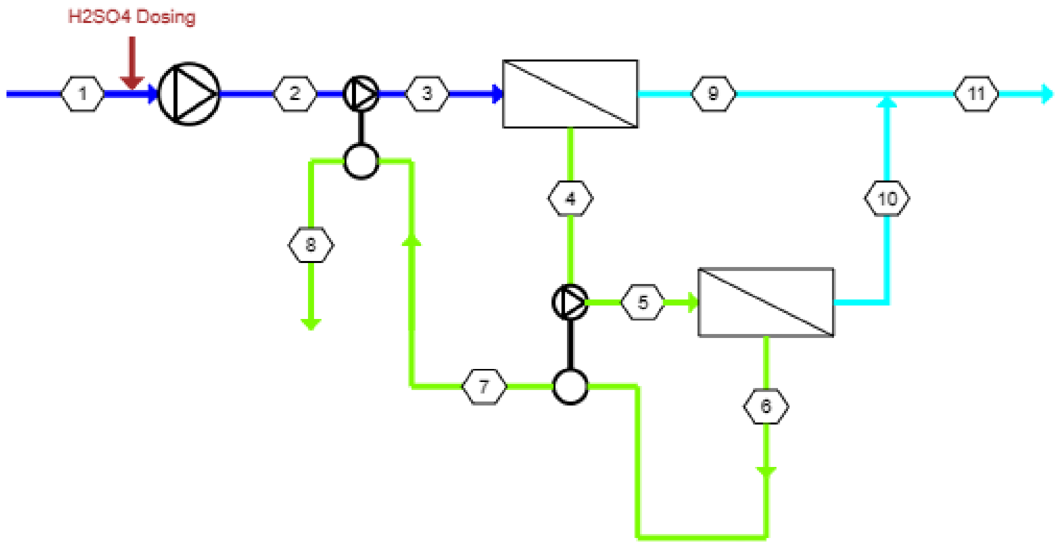


Figure 31: Flow Diagram of the Designed RO system by IMS Design

4.6 POWER CALCULATION

The significant electricity for the LED system would be from the PBR lighting for the diatoms and the electricity to control the temperature using the HVAC for the warehouse. The major electricity cost for the sunlight system would be the evaporative coolers' power requirement and the PBR's power requirement. Secondary RO pumps also accounted for a high cost of electricity. Other power sources would be the PBR pumps, greenhouse lighting, warehouse lighting and deep well injection system powers. The electricity cost/kWh was assumed to be $0.1224 for this study to estimate the power cost calculation. Table 30 includes data of the power requirement in watt for both the sunlight and LED systems for all three scenarios. Secondary RO and deep well injection power would be same for all the systems with all three scenarios and the power requirements are 131,000 and 75,000 watts, respectively. The cost of operating the deep well injection system would be $80,000 per year.

Table 30: Power Requirement for the Sunlight and LED System

System	Scenario	Specification	Power (watts/day)	Operating cost/year ($)
Sunlight	0.5 days HRT	Evaporative cooler	117,390	37,000
		Greenhouse lighting	14,256	4,000
	1.0 days HRT	Evaporative cooler	214,656	67,000
		Greenhouse lighting	26,136	7,000
	1.5 days HRT	Evaporative cooler	351,611	101,000
		Greenhouse lighting	42,768	11,500
LED	0.5 days HRT	LED lighting	1,182,050	633,500
		HVAC	1,717,600	460,600
		Warehouse lighting	48,540	48,500
	1.0 days HRT	LED lighting	2,170,678	1,164,000
		HVAC	2,467,200	661,500
		Warehouse lighting	79,536	79,500
	1.5 days HRT	LED lighting	3,434,400	1,841,500
		HVAC	3,126,000	838,000
		Warehouse lighting	94,500	103,000

4.7 CHEMICAL REQUIREMENTS

In this proposed scheme, chemicals would be required for both the PBRs and the secondary RO facility. For the PBRs, nutrients might be required for the diatoms. While for the secondary RO facility, 93% sulfuric acid (H_2SO_4) solution, antiscalant, low pH and high pH CIP solutions, bleach solution and ammonium sulfate solution would be required. Feed pH would need to be lowered using the acid solution, while antiscalant would be required to prevent scaling in the RO membranes. Cleaning of the membranes would be performed using the low and high pH CIP solutions once in a month. Bleach and ammonium sulfate solution would be added in the photobiologically treated ROC to reduce the biological fouling in the RO membranes. Dosage of the bleach, ammonium sulfate, and nutrients were calculated from the laboratory experiments while the dosage of the acid solution was the output from the IMS Design. Nutrient requirements for the photobiological treatment were also discussed in the previous studies [135] as 2 to 4 mg/L of PO_4^{3-} of orthophosphate and 12 mg/L of nitrate-N. Complete calculation of the chemical requirement calculations can be found in the appendix section (Section F, Tables 9, 10, 11, 12, 13 and 14). To achieve a 3.11 mg/L of monochloramine, as presented in Table 31, chlorine and ammonia dosages would be 4 and 0.75 mg/L, respectively. Table 31 shows the experimental results of the chloramine dosage experiment.

Table 31: Chloramine Dosage Determination Experiment

Chlorine dosage	**Monochloramine (mg/L as Cl_2)**	**Free ammonia (mg/L as NH_3-N)**	**Total chlorine (mg/L as Cl_2)**	**Free Chlorine (mg/L as Cl_2)**
1 mg/L	0.73	>0.5	0.58	0.58
2 mg/L	1.48	>0.5	1.26	1.20
3 mg/L	1.96	>0.5	1.82	1.40
4 mg/L	3.11	0.38	3.10	1.00
5 mg/L	3.1	0.33	3.05	1.00
6 mg/L	2.12	0.05	5.00	2.14

The CIP solutions and antiscalant would be added according to the manufacturer's recommendations. AWC C-227 (high pH membrane cleaning powder) and AWC C-234 (low pH membrane cleaning powder) would be used to prepare CIP solutions. AWC A-102 Ultra would be used as the antiscalant for this study. Tanks and secondary containment sizes were also designed for the chemicals. Table 32 includes the designed chemical dosages and costs. In this study, the size of the secondary containment areas was assumed to be the same as the respective tank sizes.

Table 32: Estimated Chemical Dosages and Costs

Chemicals	**Dosages**	**Costs of chemicals ($/year)**	**Tank size (gal)**
93% H_2SO_4	62.5 mg/L	30,000	7,500
Antiscalant	3 mg/L	24,000	300
Low pH CIP	17 lb./100 gal	30,000	3,000
High pH CIP	17 lb./100 gal	40,000	3,000
Bleach	4 mg/L	45,000	9,000
$(NH_4)_2SO_4$	0.75 mg/L	10,000	1,000
Nutrient	15.7 mL/100 gal	100,000	3,000

4.8 LABOR COSTS

In this study, labor cost was accounted for labor for running the PBR system. The secondary RO operation was assumed to be performed by the operators of the primary

RO facility. To operate the PBR system, as well as to harvest biomass and clean the PBR, there would be 5 operators working 10 hours a day. The operators would also switch the flow to the back-up PBR when one of the working PBRs would go through biomass harvesting. Fringe benefits for the operators were also calculated to estimate the total labor cost. The labor cost would be the same for the sunlight and LED system. Though the number of PBRs would be lower for the shortened HRT scenarios, the operators would collect biomass more often than in the higher HRT scenario (*i. e*., 1.5 days HRT). For this reason, all three HRT scenarios (1.5-, 1.0- and 0.5-days HRT) would have the same labor cost. Table 33 presents the labor cost estimation to operate the PBRs.

Table 33: Labor Cost Estimation to Operate the PBRs

Parameters	Value
No. of operators/ day	5
Working hour/ operator/ day	10
Hourly rate/ operator ($)	20
Wage/ day ($)	1,000
Wage/ year ($)	365,000
Fringe benefit/ year ($)	91,250
Total labor cost/ year ($)	456,250

4.9 INSTRUMENTATION AND TANK COSTS

For real-time water quality monitoring of the proposed PBR-secondary RO facility, there would be a silica meter, conductivity meter, turbidity meter, pH and conductivity meter, flow meter, pressure gauge, and supervisory control and data acquisition (SCADA) system. Costs for the instrumentation would be the same for the sunlight and LED system and all three HRT scenarios (1.5-, 1.0- and 0.5-days HRT). Table 34 presents the instrumentation cost estimation for the proposed PBR system.

Chemical storage tanks were designed after discussing with vendors, including both the tank supply and delivery costs. Tanks were designed to store sulfuric acid, antiscalant, low and high-pH CIP solutions, bleach and ammonium sulfate. Table 35 presents the individual tank sizes along with their costs. Tank costs would also include the costs of parts (e.g., fill line, suction line, reverse level, and vent) and delivery costs.

Table 34: Instrumentation Costs for Real-Time Monitoring of the PBR-Secondary RO Water Quality

Instrument name	Costs ($)
Conductivity and pH meter	50,000
Turbidity meter	50,000
Flow meter	20,000
Pressure gauge	10,000
SCADA system	12,000
Silica meter	50,000

Table 35: Tank Costs for Chemical Storage for the PBR-Secondary RO Facility

Name of chemical	Tank size (gallon)	Tank costs ($)
93% H_2SO_4 solution	7,500	55,000
Antiscalant	300	570
Low pH CIP	3,000	2,800
High pH CIP	3,000	2,800
Bleach	9,000	60,000
$(NH_4)_2SO_4$	9,000	60,000
Nutrient	3,000	2,800

4.10 LIFECYCLE COST ANALYSIS

4.10.1 REVENUE FROM BIORESOURCES, FRESHWATER, AND DEEP WELL INJECTION COST REDUCTION

The production rates of valuable bioresources (*e.g.*, silica, calcite, organics) from the 100-mL bench-scale experiments (Figure 17) were extrapolated to estimate the revenue from the proposed 1.0 MGD PBR-secondary RO facility. Biogas could be produced from the organics present in the biomass, which would be used to generate electricity and partially offset the power required for the secondary RO. The amount of biogas that could be extracted from the organic waste would depend on the waste itself and the design of the digester system. Some digesters can yield as much as 28,250 cubic feet of biogas per ton of biomass [136]. Assuming a digester to yield 14,125 cubic feet of biogas per ton of biomass, the biogas production was calculated in this study. The cost of setting up the anaerobic digestor would be around $1.2M [43], and this cost was used in

CAPEX calculation for both sunlight and LED systems. Table 36 presents the information on the secondary RO electricity requirement cost offset by the electricity generation from biogas. The OPEX analysis for the proposed scenarios considered the following in electricity cost calculation for secondary RO.

As a rule of thumb, to discuss profit margin, 5% is a low margin, 10% is a good margin, and 20% is a high margin [137]. Using a 15% profit margin from the sales of silica and calcite and a 100% profit margin for the freshwater sales, the total profit from the proposed facility was estimated. For the freshwater sales, all the produced permeate from the secondary RO would be blended with the primary RO permeate, and assuming no waste here, a 100% profit margin was used for the revenue calculation. Table 37 presents the annual production, annual sales and revenue from the proposed PBR-secondary RO facility, and these revenues apply to both LED and sunlight systems.

Table 36: Secondary RO Electricity Cost Reduction Through Biogas Generation

Parameters	**Value**
RO power requirement (kWh/year)	1,150,000
Electricity from biogas (kWh/year)	270,000
Remaining RO power (kWh/year)	878,000
Previous cost for RO power ($)	140,000
Cost after utilizing biogas ($)	107,000
Percent cost provided by biogas (%)	23.5

Another source of revenue for this study would be from the deep well injection cost reduction as discussed in Section 4.5. From the power calculation of Section 4.6, it was assumed that the deep well injection would cost $80,000 to dispose 0.3 MGD ROC, whereas the OPEX of the existing system with 1.0 MGD ROC disposal would cost $160,000. Assuming $80,000 yearly savings from the existing facility, the deep well injection cost reduction was included in the total revenue.

By adding all four revenues from the proposed PBR-secondary RO facility the total revenue per year would be $1,111,000 and this revenue was used in the LCCA for the cash flow analysis, NPV analysis and break-even point analysis. Complete calculation of the bioresources revenue analysis can be found the appendix section (Section G, Table 15, 16 and 17).

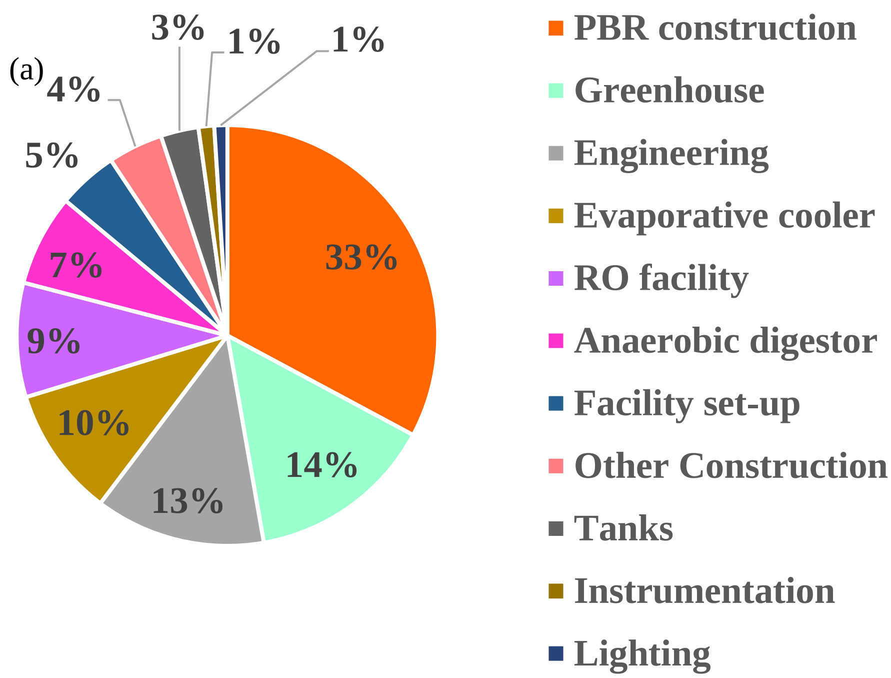
Table 37: Revenue from Bioresources, Freshwater, and Cost Saving from Deep Well Injection of the PBR-Secondary RO Facility

Resource	**Annual production**	**Annual sales ($)**	**Revenue after applying profit margin ($)**
Silica	70 metric tons/year	2,830,000	424,000
Calcite	94 metric tons/year	467,000	70,000
Freshwater	256 million gallons/year	536,300	536,300
Deep well injection cost reduction			80,000
Total revenue			1,111,000

4.10.2 CAPITAL AND OPERATIONAL EXPENDITURES OF THE SUNLIGHT SYSTEM

All the listed items in the previous sections were used for the cost analysis of the proposed PBR-secondary RO facility. CAPEX and OPEX of the sunlight system for all three scenarios are discussed this section. The CAPEX and OPEX percent breakdown for 1.5-, 1.0- and 0.5-days HRT scenarios of the sunlight system are shown in Figures 32, 33 and 34, respectively.

From the CAPEX breakdown, it is clear that PBR construction cost accounts for a significant part of the total CAPEX. The cost of the greenhouse is another major component of the CAPEX, however, this greenhouse and PBR construction costs could be reduced by shortening the HRTs which is visible from the CAPEX breakdown of the 1.0 and 0.5 days HRT (Figure 33a and Figure 34a). Greenhouse cost for the 1.5, 1.0 and 0.5 days HRT scenarios are 14%, 13% and 9%, respectively of the total CAPEX. The cost of setting up the RO facility is same for all the scenarios as all three scenarios were expected to be working at a 70% recovery rate. The engineering cost generally ranges between 5% and 15% of the overall CAPEX, however, for this study, 10% engineering cost was assumed for the cost analysis [138].



