Solar-Energy Innovative and Sustainable Solution for Freshwater and Food Production for Lake Titicaca Islands

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***Abstract*—Drought and scarcity of water resources require innovative and sustainable solutions to secure water availability for poor people. Choice of solar energy for desalination is a promising and sustainable cost-effective alternative for improving high quality water supply. Today, almost all Latin American countries use different desalination technologies except for Bolivia. Bolivia has an arid to semiarid climate and suffers from salinity problems especially the Altiplano area. Thus, there is a need to introduce innovative solution using latest technologies such solar desalination at locations with scarcity of freshwater. This study suggests implementing a small desalination plant of about 10 m^3/day as a demonstration plant and then successively extending the capacity. As well, it is suggested to build a solar energy system with bigger capacity to cater not only for the desalination plant, but also the excess energy to be benefit for homes, roads lighting, and other important purposes for the local community to improve life standard of the people.**

***Index Terms*—Food, Freshwater, Lake Titicaca Islands, Reverse Osmosis, Solar Desalination, Sustainable Energy.**

I. INTRODUCTION

During my stay in La Paz city I have had so many chat with people, national radio interview and personal meetings e.g. several hours with the county mayor and locals were talking about water resources, energy production and desalination. Due to sever water problems in Bolivia everybody was asking about freshwater and treatment of available water for drinking and other purposes. Thus, the rapid solution for many places in Bolivia is water and energy production considering the economical and environmental issues in the design of the projects in the future e.g. solar energy and challenging technology to produce freshwater.

Over 97% of the earth's water cannot be used for direct human consumption (e.g., drinking water) due to its salinity. Desalination is a challenging technology that can provide freshwater when other sources and treatment procedures are uneconomical or environmentally non-friendly. Historically, desalination has been a freshwater supply opportunity for a long time. With the rapid growth of water desalination technology in recent decades, the development has continued in many arid and semiarid areas. However, solar desalination is an alternative for small-scale solutions where no other choices exist.

Globally, the desalination capacity has increased rapidly, from 8000 m^3/day in 1970 to about 32.4 Mm^3/day in 2001 from over than 15,000 installed and contracted desalination units, out of 19.1 Mm^3/day seawater desalination plants and 13.3 Mm^3/day non-seawater [1, 2]. In the last few years, the contracted desalination plant capacity has grown to more than 90 Mm^3/day, which represents the output of over 16,000 desalination facilities with an online capacity of almost 85 Mm^3/day at the end of 2015 [3]. The total contracted capacity has now reached about 100 Mm^3/day and the online amount about 92.2 Mm^3/day, [4].

Bolivia is a landlocked country located in western-central South America with an area of 1,098,581 km2 (5.72% of Latin America) and a population of about 11,410,000 (1.72% of Latin America) inhabitants [5]. It is bordered to the north and east by Brazil, to the southeast by Paraguay, to the south by Argentina, to the southwest by Chile, and to the northwest by Peru [6]. One-third of the country is the Andean mountain range. Only 27% of the populations have access to improved sanitation, 80 to 88% have access to basic water services. Coverage in urban areas is larger than in rural areas [7].

Drought in Bolivia was officially declared in the World News, La Paz (Reuters) in November 2016 for the whole country. The severe drought was most severe for cities and towns located in valleys and mountain areas. In the city of La Paz, rationing of water affected 100 neighborhoods. Drinking water rationing is commonplace since several years in the cities of Oruro and Potosí.

The severe drought caused the following:

- Bolivia's Vice Ministry of Civil Defense estimated that the drought affected 125,000 families and threatened 290,000 ha of agricultural land, and 360,000 heads of cattle.
- The president called on local governments to devote funds and workers to drill wells and transport water to cities in vehicles, with the support of armed forces, from nearby water sources.
- The national state of emergency came after 172 of the country's 339 municipalities declared their own emergencies related to the drought.

