UNIVERSITY OF CALIFORNIA, IRVINE

Energy, Cost, and Carbon Footprint Analysis of a Solar-Powered Mixer in a Facultative Lagoon for Wastewater Treatment

THESIS

submitted in partial satisfaction of the requirements
for the degree of

MASTER OF SCIENCE

in Engineering,
with a concentration in Environmental Engineering
by

Yuyuan Jiang

Thesis Committee:
Professor Diego Rosso, Chair
Professor Sunny Jiang
Professor Soroosh Sorooshian

2015

TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

ACKNOWLEDGEMENTS

I would like to express my deepest appreciation cordially to my committee chair, Professor Diego Rosso. I am thankful for his invaluably constructive criticism and friendly advice during the whole process of this project. I would not be able to achieve this project without his guidance and support.

I would also like to thank Mr. Brian Bebee (from Inyokern Community Services District) and Mr. Al Mendoza (from Southern California Edison). The samples and data they provided make a very good foundation for my research.

In addition, I would like to express my great gratitude to my committee members, Professor Sunny Jiang and Professor Soroosh Sorooshian for their support and guidance.

Finally, I am using this opportunity to express my gratitude for the chance to study at UC Irvine. I would like to dedicate this thesis to myself and my family as a gift to commemorate the accomplishment of my Master’s study.

ABSTRACT OF THE THESIS

Energy, Cost, and Carbon Footprint Analysis of a Solar-Powered Mixer

in a Facultative Lagoon for Wastewater Treatment

By

Yuyuan Jiang

Master of Science in Engineering,

with a concentration in Environmental Engineering

University of California, Irvine, 2014

Professor Diego Rosso, Chair

Lagoon treatment is common in small communities and/or rural areas where land is available. Mixing is the energy driver for this kind of treatment. Mixing could re-suspend the settled solids and oxidize matters at the surface in contact with atmosphere air. Traditionally, the mixer for lagoon treatment is mechanical mixer that gets power from grid. Recently, with the decreasing price of photovoltaic batteries, the solar powered mixers are posed to replace the traditional grid-powered mechanical mixers. As the aeration process is the most energy intensive process, transitioning the mixers off-grid means that the energy demand will be sharply reduced, which in turn reduces the process energy importation. In this research we studied the comparative scenarios of an existing grid-powered mechanical mixer and a solar-powered mixer. Testing campaign was conducted to monitor the water quality, energy consumption and carbon emission changes to evaluate the feasibility to use off-grid solar-powered mixer in lagoon treatment. In each test, water quality was tested in field to guarantee the performance of the solar-powered mixer. The energy usage was recorded with the electrical energy monitor by the wastewater treatment utility. The result shows that after the replacement, both energy usage and cost have a significant reduction, the energy usage having decreased by 70% and the cost by 47%. Additionally, carbon-equivalent emission from electricity importation dropped by 64%, with an effect on the overall carbon emissions (i.e., including all other contributions from the process) decreasing from 3.5% to 1.3%. The studied solar-powered mixer is adequate to replace the existing mechanical mixer and is an energy and carbon-emission conservation alternative.

1. INTRODUCTION

In rural areas and/or small communities, affordable and reliable wastewater treatment has become a challenge in many parts of the world, especially in developing countries (Massoud et al., 2009). To cope with this problem, there are two strategies: one is centralized fully built wastewater treatment infrastructure, with aerated biological processes; the other is decentralized treatment infrastructure involving natural treatment systems, such as facultative lagoons (Bdour et al., 2009).

The limitations and problems for installing fully built plants in rural areas and/or small communities are progressively obvious. As the population densities are low and the households are sporadic, constructing a fully built wastewater treatment plant becomes costly both as capital and operating costs (Crites, 2006). In the fully built wastewater treatment plant, the diffused aeration system and activated sludge process are energy-intensive and are responsible for a large portion of the treatment's energy- and carbon- footprints. However, solar power is becoming one of the most promising renewable energy sources and solar cells can be used as auxiliary or supplemental power sources for wastewater treatment plants to help reduce energy importation and carbon emissions (US EPA, 2013).

For the second strategy, embedded the natural systems in decentralized plants are strongly sought after in rural and/or isolated areas. Even though the land requirement is larger than conventional full built wastewater treatment plants, these treatment systems are less resource-intensive and may be more ecologically sustainable (Anagnostopoulos and Vavatsikos, 2012; Ghirardini et al., 2012). In areas where labor and energy costs are a constraint, natural treatment systems pose as even more attractive alternatives. Among the natural treatment systems, lagoon treatment has long been recognized as the most inexpensive method (per unit load removed) of treating domestic wastewater in rural area and/or small communities (Gloyna, 1971).

For facultative wastewater lagoons, the energy driver is usually mixing. Mixing provides both re-suspension of the settled solids and oxygenation at the surface of wastewater in contact with atmospheric air (Agunwamba, 1992). There are two general categories for lagoon aeration systems to conduct mixing. One is surface aeration, characterized by mechanical mixers floating on the surface of the water to shear the surface of the lagoon in small droplets, the other is subsurface impeller that shears air being drafted from above the water surface (Aberley et al., 1974; Salter, 2000). There exist lagoons equipped with bubble diffusers, however these are the minority since they require a degree of engineering comparable to fully built treatment plants (Metcalf and Eddy, 2014).

Traditionally, lagoon mixers are on-grid units that intensively consume electricity to operate (Rich, 1980). In recent years, with the decrease of photovoltaic units, solar-powered mixers began to emerge on the market. These units are typically equipped with low power motors. Therefore, the solar-powered mixers became suitable for lagoons and other installation where gentle mixing was appropriate. For example, these installations could be water storage tanks where gentle mixing brings the bulk liquid in contact with the air surface periodically. Given their reliance on solar power, and given that the majority of power is generated employing fossil fuels, these off-grid mixers could be both an energy and carbon-emission conservation option.

The goal of this project was to test and evaluate a solar-powered mixer as complement or replacement of existing grid-powered mechanical mixers at a wastewater treatment lagoon for a small community. Water quality was field-tested to guarantee that the process performance could be compared to the former performance with mechanical mixers. Energy consumption and carbon emissions from imported power were calculated and analyzed, representing a substantial reduction after the installation of solar-powered mixer.

2. BACKGROUND

2.1 Lagoon

2.1.1 Lagoon Treatment

Lagoon treatment is the most popular and simplest treatment, using natural and energy-efficient processes to provide low-cost wastewater treatment (NESC, 1997). The lagoon treatment generally costs less than half as much as other treatment methods and requires a minimum of maintenance, which makes lagoon treatment especially suitable for small communities where lack of budget for treatment structures but land is available (US EPA, 1992, 2011). In the U.S., approximately 90% of the wastewater lagoons serve communities of 10,000 or less (Falkdenborg *et al.*, 1974; Wolverton and McDonald, 1979; Bringolf, 2003; Anagnostopoulos and Vavatsikos, 2012).

2.1.2 Facultative Lagoon

In general, the domestic wastewater lagoons can be classified into three categories: anaerobic, aerobic, and facultative lagoons. In the southern United States the most commonly used design is facultative wastewater lagoon. (Oswald, 1963; Gloyna, 1971; Metcalf and Eddy, 2014). The facultative lagoons combine the features of anaerobic and aerobic ponds, as shown in Figure 2.1. The layer of water near the surface contains dissolved oxygen due to atmospheric re-aeration and algal respiration, providing a condition that accommodates aerobic and facultative organisms. The bottom layer of the lagoon lacks oxygen and includes sludge deposits and supports anaerobic organisms. The transitional anoxic layer, termed the facultative zone, ranges from aerobic near the top to anaerobic at the bottom. (Muga and Mihelcic, 2008; Moradhassel and Mohamadi, 2014)

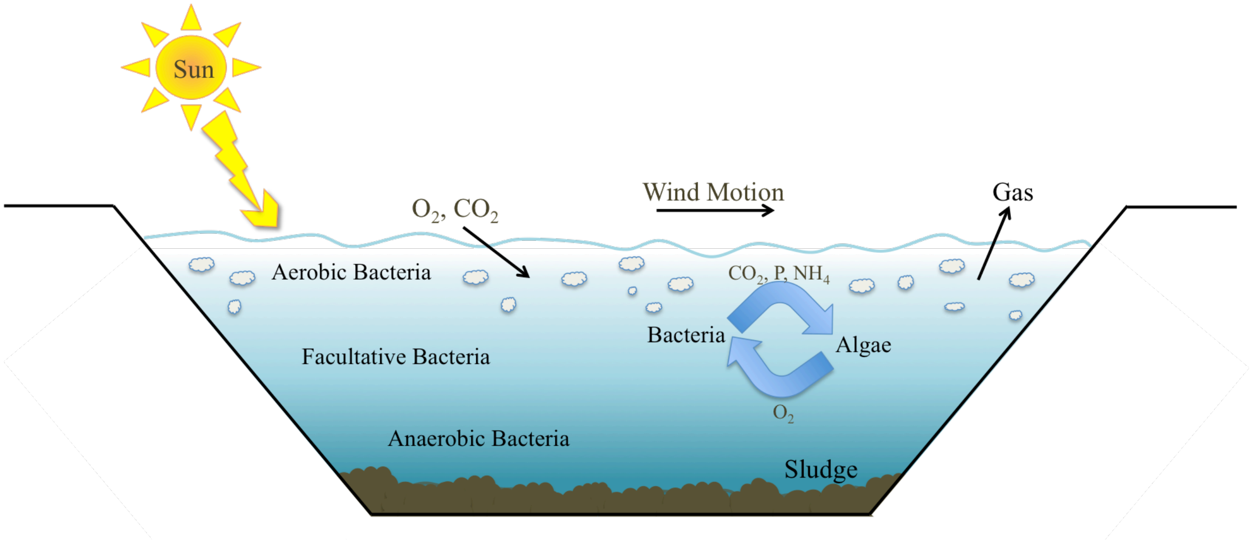


Figure 2.1 Illustration of a Facultative Lagoon

The facultative lagoons are easy and reliable to operate, ordinarily have detention times of 5-30 days (Reed *et al.*, 1995). BOD_5 removal could be count on up to 85%, but the TSS range may over the limit of 150mg/l. During warm weather, the removal of ammonia nitrogen can up to 80%. However, in the winter season, the 80% removal cannot be sustained, referable lower temperature could decelerate the nitrification rate while the phosphorus precipitation reactions occurring simultaneously with high pH condition. In spite of that, phosphorus removal can be significant, about 50%. (Houweling *et al.*, 2008; Metcalf and Eddy, 2014; Hurse, 1999) Further, with heedful design, the facultative lagoons could reduce the detention time to 10-15 days while still perform the high removal of pathogens (Oakley, 2005).

2.1.3 Advantages and Disadvantages of Lagoon Treatment

The main advantages for the lagoon processes are their ability to handle a wide range of waste characteristics including solids and oils (Metcalf and Eddy, 2014). Then, lagoons can provide open access to communities along with possessing a low user cost and less odor issues while assuring sufficient removal of organic matters, TSS, nitrogen and phosphorus (Muga and Mihelcic, 2008). The other benefits come from lagoons are the one of the simplest and most energy conservative construction (Metcalf and Eddy, 2014), effective at removing disease-causing pathogens from wastewater (NESC, 1997), providing a high effluent quality (Nameche *et al.*, 1998) and less intensity of maintenance (US EPA, 2002).

Disadvantages including the less efficient in cold climates, and potential feed flow inadequate distribution, ineffectual at removing heavy metals from wastewater (NESC, 1997). Also, high demand of large flat arable land is inaccessible for many areas, as well as the loss of valuable methane to the atmosphere (Bdour *et al.*, 2009).

2.2 Lagoon Aeration

According to the EPA 2002 Wastewater Technology Factsheet (US EPA, 2002), the purpose of aeration in wastewater treatment is twofold: the first is to provide the required oxygen to the metabolizing microorganisms; the second is to provide mixing to help microorganisms contact with the dissolved and suspended organic matter. Contemporaneously, these two purposes are also the foremost consideration when evaluating lagoon aeration technologies.

Commonly, there are two general categories for lagoon aeration systems: surface aeration and diffused aeration, are conducted by surface mixer/aerator and submerged aerator (usually is diffused aeration system), respectively. We mainly discuss the surface aeration in this thesis. The mixer used before in the studied lagoon is surface mechanical mixer; the newly installed mixer is surface solar-powered mixer.

2.2.1 Surface Mechanical Mixer

Surface mechanical mixers aerate and mix liquid using submerged or partially submerged impellers that are affixed to motor mounted on floats. The impellers rapidly move surrounding wastewater to produce water circulation and causes surface disturbance, thereby enhancing oxygen transformation to water.

The advantage of surface mixers/aerators is that they are less expensive and easy to install than a diffused aeration system by simply floating the aerator to a specific location. However, mechanical surface mixers/aerators are regarded as less energy efficient than fine-pore diffusers (US EPA, 2002).

There are also two distinct disadvantages for surface mechanical mixers/aerators. First, surface mixers/aerators do not perform well to mix deeper than 6 feet (~1.8m) below the water surface. Hence, the sludge accumulation inevitably occurs at the pond bottom, depriving the active volume of lagoon and reducing the retention time of treatment process (Cumby, 1987). Secondly, surface mechanical aerators have high maintenance requirements, despite their immunity from fouling (Boyd, 1998). Nowadays, mechanical aerators are still utilized at thousands of wastewater facilities worldwide, but are losing ground to other technological options with higher efficiency and lower maintenance requirements (Hill, 2013).

2.2.2 Solar-powered Aerators

Solar power is one of the most promising renewable energy sources today. Solar cells, also known as photovoltaic cells, can be used as auxiliary or supplemental power sources for wastewater treatment plants. (EPA, 2013). The benefits of using solar-powered mixer/aerators are the same as on-grid mixers (e.g., reduction of BOD, TSS, and ammonia from the influent) and add the reduction of greenhouse gas emission during operation.

2.3 Energy Footprint of Wastewater Treatment

2.3.1 Built Treatment Plants

Even though energy footprint may vary significantly in different wastewater treatment plant depending on its location, operation mode and the type of treatment process selected, aeration and pumping of wastewater are the most energy-intensive processes in conventional wastewater treatment plant. The energy footprint of aeration process usually accounts for 45% to 75% of the whole process energy cost (Reardon, 1995). The influent wastewater pumping energy could represent about 15% to 70% of operations' energy footprint, depending on the WWTPs site elevation and influent sewer elevation (Water Environment Federation, 2009). Commonly, conventional lagoon treatments are least energy intensive. Advanced treatment processes often more energy consuming, including primary energy usage and chemical additions associated with secondary energy usage. Figure 2.2 shows the typical annual energy footprint for different types of treatment processes, with 10MGD secondary flow.