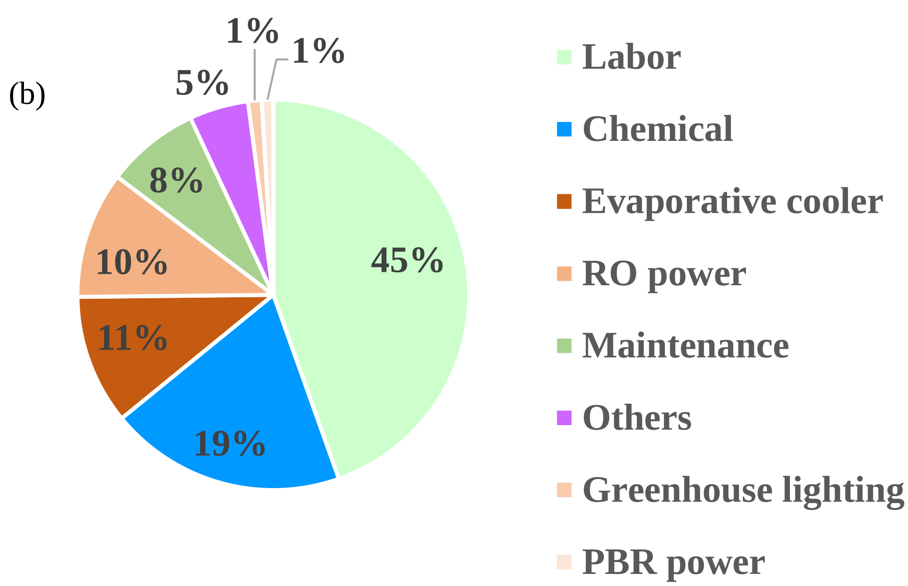


Figure 32: Sunlight System 1.5 Days HRT Scenario (a) CAPEX Breakdown (Total Cost: $17.1M), (b) OPEX Breakdown (Total Annual Cost: $1.0M)

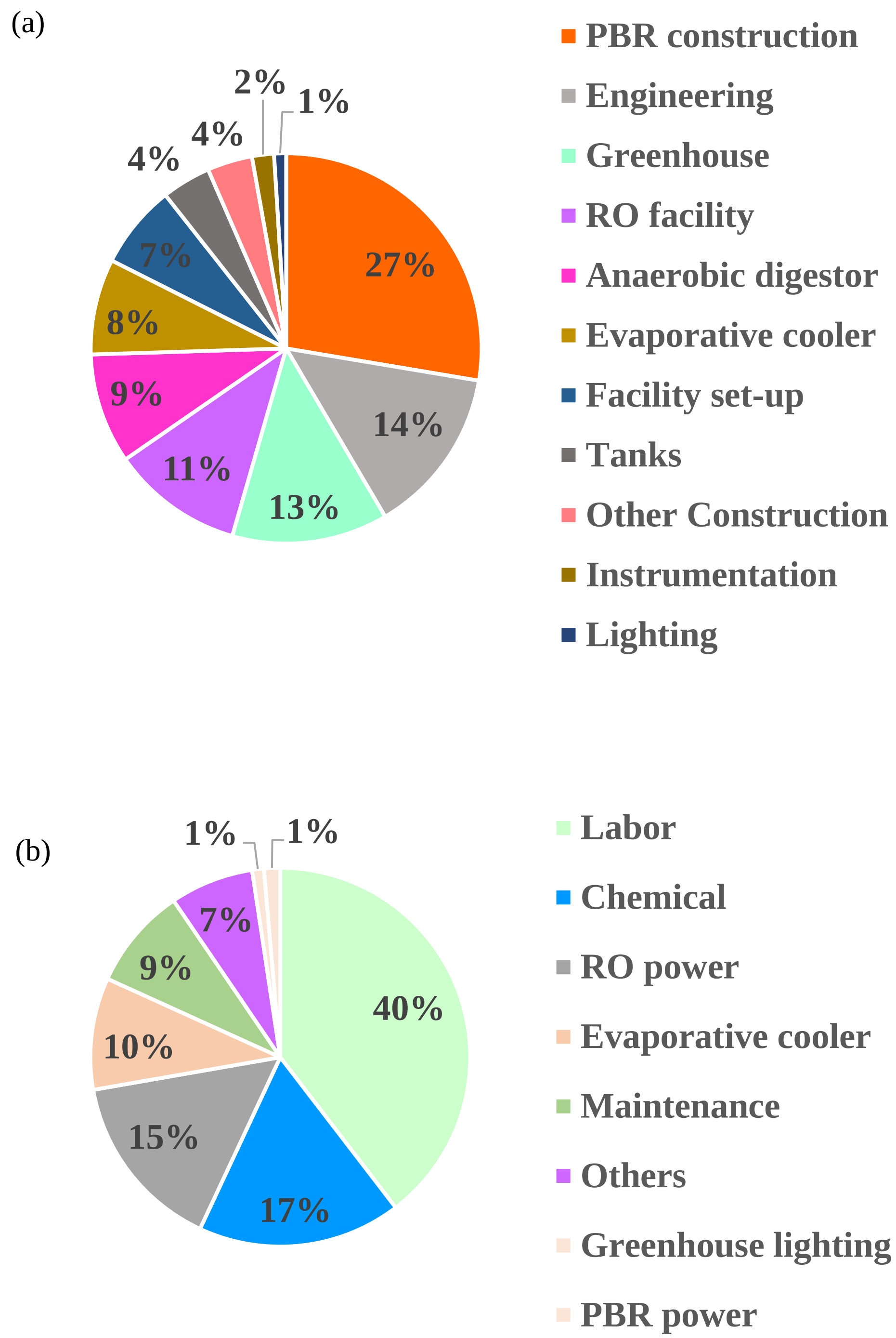


Figure 33: Sunlight System 1.0 Days HRT Scenario (a) CAPEX Breakdown (Total Cost: $13.0M), (b) OPEX Breakdown (Total Annual Cost: $0.95M)

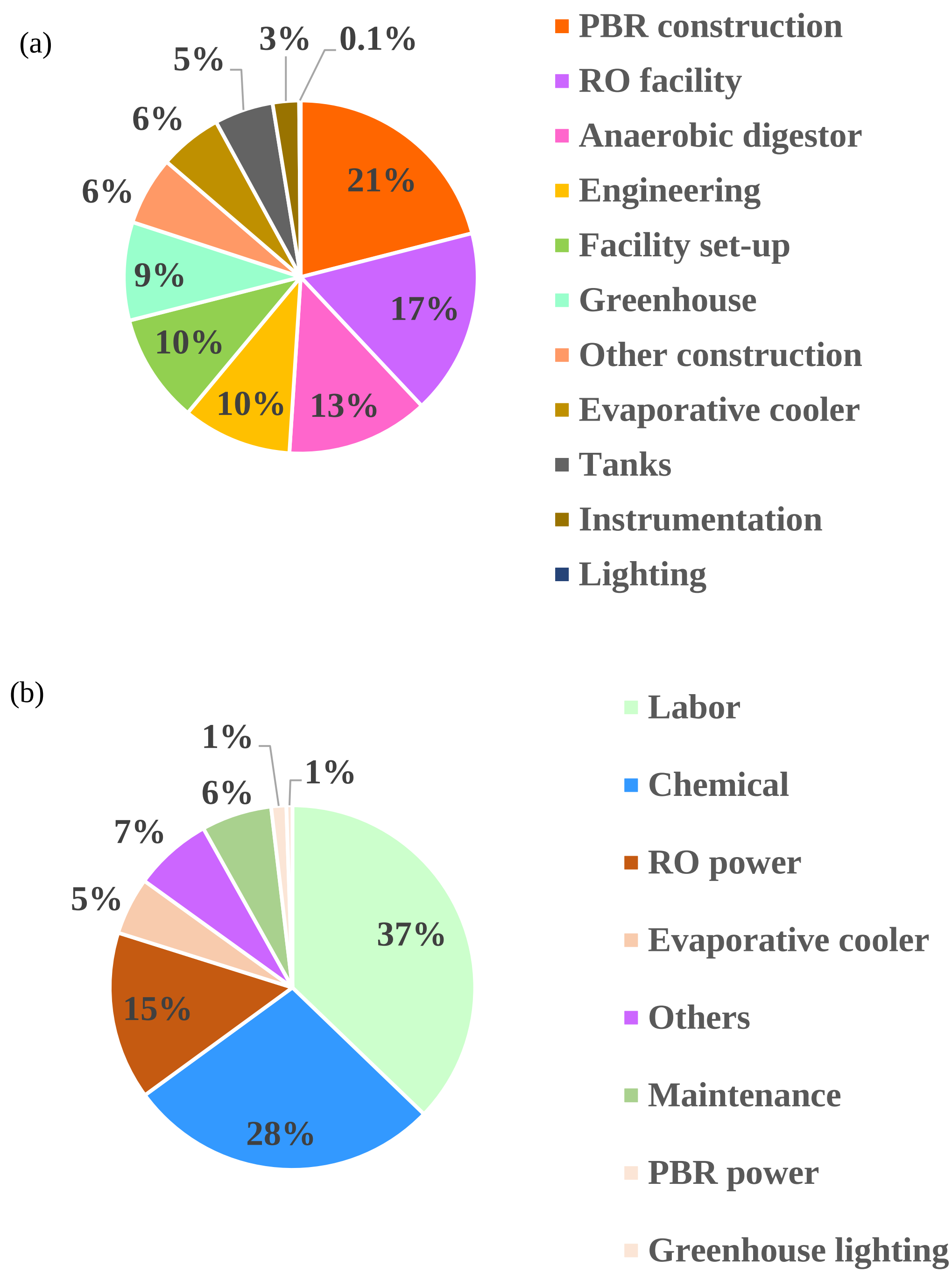


Figure 34: Sunlight System 0.5 Days HRT Scenario (a) CAPEX Breakdown: (Total Cost: $9.8M), (b) OPEX Breakdown (Total Annual Cost: $0.90M)

Facility setup cost would include the cost of storage room set-up, industrial electrical room set-up and organizing the office space (Table 27, section 4.4). Facility set-up costs would also include pumps, plumbing and instrument costs. Construction costs also included the cost of delivery, windows and doors, foundation and construction costs, toilets, control-room and lab set-up costs, and listed in the Table 27, Section 4.4. The instrumentation cost would include the cost of setting up the instruments for real time measurements of water quality parameters like silica meter, conductivity meter, turbidity meter, pH and conductivity meter, flow meter, pressure gauge and the SCADA system, and listed in Table 34, Section 4.9. The tank cost would include the storage tank costs for untreated water, treated water and chemicals (Table 35, Section 4.9).

Labor cost was estimated and listed in Table 33, Section 4.8. Labor cost would be the largest OPEX for all the scenarios, whereas the cost for chemicals would be the second largest OPEX. The other OPEX are electricity requirement for secondary RO, evaporative coolers, PBR operation and greenhouse lighting. Maintenance cost was assumed to be 0.5% of the CAPEX [113] for this study. The OPEX costs are different for three different scenarios because of the power requirement for the evaporative coolers. As the number of evaporative coolers decreased with the shortened HRTs, the power requirement for evaporative coolers was also reduced. A similar study of a hybrid algae-based biological desalination low-pressure RO system concluded that the major sources of cost for OPEX were the energy (44%) and chemicals (12%) [126]. In this LCCA study, we also found that chemicals and energy are the major sources of costs contributing to OPEX for the sunlight system. Complete OPEX cost analysis of the 1.5 days HRT scenario for the sunlight system is listed in Table 38, and the 1.0- and 0.5-days scenarios are provided in the appendix section (Section H, Tables 18 and 19).

Table 38: OPEX of 1.5 Days HRT Scenario for the Sunlight System

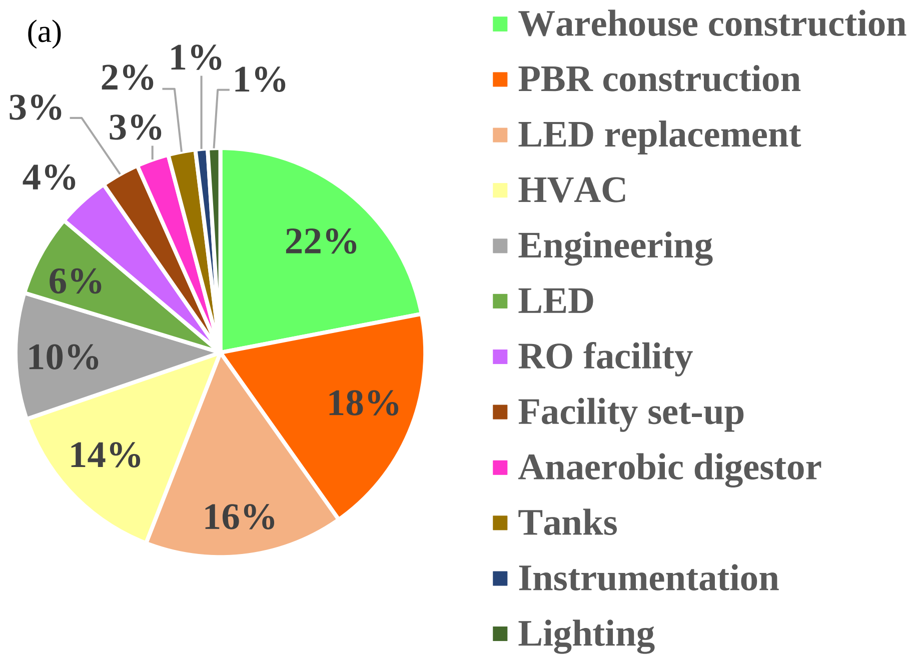
OPEX of 1.5 days HRT for the sunlight system	
Item	Cost ($)
Total greenhouse lighting cost/year	11,500
RO power cost/year	107,500
Total power cost for cooler system/year	109,000
PBR pump cost /year	9,700
Chemical cost/year	250,000
Total maintenance cost/year	80,000
Other OPEX (chemical & parts)/year	50,000
Labor/year	456,000
Total OPEX	1,100,000

4.10.3 CAPITAL AND OPERATIONAL EXPENDITURES OF THE LED SYSTEM

The CAPEX and OPEX percent breakdown for 1.5-, 1.0- and 0.5-days HRT scenarios of the LED system are shown in Figures 35, 36 and 37, respectively. The largest CAPEX for the LED system is the warehouse construction cost, which would include the costs for delivery, window and door, foundation and construction, toilets, control room and lab set up cost. HVAC installation also costs for a big percent of the total CAPEX for the LED system. For the 1.5 days HRT scenario, the HVAC installation cost was 15% of the total CAPEX of $30.8M. The warehouse construction and HVAC installation costs decreased with the shortened HRTs (*i.e.*, 1.0- and 0.5-days HRT), which can be seen in Figures 35 and 36. Cost for setting up the RO facility, deep well injection system, instrumentation and tanks are the same as sunlight system scenario. The engineering cost was assumed to be 10% of the total CAPEX. PBR construction costs for the LED system were slightly higher because of the larger area in comparison the PBRs in the sunlight system. LED installation also accounted for a vital part of the CAPEX, which decreased with the shortened HRTs. LED replacement cost was also considered as a CAPEX which would occur every 5 years. LED and HVAC power accounted for the largest portion of the OPEX costs in the LED system for all three scenarios. These two major electricity consumptive units were responsible for high OPEX of the LED system compared to the OPEX of the sunlight system. Other electricity requirements are to run the secondary RO, warehouse ambience lighting, and PBR operational. Chemical, maintenance and other costs were the same as the sunlight system as both systems would treat water of same quality and would operate at 1.0 MGD. Complete OPEX cost analysis of the 1.5 days HRT scenario for the LED system is listed in Table 39, and the 1.0- and 0.5-days scenarios are provided in the appendix section (Section I, Table 20 and 21).