A. Desalination and water reuse in Latin America

With 80% of the population living in urban areas, Latin America is one of the most urbanized regions in the world, and is expected to urbanize even further, with 86% of its population residing in cities by 2050 [8]. i) population growth (urban population has risen from 314 million in 1990 to nearly 496 million today, and is projected to reach 674 million in 2050) [8]; and ii) expansion of water supply and sanitation services is needed.

Today, there are many desalination plants in Latin America except for Bolivia. As an example, in Brazil, there

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are many small-scale and medium sized reverse-osmosis (RO) desalination plants with capacities between 0.5 and 20,000 m^3/day, mainly in the arid north-eastern part of Brazil. Of about 800 plants listed for Latin America, some 300 are in Mexico and 120 each in Brazil and Chile. Argentina has about 70, Peru and Venezuela 50 each, and Colombia and Ecuador 25 each [9].

In the dry region of the coastal strip of Patagonia in Argentina, some cities bring their water from the Andes in about 100 km long pipelines for relatively small populations. Therefore, seawater desalination has to be a more economical and environmentally friendly way to provide fresh water to people and industry, and indeed several Seawater Reverse Osmosis (SWRO) plants are being discussed. In addition, the existing larger seawater desalination plants in Peru are all between 5,000 and 10,000 m^3/day capacity and some of them are already being expanded [9].

B. Objectives and purposes

We aim to suggest sustainable solutions for securing freshwater for people (e.g. Lake Titicaca Islands) that can improve living conditions. One suggestion is small-scale solar desalination systems. At present, surface water can often not be used directly due to its salinity and other pollutants. In general, surface water exists but may contain high salinity (slightly brackish). Desalinated water can supply long term high quality fresh water to secure food for people living in the area. Three major objectives and purposes are:

1. Provide people in the area with potable water (clean and fresh drinking water) and the excess amount can be used for other purposes.
2. Use of tried-and-tested technology such as solar desalination (this method is validated and effective) that helps to preserve available water.
3. A call for international help in order to assess funds for stepwise expansion.
4. Developing the area and create more jobs in the area.
5. Improve tourism by production of fresh water, solar energy, and sanitation.

II. STUDY AREA

A. An overview

The Lake Titicaca Basin is a region with long traditions of water management (Fig. 1) [10]. The basin is shared between Bolivia and Peru and considered as an ancient lake in the high-elevation Altiplano region with high biodiversity [11]. The lake is surrounded by the eastern and western Andean Mountains between $15^0 45'$ S and $69^0 25'$ W in the northern part of the Peruvian–Bolivian Altiplano [12]. In most parts of Bolivia, precipitation is the main water source for drinking water and agriculture. The Bolivian Altiplano, however, is strongly affected by local climate and a high degree of variation [13]. The precipitation gradient decreases to the south [14].

In general, the Altiplano area represents a region with agricultural yield reductions leading to shortages of food for humans and animals due to high variability of the in general low precipitation [15,16]. The Lake Titicaca Basin has an area of about 57,300 km^2 with an annual precipitation of about 702 mm, and annual discharge of about 281 m^3/s with an annual potential evapotranspiration of about 652 mm. The Titicaca lake water is slightly brackish, with salinity ranging from 5.2 to 5.5 parts per thousand (ppt or g/l) that prevents it from direct consumption [17].

In a recent study of the Bolivian Altiplano, monthly precipitation was observed at two different stations located close to the Lake Titicaca. The Copacabana and El Belen stations represent an annual mean and summer months (Dec.-March) mean of about 764 and 527 mm for Copacabana and 599 and 408 mm for El Belen, respectively [13]. The lake has a large surface evaporation of about 1700 mm/year, which is considered a water loss affected by climate warming [12].