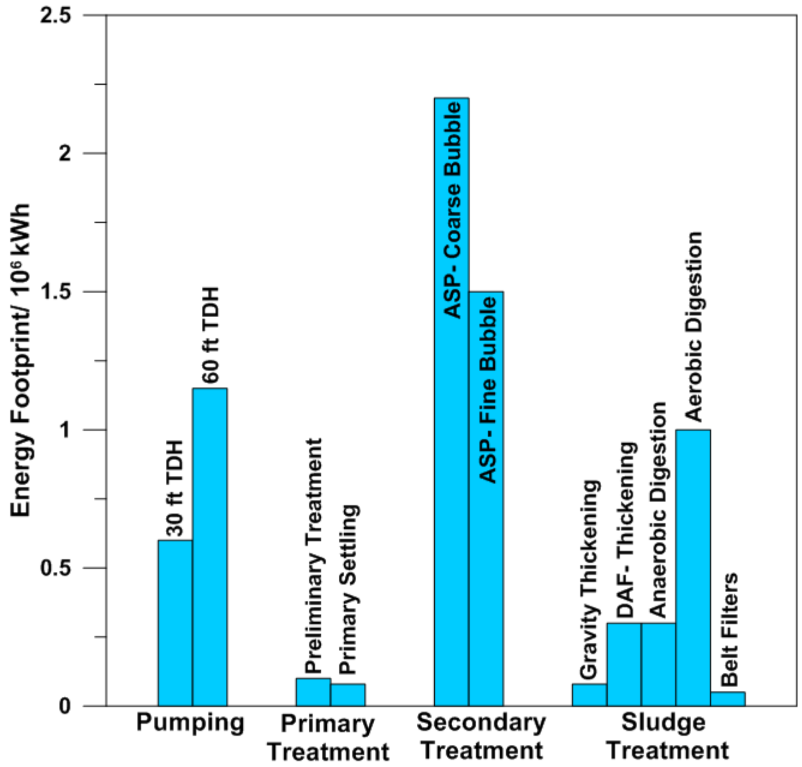


Figure 2.2 Typical Annual Energy Footprint Profiles for 10MGD Secondary Flow

The huge energy consumption in pumping and aeration sludge treatment means it will have significant margin for improvement in terms of energy footprint (Rosso and Stenstrom, 2008), as we studied.

2.3.2 Lagoons

Energy footprint of lagoon is less studied and more simplified than built wastewater treatment plant (Water Environment Federation, 2009). Table 2.2 gives the comparison between the studies of WWTPs energy footprint and lagoon treatment energy footprint.

Table 2.1 Summaries of Studies on Energy Footprint of Wastewater Treatment

	Study	**Reference**
Energy Footprint of WWTPs	Evaluating the air-blown gasification technology be used to convert wastewater solids to energy at small wastewater resource recovery facilities	Ramey *et al.*, 2015
	The potential for improvements in the sustainability of energy recovery using hydropower turbines at the outlets of WWTPs	Power *et al.*, 2014
	Assessed the anaerobic membrane bio-electrochemical reactor (AnMBER) performance for wastewater treatment and energy recovery	Tian *et al.*, 2014
	Innovated a wastewater treatment process based on high-rate SBR to provide an energy efficient treatment option for highly degradable wastewaters	Ge *et al.*, 2013
	The effect of primary sedimentation on COD and solids fractionation and consequently on the carbonaceous and energy footprints of wastewater treatment processes	Gori *et al.*, 2013
	Analyzed the energy footprint of a modular process to achieve high recovery with zero liquid discharge (ZLD) for brackish groundwater desalination	Sobhani *et al.*, 2012
	Compared the oxygen transfer and uptake, nutrient removal, and energy footprint of two parallel full-scale IFAS and activated sludge processes	Rosso *et al.*, 2011
	Analyzed the different effects of COD fractions on carbon and energy footprint in a wastewater treatment plant with activated sludge in nutrient removal mode and anaerobic digestion of the sludge with biogas energy recovery.	Gori *et al.*, 2011
Energy Footprint of Lagoons	This study	--

2.4 Carbon Footprint of Wastewater Treatment

2.4.1 CFP from Wastewater Treatment Plant

According to 2008 LGO Protocol, the greenhouse gas (GHG) emissions could be discriminated all emissions into three scopes:

Scope I- directly from sources within the treatment plant, such as the CO_2, CH_4 and N_2O emissions form wastewater treatment processes, likely biological treatment process.

Scope II- refers only to indirect emissions associated with the consumption of electricity, steam, heating, or cooling. Physically, Scope II emissions produce at the facilities where electricity is generated. For example, emissions that occur at a power plant as a result of electricity used by the functioning of wastewater treatment plant. *Knosby*'s research showed that indirect emission could contribute more than 60% of total GHG emission in wastewater treatment plants (Knosby et al., 2010).

Scope III emissions include all other indirect emissions that are not covered in Scope II. In WWTPs, Scope III usually concludes the emission from fossil fuel combustion during the biosolids transportation, and fugitive CH_4 and N_2O emissions from biosolids generated by landfill or land application.

2.4.2 CFP from Energy

The carbon footprint from energy could be calculated as carbon-equivalent emission using carbon emission intensity κ. The carbon emission intensity κ follows the daily pattern below, show as Figure 2.3.

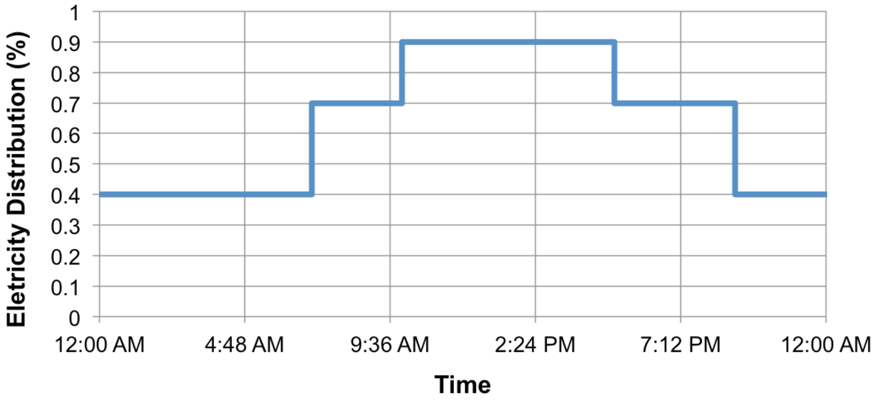


Figure 2.3 Carbon Emission Intensity Pattern

During nights from 9pm to 7am, the carbon emission intensity is undermost; after 7am, when people are beginning daily work, from 7am to 11am, carbon emission intensity is elevated; from 11am to 5pm, it is a peak of electricity usage, while the carbon emission intensity is also arrived at peak. After that, κ decreased back to the night intensity.

The average value of κ could be calculated using equation (1):

$$<\kappa> = \frac{1}{\Delta t}\int_0^t \kappa(t)\,dt \tag{1}$$

2.4.3 Summary Table

Studies on carbon footprint were summarized in Table 2.2. The CFP from wastewater treatment plants full-scale activated sludge process has been studied; the life cycle carbon emission assessment has also been analyzed; carbon emissions from dams and seawater desalination were all been studied. But no comprehensive study on CFP from power yet.

Table 2.2 Summaries of Studies on Carbon Footprint

	Study	**Reference**
CFP from Wastewater Treatment	Minimizing N_2O emissions and carbon footprint on a full-scale activated sludge sequencing batch reactor in a municipal wastewater treatment plant (WWTP)	Rodriguez-Caballero *et al.*, 2015
	Quantified the impact of direct greenhouse gas emissions on carbon footprint from the nitrification–denitrification reactors of a water reclamation plant and measured the ^{14}C content of the CO_2 to distinguish between short- and long-lived carbon emission.	Schneider *et al.*, 2015
	Six small on-site wastewater treatment plants were chosen for comparison to analyze the potential tradeoff between the reduction of local emissions and the increase in life cycle impacts in Finland.	Lehtoranta *et al.*, 2014
	Conducted a Life Cycle Assessment to determining the carbon footprint of Sludge Treatment Reed Beds (STRBs) in two full-scale STRBs located in Northern and Southern Europe (Denmark and Spain).	Uggetti *et al.*, 2012
	Presented the Direct Emissions Estimation Model (DEEM) to estimate greenhouse gases emissions in life cycle assessment and carbon footprint studies of wastewater treatment plant.	Rodriguez-Garcia *et al.*, 2012
	Analyzed the different effects of COD fractions on carbon and energy footprint in a wastewater treatment plant with activated sludge in nutrient removal mode and anaerobic digestion of the sludge with biogas energy recovery.	Gori et al., 2011
	Compared the cost and the carbon footprint of two potential water supply options: seawater desalination and water conveyance from remote locations	Shrestha *et al.*, 2011
	Studied the types and modes of greenhouse gas emissions from tropical power-dams in Brazil.	Rosa *et al.*, 2004
	Quantifying long-term emissions of two major greenhouse gases, CO_2 and CH_4, produced by the decomposition of the flooded organic matter in tropical artificial reservoirs.	Galy-Lacaux *et al.*, 1999
CFP from Power	This study	--

3. METHODOLOGY

3.1 Tested location

Our tests were conducted at the lagoon owned and operated by the Inyokern Community Services District (ICSD), located in Inyokern, CA. This location is the town with highest insolation in the United States, exceeding 350 days of sunlight per year. ICSD receives sewage from 310 urban connections and the treatment facility has lined lagoons for biological oxidation and evaporation. It serves approximately 1,000 persons, with an influent flow of approximately 50,000 gal/d. After manually cleaned screens, the sewage is routed to biological oxidation lagoon. Previously, the biological oxidation lagoon was equipped with two 7.5HP mechanical mixers, plus two units for redundancy. In this project, the campaign of complementing and replacing the two previous mechanical mixers with one solar-powered mixer were tested. The mixers' layouts are shown in Figure 3.1.

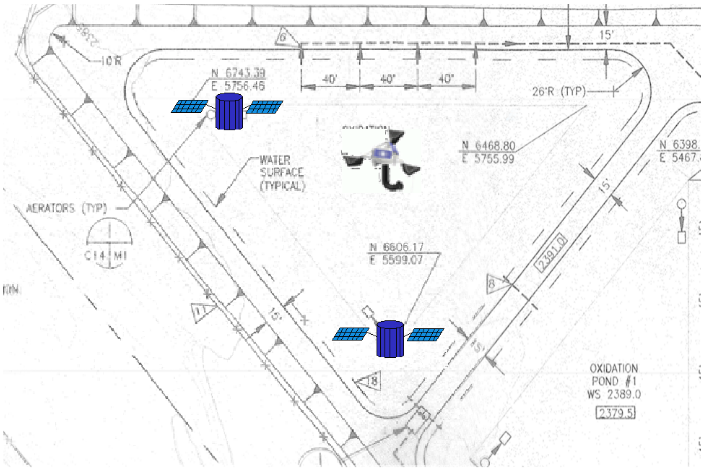


Figure 3.1 Mixers Layout. (At the lagoon center is the solar-powered mixer, while the two on-grid mechanical mixers are distributed throughout the lagoon)

3.2 Selected solar-powered mixer

Southern California Edison provided the solar-powered mixer, a SolarBee Long Distance Circulation Machine model SB5000 v18 (S/N: 443820057) to take replace the existing mechanical mixers. The SolarBee SB5000 mixer used in this project is a floating solar-powered aerator/mixer able to mobilize 10,000 gallons of water per minute over long distances (>50ft). The SolarBee is equipped with a battery with capacity of 24h of operation, providing autonomy of operation during low sunlight conditions or nightly. This mixer is generally used where power is not available or when the ponds are in large size, this makes it an excellent match for our purpose. It is equipped with a photovoltaic cell and a battery pack, with grid-connected power backup. It works by drafting liquid from the lagoon's bottom through a suction trunk, as illustrated in Figure 3.2.

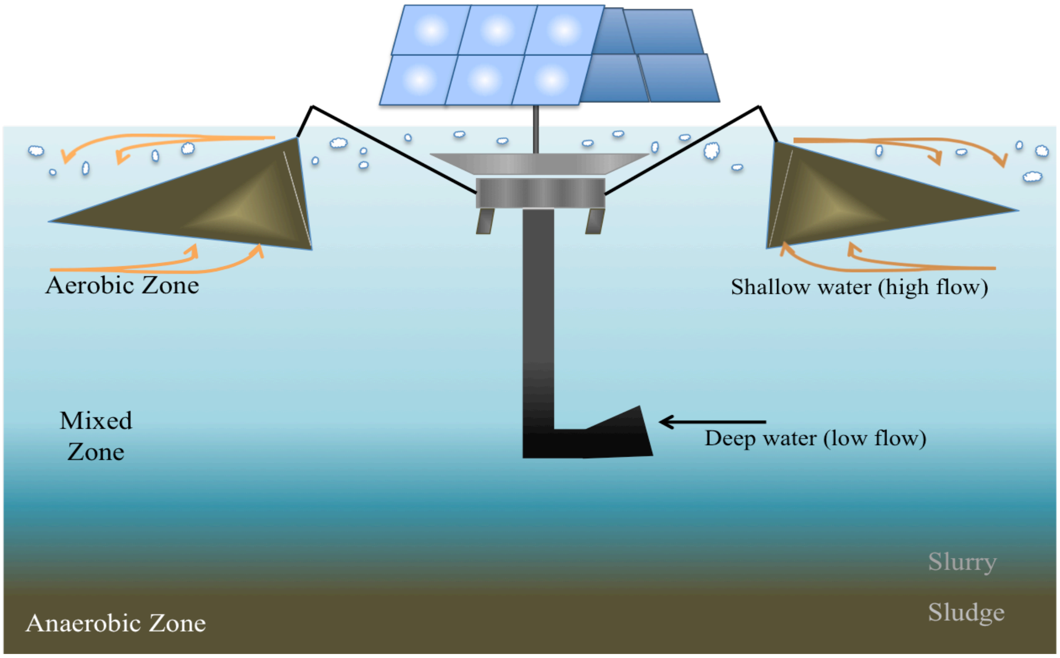


Figure 3.2 Illustration of the Solar-powered Mixer

3.3 Test Plan

Since the goal of this project was to assess whether the solar-powered mixer performs the same level of treatment as the existing technology while being more energy-efficient, the focus of the testing was on the verification that water quality was maintained the same regardless of the mixer used.

After reviewed and analyzed the data and results ICSD done before, DO and water temperature were identified as parameters to monitor continuously in the testing campaign. BOD_5 and TSS were the parameters to collect as grab samples for quality assurance, and were sent to a certified laboratory for analysis. Meanwhile, ORP and pH will be recorded by ICSD's measuring probes. This testing campaign was performed once a month from December 2012 to March 2013. The test dates during this test campaign were summarized in Table 3.1.

Table 3.1 Summary of Test Dates

Test 1	Test 2	Test 3	Test 4
2012.12.11	2013.01.22	2013.02.26	2013.03.19

Each test was performed at four stations, the locations of stations shown in Figure 3.3. For each of the four sampling stations, triplicate measurements of DO, T, ORP and pH were measured with an YSI 556a multiprobe analyzer at three different depths. The sampling depths were 1ft below the water surface, 3ft below the water surface, and full depth (5-12ft below the water surface, depending on the sedimentation on the lagoon floor). The instrument was calibrated before each test.