Table 39: OPEX of 1.5 Days HRT Scenario for the LED System

OPEX of 1.5 days HRT for the LED system	
Item	Cost ($)
Total power LED cost/year	1,841,000
Total warehouse lighting cost/year	17,000
RO power cost/year	107,000
Total power cost for HVAC system/year	838,000
PBR pump cost/year	14,000
Chemical cost/year	250,000
Total maintenance cost/year	117,000
Other OPEX (chemical & parts)/year	50,000
Labor cost/year	456,000
Total OPEX	3,600,000



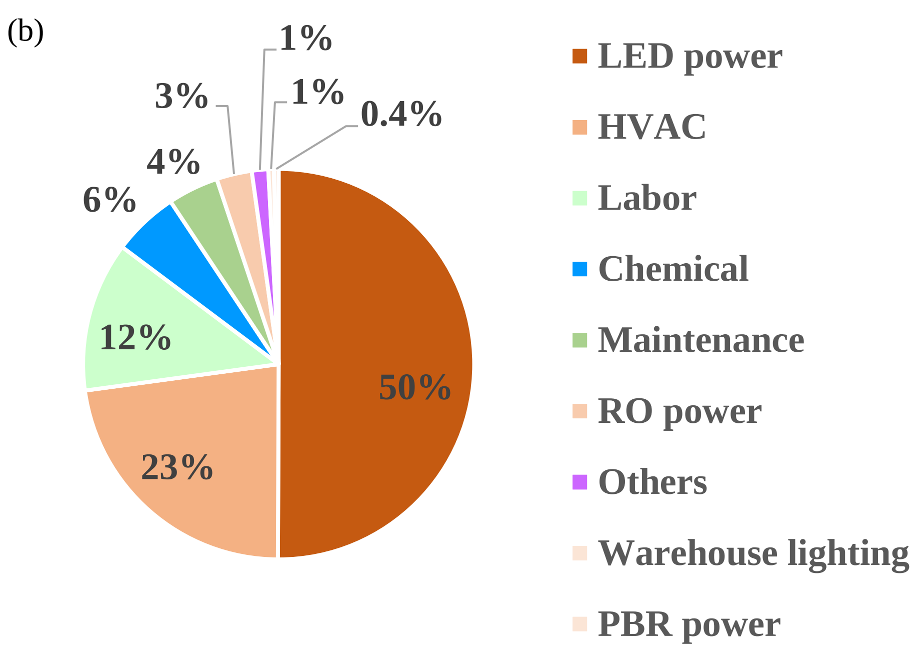
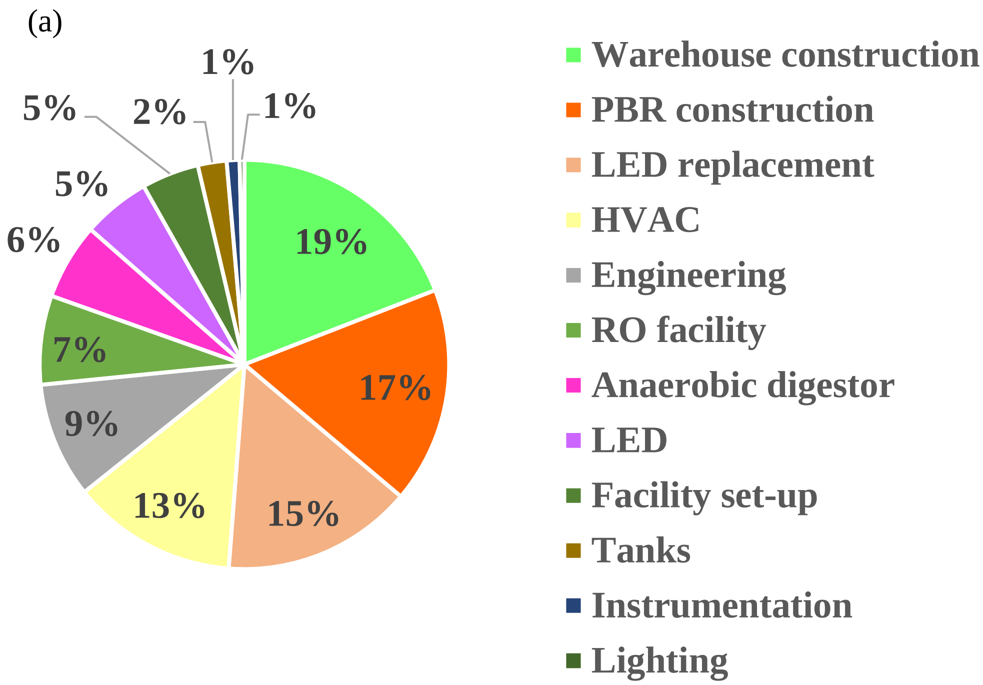


Figure 35: LED System 1.5 Days HRT Scenario (a) CAPEX Breakdown (Total Cost: $30.8M), (b) OPEX Breakdown (Total Annual Cost: $3.6M)



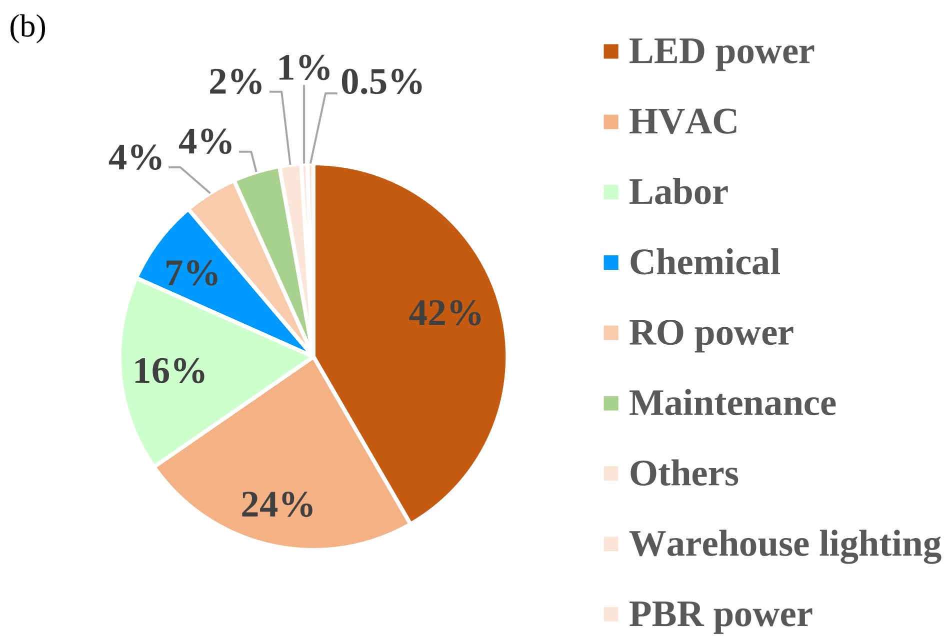


Figure 36: LED System 1.0 Days HRT Scenario (a) CAPEX Breakdown (Total Cost $23.5M), (b) OPEX Breakdown (Total Annual Cost: $2.7M)

(a)

(b)

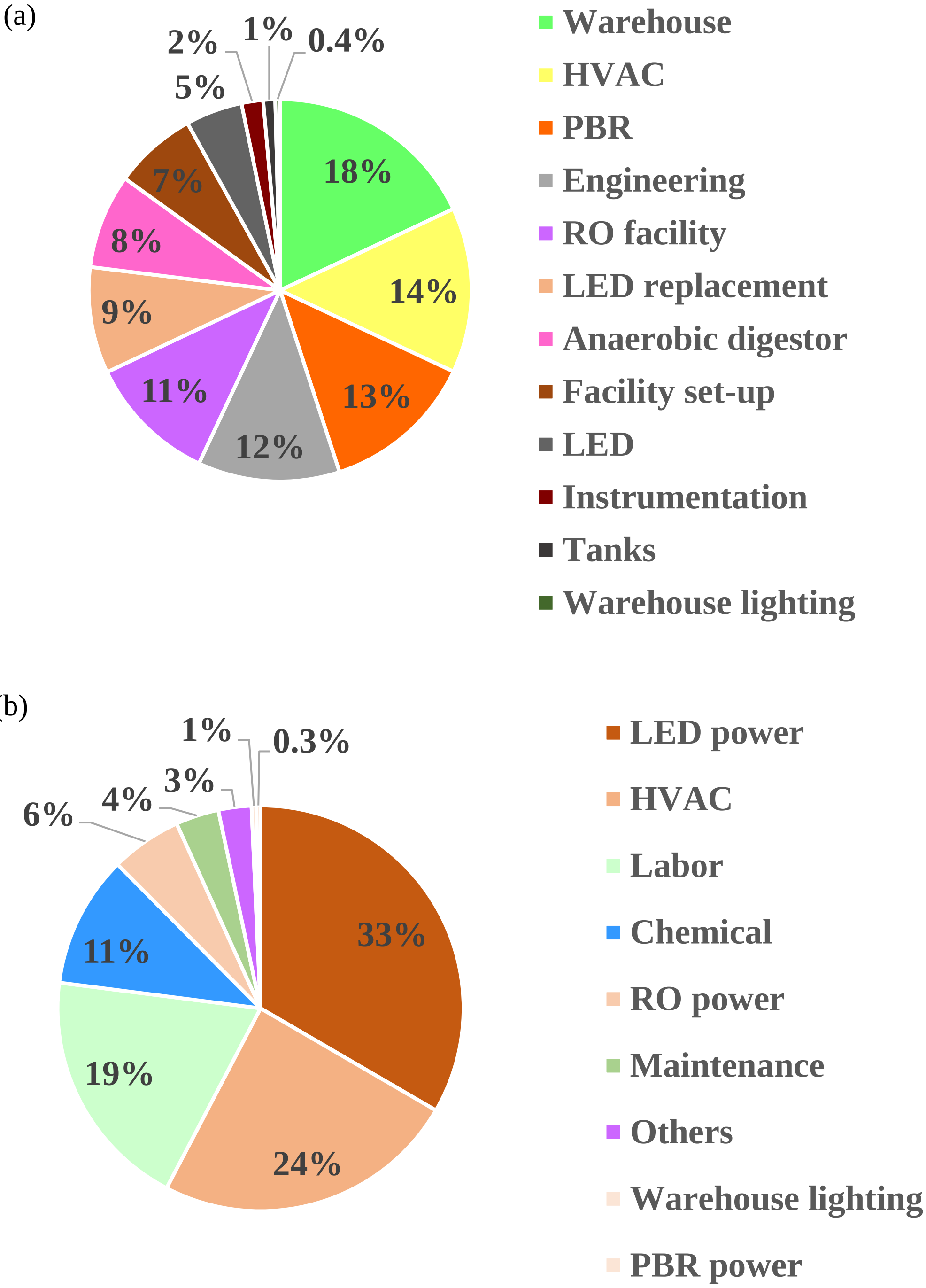


Figure 37: LED System 0.5 Days HRT Scenario (a) CAPEX Breakdown (Total Cost: $15.8M), (b) OPEX Breakdown (Total Annual Cost: $1.9M)

4.10.4 ECONOMIC ANALYSIS

4.10.4.1 CASH FLOW ANALYSIS

For the cash flow analysis, the OPEX was determined for the 20-year lifetime of the project using an inflation rate of 6.42% and equation 4 (Section 3.3.5.3). The initial CAPEX was amortized over the 20-year lifetime of the project using an interest rate of 6% and equation 5 (Section 3.3.5.3). Inflation was accounted for the revenue as well which allowed the cash flow to change every year in a profitable direction. Sunlight system with 1.5-, and 1.0-days HRT scenarios did not show any positive cash flow. The negative cash flow occurred due to high OPEX and CAPEX in the scenarios. However, when a 30% grant was considered on CAPEX, there was a positive cash flow for the sunlight system after 18, 15, and 7 years for 1.5, 1.0- and 0.5-days HRT scenarios, respectively. Additionally, there was a positive cash flow for the sunlight system with 0.5 days HRT scenario after 13 years with no grant consideration. Net cash flow for the sunlight and LED systems are listed in Table 40 for the 0.5-days HRT scenarios, and the other two scenarios are presented in the appendix section (Section J, Table 22 and 23).

From Table 40, the effect of the grant on the CAPEX can be understood. For the first year of the sunlight system, the net cash flow was -$685,337 without any grant, whereas with a 30% grant on the CAPEX, the net cash flow was -$338,072. There was a 50% reduction in the negative cash flow after a 30% grant application. Another critical point from the cash flow analysis is the difference between the sunlight and LED systems. With a 30% grant, the sunlight system with 0.5 days HRT showed a net cash flow of -$338,072, whereas the LED system showed a net cash flow of -$2,337,653, approximately 6.9 times the negative net cash flow of the sunlight system. High OPEX from the LED and HVAC operation costs, and high CAPEX from LED replacement caused the LED system to be economically unfeasible compared to the sunlight system.

Table 40: Cash Flow of Sunlight and LED System for 0.5 Days HRT With and Without a 30% Grant

Year	Sunlight system		LED system	
	Without grant	With 30% grant	Without grant	With 30% grant
1	-$685,337	-$338,072	-$2,377,653	-$1,950,351
2	-$625,382	-$270,372	-$2,503,988	-$2,001,724
3	-$591,343	-$232,184	-$2,573,301	-$2,027,303
4	-$554,314	-$190,812	-$2,647,064	-$2,052,695
5	-$514,066	-$146,017	-$2,725,563	-$2,077,801
6	-$470,353	-$97,543	-$2,809,101	-$2,102,514
7	-$422,911	-$45,116	-$2,898,003	-$2,126,713
8	-$371,457	$11,557	-$2,992,612	-$2,150,268
9	-$315,688	$72,790	-$3,093,295	-$2,173,034
10	-$255,280	$138,919	-$3,200,442	-$2,194,851
11	-$189,885	$210,304	-$3,314,467	-$2,215,547
12	-$119,131	$287,330	-$3,435,813	-$2,234,929
13	-$42,619	$370,408	-$3,564,950	-$2,252,789
14	$40,077	$459,980	-$3,702,377	-$2,268,901
15	$129,415	$556,516	-$3,848,627	-$2,283,015
16	$225,884	$660,521	-$4,004,266	-$2,294,861
17	$330,006	$772,534	-$4,169,897	-$2,304,144
18	$442,343	$893,132	-$4,346,162	-$2,310,543
19	$563,492	$1,022,931	-$4,533,742	-$2,313,710
20	$694,095	$1,162,590	-$4,733,366	-$2,313,265

4.10.4.2 NET PRESENT VALUE ANALYSIS

To analyze the NPV of the proposed systems with three scenarios and include the grants into consideration, equation 1 (Section 3.3.5.3) was used in this study. Sunlight system with 1.5-, and 1.0-days HRT scenarios did not show any positive NPV. The negative NPV occurred due to high OPEX and CAPEX in the scenarios. However, when a 30% grant was considered on CAPEX, there was a positive NPV for the sunlight system after 18, 15, and 7 years for 1.5, 1.0- and 0.5-days HRT scenarios, respectively. Additionally, there was a positive NPV for the sunlight system with 0.5 days HRT scenario after 13 years with no grant consideration. The NPV for the sunlight and LED systems are presented in Table 39 for the 0.5-days HRT scenario with and without a 30%

grant, and the other two scenarios are shown in the appendix section (Section K, Tables 24 and 25). Table 41 presents the NPV analysis results for the sunlight and LED systems with and without a 30% grant scenario.

Table 41: NPV for Sunlight and LED Systems of 0.5 Days HRT With and Without a 30% Grant

Year	Sunlight system		LED system	
	Without grant	With 30% grant	Without grant	With 30% grant
1	-$644,234	-$317,797	-$2,235,056	-$1,833,381
2	-$552,619	-$238,914	-$2,212,647	-$1,768,823
3	-$491,201	-$192,865	-$2,137,522	-$1,683,987
4	-$432,828	-$148,993	-$2,066,924	-$1,602,819
5	-$377,328	-$107,177	-$2,000,582	-$1,525,120
6	-$324,537	-$67,303	-$1,938,240	-$1,450,704
7	-$274,302	-$29,262	-$1,879,658	-$1,379,396
8	-$226,479	$7,046	-$1,824,612	-$1,311,030
9	-$180,933	$41,719	-$1,772,889	-$1,245,451
10	-$137,536	$74,845	-$1,724,289	-$1,182,511
11	-$96,168	$106,509	-$1,678,626	-$1,122,073
12	-$56,716	$136,792	-$1,635,723	-$1,064,005
13	-$19,073	$165,768	-$1,595,415	-$1,008,186
14	$16,860	$193,508	-$1,557,546	-$954,500
15	$51,178	$220,079	-$1,521,970	-$902,836
16	$83,970	$245,543	-$1,488,549	-$853,093
17	$115,319	$269,959	-$1,457,154	-$805,174
18	$145,305	$293,384	-$1,427,664	-$758,987
19	$173,999	$315,869	-$1,399,965	-$714,446
20	$201,474	$337,464	-$1,373,948	-$671,469

For the first year of the sunlight system, the NPV was -$644,234 without any grant, whereas with a 30% grant on the CAPEX, the NPV was -$317,797. There was a 51% reduction in the negative NPV after a 30% grant application. The difference between the sunlight and LED system was also visible in this analysis. With a 30% grant, the sunlight system with 0.5 days HRT showed an NPV of -$317,797, whereas the LED system showed an NPV of -$1,833,381, approximately 5.7 times the negative NPV of the sunlight system. The NPV analysis indicate that the proposed PBR-secondary RO facility might be a feasible option if the HRT could be shortened to 1.0- and 0.5-days HRT. The proposed system could also be a feasible option for the 1.5 days HRT scenario if the grant scenario is considered.

4.10.4.3 BREAK-EVEN POINT ANALYSIS

As there was no positive cash flow and NPV for the LED system, there was no break-even points for the system. For 1.5- and 1.0-days HRT scenarios of the sunlight system, there was no break-even points. However, the gap between total sales and total costs curves were getting closer (Figures 38a and 39b) when the shortened HRT (*e.g.*, 1.0 days HRT) was considered. Like the cash-flow and NPV analysis, there was break-even points for the sunlight system after 18, 15, and 7 (Figures 38b, 39a and 40a) years for 1.5, 1.0- and 0.5-days HRT scenarios when a 30% grant was considered on the CAPEX. Additionally, the sunlight system showed break-even point after 13 years with the 0.5 days HRT scenario with no grant consideration. The break-even plots for the sunlight system with a 30% grant and without any grant for 1.5, 1.0-, and 0.5-days HRT scenarios are shown in Figures 38, 39, and 40, respectively.