The Lake Titicaca Basin includes a lake surface area of about 57,000 km^2, located at about 4000 m above mean sea level. It has an outlet sill at about 3,807 to 3,810 m. The lake volume is about 903 km^3, with a corresponding mean depth of 105 m [19,20]. It is considered the largest water body in South America with extended length of about 190 km and about 80 km at its widest point [17].

B. Lake Titicaca popular islands

Fig. 2 shows most of the islands in Lake Titicaca. The islands are small to medium sizes in both Bolivia and in Peru. Some of the islands are listed below:

Uros: In 2011, the population was about 1,200 Uros living in an archipelago of 60 artificial small islands. The islands have become one of Peru's main tourist attractions.

Amantani: About 4,000 people live in 10 communities on the roughly circular 15 km^2 island.

Taquile: The island has approximately having current population around 2,200 inhabitants. Most their income is based on fishing, agriculture, and tourism representing about 40,000 visitors per year.

Suriki: Suriki population is approximately 1,800 inhabitants that are in the Bolivian part of the Lake Titicaca (in the southeastern part also known as Wiñaymarka).

Isla del Sol: It belongs to Bolivia connected with regular boat links to the Bolivian town of Copacabana. The island ("Island of the Sun") is considered as one of the largest islands w Lake Titicaca Islands is approximately 800 families depending on farming, fishing, and tourism.

Isla de la Luna: It is situated east from the larger Isla del Sol and belongs to the La Paz city in Bolivia [21].

C. Surface water

In Bolivia, the most important rivers are: Huayco, Suchez, and Keka to the north and east, and Catari and Tiwuanacu to the south. The Ramis is the most important river as it represents 26% of the tributary basin with about 76 m^3/s. This river is considered the largest among about 25 rivers draining the Titicaca Basin.

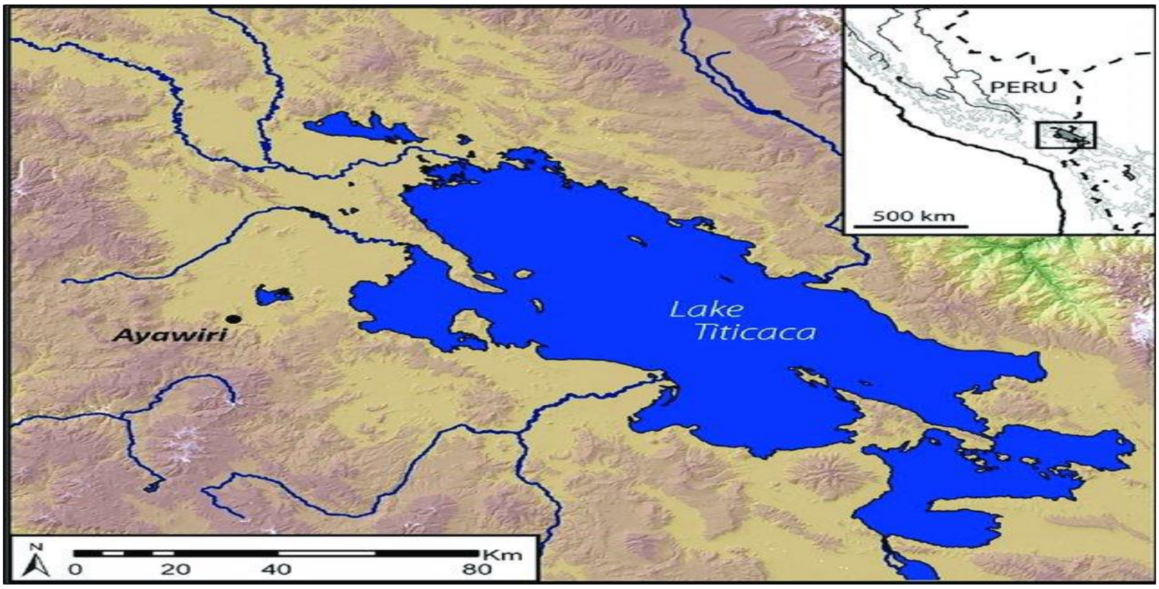

Fig. 1. Lake Titicaca location and overview [18].