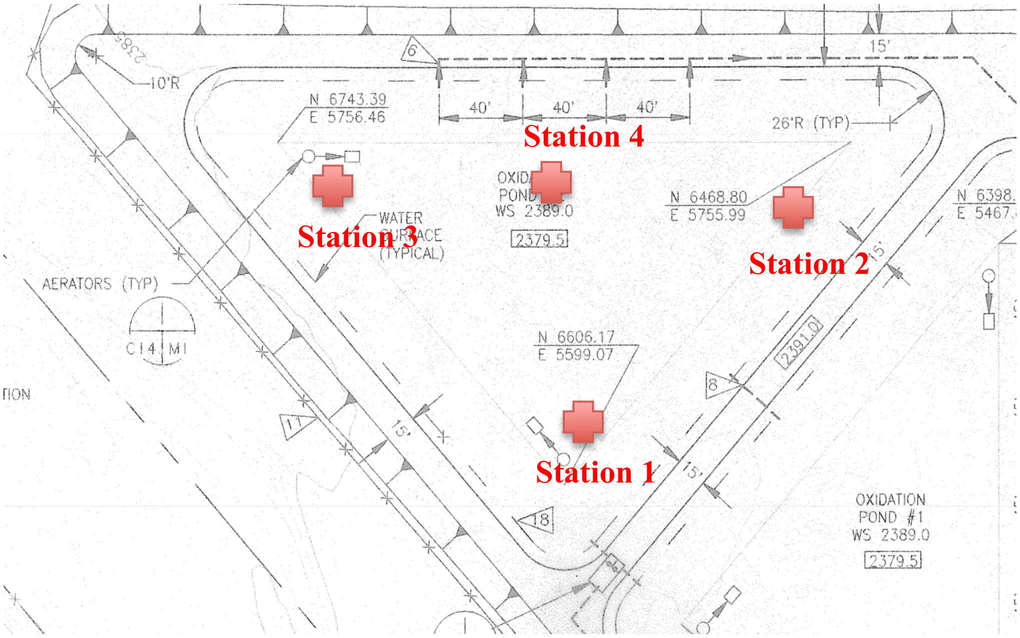


Figure 3.3 Sampling Station Layouts

For each test, the four testing stations were visited with a boat provided and captained by the ICSD Manager. In order to avoid disturbing the lagoon mixing patterns produced by the solar-powered mixer, no paddling was performed during the test. Instead, three cables were drawn across the lagoon above the water surface to pull the sampling boat slowly.

3.4 Energy Monitoring

Energy Monitoring were performed using a power meter with data logger. The power demand and energy consumption data were downloaded during each field-testing event. The power meters were installed during the first field-testing event and were removed after the last event, covering the entire winter testing period. Each downloading event included data collected from the previous testing to the moment of download. Hence, the energy consumption after replacement could be calculated with the recorded data.

The energy consumption for the previous mechanical mixers could be estimated as following:

$$BHP = 2\ mixers \times 7.5\ HP \times \frac{0.746\ kW}{HP} \times 24 \frac{h}{d} \times \frac{365\ d}{yr} = 98{,}024.4\ kWh/yr \tag{2}$$

3.5 Calculation of Carbon-Equivalent Emission

The carbon-emission reduction by replacing the mechanical mixers belongs to Scope II, i.e. the indirect carbon-emission. The reduction could be calculated with the carbon emission intensity κ, using an average value for Southern California:

$$< \kappa >= 0.4\ kg\ CO2, eq/kWh \tag{3}$$

In order to weigh the effects of these Scope II emissions reduction on the overall treatment emissions, the Scope I emission need also be calculated. Since the lagoon is the only biological treatment unit at ICSD, only process CH_4 emissions and process N_2O emissions should be considered. They could be calculated by the following equations (4) and (5):

Annual process CH_4 from Wastewater Treatment Lagoons (metric tonnes CH_4 / y)

$$\frac{dmCH4}{dt} = P \times BOD_{5\ load} \times Bo \times F_{removed} \times 365.25 \times 10^{-3} \tag{4}$$

where:

P = population served by lagoons adjusted for industrial discharge, if applicable [persons]

$BOD_{5\ load}$ = amount of BOD_5 produced per person per day [kg BOD_5/person/day] = 0.090

Bo = maximum CH_4-producing capacity for domestic wastewater [kg CH_4/kg $BOD_{5\ removed}$] = 0.6

$MCF_{anaerobic}$ = CH_4 correction factor for anaerobic systems = 0.8

$F_{removed}$ = fraction of overall lagoon BOD5 removal performance = 1

Annual process N_2O Emissions from Effluent Discharge (metric tonnes N_2O / y)

$$\frac{dmN2O}{dt} = P_{total} \times (Total\ N\ load - N\ uptake \times BOD_{5\ load}) \times EF_{effluent} \times \frac{44}{28} \times \frac{365.25}{1000} \quad (5)$$

where:

P_{total} = population served adjusted for industrial discharge, if applicable [persons]

Total N Load = total nitrogen load [kg N/person/day] = 0.026

N uptake = nitrogen uptake for cell growth in anaerobic system (e.g., lagoon) = 0.0051(kg N/kg BOD_5)

BOD_5 load = amount of BOD_5 produced per person per day [kg BOD_5/person/day] = 0.090

EF effluent = emission factor [kg N_2O-N/kg sewage-N produced] = 0.005

44/28 = molecular weight ratio of N_2O to N_2 = 1.57

4. RESULTS AND DISCUSSION

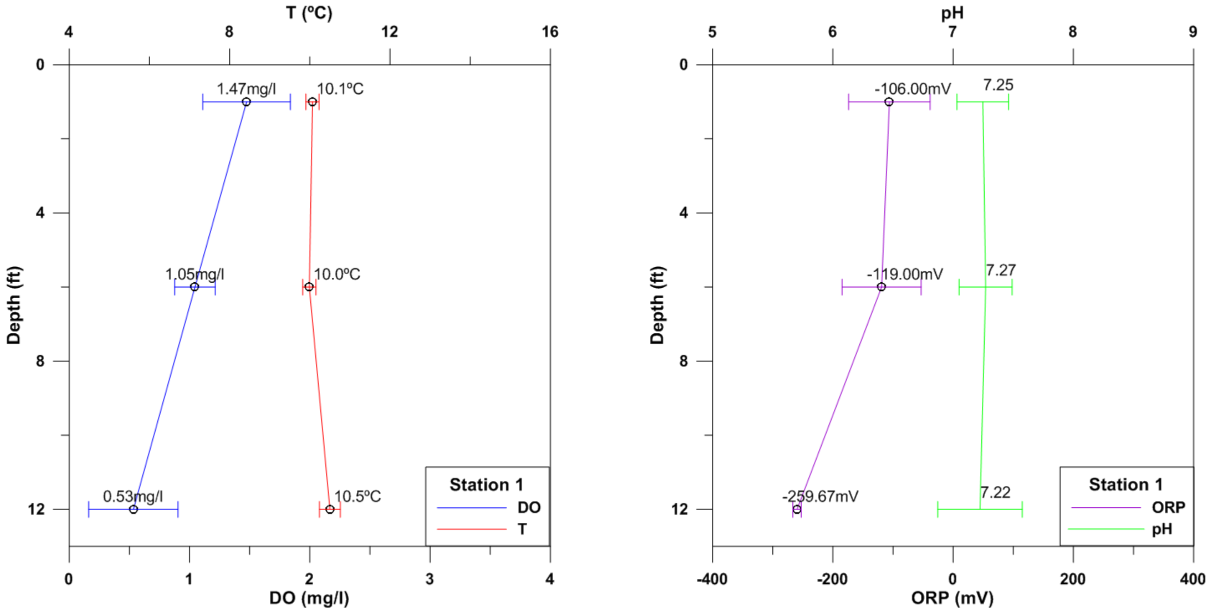
4.1 Water Quality

4.1.1 Test 1

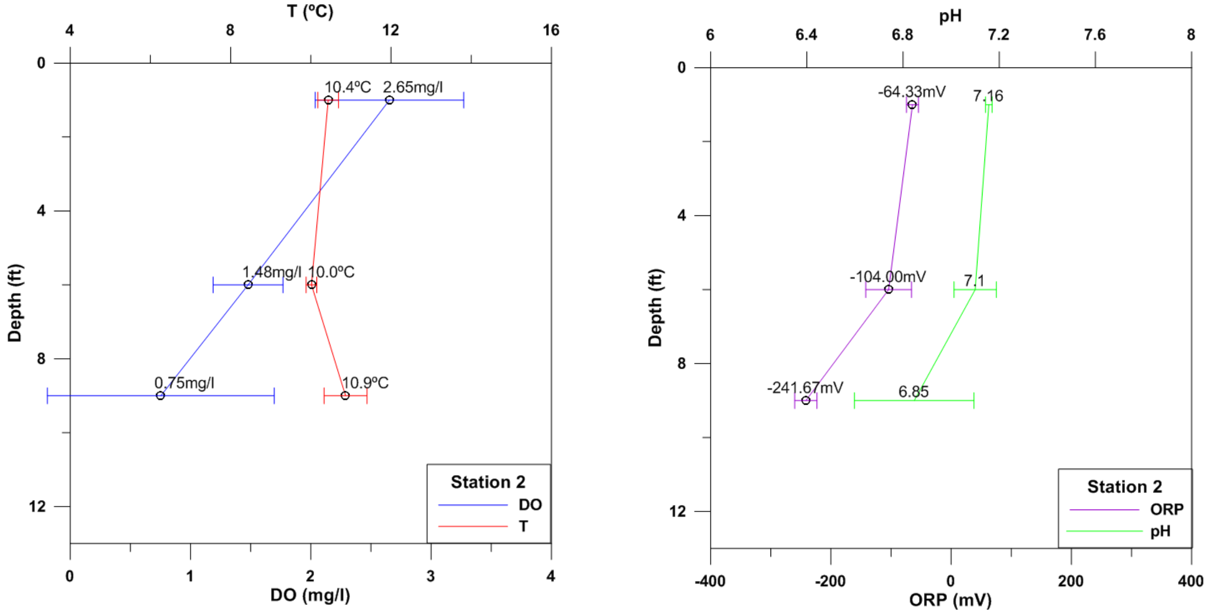
In Test 1, the sampling depths were 1ft below the water surface, 6ft below the water surface, and full depth was 12ft below the water surface for Stations 1 and 3, 9ft for Stations 2 and 4. The difference of sampling depths between stations due to change of sediment accumulation. Four parameters (DO, T, ORP and pH) were tested during this test, the average value of each parameter was summarized in Table 4.1. The 2D profiles, Figure 4.1, depict the vertical performance of new installed solar-powered mixer. The 3D Figure 4.2 has a favorable view of the horizontal performance (the full depths were estimated at the same depth layer, 9ft).

Table 4.1 Results of Test 1

Station	**Depth** ft	**avg. DO** mg/l	**avg. T** ^{o}C	**avg. ORP** mV	**avg. pH**
S1	1	1.47	10.07	-106.00	7.25
S1	6	1.05	9.99	-119.00	7.27
S1	12	0.53	10.50	-259.67	7.22
S2	1	2.65	10.43	-64.33	7.16
S2	6	1.48	10.02	-104.00	7.10
S2	9	0.75	10.87	-241.67	6.85
S3	1	2.04	10.17	-90.00	7.41
S3	6	1.00	9.94	-112.00	7.41
S3	12	0.42	10.09	-288.00	7.60
S4	1	2.93	10.58	-44.33	7.40
S4	6	1.04	9.97	-65.33	7.29
S4	9	0.14	10.18	-240.67	7.07

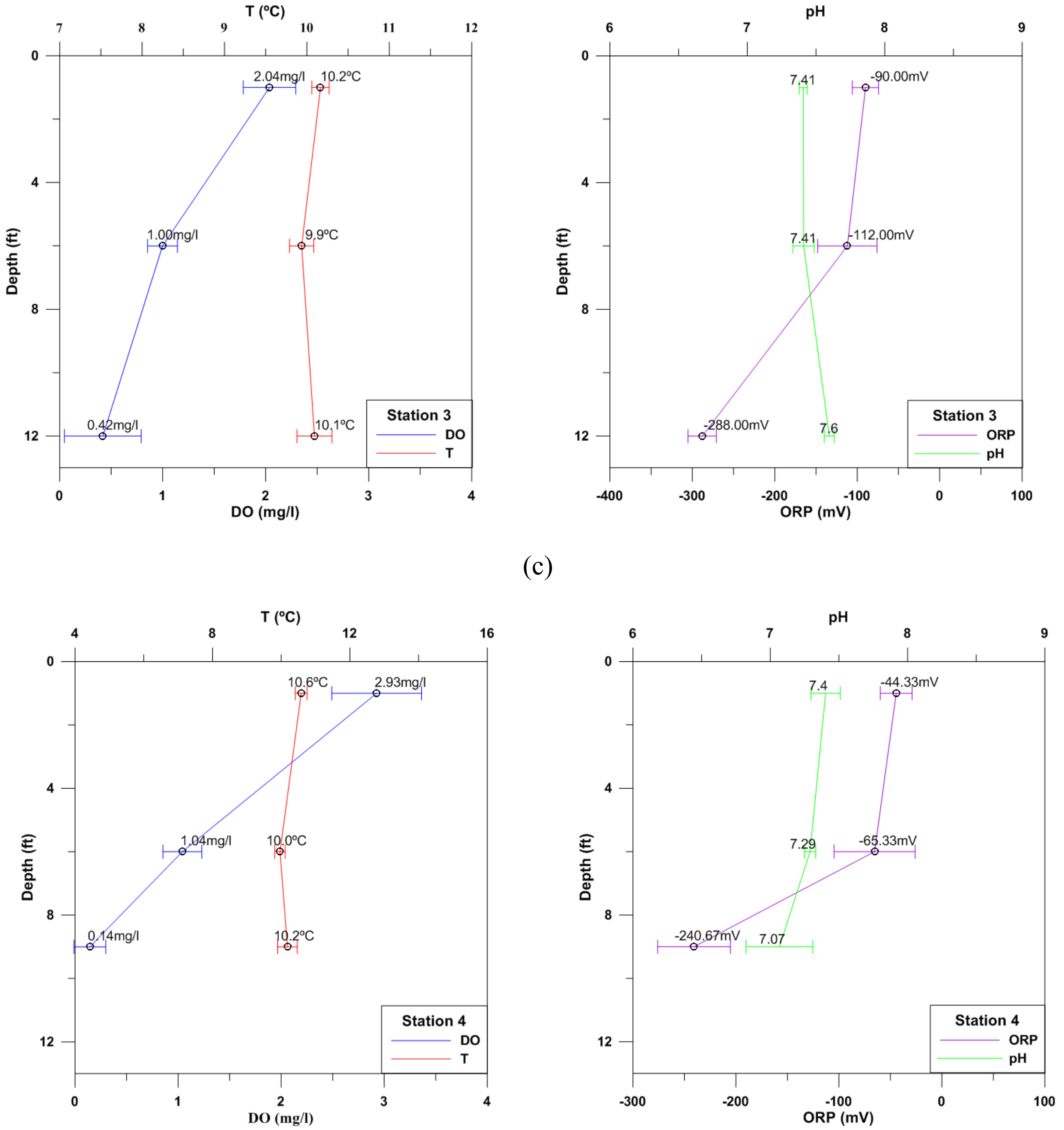


(a)



(b)

(continues overleaf)



(c)

(d)

Figure 4.1 2D Profiles for Test 1. (a) Station 1; (b) Station2; (c) Station 3; (d) Station 4. (In each figure, DO is in blue in the left figure, in mg/l; T is in red in the left figure, in °C, pH is in green in the left figure; ORP is in purple in the right figure, in mV)