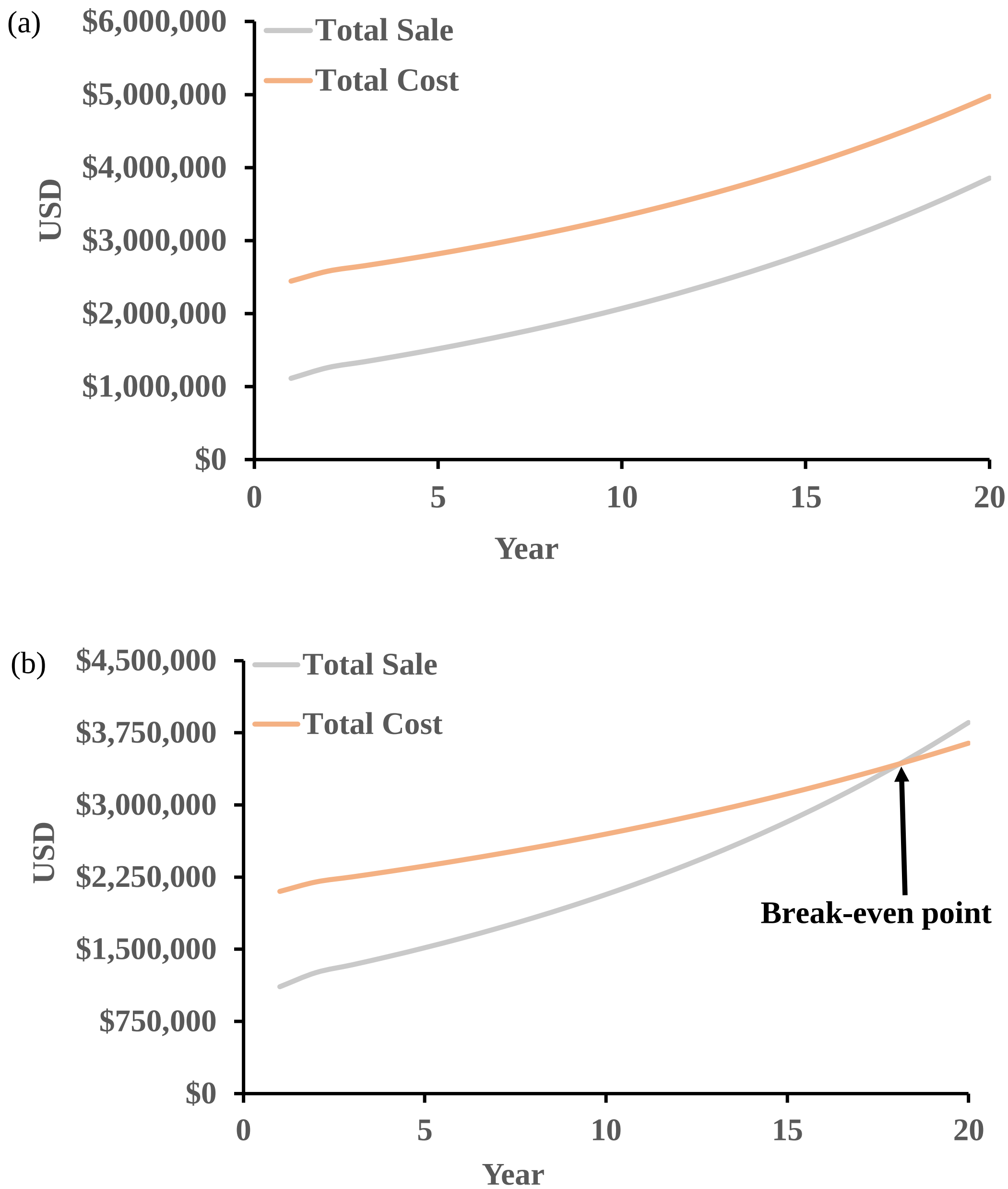


Figure 38: Break-Even Points of Sunlight System 1.5 Days HRT (a) No Grant on CAPEX, (b) 30% Grant ($5.1M) on CAPEX

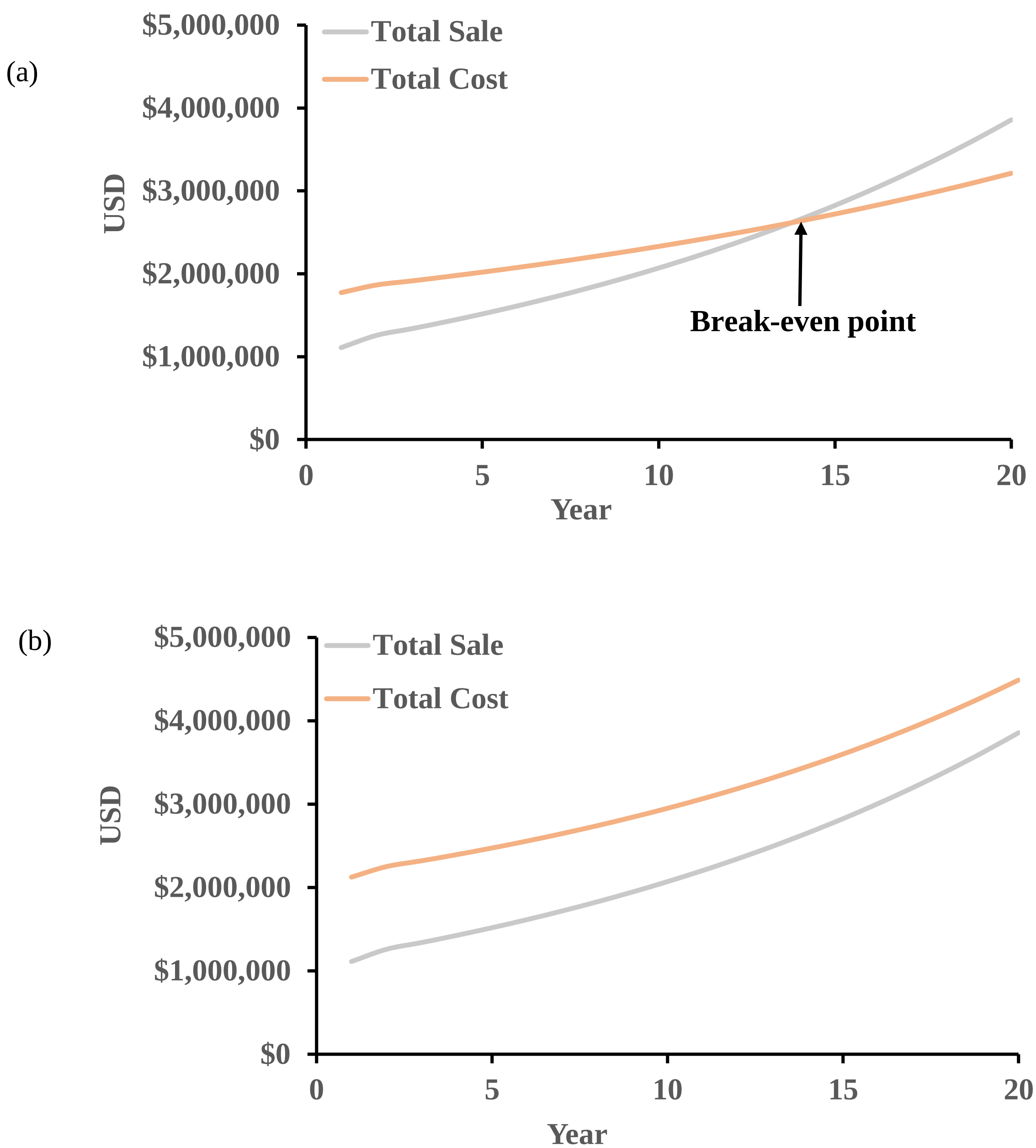


Figure 39: Break-Even Points of Sunlight System 1.0 Days HRT (a) 30% Grant ($3.9M) on CAPEX, (b) No Grant on CAPEX

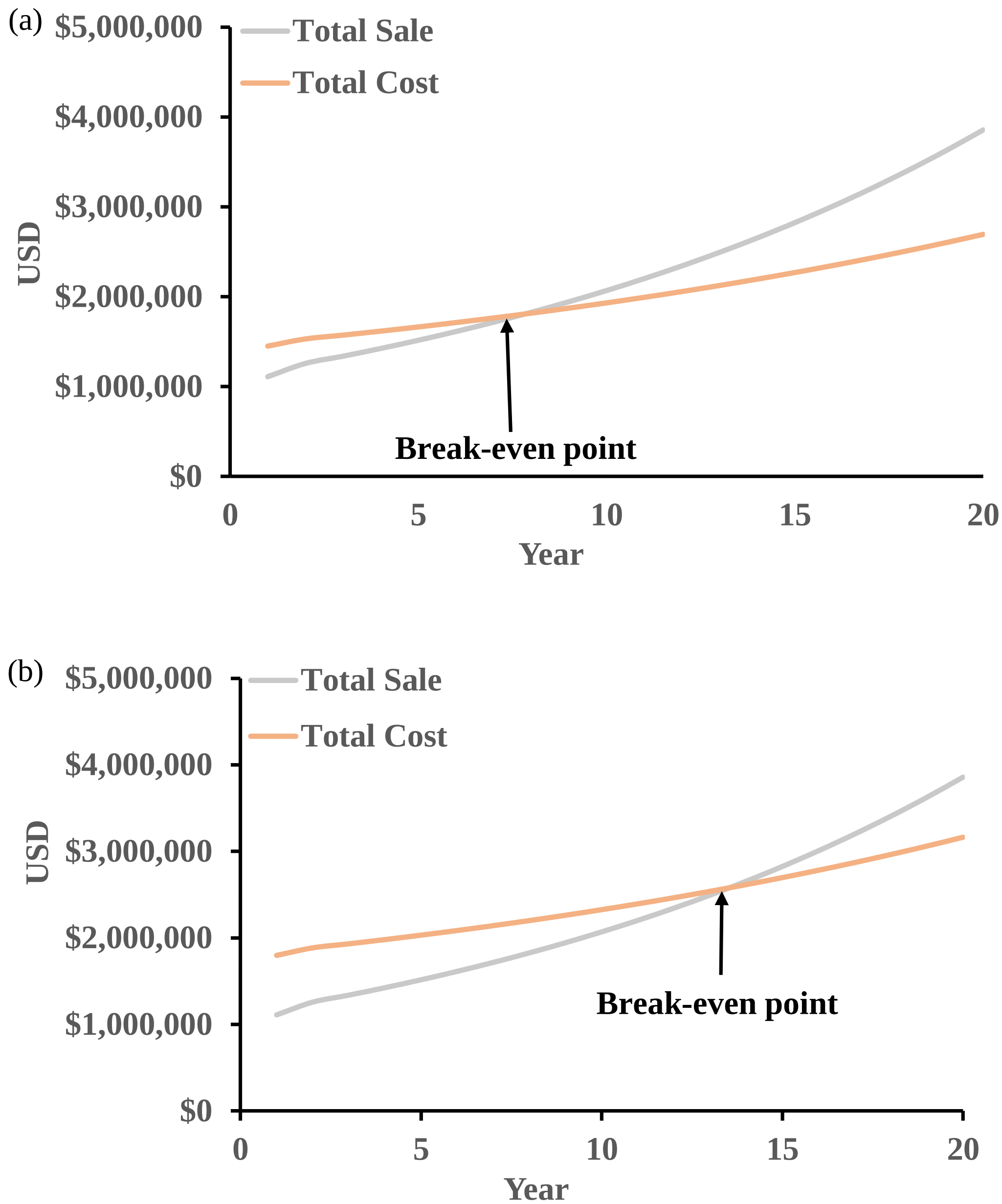


Figure 40: Break-Even Points of Sunlight System 0.5 Days HRT (a) 30% Grant ($2.9M) on CAPEX ($2.5M) (b) No Grant on CAPEX

4.10.5 RENEWABLE ENERGY SCENARIO

To propose the facility as a green system, solar energy was considered in this study as the power source. The RETScreen Expert was used to analyze the installation cost, OPEX, revenue generation and greenhouse gas reduction for the sunlight scenarios with and without grant.

The total power requirement for the 1.0-day HRT scenario is 475 kW, and the facility location was assumed to be central Texas. Using the power requirement, and facility location with the discount rate and inflation factors used in this study for the LCCA, the cost analysis was performed. From the analysis, the initial CAPEX for setting up a solar PV energy system would be around $0.9M and this system would save $9,000 annual OPEX. After meeting the power requirement of the PBR-secondary RO system, the solar system would supply 688 MWh electricity to the grid, which would generate a revenue of $68,000 per year, and the solar system would reduce 93% of gross annual greenhouse gas emissions. Assuming 500 W solar panels to be installed which requires an area of 27.5 square feet [139], the 550 kW PV plant would require a total of 1,050 panels, and 28,750 square feet of area. The footprint of the PV plant is almost 37% of a typical soccer field where the area of a soccer field is 76,900 square feet [140].

For the 1.5 days HRT scenario, the power requirement was 545 kW, and the facility location remained the same. The initial CAPEX for setting up a PV system for this demand would cost around $1.1M, saving $10,000 annual OPEX cost. After meeting the power requirement of the PBR-secondary RO system, the solar system would supply 790 MWh electricity to the grid, which would generate a revenue of $75,000 per year, and the solar system would reduce 93% of gross annual greenhouse gas emissions. Using the same configuration panel as the 1.0 days HRT scenario, the PV plant would require a total of 1,130 panels which would require 33,200 square feet of area. The footprint of the proposed PV plant would be 43% of a typical soccer field.

For the 0.5 days HRT scenario, the electricity requirement was 415 kW, and the facility location remained the same. The initial CAPEX for setting up a PV system for this demand would cost around $0.66M, saving $7,000 annual OPEX.

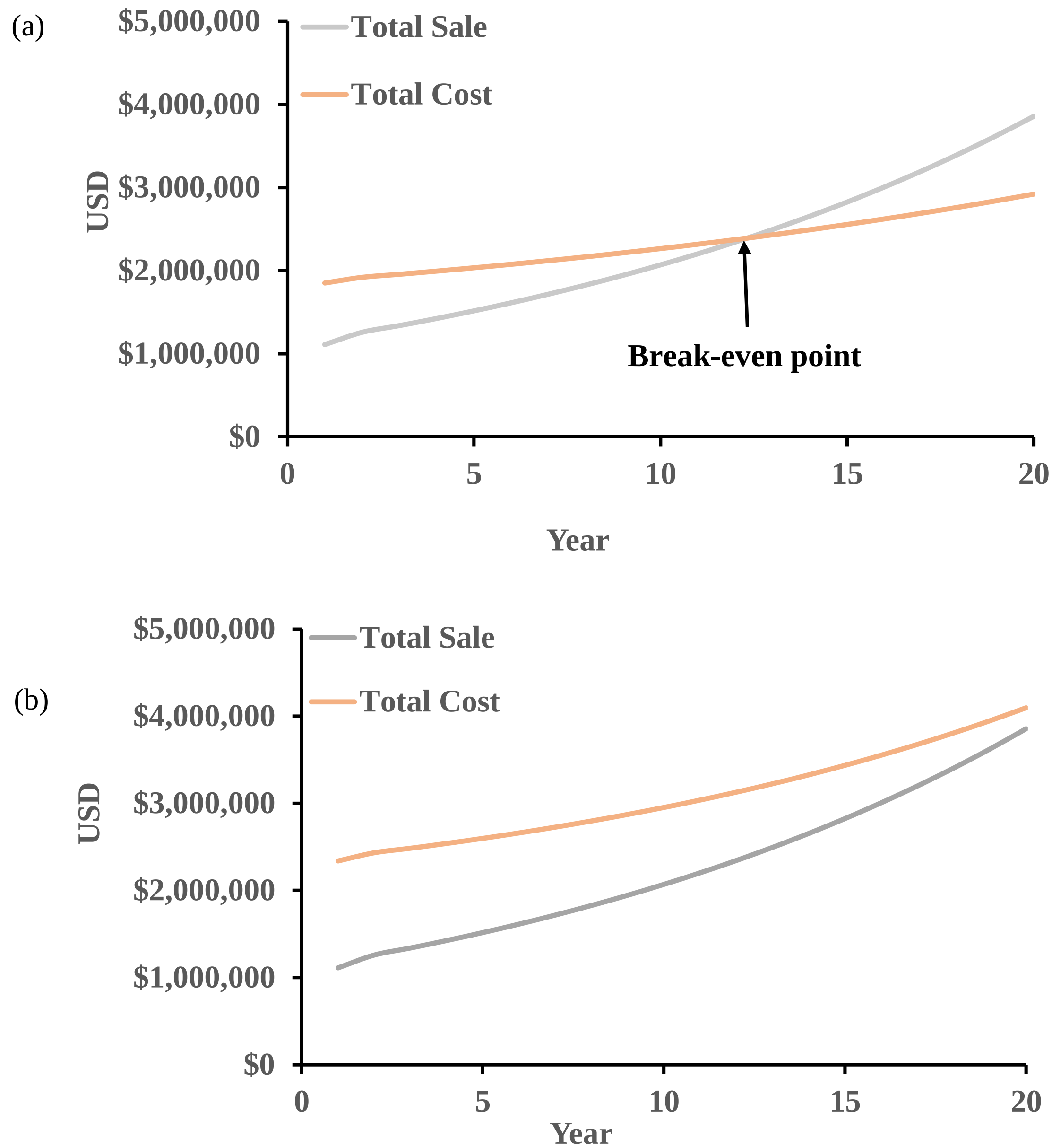


Figure 41: Break-Even Point of PV with Sunlight System 1.5 Days HRT (a) 30% Grant ($5.4M) on CAPEX, (b) No Grant on CAPEX