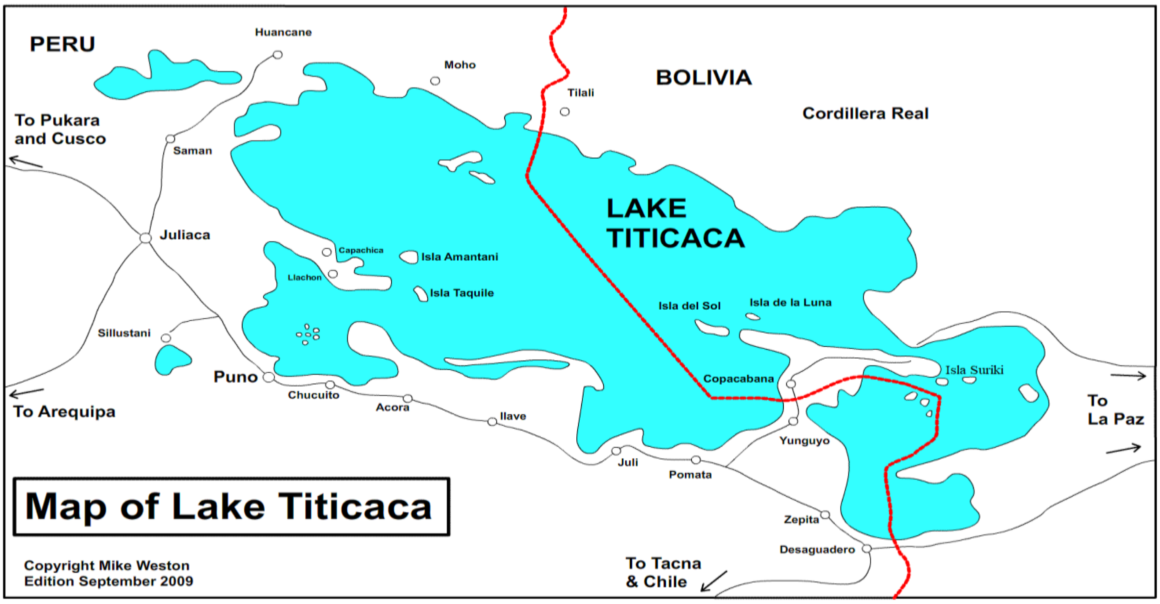

Fig. 2. Most islands in the Lake Titicaca (after Mike Weston).

Overflow from Lake Titicaca, observed at the source of the Desaguadero River, amounts to 35 m^3/s. This flow represents only 19% of the inflow of the five main tributaries, demonstrating the great volume lost through evaporation. This single outlet discharges only 5% of the lake's excess water and the rest is lost due to high evaporation rate [17].

D. Human impact and socio-economic characteristics

Almost all people living in the lake islands are not connected to sanitation or freshwater network. Thus, uncontrolled human activities lead to organic and bacteriological contamination in the area, in particular urban wastes, wastewater, and mining. It is also leads to negative health effects for humans and animals. Considering the current situation and the weakness the system with regard to water usage, a series of flow regulation works have to be defined at the basic level of living standard to help the people in the area. As a first step, island people should be provided by safe water supply ad sanitation. Aquaculture, agriculture, and cattle-raising activities, all focus on food production as the main economic activity for income by islanders.

III. Methods and Materials

A. Future design, procedure, and analysis

For designing a reverse osmosis (RO) plant, many considerations must be taken into account such as water balances for the Titicaca Lake. The lake is a large and has a good potential, but many variables such as chemical composition need to be measured at different sampling locations. The lake temperature and salt concentration are low on average, which is preferable for desalination and treatment in general.