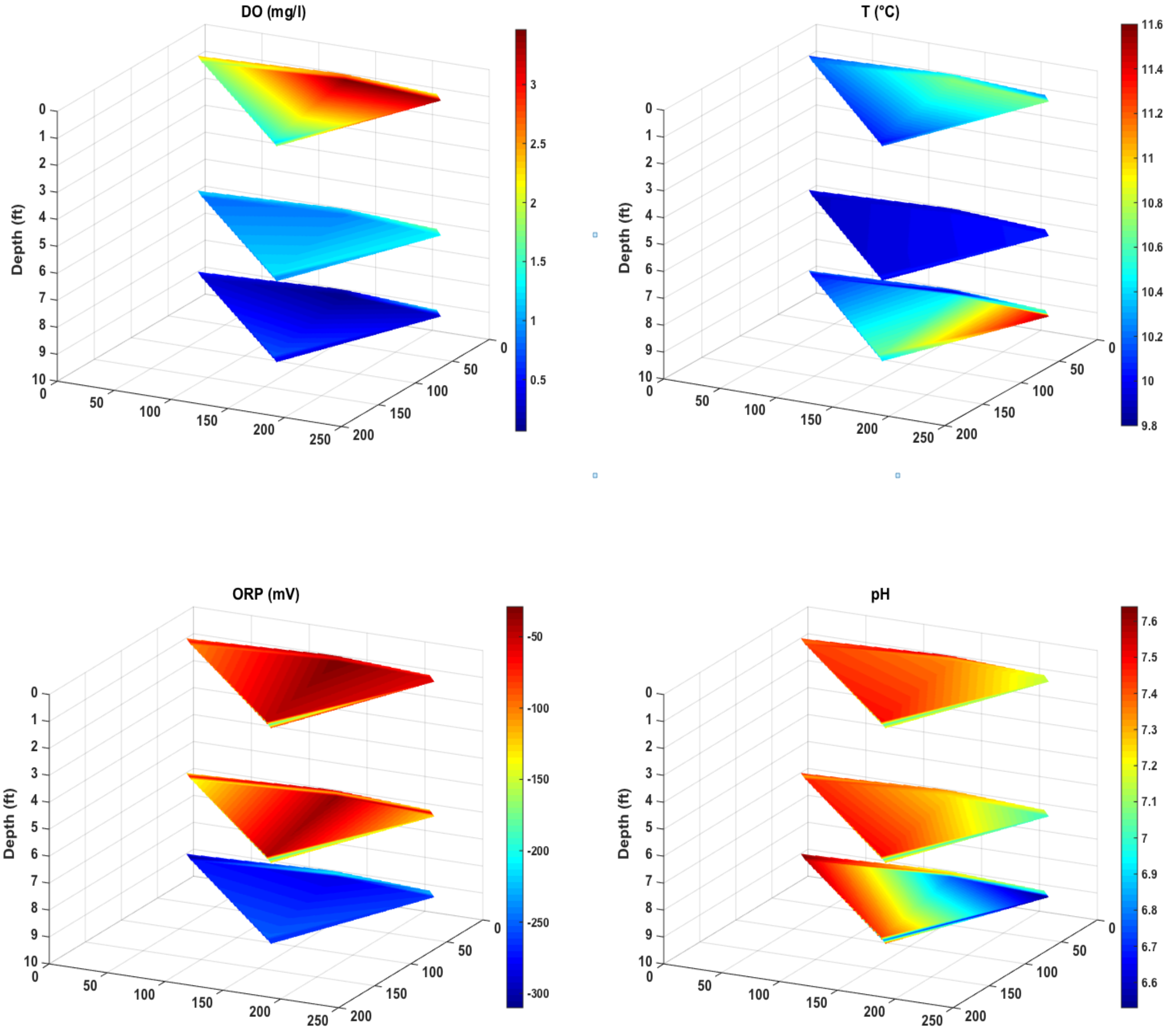


Figure 4.2 3D Profiles for Test 1

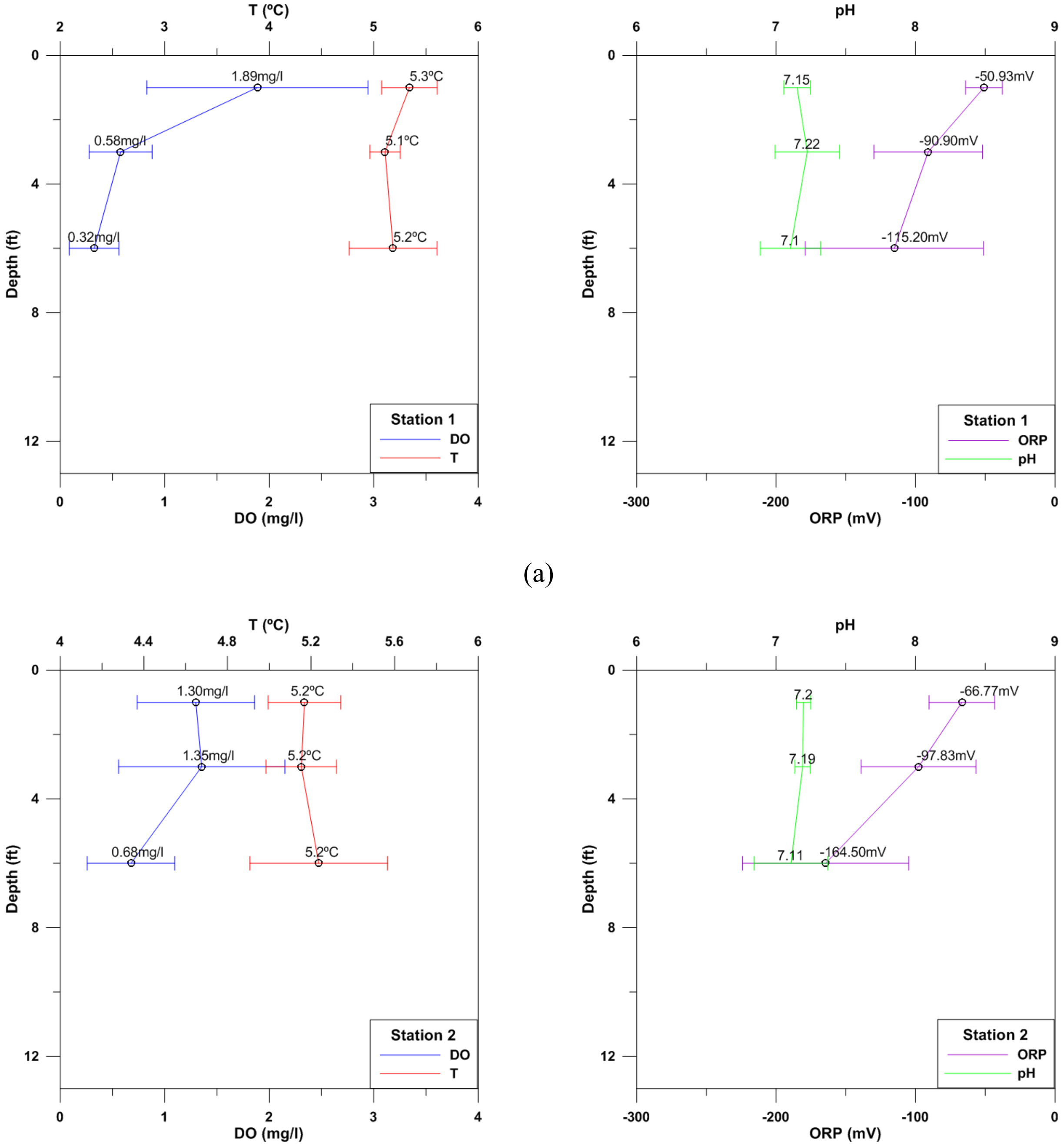
(DO is on top left; T is on top right; ORP is on bottom left; pH is on bottom right)

4.1.2 Test 2

In Test 2, the sampling depths were 1ft below the water surface, 3ft below the water surface, and full depth was 6ft below the water surface for Stations 1 and 2, 9ft for Stations 3 and 4.The testing depths were changed due to the sludge accumulation and movement over time at the lagoon bottom. Four parameters (DO, T, ORP and pH) were tested during this test, the average value of each parameter was summarized in Table 4.2. The 2D profiles, Figure 4.3, depict the vertical performance of new installed solar-powered mixer. The 3D Figure 4.4 has a favorable view of the horizontal performance (the full depths were estimated at the same depth layer, 6ft).

Table 4.2 Results of Test 2

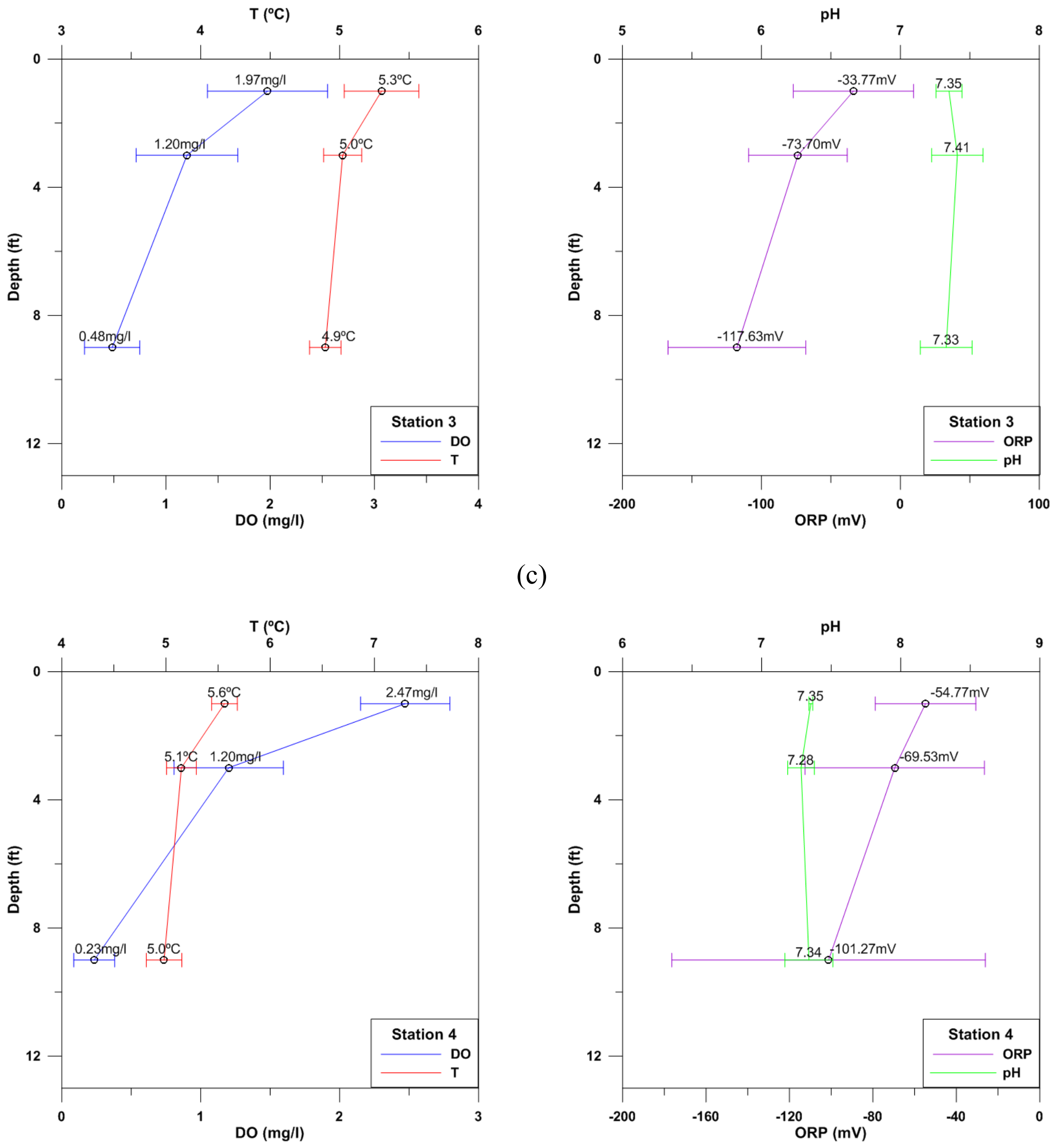
Station	**Depth** ft	**avg. DO** mg/l	**avg. T** ^{o}C	**avg. ORP** mV	**avg. pH**
S1	1	1.89	5.34	-50.93	7.15
S1	3	0.58	5.11	-90.90	7.22
S1	6	0.32	5.19	-115.20	7.10
S2	1	1.30	5.17	-66.77	7.20
S2	3	1.35	5.15	-97.83	7.19
S2	6	0.68	5.24	-164.50	7.11
S3	1	1.97	5.30	-33.77	7.35
S3	3	1.20	5.02	-73.70	7.41
S3	9	0.48	4.90	-117.63	7.33
S4	1	2.47	5.56	-54.77	7.35
S4	3	1.20	5.15	-69.53	7.28
S4	9	0.23	4.98	-101.27	7.34



(a)

(b)

(continues overleaf)



(c)

(d)

Figure 4.3 2D Profiles for Test 2. (a) Station 1; (b) Station 2; (c) Station 3; (d) Station 4. (In each figure, DO is in blue in the left figure, in mg/l; T is in red in the left figure, in °C, pH is in green in the left figure; ORP is in purple in the right figure, in mV)