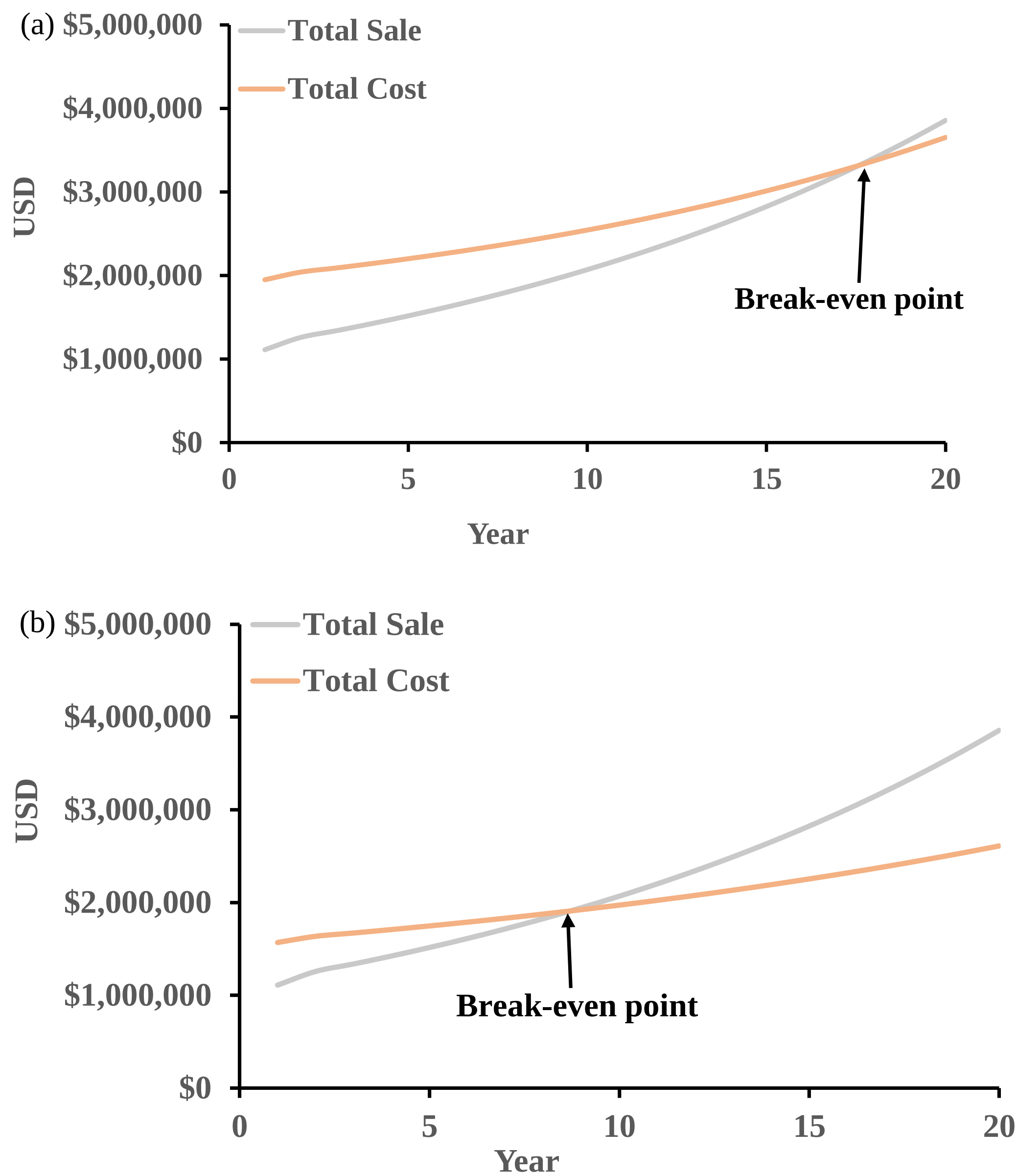
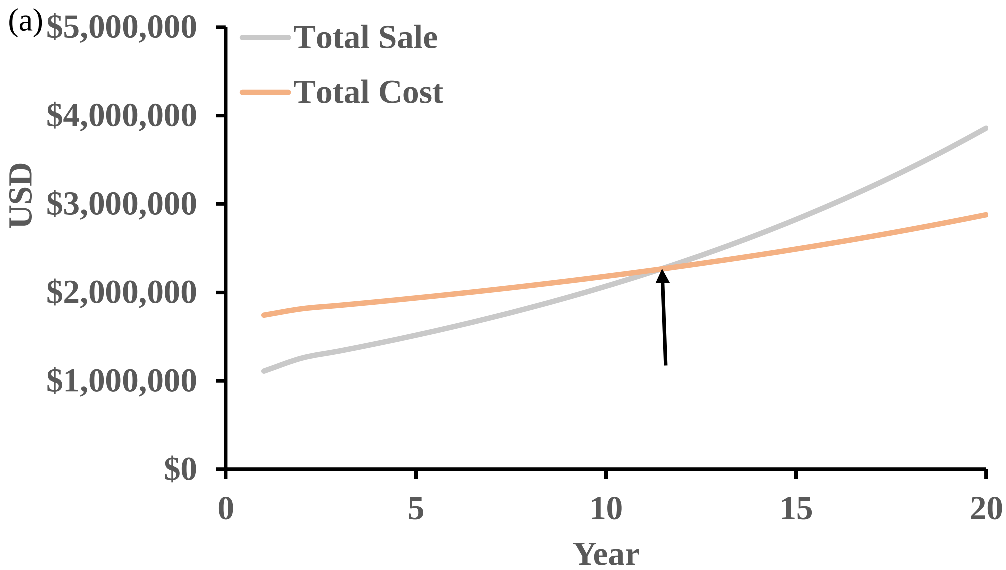


Figure 42: Break-Even Point of PV with Sunlight System 1.0 Days HRT (a) No Grant on CAPEX; (b) 30% Grant ($4.2M) on CAPEX



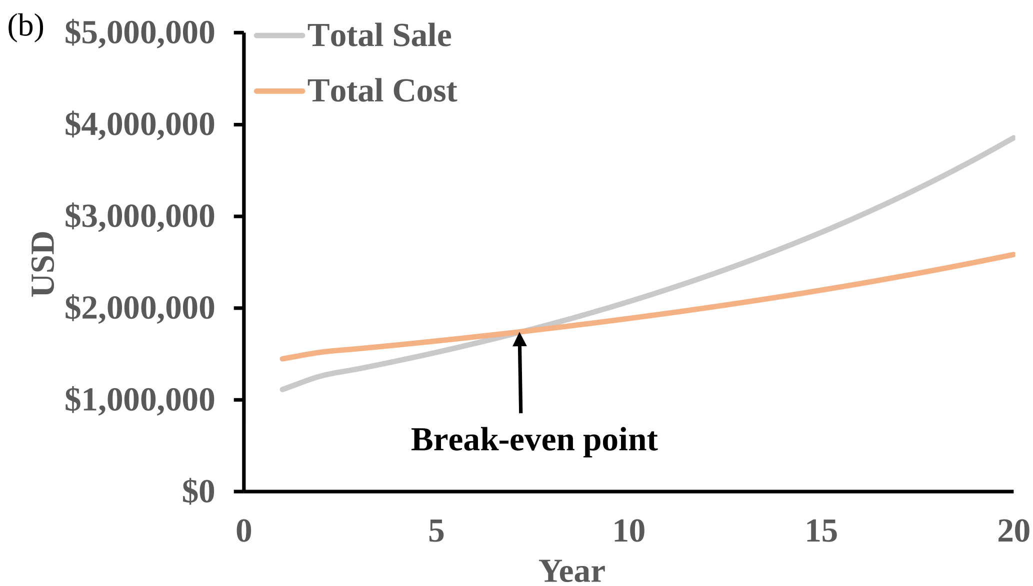


Figure 43: Break-Even Point of PV with Sunlight System 0.5 Days HRT (a) No Grant on CAPEX; (b) 30% Grant ($3.3M) on CAPEX

After meeting the power requirement of the PBR-secondary RO system, the solar system would supply 560 MWh electricity to the grid, which would generate a revenue of $55,000 per year, and the solar system would reduce 94% of gross annual greenhouse gas emissions. Using the same configuration panel as the 1.0 days HRT scenario, the PV plant would require a total of 870 panels which would require 22,000 square feet of area. The footprint of the proposed PV plant would be 26% of a typical soccer field.

Due to high OPEX and CAPEX, there was no clear break-even point for the LED system. Break-even points for the HRT scenarios (1.5-, 1.0- and 0.5-days HRT) of the sunlight system with and without grant and discussed under Figures 41, 42 and 43.

Only for the 1.5 days HRT scenario without any grant consideration did not show any break-even point for the solar PV scenario. However, the gap between the total sale and total cost curves also came closer in comparison to the curves without PV consideration (Figures 38a and 39b, Section 4.10.4.3). For the all the scenarios with a 30% grant consideration including PV installation, the sunlight system showed break-even points after 13, 18 and 6 years for 1.5-, 1.0- and 0.5-days of HRT, respectively. The 1.0-, and 0.5-days HRT scenarios without any grant considerations also showed a certain break-even point for the proposed facility after 16 and 12 years, respectively. Results from this PV installation study indicates that, including a PV system in the proposed PBR-secondary RO facility would be a profitable scenario for the sunlight system.

The approximate size of the proposed PBR-secondary RO facility in an existing brackish groundwater desalination plant in Texas is shown in Figure 44 to understand the footprint of the sunlight system and the PV system. For the greenhouse system detailed layout, please refer to Figure 24, Section 4.3.2.

Figure 44: Estimated Footprint of a Full-Scale PBR-Secondary RO Facility with PV in the Sunlight System of 1.5 Days HRT Scenario within the Property of an Existing Brackish Groundwater Desalination Facility in Texas (Source: Google Maps)

4.11 FRESHWATER PRODUCTION COSTS

Freshwater production costs for both the sunlight and LED systems with all the scenarios were calculated and analyzed in this study. The freshwater cost was calculated for all the 20-years of the project lifetime, and the average is listed in this study. Table 43 shows the production cost of freshwater by the proposed scenarios. Complete freshwater production cost calculations for the sunlight system with 1.5 days HRT without any grant is presented in Table 42, and the other scenarios are listed in the appendix section (Section L, Table 26, 27, 28, 29, 30, 31, 32, 33, 34, 35 and 36). The freshwater production costs by the sunlight system were between \$5.33 to \$0.02. The lowest freshwater production cost is \$0.02 for the sunlight system with 0.5 days HRT scenario with a 30% grant on the CAPEX. In 2012, the Texas Water Development Board estimated that the total production cost of desalinating brackish groundwater ranges from \$1.09 to \$2.49 per thousand gallons [141]. With the 1.5 days HRT with a 30% grant, the proposed system could produce freshwater in this commercial range. With the 1.0-, and 0.5-days HRT scenarios with a 30% grant, the proposed system would produce freshwater below this range. A Water Reuse Association study in 2012 showed that cost trends for large SWRO projects appear to be $3.00 to $9.00 per thousand gallons [142], indicating the SWRO to be one of the most expensive water treatment methods currently employed. For the LED systems, the unit cost of water per thousand gallons was found to be the lowest at $9.77 with 0.5 days HRT with a 30% grant scenario suggesting the LED system to be an economically impractical solution. Freshwater production costs from different conventional and alternative sources are presented in Table 44.

Table 42: Freshwater Production Cost of Sunlight System of 1.5 Days HRT with No Grant Scenario

Sunlight System 1.5 Days HRT No Grant Scenario				
Year	Cost ($)	Profit ($)	Unit cost ($/1,000 gal)	Average
1	2,562,235	1,111,000	$5.68	$5.33
2	2,698,480	1,258,232	$5.64	
3	2,772,949	1,339,010	$5.61	
4	2,852,199	1,424,974	$5.59	
5	2,936,538	1,516,458	$5.56	
6	3,026,290	1,613,814	$5.53	
7	3,121,805	1,717,421	$5.50	
8	3,223,452	1,827,680	$5.46	
9	3,331,624	1,945,017	$5.43	
10	3,446,741	2,069,887	$5.39	
11	3,569,249	2,202,774	$5.35	
12	3,699,622	2,344,192	$5.31	
13	3,838,364	2,494,689	$5.26	
14	3,986,014	2,654,848	$5.21	
15	4,143,143	2,825,289	$5.16	
16	4,310,360	3,006,673	$5.10	
17	4,488,312	3,199,701	$5.04	
18	4,677,688	3,405,122	$4.98	
19	4,879,223	3,623,731	$4.91	
20	5,093,696	3,856,374	$4.84	

Comparing freshwater production costs from surface water and direct potable reuse to the freshwater production costs of the proposed PBR-secondary RO facility, the LED system is instead an impractical option to propose on an industrial scale. However, the sunlight system could provide a competitive solution to produce freshwater from brackish water ROC. The freshwater production costs were also calculated for the renewable energy scenarios in the sunlight system.

Table 43: Freshwater Production Costs by the Sunlight and LED Systems

System	Scenario	Specification	The unit cost of freshwater ($/1,000 gallons)
Sunlight	0.5 days HRT	Without grant	$2.49
		With a 30% grant	$0.02
	1.0 days HRT	Without grant	$3.34
		With a 30% grant	$0.58
	1.5 days HRT	Without grant	$5.33
		With a 30% grant	$2.04
LED	0.5 days HRT	Without grant	$13.20
		With a 30% grant	$9.77
	1.0 days HRT	Without grant	$21.46
		With a 30% grant	$14.98
	1.5 days HRT	Without grant	$31.12
		With a 30% grant	$22.59

Table 44: Freshwater Production Costs of Conventional and Alternative Sources and the Sunlight System of the Proposed PBR-Secondary RO Facility

Water Type	Cost ($/1,000 gallons)
Brackish water	1.09 - 2.49
Seawater	3.00 - 9.00
Surface water	1.512 [143]
Direct potable reuse	1.7 - 2.84 [144]
Sunlight system of the proposed PBR-secondary RO facility	0.02 - 5.33
LED system of the proposed PBR-secondary RO facility	9.77 – 31.12

Freshwater production costs decreased by a good margin when the PV system was considered instead of electricity supply from the grid. For 1.5-, 1.0- and 0.5- days HRTs, the freshwater production costs would be $0.23, -$0.92 and -$1.24, respectively when a 30% grant on the CAPEX were considered. With PV consideration for the 1.0 days HRT scenario the sunlight system would produce freshwater for $1.55 per thousand gallons without any grant consideration proving the cost between the commercial freshwater production cost from brackish water desalination. For the 1.5 days HRT system without any grant, the unit cost reduced by 40%, and for the 1.0- and 0.5-days HRT system without any grant, the unit cost reduced by 53%, and 59%, respectively. Further research by introducing the PV system as the primary energy source for the system, bench and pilot scale studies must be conducted as future research to confirm these estimates. Table 45 compares the freshwater production cost of the sunlight system using with and without solar PV.

Table 45: Freshwater Production Cost Comparison of the Sunlight System with and Without Renewable Energy Scenario

System	**Scenario**	**Specification**	**The unit cost of freshwater ($/1,000 gallons)**
Sunlight system without PV	0.5 days HRT	Without grant	$2.49
		With a 30% grant	$0.02
	1.0 days HRT	Without grant	$3.34
		With a 30% grant	$0.58
	1.5 days HRT	Without grant	$5.33
		With a 30% grant	$2.04
Sunlight system with PV	0.5 days HRT	Without grant	$1.02
		With a 30% grant	-$1.24
	1.0 days HRT	Without grant	$1.55
		With a 30% grant	-$0.92
	1.5 days HRT	Without grant	$3.17
		With a 30% grant	$0.23

Comparing the freshwater production costs with and without PV installation consideration it can be said that PV installation would make the proposed system more economical by production freshwater at a cheaper rate. Also, with the PV consideration, the proposed PBR-secondary RO facility would produce freshwater within the commercial brackish water range with the 1.0 days HRT without any grant on the CAPEX. Complete details of the freshwater production costs with all the discussed scenarios can be found in the appendix section (Section M, Tables 37, 38. 39, 40, 41 and 42).

5. CONCLUSIONS

To understand the economic feasibility of proposing a diatom-based photobiological treatment with brackish water diatom and secondary RO, a detailed LCCA was performed in this study. This research work proposed an industry-scale 1.0 MGD PBR-secondary RO facility to treat the brackish groundwater ROC by considering two different light sources (*e.g.*, LED and sunlight) with three probable HRT scenarios (1.5-, 1.0- and 0.5-days HRT). In the sunlight system, the PBRs were assumed to be installed inside greenhouses, whereas the PBRs would be installed inside a warehouse for the LED system. CAPEX for the LED and sunlight systems were $30.8M and $17.1M, respectively. The number of PBRs reduced when the shortened HRTs were considered, which reduced the CAPEX. OPEX also got reduced with the shortened HRTs as the power requirement for the LED to run the PBRs and to operate the HVAC and evaporative coolers would be reduced. CAPEX and OPEX for the LED system were higher than the sunlight system due to the high construction cost of building a warehouse and the power requirement for the LED as a light source for the diatoms. The most significant CAPEX for the LED system was the construction cost of building a warehouse which accounted for 25% of the total CAPEX. In contrast, for the sunlight system, the largest was PBR construction cost which accounted for 35% of the total CAPEX for the 1.5 days HRT scenario.