Variables that will be measured are floatables, pH, TSS, DO, turbidity, BOD, COD, total Kjeldahl nitrogen (TKN), total chlorinated hydrocarbons, oil and grease, phenols, N ammonia, total phosphorus, CHNS, LOI, TOC, active biomass, biological/microbial strains (HPC/ATP), total coliform, As, Cd, Cr, Cu, CN, Pb, Hg, Ni, Zn, Fe, Ba, B, and Al. These are vital parameters to be able to design pre-treatment regime and select membrane configuration and type. Routine analyses of Cl, Br, K, Na, SO_4, Ca, Mg, NO_3, NO_2, alkalinity, carbonate, and bicarbonate should also be carried out. These chemical parameters are necessary to measure in order to determine the desalination technique as a function of the drinking water (WHO) standards. Some of the parameters are easy to handle but others (biological) are to be handled carefully during sampling collection and storage of samples.

The following is a description of suggested sampling points and how they are denoted:

1. Five reference points will be selected taking into consideration the ecological status and bathing areas 100 m from the island border forming a semi-circle following the coastline.
2. Five samples are to be collected in the open water separated with a distance of 100 m between each point in all directions and following radial lines starting from any recharge point with a separation from midline of about 30 to 45° between each point.
3. In total, we plan 10 samples for the whole analysis to be sure about the tests and the selection of the intake system for the safety of the RO membranes.

B. Solar desalination

Solar energy technology is one among several techniques to use for desalination. Solar energy is considered a renewable source of energy unlike non- renewable sources such as fossil fuel. The solar cell collectors must be placed at the same selected area as the desalination plant. About 130 desalination plants have been built during the last few years worldwide operating with renewable energy [22]. Currently, the highest percentage of renewable desalination plants goes to solar energy of approximately 70% [23].

Desalination using renewable energy offers a win-win solution to the energy to water supply problems. Solar energy for desalination technology provides sustainability and reduces the carbon footprint compared to other resources of renewable energy [24].

For long-term planning, the cost for producing freshwater by solar system is going to be reduced compared to conventional desalination systems. However, for small-scale solar desalination demands such as small islands, villages or household size is good solution.

RO desalination through solar energy is a rapidly increasing area of research that is growing fast in many countries with significant progress in the last few years. Solar energy in particular can be considered as an attractive source of energy to power desalination, fresh water scarcity and amount of solar irradiation coincide in many regions. Also, solar energy can be harnessed as electrical energy using solar Photovoltaic (PV) technology [25]. As the most dominant desalination technology, RO is well suited to be driven by solar energy systems.

The use of solar energy technology is not new for most countries but for desalination it is a novel technique, especially for Bolivia. Solar energy can be collected and managed to be used directly and turned into electricity for housing, roads, desalination, and other purposes. Solar energy has many advantages and is cost effective compared to currently available energy sources. However, it is still not tested for large scale seawater desalination water production. It can be observed that reverse osmosis is the most suitable technology to operate small-scale solar powered desalination plants. Globally during 2017, renewable solar power generation technology capacity was the fastest growing renewable energy type [26]. It is clear that solar power alone, show more new capacity as compared to both fossil and nuclear energy (see Table I).

C. Recent examples

Namibia stands out as the driest country in Africa and one region directly affected by climate change. Thus, it's time to examine the potential of coastal agriculture for effective carbon binding by introducing innovative solutions, e.g., solar desalination [28]. The solar desalination solution costs are more than 70% lower than conventional systems due to saving energy costs and excluding the need for fossil fuels (CEO of Solar Water Solutions Antti Pohjola says) [28].

This innovative solution is the first solar desalination systems in the world to operate on 100% renewable energy that was designed and delivered by the Finnish company Solar Water Solutions. Thus, solar-powered desalination produces high-quality water directly from the ocean for freshwater and agriculture purposes. The project was commissioned as a joint initiative of the University of Namibia (UNAM) and the University of Turku, Finland (see Fig. 3).