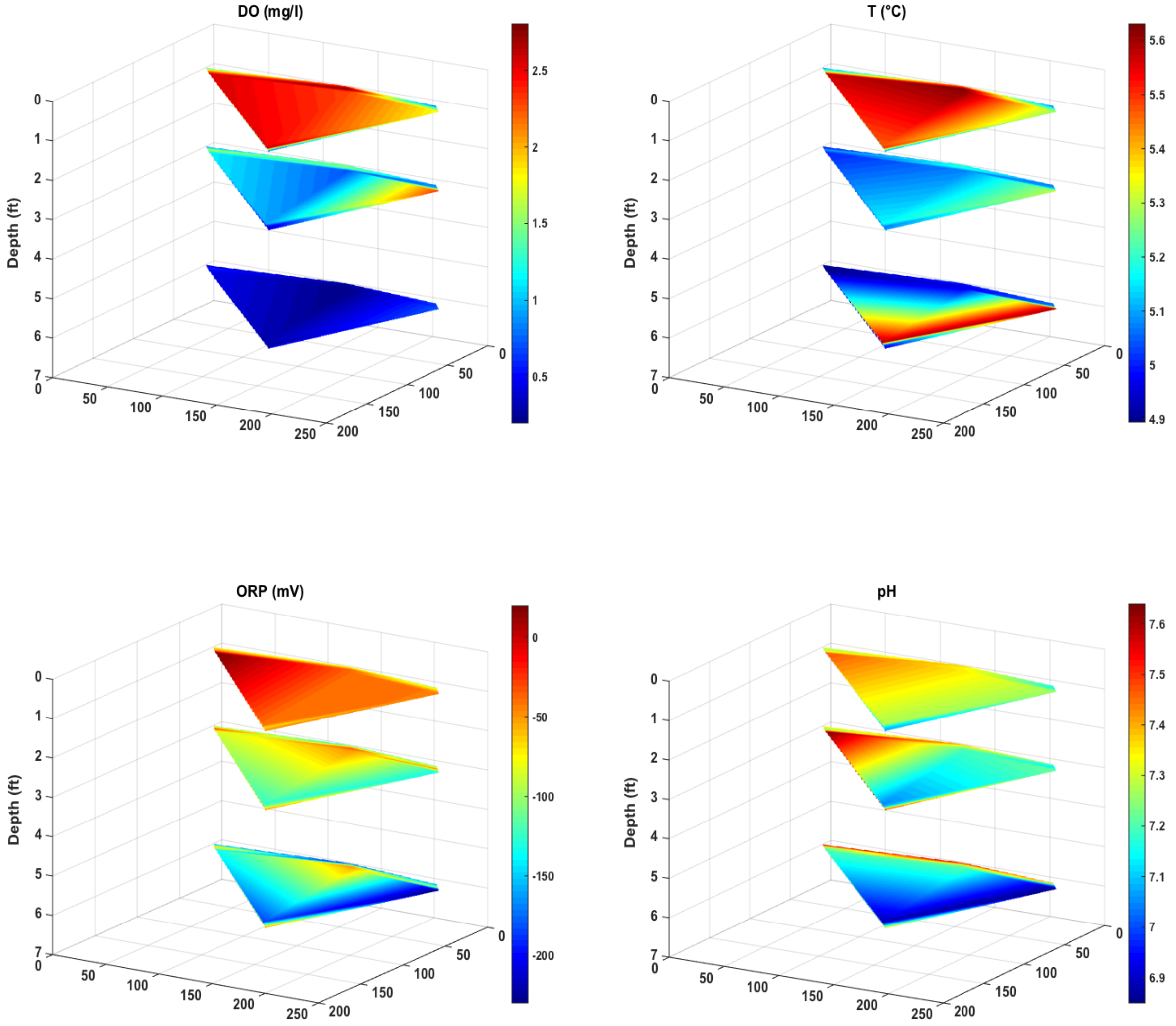


Figure 4.4 3D Profiles for Test 2

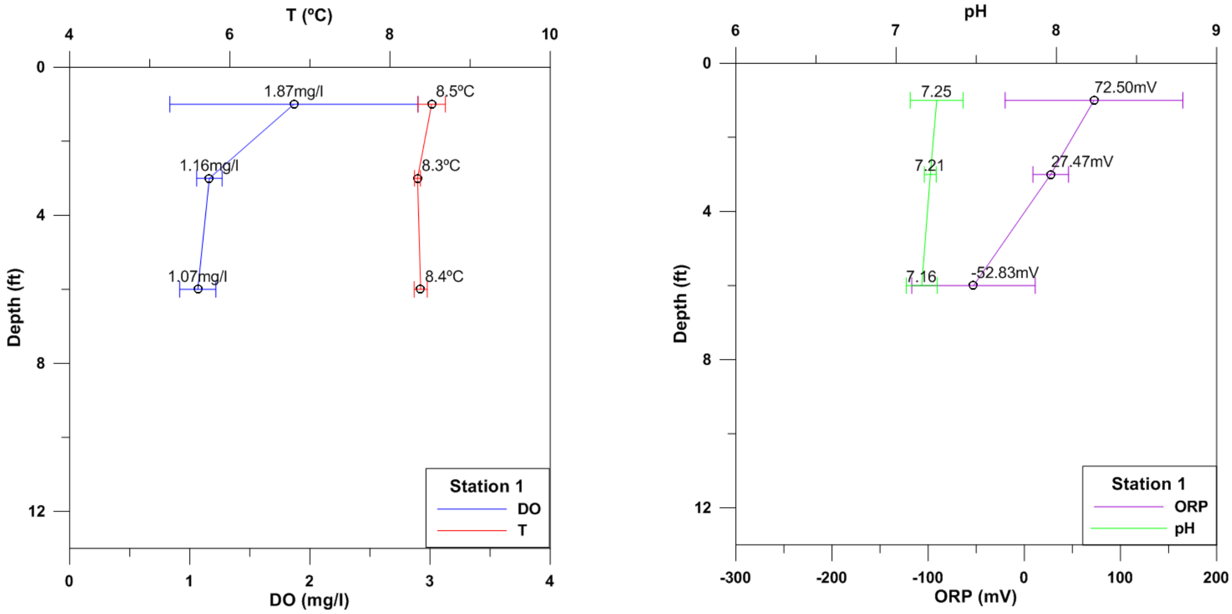
(DO is on top left; T is on top right; ORP is on bottom left; pH is on bottom right)

4.1.3 Test 3

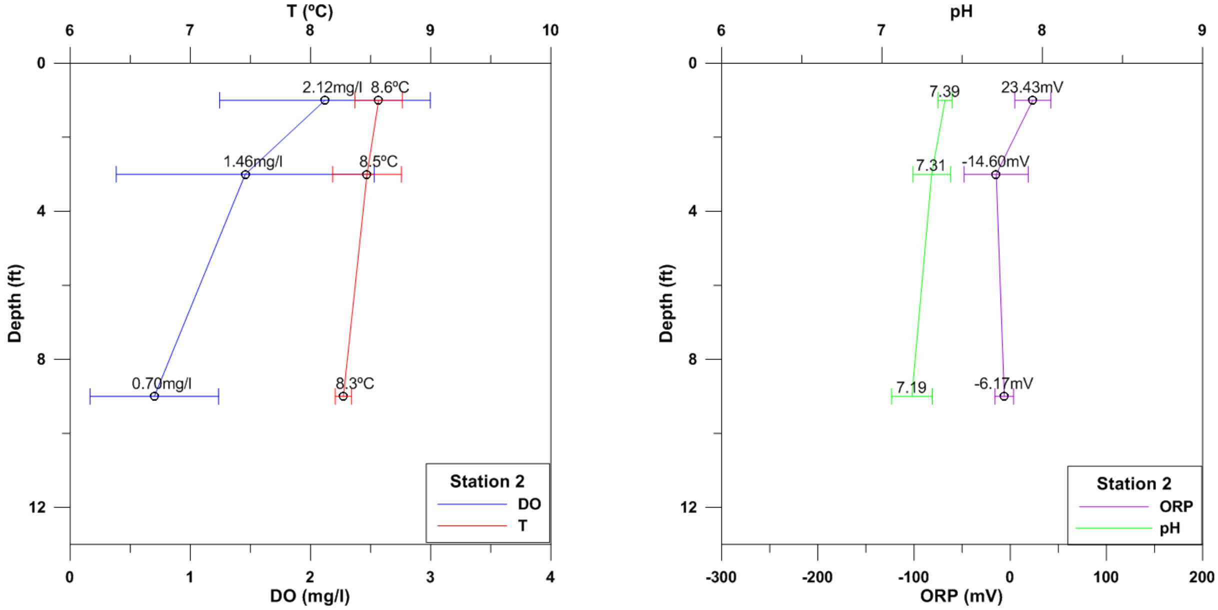
In Test 3, the sampling depths were 1ft below the water surface, 3ft below the water surface, and full depth was 6ft below the water surface for Stations 1, 9ft for Stations 2, 3 and 4.The testing depths were changed due to the sludge accumulation and movement over time at the lagoon bottom. Four parameters (DO, T, ORP and pH) were tested during this test, the average value of each parameter was summarized in Table 4.3. The 2D profiles, Figure 4.5, depict the vertical performance of new installed solar-powered mixer. The 3D Figure 4.6 has a favorable view of the horizontal performance (the full depths were estimated at the same depth layer, 9ft).

Table 4.3 Results of Test 3

Station	**Depth** ft	**avg. DO** mg/l	**avg. T** ^{o}C	**avg. ORP** mV	**avg. pH**
S1	1	1.87	8.52	72.50	7.25
S1	3	1.16	8.34	27.47	7.21
S1	6	1.07	8.38	-52.83	7.16
S2	1	2.12	8.57	23.43	7.39
S2	3	1.46	8.47	-14.60	7.31
S2	9	0.70	8.27	-6.17	7.19
S3	1	1.80	8.64	-78.00	7.39
S3	3	0.90	8.33	-81.07	7.31
S3	9	0.16	8.38	-119.47	6.85
S4	1	2.45	8.75	-54.17	7.54
S4	3	2.37	8.75	-38.13	7.27
S4	9	0.27	8.32	-100.37	6.93

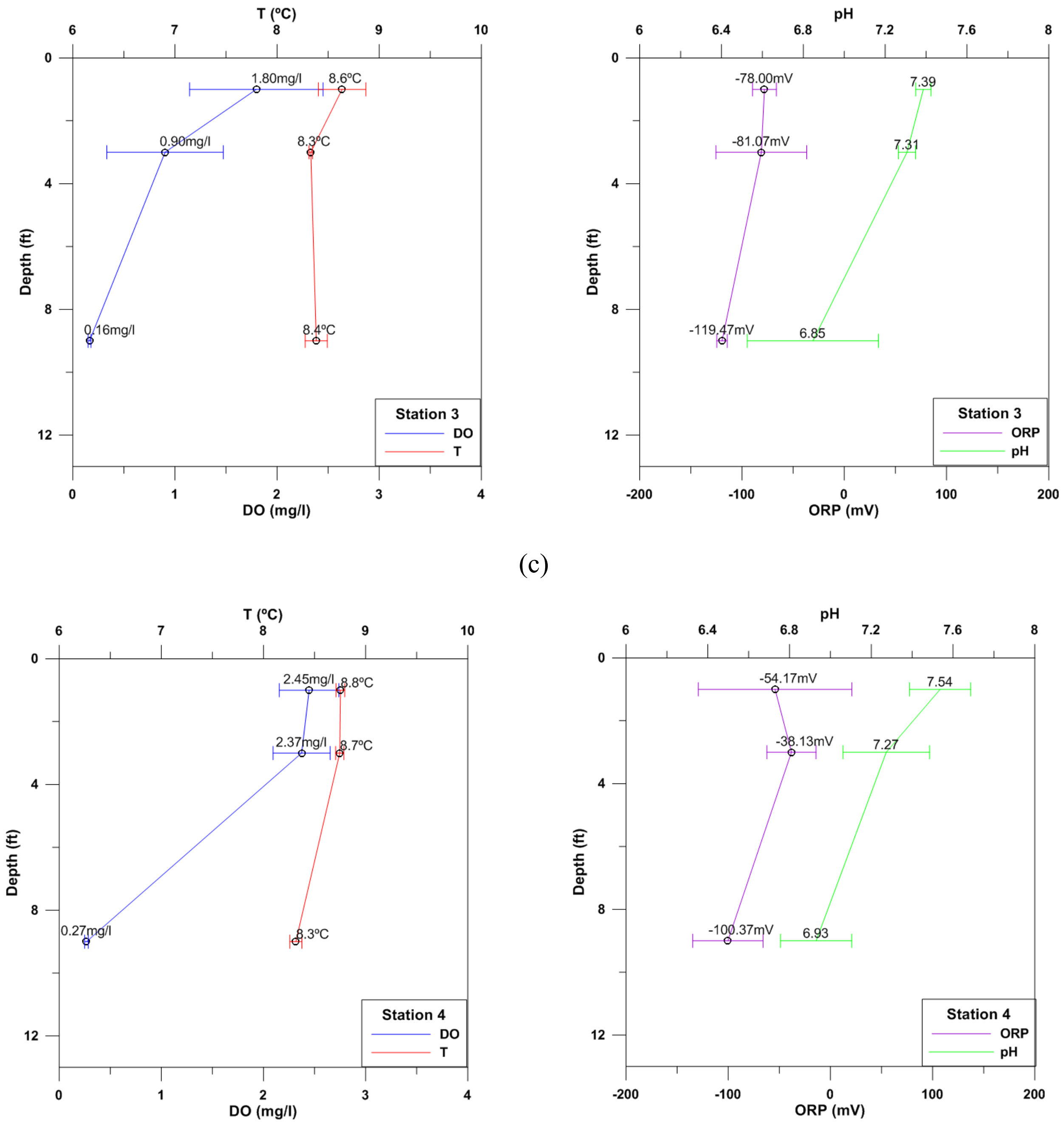


(a)



(b)

(continues overleaf)



(c)

(d)

Figure 4.5 2D Profiles for Test 3. (a) Station 1; (b) Station2; (c) Station 3; (d) Station 4. (In each figure, DO is in blue in the left figure, in mg/l; T is in red in the left figure, in °C, pH is in green in the left figure; ORP is in purple in the right figure, in mV)