Biomass fractionation and characterization were conducted in this research by lab experiments on biomass collected from photobiological treatment of ROC from a brackish groundwater desalination facility and ROC from an advanced water purification facility. Biomass characterization study showed that the production rate and percentage of bioresources (*e.g.*, silica, calcite, and organics) present in the biomass. The average percentages of silica, calcite and organics in the biomass was found to be 27%, 35% and 38%, respectively, while their average production rates were 0.0046, 0.0048 and 0.0083 grams/day in a 100-mL semi-batch study. Assuming revenue could be made by commercializing silica, calcite and freshwater, a total of $1,111,000 revenue could be made from the proposed PBR-secondary RO facility. Biogas could be generated by using anaerobic digestion of biomass from the PBR and it would offset 23.5% power requirement of the secondary RO.

All these HRTs were divided into two categories: without grant scenarios and considering a 30% grant scenario from local, federal, and state agencies on the CAPEX to understand the effect of a grant on reducing the overall cost and proposing a profitable scenario. The NPV, cash-flow analysis and break-even point analysis indicated that due to high OPEX from labor and electricity requirements, none of the scenarios of LED system would generate a positive cash flow, NPV or a clear break-even point. However, there was a positive cash flow and NPV, and certain break-even points for the sunlight system after 18, 15, and 7 years for 1.5, 1.0- and 0.5-days HRT scenarios, respectively when a 30% grant was considered on the CAPEX. Additionally, there was a positive cash flow for the sunlight system with 0.5 days HRT scenario after 13 years with no grant consideration. This economic analysis showed a clear difference between the light sources (sunlight and LED), as the LED system would always show a higher negative cash flow and NPV than the sunlight system. According to the LCCA, the LED system would be economically impractical for industrial applications due to its high CAPEX and OPEX, whereas the sunlight system could be implemented in the industry after shortening its HRT and exploring other revenue-generating opportunities through further research. As a renewable energy source, the probable installation of a PV system was also considered in this study which reduced the OPEX for sunlight and LED systems for all the scenarios, hence showed better results in cash flow, NPV, and break-even point analysis in comparison to the scenarios where electricity supply from the grid was considered.

Freshwater production costs for all the scenarios were calculated. The LED system would generate 1,000 gallons of freshwater at a cost between $31.12 (1.5 days HRT with no grant) and $9.77 (0.5 days HRT with a 30% grant). On the contrary, the sunlight system would produce 1,000 gallons of freshwater between $5.33 (1.5 days HRT with no grant) and $0.02 (0.5 days HRT with a 30% grant). Considering the use of renewable energy (*i.e.*, solar PV) the freshwater production cost could be reduced to $1.02 for 0.5 days HRT without grant and $1.55 for 1.0 days HRT without any grants on the CAPEX. Further research could make the proposed PBR-secondary RO facility an economically feasible option if the HRT could be shortened to 1.0 and 0.5 days HRTs, reducing freshwater production costs as presented in this study by reducing the CAPEX and OPEX.

The impact of salt concentration on the silica removal from ROC by brackish water diatom was also investigated by performing photobiological treatment on a silica-rich water sample with a wide range of TDS (including 222, 1,000, 2,000, 4,000, 8,000, 16,000, 32,000 and 64,000 mg/L). The results from these experiments showed that the diatoms could remove silica from a wide range of TDS concentrations except for the samples with very low TDS (*i.e.*, 222 and 1,000 mg/L).

There were some unsolved questions and challenges that need further studies, such as:

- Feasibility of biofuel production from biomass needed to be investigated on the lab scale by utilizing high-temperature deconstruction processes (*e.g.*, hydrothermal liquefaction, pyrolysis, and gasification). Additionally, the production of pigments from biomass also needed to be considered in further studies to generate more revenue.
- Technical feasibility of the proposed 1.0- and 0.5-days HRT scenarios also demand further research to lower the overall cost of the proposed PBR-secondary RO facility.
- Cost analysis is required by considering other probable renewable energy sources (*e.g.*, wind turbine, hydro energy).
- Detailed carbon footprint by analyzing every electricity consumptive unit is required to perform to propose the plant as a green facility.
- To reduce the CAPEX of the LED system, chiller system could be considered for ventilation instead of a HVAC system.
- Underwater lighting could be considered for the PBRs in LED system which may reduce the power requirement cost.

APPENDIX SECTION

A. BIOMASS CHARACTERIZATION:

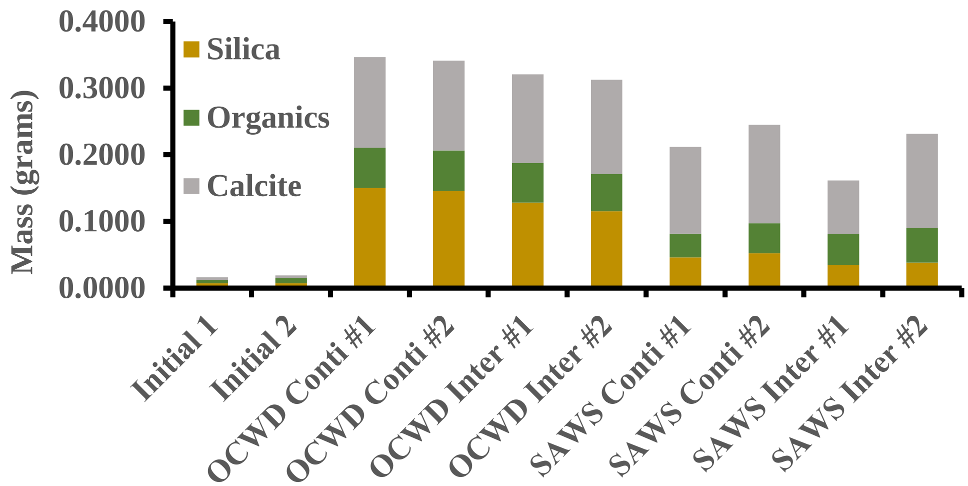


Figure 1: Silica. Calcite and Organics Proportions in OCWD and SAWS ROC for the Intermittent (12 hours a day) vs. Continuous Light (24 hours a day) Treatment Experiment

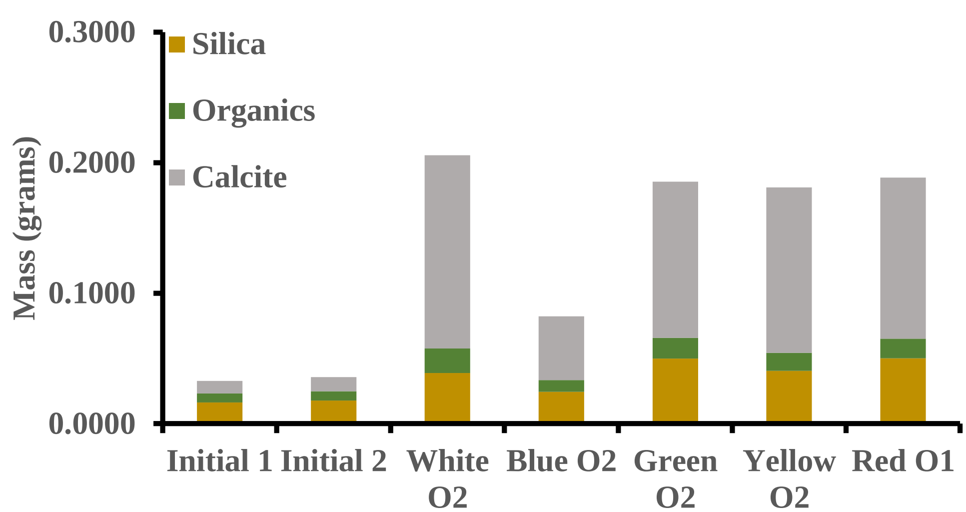


Figure 2: Silica. Calcite and Organics Proportions for the Light Color Experiment on OCWD ROC

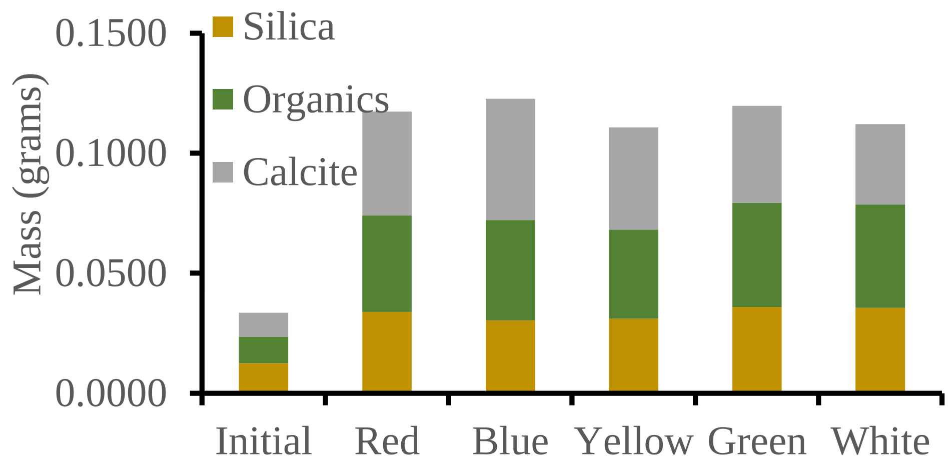


Figure 3: Silica. Calcite and Organics Proportions for the Light Color Experiment on OCWD ROC

B. PBR CONSTRUCTION COST BREAKDOWN

Table 1: PBR Construction Cost Breakdown for 1.0 Days HRT Scenario

PBR Cost Breakdown		
Costs	LED System	Sunlight System
Foundation cost	$850,052	$1,120,000
Construction cost	$1,200,000	$1,200,000
Engineering	$1,645,344	$1,063,288
Delivery	$82,267	$53,164
Clear cover	$79,692	$73,260
Total	$3,857,356	$3,509,713

Table 2: PBR Construction Cost Breakdown for 0.5 Days HRT Scenario

PBR Cost Breakdown		
Costs	LED System	Sunlight System
Foundation cost	$425,026	$640,000
Construction cost	$264,000	$425,538
Engineering	$1,134,124	$780,820
Delivery	$56,706	$39,041
Clear cover	$39,846	$39,894
Total	$1,919,702	$1,925,294

C. EVAPORATIVE COOLER DESIGN FOR THE SUNLIGHT SYSTEM

Table 3: Evaporative Cooler Design for the Sunlight System

Specification	0.5 days HRT	1.0 days HRT	1.5 days HRT
Total no. of greenhouse	12	22	36
Greenhouse length (ft)	144	144	144
Greenhouse width (ft)	40	40	40
Greenhouse height (ft)	15	15	15
Greenhouse total height (ft)	20	20	20
Gutter (width x height) ft^2	600	600	600
Ridge (width x total height in ft^2)	800	800	800
Gutter end wall (ft^2)	100	100	100
End wall area (ft^2)	700	700	700
Volume of air (ft^3)	100,800	100,800	100,800
Air change required (Cubic ft. per min.)	131,040	131,040	131,040
Using model 7500 D (CFM/ cooler)	7,500	7,500	7,500
Total number of cooler req/greenhouse	17	17	17
Total cooler req. for the sunlight system	210	384	629

D. AMBIENCE LIGHTING CALCULATION FOR THE LED AND SUNLIGHT SYSTEMS

Table 4: Ambience Lighting for the Sunlight and LED Systems with 1.5 Days HRT

Lighting calculation 1.5 days HRT		
Specifications	Sunlight	LED
Area/Greenhouse	5,760	N/A
Area/warehouse	N/A	360,000
Total area	207,360	360,000
Required illumination/greenhouse (watts)	1,188	N/A
Total illumination (watts)	42,768	94,500
Cost of one light of 25 W	$27.29	$27.29
Power of one light (watts)	25	25
Total no. of lights required	1,711	3,780
Total lighting cost	$42,768	$103,156

Table 5: Ambience Lighting for the Sunlight and LED Systems with 1.0 Days HRT

Lighting calculation 1.0 days HRT		
Specifications	Sunlight	LED
Area/Greenhouse	5,760	N/A
Area/warehouse	N/A	236,076
Total area	126,720	236,076
Required illumination/greenhouse (watts)	1,188	N/A
Total illumination (watts)	26,136	79,536
Cost of one light of 25 W	$27.29	$27.29
Power of one light (watts)	25	25
Total no. of lights required	1,045	3,181
Total lighting cost	$26,136	$86,821

Table 6: Ambience Lighting for the Sunlight and LED Systems with 0.5 Days HRT

Lighting calculation 0.5 days HRT		
Specifications	Sunlight	LED
Area/Greenhouse	5,760	N/A
Area/warehouse	N/A	143,698
Total area	69,120	143,698
Required illumination/greenhouse (watts)	1,188	N/A
Total illumination (watts)	14,256	48,540
Cost of one light of 25 W	$27.29	$27.29
Power of one light (watts)	25	25
Total no. of lights required	570	1,942
Total lighting cost	$14,256	$52,986

E. GREENHOUSE AND WAREHOUSE CONSTRUCTION COSTS

Table 7: Greenhouse and Warehouse Construction Costs for Sunlight and LED Systems with 1.0 Days HRT Scenario

Cost Item	**Sunlight System ($)**	**LED System ($)**
Engineering	197,925	235,870
Greenhouse	1,502,248	N/A
Foundation	174,000	1,886,960
Window and door	43,000	214,642
Toilet	13,350	13,350

Control room	30,000	30,000
Laboratory	200,000	200,000
Storage room	10,000	10,000
Industrial electrical room	100,000	100,000
Educational room	N/A	100,000
Conference room	N/A	50,000
Office room	50,000	50,000

Table 8: Greenhouse and Warehouse Construction Costs for Sunlight and LED Systems with 1.0 Days HRT Scenario

Cost Item	**Sunlight System ($)**	**LED System ($)**
Engineering	197,925	1,307,647
Greenhouse	819,408	N/A
Foundation	174,000	1,149,580
Window and door	30,000	130,765
Toilet	13,350	13,350
Control room	30,000	30,000
Laboratory	200,000	200,000
Storage room	10,000	10,000
Industrial electrical room	100,000	100,000
Educational room	N/A	100,000
Conference room	N/A	50,000

F. CHEMICAL DOSING CALCULATIONS

Table 9: Low pH and High pH CIP Solution Dosage Calculations for the Secondary RO

Low and High pH CIP dosage calculation			
Property	AWC C-227	AWC C-234	Unit
CIP tank	3,000.00	3,000.00	Gallons
Total cleaning solution	2,000.00	2,000.00	Gallons
Cleaning agent dosage	2%/wt.	2%/wt.	17 lb./100 gal of permeate
Permeate	1,960.00	1,960.00	Gallons
Cleaning agent required	333.20	333.20	lbs.
Cleaning agent required	39.93	39.93	Gallons
Sum	1,999.93	1,999.93	Gallons
Cost	478.00	334.00	$/per 5-gallon pail
Cost/cleaning	3,200.94	2,667.07	$

Cost/month	3,200.94	2,667.07	$
Cost/year	38,400.30	30,000.00	$
Cleaning agent required/ cleaning	39.93	39.93	Gallons

Table 10: Antiscalant Dosage Calculation for the Secondary RO

Antiscalant dosage calculation		
Name	**Property**	**Unit**
Name of chemical	AWC A-102 Ultra	N/A
Dosage	3	mg/L
Operational time	24	hrs./day
Volume of treated ROC	3,785,412	L/day
Chemical req.	11,356,236	mg/day
Chemical req.	25	lbs./day
Solution req.	3.00	gallons/day
Solution req.	20.98	gallons/week
Solution req.	251.80	gallons/2 months
Tank volume	302.16	gallons
Secondary containment volume	302.16	gallons
Consumption	9125	lbs./year
Unit cost	2.728	$/lbs.
Total cost/year	24,893.00	$

Table 11: Sulfuric Acid Dosage Calculation for the Secondary RO

Sulfuric acid dosage calculation	
Desired acid concentration (mg/L)	62.5
Total treated ROC volume (L)	3785412
Total acid required (mg)	236,588,250
Acid percentage in solution (%)	93
Acid concentration in solution (mg/L)	930,000
Solution required for ROC/day (L)	254.40

Table 12: Commercial Bleach Dosage Calculation for the Secondary RO

Commercial bleach dosage calculation	
Desired NaOCl (mg/L as Cl_2)	4
Total ROC volume (L)	3,785,412

Total NaOCl required (mg as Cl_2)	15,141,648
NaOCl percentage in bleach (%)	12.5
NaOCl concentration in bleach (mg/L as Cl_2)	125,000
Bleach required for ROC/day (L)	121.13

Table 13: Ammonium Sulfate Dosage Calculation for the Secondary RO

Ammonium sulfate dosage calculation	
Desired NH_3-N (mg/L)	0.75
Total ROC volume (L)	3,785,412
Total NH_3-N required (mg)	2,839,059
NH_3-N percentage in solution (%)	10.0
NH_3-N concentration in solution (mg/L)	100,000
Solution required for ROC/day (L)	28.39