TABLE I: NET POWER GENERATING CAPACITIES WERE ADDED IN YEAR 2017 [AFTER 26]

Type of Energy	Capacity (GW)	Capacity (%)
Solar	98	38
Wind	52	20
Gas	38	15
Coal	35	13
Large Hydro.	19	7
Nuclear	11	4
Other Res.	7	3

D. RO desalination plant capacity and cost

Bashitialshaaer and Persson was calculated unit and capital costs for desalination and energy from more than 20 desalination projects in different countries mostly for SWRO desalination plants. Compared to seawater, Lake Titicaca water is much cheaper to desalinate due to low salinity concentration. The capital cost for desalination plant production would about \$1 million for a project capacity of 1000 m^3/day of desalinated water and a unit cost of about \$ 0.79/m^3 (approx. 4.5 kWh for 1 m^3). Also, the obtained capital cost for the power plant to produce 1 MW of energy is about \$ 1 million and the average unit cost to produce 1 W from the power plant is about \$ 1 [28].

Fig. 3. The UNAM sustainable seawater desalination plant [28].

Fig. 4. Mobile system container RO desalination plant (photo: Bashitialshaaer, 2015 [30]).

E. RO desalination plant capacity and cost

Bashitialshaaer and Persson was calculated unit and capital costs for desalination and energy from more than 20 desalination projects in different countries mostly for SWRO desalination plants. Compared to seawater, Lake Titicaca water is much cheaper to desalinate due to low salinity concentration. The capital cost for desalination plant production would about $1 million for a project capacity of 1000 m^3/day of desalinated water and a unit cost of about $ 0.79/m^3 (approx. 4.5 kWh for 1 m^3). Also, the obtained capital cost for the power plant to produce 1 MW of energy is about $ 1 million and the average unit cost to produce 1 W from the power plant is about $ 1 [28].

Nowadays, RO processes dominate the market for both seawater and brackish water desalination accounting for 70% of the total installed capacity. In 1999 the installed capacity of RO processes was 31% and MSF was 65%, and in mid-2014, RO significantly increased and reached 66% while MSF declined to 20%, since it requires more energy [29].

As well, the global distribution of total membrane systems reached 93% while the total thermal processes decreased to 7% (calculated from ID-Books) [4, 29] .

For different water sources as of before 2001, brackish water RO desalination cost was higher than that for pure and river water. In general, from 2005 to 2010, the average cost decreased to 0.3 $/$m^3$, while from 2015 onward it decreases to 0.2 $/$m^3$ for the same source of water [29]. Also, RO seawater desalination cost clearly trended downwards no matter what kind of used technology. The present average value is about US $ 0.5 for 1 m^3. The low cost of desalination is a benchmark in implementing solar desalination systems to be sustainable.

Due to high technology in solar energy for desalination production the capital and unit cost results can be decreased compared to traditional desalination. We plan to use solar desalination together with a mobile desalination system that is functioning with RO membrane for easy handling as seen in Fig. 4. RO mobile desalination system is a full package with different capacity that can start from 10 to 5,000 m^3/day, which will be enough for a start.

IV. Discussion and Recommendations

Planning for innovative solutions such as small-scale solar desalination for freshwater production using water from the Lake Titicaca is important for many reasons. This

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could solve and/or minimize the problems of water scarcity and shortage of electricity. Such solutions can also decrease the tension when providing clean environment and more jobs for the people living in the area. Small-scale solutions may be safer than large scale projects as the small-scale projects can be successively evaluated.

The success of the above plan depends on the responsibility and the response of the local people regarding the whole system the funding. Some of the consumers may receive subsidies for water consumption. However, in the long-term, cost-recovery should pay for operation costs and maintenance, pre-treatment, and post-treatment. The plan is to begin with at least 10 m^3/day, to reach an amount of 100 m^3/day depending on actual cost-recovery. Eventually, funding could be enough to serve more than 100 to several thousands of local people and tourists.