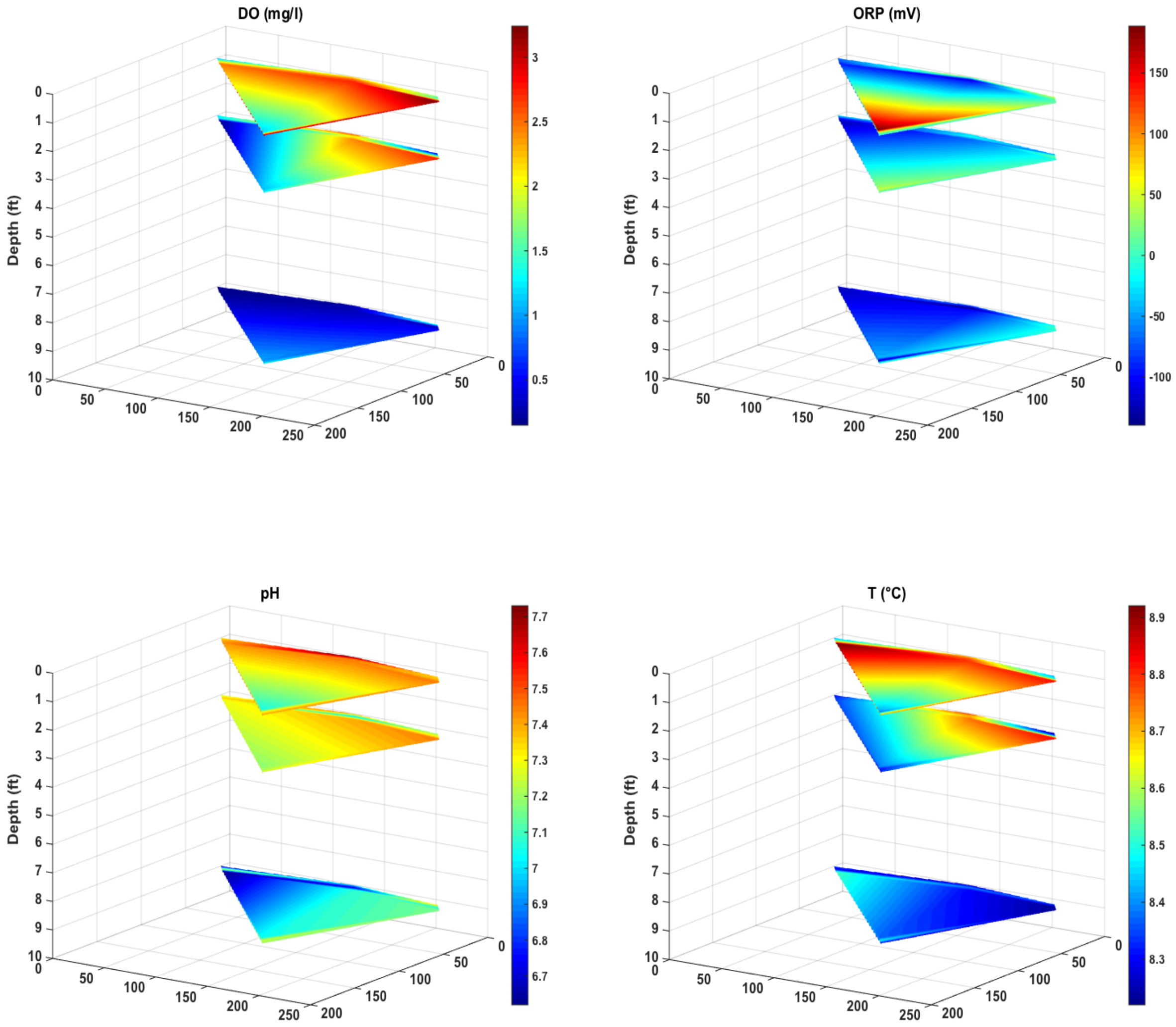


Figure 4.6 3D Profiles for Test 3

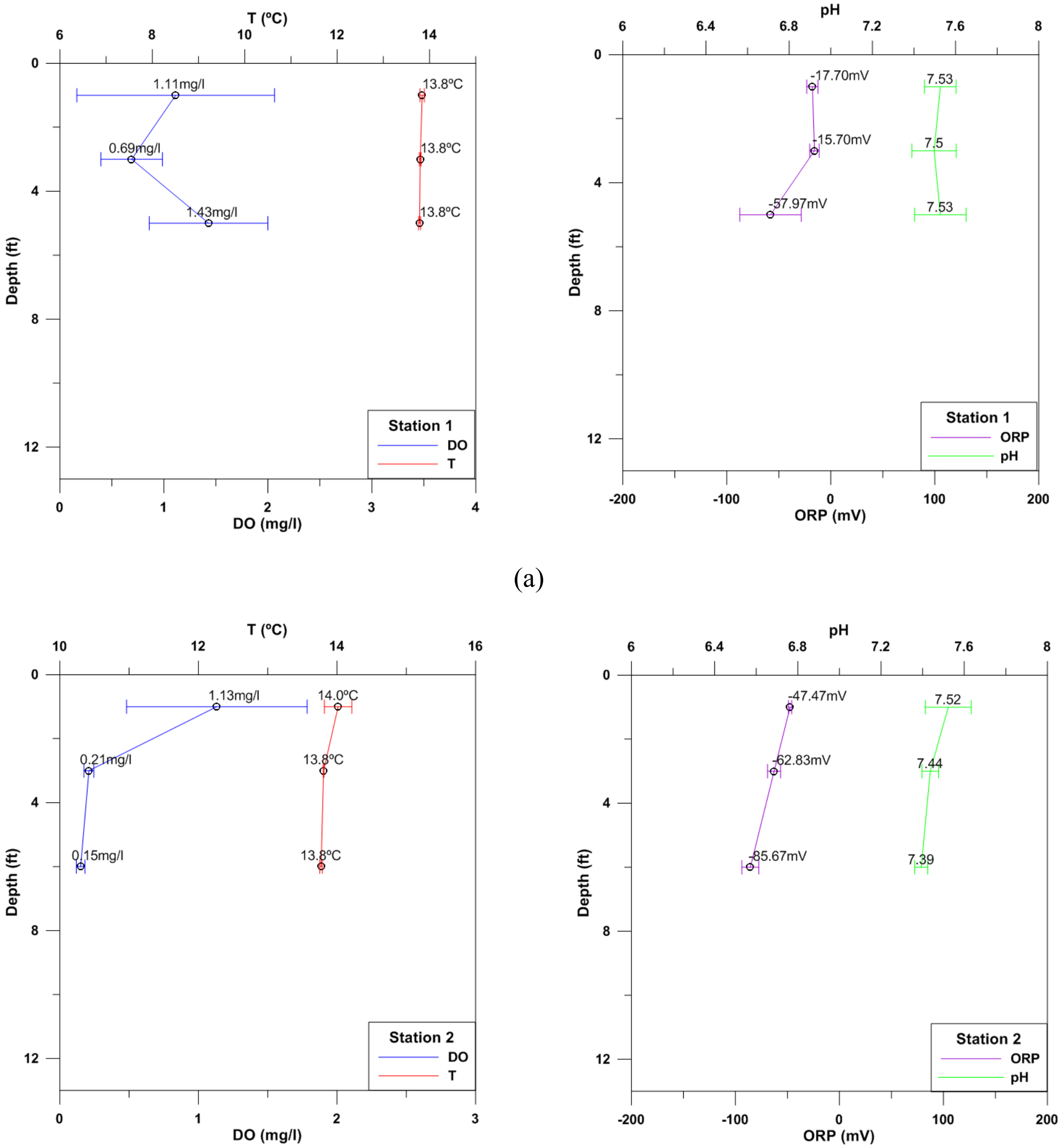
(DO is on top left; T is on top right; ORP is on bottom left; pH is on bottom right)

4.1.4 Test 4

In Test 4, the sampling depths were 1ft below the water surface, 3ft below the water surface, and full depth was 5ft below the water surface for Stations 1, 6ft for Stations 2 and 3, 8ft for Station 4.The testing depths were changed due to the sludge accumulation and movement over time at the lagoon bottom. Four parameters (DO, T, ORP and pH) were tested during this test, the average value of each parameter was summarized in Table 4.4. The 2D profiles, Figure 4.7, depict the vertical performance of new installed solar-powered mixer. The 3D Figure 4.8 has a favorable view of the horizontal performance (the full depths were estimated at the same depth layer, 6ft).

Table 4.4 Results of Test 4

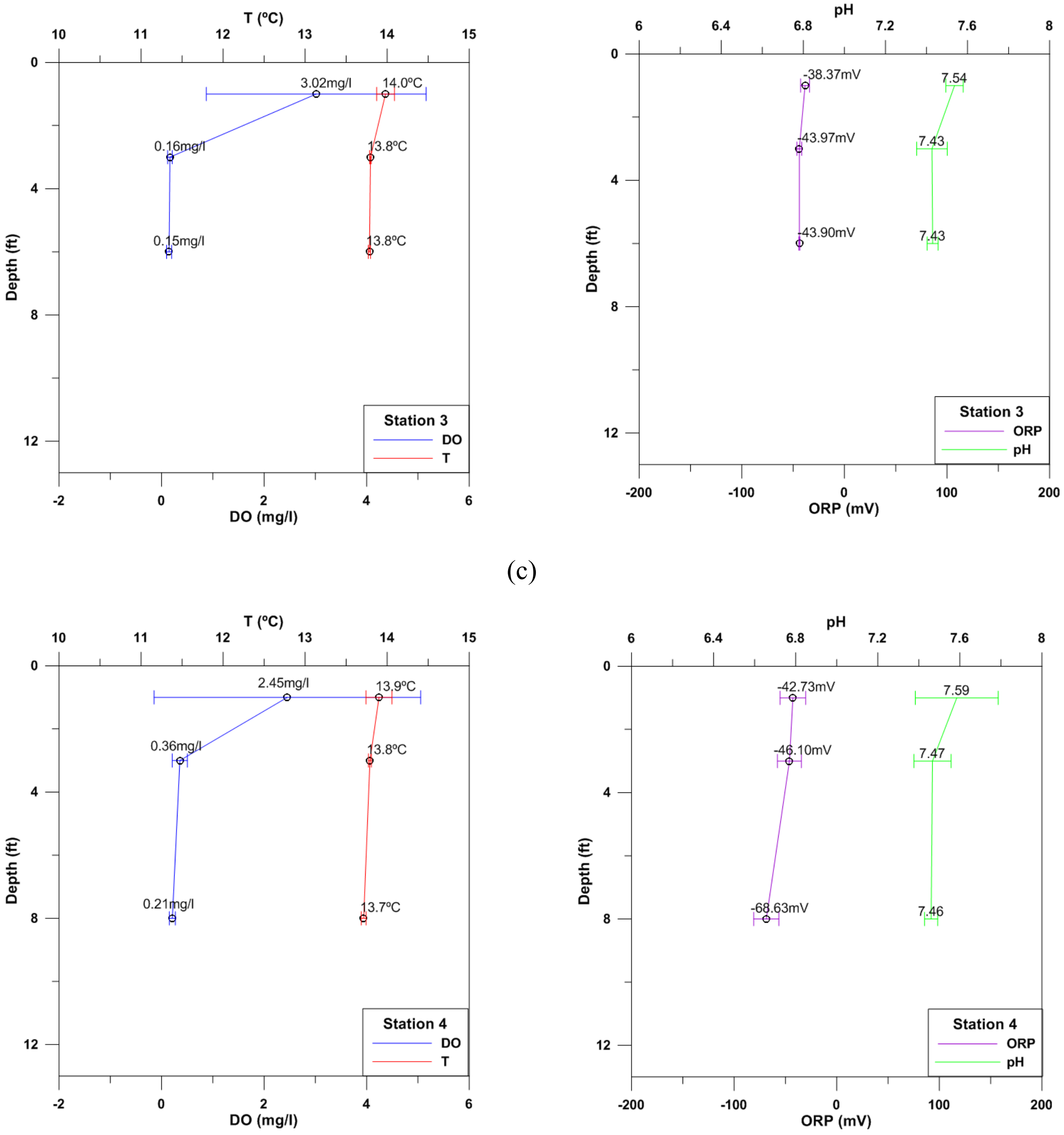
Station	**Depth** ft	**avg. DO** mg/l	**avg. T** ^{o}C	**avg. ORP** mV	**avg. pH**
S1	1	1.11	13.84	-17.70	7.53
S1	3	0.69	13.80	-15.70	7.50
S1	5	1.43	13.78	-57.97	7.53
S2	1	1.13	14.02	-47.47	7.52
S2	3	0.21	13.81	-62.83	7.44
S2	6	0.15	13.77	-85.67	7.39
S3	1	3.02	13.98	-38.37	7.54
S3	3	0.16	13.80	-43.97	7.43
S3	6	0.15	13.78	-43.90	7.43
S4	1	2.45	13.90	-42.73	7.59
S4	3	0.36	13.79	-46.10	7.47
S4	8	0.21	13.71	-68.63	7.46



(a)

(b)

(continues overleaf)



(c)

(d)

Figure 4.7 2D Profiles for Test 4. (a) Station 1; (b) Station 2; (c) Station 3; (d) Station 4. (In each figure, DO is in blue in the left figure, in mg/l; T is in red in the left figure, in °C, pH is in green in the left figure; ORP is in purple in the right figure, in mV)

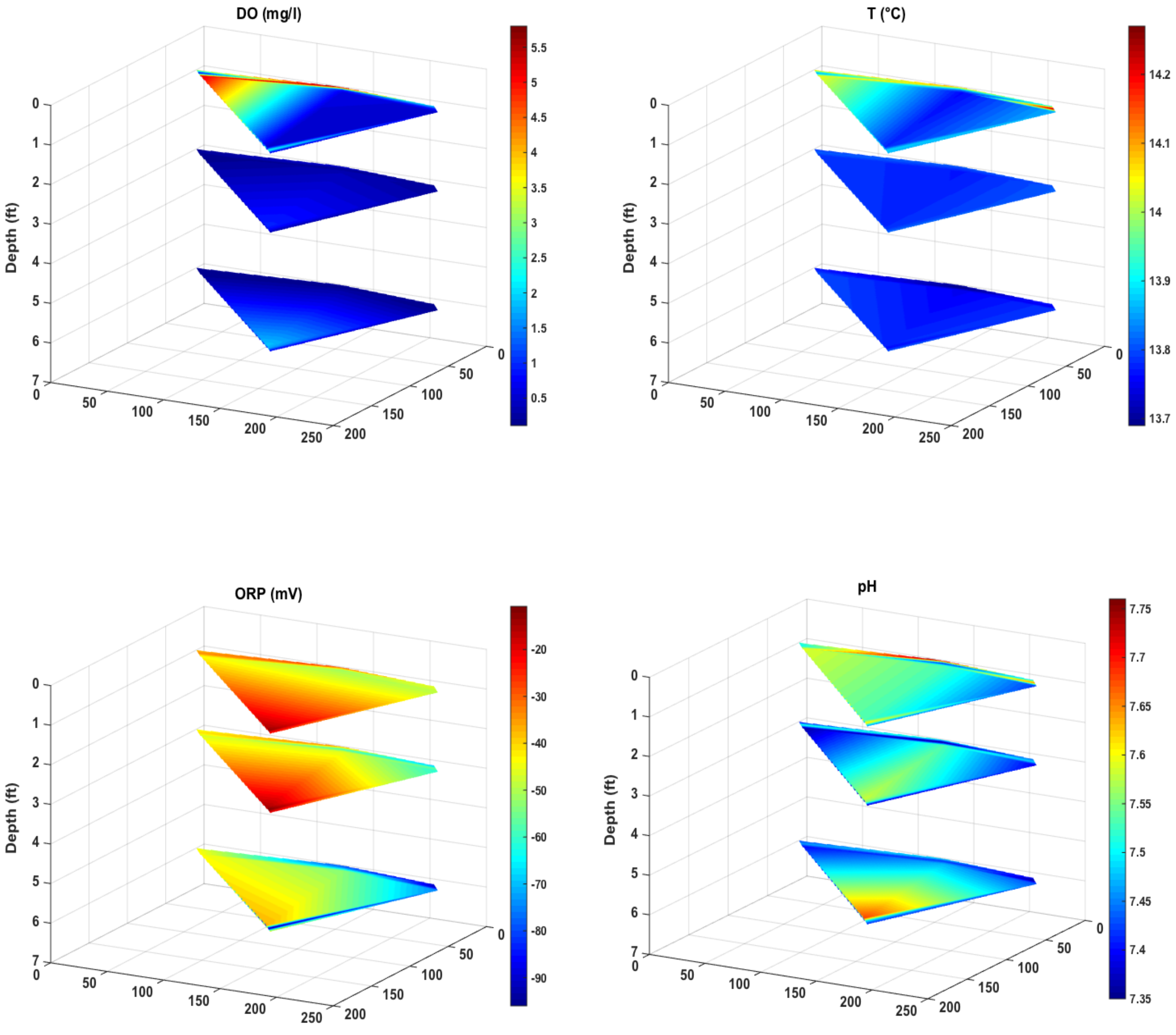


Figure 4.8 3D Profiles for Test 4

(DO is on top left; T is on top right; ORP is on bottom left; pH is on bottom right)

These 2D and 3D profiles provide a good illustration of the solar-powered mixer performance in both vertical direction and horizontal directions. The 2D profiles show the DO concentration decreasing pattern, from approximately DO~2mg/l (aerobic zone) to 0.2mg/l<DO<1mg/l (anoxic zone) to DO<0.2mg/l (anaerobic zone). Combined with the ORP plots, the decrease between the surface and middle depths is much sharper, because of the rapid oxygen depletion along the depth, caused by the excess of oxygen demand when compared to the surface oxygen supply. In test 4, the ORP plot is extremely uniform, which is an indicator that oxygenation has been brought to depth by mixing. Additionally, there is no significant temperature change during the whole testing campaign, since the maximum temperature gradient ΔT is 0.85°C, 0.6°C, 0.5°C and 0,4°C during each test, respectively. Temperature alone is a necessary condition associated with thorough mixing, but due to the large heat capacity of water it is not sufficient (in fact, an almost isothermal reactor could have large concentration gradients within its volume, hence would not be well-mixed). Despite the temperature gradient being very small, the pH of the surface water is consistently higher than the pH of full depth water, indicating that different bacterial metabolisms are occurring at different depths: as the suspended solids tend to accumulate on the lagoon floor, their hydrolysis and fermentation will result in a slightly more acidic environment with increasing depth. The change in pH over the water column was never above 0.64 pH points, further indicating that for the purpose of treatment this mixing technology was adequate.

In the 3D profiles, each depth was plotted as a layer to compare horizontal mixing in the lagoon. From the DO's 3D profile, the three layers and corresponding ranges could show the clearly distinguished aerobic zone, anoxic zone and anaerobic zone of the facultative lagoon. At the surface layer, the highest DO concentration was detected around station 4 (solar-powered mixer) in test 1 and 3. In tests 2 and 4, the DO profiles showed more gradient, indicating a more moderate mixing condition. Besides, ORP, T and pH are consistent with the DO horizontal distribution.

Based on the results and analysis above, the solar-powered mixer could provide a sufficient mixing during this testing campaign. In more detail, the DO at Stations 2 and 4 is slightly higher than the other two stations in Tests 1 and 3, which indicates that zone of influence of the mixer is limited to the central volume of the lagoon, thus this selected solar-powered mixer may be undersized for this lagoon geometry. As reported by Upadhyay (2013), the impact of solar mixers can be highly localized. Future work should analyze the same lagoon geometry with a second solar-operated device or a larger single unit, in order to extend the mixing zone of influence over a larger volume.