Table 14: Nutrient Dosage Calculation for the PBR

Nutrient dosage calculation	
Dosage (mL/95 gal)	15
Feed water volume (gal/day)	1,000,000
Solution required (mL/day)	157,895
Solution required (L/day)	140
Solution required (gal/day)	35

G. PROFIT FROM BIORESOURCES CALCULATION

Table 15: Bioresources Production in 100-mL Scale

Silica and calcite production in 100-mL scale	
Sample	SAWS #2 200 PAR
Initial biomass (g)	0.0164
Final biomass (g)	0.1744
Experiment time (days)	8
Biomass production (grams/day)	0.0198
Silica (%)	30
Silica production (grams/day)	0.0059
Calcite (%)	35
Calcite production (grams/day)	0.0089

Table 16: Bioresources Production in 1.0 MGD Scale

Silica and calcite production in 1.0 MGD scale	
Sample	SAWS #2 200 PAR
Silica production (grams/day)	227,884.62
Silica production (kg/day)	227.88
Silica production (kg/year)	83,177.88
Silica production (metric ton/year)	83.18
Assuming 15% loss, gross production (metric ton/ year)	70.70
Calcite production (grams/day)	341,826.92
Calcite production (kg/day)	341.83
Calcite production (kg/year)	124,766.83
Calcite production (metric ton/year)	124.77
Assuming 25% loss, gross production (metric ton/ year)	93.58

Table 17: Biogas Production Rate Calculation

Biogas production rate calculation	
Scale 100 mL or 0.026 gal	
Biomass production (g/day)	0.02
Scale 1,000,000 gal	
Biomass production (g/day)	769,230.77
Biomass production (kg/day)	769.23
Organics (%)	40
Organics production (kg/day)	307.69
Organics production (kg/year)	112,307.69
Organics production (ton/year)	112.31
Biogas from organics (m^3/ton)	400.00
Total biogas production (m^3)	44,923.08
Electricity production (kWh/m^3 biogas)	6.96
Total electricity (kWh/year)	269,538.46

H. OPEX CALCULATION FOR THE SUNLIGHT SYSTEM

Table 18: Sunlight System OPEX for 1.0 Days HRT Scenario

Sunlight System OPEX for 1.0 days HRT	
Item	Cost
Total greenhouse lighting cost/year	$7,006
RO power cost/year	$107,470

Total power cost for cooler system/year	$67,137
PBR pump cost/year	$9,693
Chemical cost/year	$250,000
Total maintenance cost/year	$61,139
Other OPEX (chemical & parts)/year	$50,000
Labor/year	$456,000
Total OPEX	$900,000

Table 19: Sunlight System OPEX for 0.5 Days HRT Scenario

Sunlight System OPEX for 0.5 days HRT	
Item	Cost
Total greenhouse lighting cost/year	$3,821
RO power cost/year	$107,470
Total power cost for cooler system/year	$36,716
PBR pump cost/year	$9,652
Chemical cost/year	$250,000
Total maintenance cost/year	$44,897
Other OPEX (chemical & parts)/year	$50,000
Labor/year	$456,000
Total OPEX	$908,000

I. OPEX CALCULATION FOR THE LED SYSTEM

Table 20: LED System OPEX for 1.0 Days HRT Scenario

LED System OPEX cost 1.0 days HRT	
Item	Cost
Total power LED cost/year	$1,163,854
Total warehouse lighting cost/year	$14,214
RO power cost/year	$107,470
Total power cost for HVAC system/year	$661,420
PBR pump cost/year	$14,154
Chemical cost/year	$250,000
Total maintenance cost/year	$94,607
Other OPEX (chemical & parts/year	$50,000
Labor/year	$456,000
Total OPEX	$2,742,031

Table 21: LED System OPEX for 0.5 Days HRT Scenario

LED System OPEX cost 0.5 days HRT	
Item	Cost
Total power LED cost/year	$633,781
Total warehouse lighting cost/year	$7,087
RO power cost/year	$107,470
Total power cost for HVAC system/year	$460,600
PBR pump cost/year	$6,435
Chemical cost/year	$250,000
Maintenance cost equation/year	0.5% of CAPEX
Total maintenance cost/year	$65,212
Other OPEX (chemical & parts)/year	$50,000
Labor/year	$456,000
Total OPEX	$1,966,897

J. CASH FLOW ANALYSIS

Table 22: Cash Flow Analysis of Sunlight and LED Systems for 1.0 Days HRT

Year	1.0 days HRT scenario			
	Sunlight system		LED system	
	Without grant	With 30% grant	Without grant	With 30% grant
1	-$1,013,960	-$662,864	-$3,762,804	-$3,128,113
2	-$993,466	-$607,592	-$3,981,089	-$3,246,242
3	-$982,221	-$576,060	-$4,100,852	-$3,307,570
4	-$970,255	-$541,657	-$4,228,302	-$3,370,390
5	-$957,521	-$504,158	-$4,363,936	-$3,434,684
6	-$943,969	-$463,323	-$4,508,276	-$3,500,427
7	-$929,547	-$418,894	-$4,661,884	-$3,567,585
8	-$914,199	-$370,595	-$4,825,353	-$3,636,117
9	-$897,865	-$318,130	-$4,999,317	-$3,705,974
10	-$880,483	-$261,180	-$5,184,449	-$3,777,097
11	-$861,986	-$199,406	-$5,381,467	-$3,849,414
12	-$842,300	-$132,444	-$5,591,133	-$3,922,844
13	-$821,351	-$59,901	-$5,814,260	-$3,997,293
14	-$799,057	$18,640	-$6,051,712	-$4,072,653
15	-$775,332	$103,626	-$6,304,408	-$4,148,800
16	-$750,083	$195,539	-$6,573,327	-$4,225,594
17	-$723,214	$294,892	-$6,859,511	-$4,302,878
18	-$694,619	$402,234	-$7,164,068	-$4,380,474

19	-$664,189	$518,154	-$7,488,177	-$4,458,183
20	-$631,805	$643,283	-$7,833,094	-$4,535,785

Table 23: Cash Flow Analysis of Sunlight and LED Systems for 1.5 Days HRT

Year	1.5 days HRT scenario			
	Sunlight system		LED system	
	Without grant	With 30% grant	Without grant	With 30% grant
1	-$1,451,235	-$990,191	-$5,307,307	-$4,474,537
2	-$1,440,248	-$941,499	-$5,642,774	-$4,677,738
3	-$1,433,939	-$913,491	-$5,826,827	-$4,784,623
4	-$1,427,225	-$882,777	-$6,022,696	-$4,895,142
5	-$1,420,080	-$849,140	-$6,231,140	-$5,009,377
6	-$1,412,476	-$812,349	-$6,452,967	-$5,127,407
7	-$1,404,384	-$772,155	-$6,689,034	-$5,249,311
8	-$1,395,772	-$728,289	-$6,940,257	-$5,375,161
9	-$1,386,607	-$680,465	-$7,207,609	-$5,505,031
10	-$1,376,855	-$628,376	-$7,492,125	-$5,638,986
11	-$1,366,475	-$571,690	-$7,794,906	-$5,777,089
12	-$1,355,430	-$510,054	-$8,117,126	-$5,919,397
13	-$1,343,676	-$443,089	-$8,460,033	-$6,065,962
14	-$1,331,166	-$370,388	-$8,824,954	-$6,216,826
15	-$1,317,854	-$291,516	-$9,213,303	-$6,372,026
16	-$1,303,687	-$206,005	-$9,626,585	-$6,531,589
17	-$1,288,611	-$113,355	-$10,066,398	-$6,695,532
18	-$1,272,567	-$13,030	-$10,534,448	-$6,863,860
19	-$1,255,492	$95,543	-$11,032,547	-$7,036,566
20	-$1,237,322	$212,979	-$11,562,624	-$7,213,630

K. NPV ANALYSIS

Table 24: NPV Analysis of Sunlight and LED Systems for 1.0 Days HRT

Year	1.0 days HRT scenario			
	Sunlight system		LED system	
	Without grant	With 30% grant	Without grant	With 30% grant
1	-$953,149	-$623,110	-$3,537,135	-$2,940,509
2	-$877,875	-$536,899	-$3,517,888	-$2,868,540
3	-$815,886	-$478,507	-$3,406,388	-$2,747,445

4	-$757,611	-$422,945	-$3,301,612	-$2,631,723
5	-$702,827	-$370,055	-$3,203,158	-$2,521,082
6	-$651,325	-$319,686	-$3,110,646	-$2,415,245
7	-$602,908	-$271,697	-$3,023,720	-$2,313,952
8	-$557,392	-$225,954	-$2,942,044	-$2,216,961
9	-$514,602	-$182,333	-$2,865,305	-$2,124,039
10	-$474,375	-$140,715	-$2,793,205	-$2,034,971
11	-$436,556	-$100,990	-$2,725,466	-$1,949,552
12	-$401,003	-$63,054	-$2,661,828	-$1,867,589
13	-$367,578	-$26,807	-$2,602,044	-$1,788,900
14	-$336,154	$7,841	-$2,545,883	-$1,713,316
15	-$306,611	$40,980	-$2,493,128	-$1,640,675
16	-$278,836	$72,690	-$2,443,574	-$1,570,826
17	-$252,724	$103,049	-$2,397,030	-$1,503,624
18	-$228,174	$132,129	-$2,353,314	-$1,438,935
19	-$205,093	$160,000	-$2,312,258	-$1,376,633
20	-$183,393	$186,725	-$2,273,702	-$1,316,597

Table 25: NPV Analysis of Sunlight and LED Systems for 1.5 Days HRT

Year	**1.5 days HRT scenario**			
	Sunlight system		**LED system**	
	Without grant	**With 30% grant**	**Without grant**	**With 30% grant**
1	-$1,364,199	-$930,806	-$4,989,009	-$4,206,183
2	-$1,272,675	-$831,956	-$4,986,234	-$4,133,481
3	-$1,191,107	-$758,795	-$4,840,076	-$3,974,365
4	-$1,114,429	-$689,304	-$4,702,740	-$3,822,305
5	-$1,042,348	-$623,275	-$4,573,699	-$3,676,916
6	-$974,588	-$560,510	-$4,452,455	-$3,537,838
7	-$910,890	-$500,823	-$4,338,539	-$3,404,728
8	-$851,010	-$444,042	-$4,231,513	-$3,277,265
9	-$794,719	-$390,001	-$4,130,963	-$3,155,149
10	-$741,802	-$338,547	-$4,036,502	-$3,038,093
11	-$692,057	-$289,535	-$3,947,763	-$2,925,831
12	-$645,294	-$242,827	-$3,864,404	-$2,818,108
13	-$601,332	-$198,295	-$3,786,101	-$2,714,687
14	-$560,006	-$155,818	-$3,712,553	-$2,615,344
15	-$521,156	-$115,282	-$3,643,473	-$2,519,868
16	-$484,634	-$76,580	-$3,578,594	-$2,428,058

17	-$450,300	-$39,611	-$3,517,664	-$2,339,728
18	-$418,024	-$4,280	-$3,460,446	-$2,254,700
19	-$387,681	$29,502	-$3,406,717	-$2,172,806
20	-$359,156	$61,821	-$3,356,268	-$2,093,891

L. FRESHWATER PRODUCTION COSTS:

Table 26: LED System 1.5 Days HRT No Grant Scenario

LED system 1.5 days HRT no grant scenario				
Year	Cost ($)	Profit ($)	Unit cost ($/1,000 gal)	Average
1	6,418,307	1,111,000	$20.77	$31.12
2	6,901,005	1,258,232	$22.09	
3	7,165,837	1,339,010	$22.81	
4	7,447,671	1,424,974	$23.57	
5	7,747,598	1,516,458	$24.39	
6	8,066,781	1,613,814	$25.26	
7	8,406,456	1,717,421	$26.18	
8	8,767,937	1,827,680	$27.16	
9	9,152,626	1,945,017	$28.21	
10	9,562,011	2,069,887	$29.32	
11	9,997,680	2,202,774	$30.51	
12	10,461,318	2,344,192	$31.77	
13	10,954,722	2,494,689	$33.11	
14	11,479,802	2,654,848	$34.54	
15	12,038,592	2,825,289	$36.06	
16	12,633,257	3,006,673	$37.68	
17	13,266,099	3,199,701	$39.40	
18	13,939,570	3,405,122	$41.23	
19	14,656,278	3,623,731	$43.18	
20	15,418,998	3,856,374	$45.25	

Table 27: Sunlight System 1.5 Days HRT with a 30% Grant Scenario

Sunlight system 1.5 days HRT 30% grant scenario				
Year	Cost ($)	Profit ($)	Unit cost ($/1,000 gal)	Average
1	2,101,191	1,111,000	$3.88	$2.04
2	2,199,731	1,258,232	$3.68	
3	2,252,501	1,339,010	$3.58	
4	2,307,751	1,424,974	$3.46	

5	2,365,598	1,516,458	$3.32	
6	2,426,164	1,613,814	$3.18	
7	2,489,576	1,717,421	$3.02	
8	2,555,969	1,827,680	$2.85	
9	2,625,482	1,945,017	$2.66	
10	2,698,262	2,069,887	$2.46	
11	2,774,463	2,202,774	$2.24	
12	2,854,246	2,344,192	$2.00	
13	2,937,778	2,494,689	$1.73	
14	3,025,236	2,654,848	$1.45	
15	3,116,805	2,825,289	$1.14	
16	3,212,677	3,006,673	$0.81	
17	3,313,056	3,199,701	$0.44	
18	3,418,152	3,405,122	$0.05	
19	3,528,188	3,623,731	-$0.37	
20	3,643,395	3,856,374	-$0.83	

Table 28: LED System 1.5 Days HRT with a 30% Grant Scenario

LED system 1.5 days HRT 30% grant scenario				
Year	Cost ($)	Profit ($)	Unit cost ($/1,000 gal)	Average
1	5,585,537	1,111,000	$17.51	$22.59
2	5,935,969	1,258,232	$18.31	
3	6,123,633	1,339,010	$18.73	
4	6,320,116	1,424,974	$19.16	
5	6,525,835	1,516,458	$19.61	
6	6,741,222	1,613,814	$20.07	
7	6,966,732	1,717,421	$20.55	
8	7,202,841	1,827,680	$21.04	
9	7,450,047	1,945,017	$21.55	
10	7,708,873	2,069,887	$22.07	
11	7,979,862	2,202,774	$22.61	
12	8,263,589	2,344,192	$23.17	
13	8,560,650	2,494,689	$23.74	
14	8,871,674	2,654,848	$24.33	
15	9,197,315	2,825,289	$24.94	
16	9,538,262	3,006,673	$25.56	
17	9,895,233	3,199,701	$26.21	
18	10,268,982	3,405,122	$26.86	

19	10,660,297	3,623,731	$27.54	
20	11,070,004	3,856,374	$28.23	

Table 29: Sunlight System 1.0 Days HRT with a 30% Grant Scenario

Sunlight system 1.0 days HRT 30% grant				
Year	Cost ($)	Profit ($)	Unit cost ($/1,000 gal)	Average
1	1,774,377	1,111,000	$2.60	$0.58
2	1,866,386	1,258,232	$2.38	
3	1,915,659	1,339,010	$2.26	
4	1,967,248	1,424,974	$2.12	
5	2,021,261	1,516,458	$1.98	
6	2,077,813	1,613,814	$1.82	
7	2,137,023	1,717,421	$1.64	
8	2,199,016	1,827,680	$1.45	
9	2,263,922	1,945,017	$1.25	
10	2,331,879	2,069,887	$1.03	
11	2,403,030	2,202,774	$0.78	
12	2,477,525	2,344,192	$0.52	
13	2,555,522	2,494,689	$0.24	
14	2,637,184	2,654,848	-$0.07	
15	2,722,684	2,825,289	-$0.40	
16	2,812,203	3,006,673	-$0.76	
17	2,905,929	3,199,701	-$1.15	
18	3,004,061	3,405,122	-$1.57	
19	3,106,804	3,623,731	-$2.02	
20	3,214,377	3,856,374	-$2.51	

Table 30: LED System 1.0 Days HRT with a 30% Grant Scenario

LED system 1.0 days HRT 30% grant				
Year	Cost ($)	Profit ($)	Unit cost ($/1,000 gal)	Average
1	4,239,113	1,111,000	$12.24	$14.98
2	4,504,474	1,258,232	$12.71	
3	4,646,580	1,339,010	$12.95	
4	4,795,364	1,424,974	$13.19	
5	4,951,142	1,516,458	$13.44	
6	5,114,241	1,613,814	$13.70	
7	5,285,006	1,717,421	$13.96	

8	5,463,797	1,827,680	$14.23	
9	5,650,991	1,945,017	$14.50	
10	5,846,983	2,069,887	$14.78	
11	6,052,187	2,202,774	$15.07	
12	6,267,036	2,344,192	$15.35	
13	6,491,982	2,494,689	$15.64	
14	6,727,501	2,654,848	$15.94	
15	6,974,089	2,825,289	$16.24	
16	7,232,266	3,006,673	$16.54	
17	7,502,579	3,199,701	$16.84	
18	7,785,595	3,405,122	$17.14	
19	8,081,914	3,623,731	$17.45	
20	8,392,159	3,856,374	$17.75	