The first step for desalination production can be for drinking purposes, e.g., 10 m^3/day (10,000 lt/day), about 1,000 persons could get 10 lt/day of fresh water and about 10,000 persons using 10 lt/day if a first step with about 100 m^3/day (100,000 lt/day). An investment cost for the planned project would be approximately $ 10,000 to produce a capacity of 10 m^3/day and $ 100,000 to produce capacity of 100 m^3/day.

The latest technology RO membrane can cover up to 90% of the feed water from Lake Titicaca because the water is slightly brackish and that means a lower concentration and a higher recovery production rate with low environmental impact. Also, the unit and running cost will be very low compared to seawater reverse osmosis, keeping in mind the capital cost is the same. The long time trend for a unit cost of brackish water RO desalination is about 0.3 $/$m^3$, while from 2015 onward it decreased to reach 0.2 $/$m^3$ (3 - 4.5 kWh for 1 m^3) [31].

Several renewable energy projects are running worldwide, e.g., solar, wind, geothermal, wave and tidal energy. It has been observed that solar energy is the most sustainable source of renewable energy to be integrated with the desalination and production of heat and electricity. There are two desalination projects that may serve as examples using solar energy. The Keio University plant, Japan, is producing about 100 m^3/day functioning with multi-effect distillation (MED). In Morocco, a RO desalination plant with capacity of about 12-24 m^3/d using PV energy is running [32].

In view of the above, it is suggested to build a solar energy system with larger capacity than required for running the desalination unit and to use the excess energy for homes, road lights, and other important purposes that will suggested by local people living in the area. For solar energy production with very high irradiation and secured financing environment, the benchmark has to be planned a bit lower than US 2 cents/kWh range for tenders to win any new project specifically in the Middle East region [26].

Surprisingly low solar energy costs have been achieved in 2016, as a result of the boost in solar technology. In this year, some bids were recorded and awarded for 2.95 US cents in a Dubai project to produce 800 MW, a Chile contract with about 2.91 US cent for power supply and then an even cheaper one for Abu Dhabi with about 2.42 US cents for the 'winter' supply part of the 1.18 GW plant [26]. Table II shows top 8 bids in February 2018 for 300 MW project in Saudi Arabia that was won by a local company at a new world record low price of 2.34 US cents/kWh, despite, the lowest bid of 1.79 US cents/kWh because they prefer their own companies.

Although, the lowest bid 'Masdar/EDF' of 1.79 US cents/kWh was later disqualified because it is based on bifacial module technology that is not acceptable right now.

TABLE II: TOP 8 BIDS FOR 300 MW SAKAKA PV PROJECT IN SAUDI ARABIA [EXCERPTED FROM 26]

Company name	Cost US cents/kWh
Masdar/EDF	1.79
ACWA	2.23
Marubeni	2.66
Engie	2.77
JGC/Trina	2.78
Mitsui & Co.	2.86
Total	2.86
Cobra	3.37

V. CONCLUSION

Safe water and sanitation are missing for the Lake Titicaca island people, as well as electricity, education, health, and sustainable development. Freshwater and electricity production from a challenging technology using renewable energy are vital for sustainable development. Thus, building a small-scale solar desalination (RO) plant is considered innovative because freshwater and electricity are the main driving force for a basic healthy life that can directly improve livings standards. Solar renewable energy production is the fastest growing energy type among other renewable energy technologies with high efficiency and continuously decreasing cost.

The second step in the plan is to expand the project and capacities both for freshwater and solar energy and the excess can be used for homes, road lights and other important purposes chosen by the people living in the area. Also, a further target is to develop agriculture, aquaculture, and other sustainable economic developments. This will help a maximum number of people and several thousands of tourists visiting the lake islands every year that will lead to increase in income and number of tourists for the whole area. The target of this study is poorest people in order to improve their life standard and health conditions.

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