4.1.5 ORP & DO Analysis

In order to improve our understanding of the lagoon treatment performance, ORP was measured during the campaign at all times. Figure 4.9 shows the relationship between DO and ORP, the outlier values out of ($\text{mean}_{\text{DO or ORP}} \pm 2\sigma_{\text{DO or ORP}}$) have been identified and highlighted. The result shows that ORP has a general albeit much scattered trend with the logarithmic increase in DO.

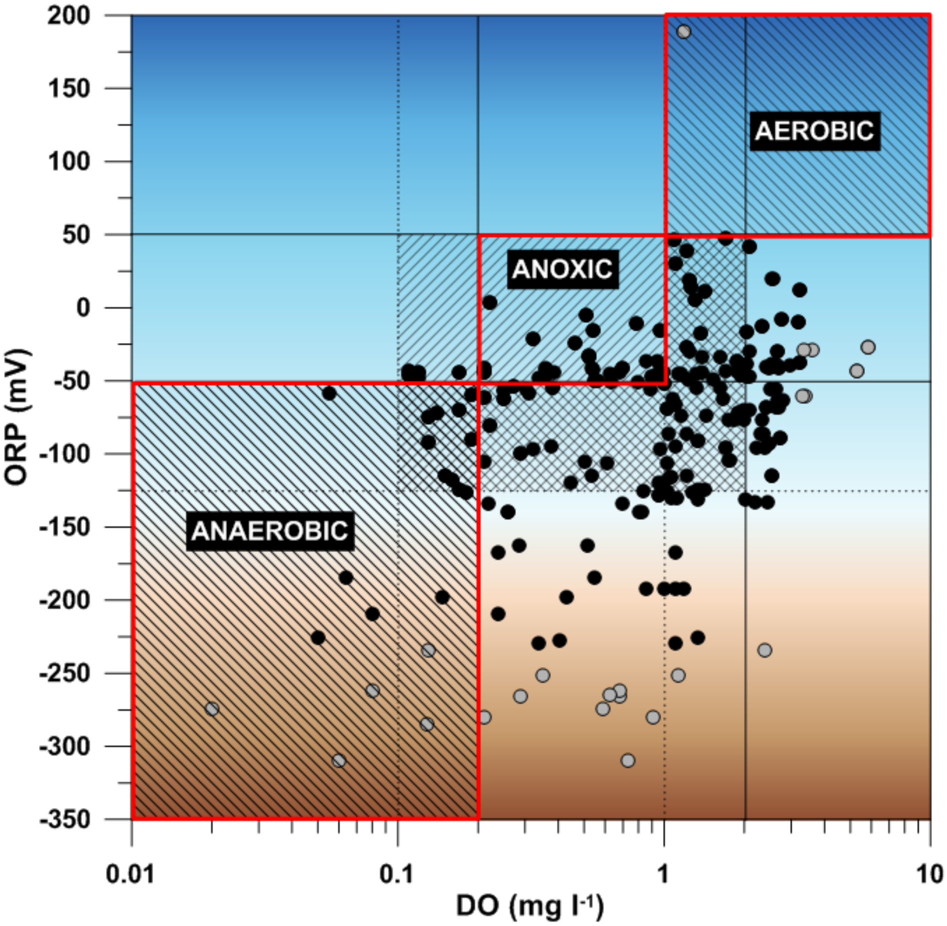


Figure 4.9 ORP versus DO during the testing campaign

In the highlighted three zones, DO and ORP in theory define the metabolic state of the mixed liquor. The red box in the left bottom is the strictly anaerobic zone, where ORP<-50mV and DO<0.2mg/l. The red box in the middle shows the anoxic zone, where -50mV<ORP<+50mV and 0.2mg/l<DO<1mg/l. Right top red box is the strictly aerobic zone where ORP>50mV and DO>2mg/l. However, we shaded the areas of transition to highlight how the majority of points fell out of the theoretical definitions for the biokinetic conditions. In the middle of the figure, the zone with double diagonal lines is the broader anoxic zone, where 0.1mg/l< DO< 2mg/l and

-125mV< ORP< 50mV, combined the transitional zones from anaerobic to anoxic zones (ORP from -50mV to -125mV) and the anoxic to aerobic zones (DO from 1mg/l to 2mg/l). The results in these three zones are the majority of data points.

The data in these three zones need to be further discussed, especially the data located at the right bottom of figure, characterized by elevated DO (over 2mg/l) and abnormally low ORP (lower than -125mV). One of the drawbacks of ORP stems from the measurement itself. The ORP measurements are made by determining the potential difference between an inert electrode and a reference electrode which may therefore, be affected by oxides and sulfide coatings on the electrodes (Heduit and Thevenot, 1992). Andersen (2014) explained that the ORP electrode does not react sufficiently fast with oxygen, and apparently faster with sulfide. A redox level of about -125 mV to -200mV is typical for the redox equilibrium between sulfate and sulfide, so the ORP and DO may mismatch. In addition, some substance may not sufficiently electro-active to impose potentials on the inert electrode resulting in underestimation of the total potential difference (Ndegwa *et al.*, 2007).

Some data in upper left zone were also irregular, with low DO (lower than 0.2mg/l, should be anaerobic) but relatively high ORP (above 50mV, should be aerobic). According to Lie and Welander (1994), a problem occasionally encountered during ORP measurements was the accumulation of fibrous sludge on the platinum electrode. During the testing in this project the probe was kept clean throughout the testing events, to avoid such interference.

4.2 Energy Consumption

From the power meter, historical data of total monthly energy usage were collected and plotted in Figure 4.10. Concurrently, the historical power bill cost for ICSD were collected from Southern California Edison and were plotted in Figure 4.11.

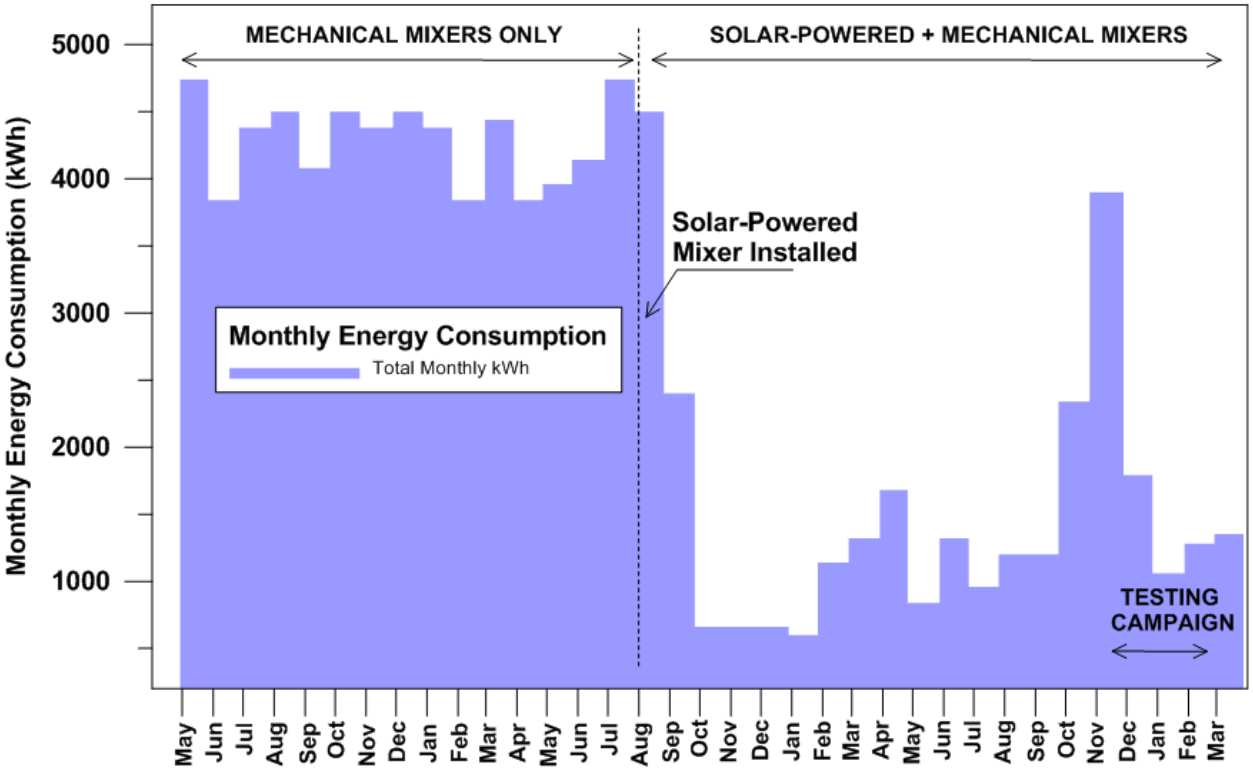


Figure 4.10 Energy Consumption from May 2010 to April 2013

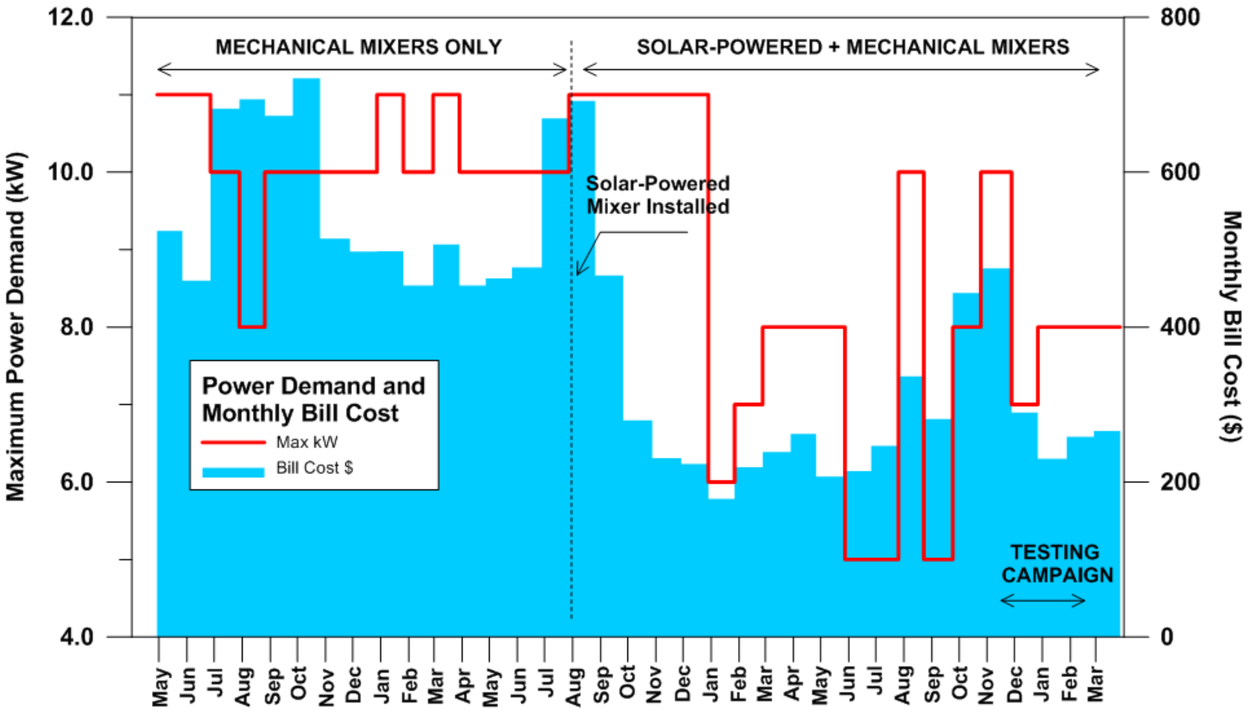


Figure 4.11 Maximum Power Demand and Monthly Bill Cost from May 2010 to April 2013

In the Table 4.5, we highlighted four months' (December- March) energy consumption to correspond the testing campaign period to make a more detailed comparison of energy saving before and after the solar-powered mixer's installation.

Table 4.5 Energy and Cost Reductions for Before and After Solar-Powered Mixer's Installation

Chosen Period	**Month**	**Total Usage** kWh	**Max. Demand** kW	**Daily Avg.** kWh	**Bill Cost** $
December 2010 - March 2011	December 2010	4,380	11	146	$498
	January 2011	3,840	10	132	$454
	February 2011	4,440	11	135	$507
	March 2011	3,840	10	132	$453
	Summary	**16,500**	**11**	**136.25**	**$1,912**
December 2012 - March 2013	December 2012	1,059	8	37	$230
	January 2013	1,280	8	40	$258
	February 2013	1,354	8	45	$266
	March 2013	1,240	8	43	$258
	Summary	**4,933**	**8**	**41.25**	**$1,012**
Reduction		**11,567**	**3**	**95**	**$900**
%		**70%**			**47%**

Since the applied technologies for wastewater treatment are typically energy intensive, any energy-efficiency improvements during operations provide an opportunity for energy and carbon footprint minimization.

In the Figure 4.10 and 4.11, there is a significant decrease in monthly energy consumption after the solar-powered mixer was installed. Coordinately, the monthly bill cost also decreased sharply. In the four months' energy comparison, after the solar-powered mixer was installed, the total energy usage was decreased from 16,500kWh quarterly to 4,933kWh quarterly, decreased 70%; the bill cost was decreased from $1,911 quarterly to $1,012 quarterly, as 47% of energy payment was saved. Additional, the maximum power demand decreased from 11kW to 8kW, it meant the solar-powered mixer installation had abated the power demand a lot. Because in the winter, the lower temperature will cause higher oxygen saturate concentration but slower metabolism activities, so the oxygenation for the lagoon mainly depended on mixing.

From all above, after the installation of solar-powered mixer, lots of energy was saved and the solar-powered mixer is an energy-efficient technology.

4.3 Carbon Footprint

4.3.1 Scope I

Since lagoon is the only biological treatment in ICSD, only process CH_4 emissions and process N_2O emissions should be considered. So, the carbon emission for ICSD of Scope I was calculated as following, with the converting from CH_4 and N_2O to CO_2 is 25GWP and 310GWP, respectively.

Annual process CH_4 from wastewater treatment lagoons calculated by Equation (4) as 21.696 metric tons, so the equivalent to CO_2 emission is 542.4 $MTCO_{2, eq}$ per year. Annual process N_2O emissions from effluent discharge was calculated by Equation (5) as 0.081metric tons, so the equivalent to N_2O emission is 25.0 $MTCO_{2, eq}$. Thus, the total annual emission comes from treatment process (Scope I) is 567.4 $MTCO_{2, eq}$, summarized below in Table 4.6.

Table 4.6 Scope I Annual Emissions

Process CH_4 Emission	**Process N_2O Emission**	**Total Process Emission**
542.4 $MTCO_{2, eq}$	25.0 $MTCO_{2, eq}$	567.4 $MTCO_{2, eq}$

4.3.2 Scope II

The carbon-emission reduction after replacing the mechanical mixers belongs to this Scope, i.e. the indirect carbon-emission associated with imported electric power. The monthly carbon emission showed in Figure 4.7. From the figure, we could find a dramatically drop after the solar-powered mixer's installation.