Table 31: Sunlight System 1.0 Days HRT No Grant Scenario

Sunlight system 1.0 days HRT no grant				
Year	Cost ($)	Profit ($)	Unit cost ($/1,000 gal)	Average
1	2,124,960	1,111,000	$3.97	$3.34
2	2,251,697	1,258,232	$3.89	
3	2,321,231	1,339,010	$3.84	
4	2,395,230	1,424,974	$3.80	
5	2,473,979	1,516,458	$3.75	
6	2,557,783	1,613,814	$3.69	
7	2,646,968	1,717,421	$3.64	
8	2,741,878	1,827,680	$3.58	
9	2,842,882	1,945,017	$3.51	
10	2,950,370	2,069,887	$3.45	
11	3,064,759	2,202,774	$3.37	
12	3,186,492	2,344,192	$3.30	
13	3,316,040	2,494,689	$3.21	
14	3,453,905	2,654,848	$3.13	
15	3,600,621	2,825,289	$3.03	
16	3,756,756	3,006,673	$2.94	
17	3,922,914	3,199,701	$2.83	
18	4,099,741	3,405,122	$2.72	
19	4,287,919	3,623,731	$2.60	
20	4,488,179	3,856,374	$2.47	

Table 32: LED System 1.0 Days HRT No Grant Scenario

LED system 1.0 days HRT no grant				
Year	Cost ($)	Profit ($)	Unit cost ($/1,000 gal)	Average
1	4,873,804	1,111,000	$14.73	$21.46
2	5,239,321	1,258,232	$15.58	
3	5,439,862	1,339,010	$16.05	
4	5,653,277	1,424,974	$16.55	
5	5,880,393	1,516,458	$17.08	
6	6,122,091	1,613,814	$17.64	
7	6,379,305	1,717,421	$18.25	
8	6,653,033	1,827,680	$18.89	
9	6,944,334	1,945,017	$19.57	
10	7,254,336	2,069,887	$20.29	
11	7,584,241	2,202,774	$21.06	
12	7,935,325	2,344,192	$21.88	
13	8,308,949	2,494,689	$22.76	
14	8,706,560	2,654,848	$23.69	
15	9,129,697	2,825,289	$24.67	
16	9,580,000	3,006,673	$25.73	
17	10,059,212	3,199,701	$26.85	
18	10,569,189	3,405,122	$28.04	
19	11,111,908	3,623,731	$29.31	
20	11,689,468	3,856,374	$30.66	

Table 33: Sunlight System 0.5 Days HRT with a 30% Grant Scenario

Sunlight System 0.5 days HRT with grant					
Year	Cost	Profit	Cn	Unit cost ($/1,000 gal)	Average
1	$1,527,631	$957,639	$569,993	$2.23	-$0.05
2	$1,622,605	$1,084,546	$538,059	$2.11	
3	$1,673,466	$1,154,174	$519,292	$2.03	
4	$1,726,717	$1,228,272	$498,445	$1.95	
5	$1,782,471	$1,307,127	$475,343	$1.86	
6	$1,840,845	$1,391,045	$449,800	$1.76	
7	$1,901,963	$1,480,350	$421,613	$1.65	
8	$1,965,953	$1,575,389	$390,565	$1.53	
9	$2,032,951	$1,676,528	$356,422	$1.39	
10	$2,103,098	$1,784,162	$318,936	$1.25	
11	$2,176,541	$1,898,705	$277,837	$1.09	

12	$2,253,437	$2,020,602	$232,835	$0.91	
13	$2,333,947	$2,150,324	$183,622	$0.72	
14	$2,418,240	$2,288,375	$129,865	$0.51	
15	$2,506,496	$2,435,289	$71,207	$0.28	
16	$2,598,899	$2,591,634	$7,265	$0.03	
17	$2,695,645	$2,758,017	-$62,372	-$0.24	
18	$2,796,939	$2,935,082	-$138,143	-$0.54	
19	$2,902,993	$3,123,514	-$220,521	-$0.86	
20	$3,014,032	$3,324,044	-$310,012	-$1.21	

Table 34: LED System 0.5 Days HRT with a 30% Grant Scenario

LED system 0.5 days HRT grant					
Year	Cost ($)	Profit ($)	Cn ($)	Unit cost ($/1,000 gal)	Average
1	2,849,327	957,639	1,891,688	$7.40	$8.94
2	3,047,932	1,084,546	1,963,385	$7.68	
3	3,154,289	1,154,174	2,000,115	$7.83	
4	3,265,645	1,228,272	2,037,373	$7.97	
5	3,382,235	1,307,127	2,075,107	$8.12	
6	3,504,304	1,391,045	2,113,259	$8.27	
7	3,632,110	1,480,350	2,151,760	$8.42	
8	3,765,924	1,575,389	2,190,535	$8.57	
9	3,906,027	1,676,528	2,229,498	$8.73	
10	4,052,714	1,784,162	2,268,553	$8.88	
11	4,206,296	1,898,705	2,307,591	$9.03	
12	4,367,096	2,020,602	2,346,495	$9.18	
13	4,535,454	2,150,324	2,385,130	$9.34	
14	4,711,725	2,288,375	2,423,350	$9.48	
15	4,896,280	2,435,289	2,460,991	$9.63	
16	5,089,510	2,591,634	2,497,875	$9.78	
17	5,291,821	2,758,017	2,533,804	$9.92	
18	5,503,641	2,935,082	2,568,559	$10.05	
19	5,725,416	3,123,514	2,601,902	$10.18	
20	5,957,615	3,324,044	2,633,571	$10.31	

Table 35: Sunlight System 0.5 Days HRT No Grant Scenario

Sunlight system 0.5 days HRT no grant					
Year	Cost ($)	Profit ($)	Cn ($)	Unit cost ($/1,000 gal)	Average
1	1,759,260	957,639	801,622	$3.14	$3.26
2	1,890,081	1,084,546	805,535	$3.15	
3	1,961,856	1,154,174	807,681	$3.16	
4	2,038,238	1,228,272	809,966	$3.17	
5	2,119,525	1,307,127	812,397	$3.18	
6	2,206,030	1,391,045	814,985	$3.19	
7	2,298,088	1,480,350	817,738	$3.20	
8	2,396,057	1,575,389	820,669	$3.21	
9	2,500,316	1,676,528	823,787	$3.22	
10	2,611,267	1,784,162	827,106	$3.24	
11	2,729,342	1,898,705	830,637	$3.25	
12	2,854,998	2,020,602	834,396	$3.27	
13	2,988,720	2,150,324	838,396	$3.28	
14	3,131,027	2,288,375	842,652	$3.30	
15	3,282,471	2,435,289	847,182	$3.32	
16	3,443,637	2,591,634	852,003	$3.33	
17	3,615,150	2,758,017	857,133	$3.35	
18	3,797,674	2,935,082	862,592	$3.38	
19	3,991,916	3,123,514	868,402	$3.40	
20	4,198,629	3,324,044	874,585	$3.42	

Table 36: LED System 0.5 Days HRT No Grant Scenario

LED system 0.5 days HRT no grant					
Year	Cost ($)	Profit ($)	Cn ($)	Unit cost ($/1,000 gal)	Average
1	3,185,762	957,639	2,228,123	$8.72	$13.26
2	3,459,327	1,084,546	2,374,781	$9.29	
3	3,609,419	1,154,174	2,455,245	$9.61	
4	3,769,147	1,228,272	2,540,875	$9.94	
5	3,939,129	1,307,127	2,632,002	$10.30	
6	4,120,024	1,391,045	2,728,979	$10.68	
7	4,312,532	1,480,350	2,832,182	$11.08	
8	4,517,400	1,575,389	2,942,011	$11.51	
9	4,735,420	1,676,528	3,058,892	$11.97	
10	4,967,437	1,784,162	3,183,275	$12.46	
11	5,214,349	1,898,705	3,315,644	$12.98	
12	5,477,113	2,020,602	3,456,512	$13.53	

13	5,756,747	2,150,324	3,606,423	$14.12	
14	6,054,333	2,288,375	3,765,958	$14.74	
15	6,371,024	2,435,289	3,935,735	$15.40	
16	6,708,047	2,591,634	4,116,413	$16.11	
17	7,066,706	2,758,017	4,308,689	$16.86	
18	7,448,392	2,935,082	4,513,310	$17.66	
19	7,854,581	3,123,514	4,731,067	$18.52	
20	8,337,823	3,324,044	5,013,780	$19.62	

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Table 37: Sunlight System 0.5 Days HRT with a 30% Grant Scenario and PV

Sunlight system 0.5 days HRT grant					
Year	Cost ($)	Profit ($)	Cn ($)	Unit cost ($/1,000 gal)	Average
1	1,363,519	957,639	405,880	$1.59	-$0.33
2	1,436,111	1,084,546	351,565	$1.38	
3	1,474,986	1,154,174	320,811	$1.26	
4	1,515,687	1,228,272	287,415	$1.12	
5	1,558,302	1,307,127	251,175	$0.98	
6	1,602,920	1,391,045	211,875	$0.83	
7	1,649,634	1,480,350	169,284	$0.66	
8	1,698,545	1,575,389	123,156	$0.48	
9	1,749,754	1,676,528	73,225	$0.29	
10	1,803,369	1,784,162	19,208	$0.08	
11	1,859,505	1,898,705	-39,200	-$0.15	
12	1,918,279	2,020,602	-102,322	-$0.40	
13	1,979,816	2,150,324	-170,509	-$0.67	
14	2,044,244	2,288,375	-244,131	-$0.96	
15	2,111,701	2,435,289	-323,587	-$1.27	
16	2,182,329	2,591,634	-409,306	-$1.60	
17	2,256,275	2,758,017	-501,742	-$1.96	
18	2,333,698	2,935,082	-601,384	-$2.35	
19	2,414,759	3,123,514	-708,755	-$2.77	

20	2,499,630	3,324,044	- 824,414	-$3.23	

Table 38: Sunlight System 0.5 Days HRT no Grant Scenario and PV

Sunlight System 0.5 days HRT no grant					
Year	Cost ($)	Profit ($)	Cn ($)	Unit cost ($/1,000 gal)	Average ($)
1	1,624,515	957,639	666,877	2.61	
2	1,724,507	1,084,546	639,960	2.50	
3	1,779,367	1,154,174	625,192	2.45	
4	1,837,749	1,228,272	609,476	2.39	
5	1,899,879	1,307,127	592,751	2.32	
6	1,965,998	1,391,045	574,953	2.25	
7	2,036,362	1,480,350	556,012	2.18	
8	2,111,243	1,575,389	535,854	2.10	
9	2,190,931	1,676,528	514,403	2.01	
10	2,275,736	1,784,162	491,574	1.92	1.78
11	2,365,985	1,898,705	467,280	1.83	
12	2,462,028	2,020,602	441,426	1.73	
13	2,564,237	2,150,324	413,913	1.62	
14	2,673,008	2,288,375	384,632	1.51	
15	2,788,761	2,435,289	353,473	1.38	
16	2,911,947	2,591,634	320,312	1.25	
17	3,043,040	2,758,017	285,023	1.12	
18	3,182,550	2,935,082	247,468	0.97	
19	3,331,017	3,123,514	207,503	0.81	
20	3,489,015	3,324,044	164,971	0.65	

Table 39: Sunlight System 1.0 Days HRT with a 30% Grant Scenario and PV

Sunlight System 1.0 days HRT with PV					
Year	Cost	Profit	Cn	Unit cost ($/1,000 gal)	Average
1	1,487,848	957,639	530,209	2.08	
2	1,554,191	1,084,546	469,644	1.84	
3	1,589,718	1,154,174	435,544	1.70	
4	1,626,916	1,228,272	398,644	1.56	-0.02
5	1,665,862	1,307,127	358,735	1.40	
6	1,706,638	1,391,045	315,593	1.24	
7	1,749,331	1,480,350	268,981	1.05	

8	1,794,031	1,575,389	218,642	0.86	
9	1,840,831	1,676,528	164,302	0.64	
10	1,889,831	1,784,162	105,669	0.41	
11	1,941,134	1,898,705	42,429	0.17	
12	1,994,848	2,020,602	-25,754	-0.10	
13	2,051,086	2,150,324	-99,238	-0.39	
14	2,109,968	2,288,375	-178,407	-0.70	
15	2,171,618	2,435,289	-263,671	-1.03	
16	2,236,165	2,591,634	-355,470	-1.39	
17	2,303,745	2,758,017	-454,272	-1.78	
18	2,374,502	2,935,082	-560,580	-2.19	
19	2,448,584	3,123,514	-674,930	-2.64	
20	2,526,149	3,324,044	-797,895	-3.12	

Table 40: Sunlight System 1.0 Days HRT no Grant Scenario and PV

Sunlight system 1.0 days HRT no grant					
Year	Cost	Profit	Cn	Unit cost ($/1,000 gal)	Average
1	1,829,968	957,639	872,329	3.41	2.32
2	1,921,351	1,084,546	836,804	3.28	
3	1,971,488	1,154,174	817,313	3.20	
4	2,024,844	1,228,272	796,571	3.12	
5	2,081,625	1,307,127	774,497	3.03	
6	2,142,051	1,391,045	751,006	2.94	
7	2,206,357	1,480,350	726,007	2.84	
8	2,274,792	1,575,389	699,403	2.74	
9	2,347,620	1,676,528	671,091	2.63	
10	2,425,123	1,784,162	640,962	2.51	
11	2,507,603	1,898,705	608,898	2.38	
12	2,595,377	2,020,602	574,775	2.25	
13	2,688,787	2,150,324	538,462	2.11	
14	2,788,193	2,288,375	499,818	1.96	
15	2,893,981	2,435,289	458,693	1.80	
16	3,006,561	2,591,634	414,927	1.62	

17	3,126,369	2,758,017	368,352	1.44	
18	3,253,868	2,935,082	318,786	1.25	
19	3,389,553	3,123,514	266,039	1.04	
20	3,533,948	3,324,044	209,904	0.82	

Table 41: Sunlight System 1.5 Days HRT with a 30% Grant Scenario and PV

Sunlight System 1.5 days HRT grant					
Year	Cost ($)	Profit ($)	Cn ($)	Unit cost ($/1,000 gal)	Average ($)
1	1,774,950	957,639	817,312	3.20	1.16
2	1,843,326	1,084,546	758,780	2.97	
3	1,879,943	1,154,174	725,768	2.84	
4	1,918,280	1,228,272	690,008	2.70	
5	1,958,420	1,307,127	651,293	2.55	
6	2,000,446	1,391,045	609,401	2.39	
7	2,044,447	1,480,350	564,097	2.21	
8	2,090,517	1,575,389	515,128	2.02	
9	2,138,751	1,676,528	462,223	1.81	
10	2,189,253	1,784,162	405,091	1.59	
11	2,242,128	1,898,705	343,423	1.34	
12	2,297,489	2,020,602	276,887	1.08	
13	2,355,451	2,150,324	205,127	0.80	
14	2,416,137	2,288,375	127,762	0.50	
15	2,479,676	2,435,289	44,387	0.17	
16	2,546,201	2,591,634	-45,433	-0.18	
17	2,615,853	2,758,017	-142,164	-0.56	
18	2,688,778	2,935,082	-246,303	-0.96	
19	2,765,131	3,123,514	-358,383	-1.40	
20	2,845,073	3,324,044	-478,971	-1.87	

Table 42: Sunlight System 1.5 Days HRT no Grant Scenario and PV

Sunlight System 1.5 days HRT no grant					
Year	Cost ($)	Profit ($)	Cn ($)	Unit cost ($/1,000 gal)	Average ($)
1	2,231,056	957,639	1,273,418	4.98	3.97

2	2,325,240	1,084,546	1,240,693	4.86	
3	2,376,914	1,154,174	1,222,739	4.79	
4	2,431,905	1,228,272	1,203,632	4.71	
5	2,490,426	1,307,127	1,183,299	4.63	
6	2,552,705	1,391,045	1,161,660	4.55	
7	2,618,982	1,480,350	1,138,632	4.46	
8	2,689,513	1,575,389	1,114,125	4.36	
9	2,764,573	1,676,528	1,088,045	4.26	
10	2,844,452	1,784,162	1,060,291	4.15	
11	2,929,459	1,898,705	1,030,755	4.03	
12	3,019,924	2,020,602	999,322	3.91	
13	3,116,196	2,150,324	965,872	3.78	
14	3,218,649	2,288,375	930,274	3.64	
15	3,327,680	2,435,289	892,391	3.49	
16	3,443,710	2,591,634	852,076	3.33	
17	3,567,190	2,758,017	809,172	3.17	
18	3,698,596	2,935,082	763,515	2.99	
19	3,838,440	3,123,514	714,925	2.80	
20	3,987,261	3,324,044	663,217	2.60	

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