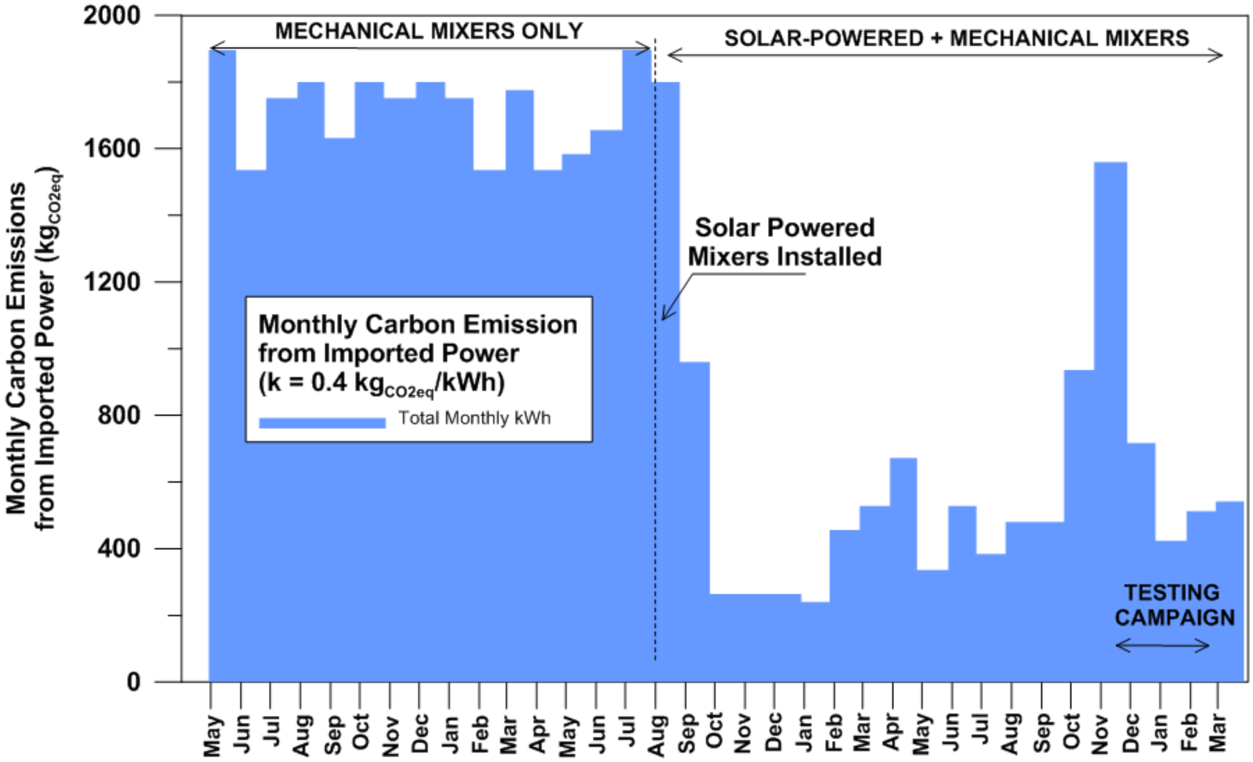


Figure 4.12 Monthly Carbon Emission from May 2010 to April 2013

The reductions of carbon emission before and after the solar-powered mixer installation were summarized in Table 4.7. The chosen of comparison time period is two years: May 2010 to April 2011 (with mechanical mixer) and May 2012 to April 2013 (with solar-powered mixer).

Table 4.7 CFP Reductions for Before and After Solar-Powered Mixer's Installation

Chosen **Period**	**Total Usage** kWh	**κ** kg CO2,eq/kWh	**Scope II CFP** $MTCO_{2,eq}$	**Scope II Emission** %
2010-2011	51,420	0.4	20.57	3.5%
2012-2013	18,485	0.4	7.39	1.3%
Reduction	32,935	0.4	13.18	
%	64.05%		64.07%	

The result shows that after installed the solar-powered mixer, the Scope II carbon emission was dropped from 20.57$MTCO_{2,\ eq}$ to 7.39$MTCO_{2,\ eq,}$ reduced 64.07% compared with previous year. Moreover, the Scope II carbon emission has reduced from 3.5% to 1.3% in the overall carbon emission, it's because Scope I emission is the domain and most carbon-emission came from the processes emission. In order to reduce more carbon emission, a covered lagoon should be considered. The covered lagoon could achieve almost zero-emission during the process and collect the combustible gas for consumption at the same time.

5. CONCLUSIONS

Lagoon treatment is a sustainable alternative for small communities and/or rural areas. As the price of the photovoltaic batteries is decreasing, replacing the existing mechanical mixer to solar-powered mixer is an energy and carbon-emission conservation strategy.

For the lagoon in ICSD, after changed the existing grid-powered mechanical mixer to the solar-powered mixer. The results of testing campaigns show that this mixer is adequate for the lagoon to retain a good water quality. Moreover, both energy usage and bill cost has a significant reduction after the solar-powered mixer was installed, the energy usage decreased 70% quarterly and the bill cost was saved 47% than previous period. Additionally, carbon emission from electricity importation dropped 64% and overall carbon emission was decreased from 3.5% to 1.3%.

REFERENCE

Aberley, R.C., Rattray, G.B. and Dougas, P.P. (1974) Air Diffusion Unit. *Journal WPCF*. **46**(5): 895-910.

Agunwamba, J.C. (1992) A New Method for Dispersion Number Determination in Waste Stabilization Pond. *Water Air Soil Pollut.* **63**(3-4): 361–369.

Anagnostopoulos, K. and Vavatsikos, A. (2012) Site Suitability Analysis for Natural Systems for Wastewater Treatment with Spatial Fuzzy Analytic Hierarchy Process. *Journal Of Water Resources Planning And Management*. **138**(2): 125-134.

Bdour, A.N., Hamdi, M.R., et al. (2009) Perspectives on Sustainable Wastewater Treatment Technologies and Reuse Options in the Urban Areas of the Mediterranean Region. *Desalination.* **237**(1–3): 162-174.

Boyd, C.E. (1998). Pond Water Aeration Systems. *Aquacultural Engineering.* **18**: 9-40.

Bringolf, R.B. and Summerfelt, R.C. (2003) Reduction of Estrogenic Activity of Municipal Wastewater by Aerated Lagoon Treatment Facilities. *Environmental Toxicology and Chemistry*. **22**(1): 77–83.

California Air Resources Board, California Climate Action Registry, ICLEI - Local Governments for Sustainability and the Climate Registry. (2008) Local Government Operations Protocol: For the Quantification And Reporting of Greenhouse Gas Emissions Inventories.

Crites, R.W., Middlebrooks, E.J., and Reed, S.C. (2006). Natural Wastewaters Treatment Systems. CRC Press, Boca Raton, FL.

Cumby, T.R. (1987). A Review Of Slurry Aeration: Performance Of Aerators. *Journal of Agricultural Engineering Research.* **36**(3): 175-206.

Falkdenborg, D.H., Lewis, R.F., Ehreth, D.J. (1974) Upgrading Wastewater Stabilization Ponds to Meet New Discharge Standards. *Reports.* Paper 502.

Galy-Lacaux, C., Delmas, R., *et al.* (1999) Long-term Greenhouse Gas Emissions from Hydroelectric Reservoirs in Tropical Forest Regions. *Global Biogeochemical Cycles.* **13**(2): 503-517.

Ge, H., Batstone, D.J., *et al.* (2013) Operating Aerobic Wastewater Treatment at Very Short Sludge Ages Enables Treatment and Energy Recovery Through Anaerobic Sludge Digestion. *Water Research.* **47**(17): 6546-6557.

Ghirardini, A., *et al*. (2012) To Centralise or to Decentralise: An Overview of the Most Recent Trends in Wastewater Treatment Management. *Journal of Environmental Management*. **94**(1): 61-68.

Gloyna, E.F. (1971) Waste Stabilization Ponds. *World Health Organization Monograph Series*, Geneva, Switzerland.

Gori, R., Giaccherini, F., et al. (2013) Role of primary sedimentation on plant-wide energy recovery and carbon footprint. Water Sci Technol 68(4), 870-878.

Gori, R., Jiang, L.M., *et al.* (2011) Effects of Soluble and Particulate Substrate on the Carbon and Energy Footprint of Wastewater Treatment Processes. *Water Res.* **45**(18): 5858-5872.

Heduit, A. and Thevenot, D.R. (1992) Elements in the Interpretation of Platinum Electrode Potentials in Biological Treatment. Water Sci Tech. 26(5–6): 1244–335.

Hill, P. (2013) Lagoon Aeration Alternatives: An Overview. *Triplepoint's Lagoon Blog.*

Houweling, D., Kharoune, L., *et al.* (2008) Dynamic Modeling of Nitrification in an Aerated Facultative Lagoon. *Water Research.* **42**(1–2): 424-432.

Hurse, T.J. and Connor, M.A. (1999) Nitrogen Removal from Wastewater Treatment

Lagoons. *Water Science and Technology.* **39**(6): 191-198.

Lehtoranta, S., Vilpas, R., *et al.* (2014) Comparison of Carbon Footprints and Eutrophication Impacts of Rural On-site Wastewater Treatment Plants in Finland. *Journal of Cleaner Production.* **65**(0): 439-446.

Lie, E. and Welander, T. (1994) Influence of Dissolved Oxygen and Oxidation-Reduction Potential on the Denitrification Rate of Activated Sludge. Wat. Sci. Tech. 30(6): 91-100.

Massoud, M.A., Tarhini, A., *et al.* (2009) Decentralized Approaches to Wastewater Treatment and Management: Applicability in Developing Countries. *Journal of Environmental Management*. **90**(1): 652-659.

Metcalf & Eddy, Inc. (2014). Wastewater Engineering: Treatment and Resource Recovery - 5th edition. (Tchobanoglous, G., Burton, F.L. and Stensel, H.D. Eds.). *McGraw-Hill series in civil and environmental engineering*, New York.

Moradhasseli, M., Mohamadi, S. (2014) Performance Evaluation of A Facultative Aerated Lagoon for the Purpose of Reviewing the Design Parameters. *Scientia Iranica.* **21**(2): 231-240.

Muga, H.E., Mihelcic, J.R. (2008) Sustainability of Wastewater Treatment Technologies. *J Environ Manage.* **88**(3): 437-447

Nameche, T. and VASEL, J.L. (1998) Hydrodynamic Studies and Modelization for Aerated Lagoons and Waste Stabilization Ponds. *Wat. Res.* **32**(10): 3039-3045.

National Environmental Services Center -NESC (1997) Small Community Wastewater Issues Explained to the Public. *Pipeline-National Small Flows Clearinghouse*, **8**(2): 1-8, Morgantown, WV.

Ndegwa, P.M., Wang, L. and Vaddella, V.K. (2007) Potential Strategies for Process Control and Monitoring of Stabilization of Dairy Wastewaters in Batch Aerobic Treatment Systems.

Process Biochemistry. 42(2007): 1272–1278.

Oakley, S.M. (2005) A Case Study of the Use of Wastewater Stabilization Ponds in Honduras. *Small Flows Quarterly.* **6** (2): 36–51.

Oswald, W. J. (1963) Advances in Biological Waste Treatment. (W.W. Eckenfelder, Jr., and Brother Joseph Mc Cabe Eds). *The MacMillan Co.*, New York

Power, C., McNabola, A. *et al.* (2014) Development of an Evaluation Method for Hydropower Energy Recovery in Wastewater Treatment Plants: Case Studies in Ireland and the UK. *Sustainable Energy Technologies and Assessments.* **7**(0): 166-177.

Ramey, D.F., Lumley, N.P.G., *et al.* (2015) Evaluating Air-Blown Gasification for Energy Recovery from Wastewater Solids: Impact of Biological Treatment and Point of Generation on Energy Recovery. *Sustainable Energy Technologies and Assessments.* **9**(0): 22-29.

Reardon, D.J. (1995) Turning Down the Power. *Civil Engineering- ASCE*. **65**(8): 54-56.

Reed, S.C., Crites, R.W. and Middlebrooks, E.J. (1995) Natural Systems for Waste Management and Treatment- 2nd edition. *McGraw-Hill Inc.,* New York.

Rich, L.G. (1980) Low-Maintenance, Mechanically Simple Wastewater Treatment Systems, McGraw-Hill, New York.

Rodriguez-Caballero, A., Aymerich, I., *et al.* (2015) Minimizing N_2O Emissions and Carbon Footprint on a full-Scale Activated Sludge Sequencing Batch Reactor. *Water Research.* **71**(0): 1-10.

Rodriguez-Garcia, G., Hospido, A., *et al.* (2012) A Methodology to Estimate Greenhouse Gases Emissions in Life Cycle Inventories of Wastewater Treatment Plants. *Environmental Impact Assessment Review.* **37**(0): 37-46.

Rosa, L., dos Santos, M., *et al.* (2004) Greenhouse Gas Emissions from Hydroelectric Reservoirs in Tropical Regions. *Climatic Change.* **66**(1-2): 9-21.

Rosso, D. and Stenstrom, M.K. (2008) The Carbon-Sequestration Potential of Municipal Wastewater Treatment. *Chemosphere.* **70**(8): 1468–1475.

Rosso, D., Lothman, S.E., *et al.* (2011) Oxygen Transfer and Uptake, Nutrient Removal, and Energy Footprint of Parallel Full-Scale IFAS and Activated Sludge Processes. *Water Research.* **45**(18): 5987-5996.

Salter, H.E., Ta, C.T., Ouki, S.K. and S.C. Williams (2000) Three-Dimensional Computational Fluid Dynamic Modeling of a Facultative Lagoon. *Water Science and Technology.* **42**(10-11): 335–342.

Schneider, A.G., Townsend-Small, A., *et al.* (2015) Impact of Direct Greenhouse Gas Emissions on the Carbon Footprint of Water Reclamation Processes Employing Nitrification–Denitrification. *Science of The Total Environment.* **505**(0): 1166-1173.

Shrestha, E., Ahmad, S., *et al.* (2011) Carbon Footprint of Water Conveyance Versus Desalination as Alternatives to Expand Water Supply. *Desalination.* **280**(1–3): 33-43.

Sobhani, R., Abahusayn, M., *et al.* (2012) Energy Footprint Analysis of Brackish Groundwater Desalination with Zero Liquid Discharge in Inland Areas of the Arabian Peninsula. *Desalination*. **291**(0): 106-116.

Tian, Y., Ji, C., *et al.* (2014) Assessment of an Anaerobic Membrane Bio-Electrochemical Reactor (AnMBER) for Wastewater Treatment and Energy Recovery. *Journal of Membrane Science.* **450**(0): 242-248.

U.S. Environmental Protection Agency – US EPA (1992). Manual- Wastewater Treatment /Disposal for Small Communities, EPA/625/R-92/005, Cincinnati, OH and Washington DC.

U.S. Environmental Protection Agency – US EPA (2002) Wastewater Technology Fact Sheet: Facultative Lagoons, EPA/832/F-02/008.

U.S. Environmental Protection Agency – US EPA (2011). Principles of Designs and

Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers and Managers, EPA/600/R-11/088, Cincinnati, OH.

U.S. Environmental Protection Agency – US EPA (2013) Renewable Energy Fact Sheet: Solar Cells, EPA/832/F-13/019, Washington, DC.

Uggetti, E., Ferrer, I., *et al.* (2012) Carbon Footprint of Sludge Treatment Reed Beds. *Ecological Engineering.* **44**(0): 298-302.

Upadhyay, S., Bierlein, K.A., et al. (2013) Mixing Potential of a Surface-Mounted Solar-Powered Water Mixer (SWM) for Controlling Cyanobacterial Blooms. Ecological Engineering. 61: 245-250.

Water Environment Federation. (2009) Energy Conservation in Water and Wastewater Facilities- WEF Manual of Practice vol. 32 – 1st edition. *McGraw-Hill Inc.,* New York.

Wolverton, B.C. and McDonald, R.C. (1979) Upgrading Facultative Wastewater Lagoons with Vascular Aquatic Plants. *Water Pollution Control Federation*. **51**(2): 305-313.