Novel design of Cost-effective Solar Powered Brackish Water Reverse Osmosis Plant: A possible solution for an affordable supply of safe drinking water for the rural communities in CKDu-affected areas in Sri Lanka

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Abstract: *The government of Sri Lanka has established a Community-Based Organization (CBO) to supply safe drinking water on a payment basis through the application of electrically driven Brackish Water Reverse Osmosis (BWRO) plants in CKDu-impacted areas. Due to major drawbacks such as cost, issues in regular maintenance, membrane clogging, lack of expertise to rectify the defects encountered in electrically driven BWRO plants, etc. In this design, a multistage centrifugal high-pressure pump was integrated with the BWRO plant and drastically, bring down the manufacturing cost. Then, evaluate the performance of the Brackish Water Reverse Osmosis system powered by solar electric energy under Sri Lankan weather, and environmental circumstances, and enhance the recovery ratio up to 75% through an automated mixture. The novel design of the solar-powered BWRO plant can be manufactured locally at a low cost, and hence it would be the ideal replacement for imported BWRO plants to access high-quality drinking water for the farming community who could not have sufficient wealth to obtain safe drinking water on a payment basis The solar-powered BWRO plant is considerably reduced the government overheads to subsidize the water purification cost up to 90% of the existing expenses. Further, it leads to protecting the environment by reducing Green House Gas (GHG) emissions with a more than 75% of recovery ratio. Further, cost comparison of SLN manufactured BWRO vs imported BWRO in a similar capacity revealed that the SLN-manufactured BWRO plant was 7fold cheaper than that of the imported BWRO plant.*

Keywords: *Brackish Water Reverse Osmosis; Chronic Kidney Disease unknown etiology, Safe Drinking Water; Sri Lanka; Net Metering System*

1. Introduction

A newly published United Nations (UN) world water development report 2019 mentioned that the climate is continuously changing and it impacts societies mostly due to decreasing water bodies (International standards for drinking water, 2019) . Further, this article brings out the facts; that water contamination is one of the major catastrophes that lead to jeopardizing global sustainable development goals and threatening the lives of billions of people . According to the water quality standards defined by World Health Organization (WHO), Total Dissolved Solids (TDS) in safe drinking water should be below 500 mg L-1 [1]. However, in seawater TDS is 35, 000 mg L-1 or more while in brackish water it is around 1000 to 15 000 mg L-1.

Brackish Water Reverse Osmosis (BWRO) is an elementary water purification application; that is more commonly used to overcome freshwater scarcity in many regions of the world. However, it is contributing to Green House Gas (GHG) emissions. Therefore, many scientists and engineers are investigating integrating renewable energy with BWRO plants as a possible alternative solution to reduce the production cost of product water. Countries such as Australia, Singapore, Spain, and Arabian countries are the usual contenders in reverse osmosis operation in a global context and accessing safe drinking water to billions of people without operational difficulties. However, the operation of the BWRO plant is an energy-intensive process; and the manufacturing cost is also very high. Therefore, this BWRO application is not practically feasible for lower-income communities that are combating to access clean drinking water

Due to the deaths of over 22,000 people from CKDu in Anuradhapura district in the North Central Province (NCP) in Sri Lanka since it was first identified in 1991, WHO had recommended several measures to control the prevailing situation such as regulating fertilizers and agrochemicals use, providing safe drinking water, better health facilities, and also financial support for the victims (Wanasinghe, et al, 2018) Therefore, the government of Sri Lanka has established a Community-Based Organization (CBO) to supply safe drinking water through the application of BWRO plants in CKDu-impacted areas on a payment basis(Dissanayake ,et al,2021). Further, Sri Lanka National Water Supply and Drainage Board (NWSDB) and Non-Governmental Organizations (NGOs) also installed BWRO plants that had been imported from Israel and the USA at a very high cost. However, due to several reasons such as insufficient wealth of the farming community to obtain safe drinking water on a payment basis, walking a longer distance to access purified water, regular membrane clogging, non-availability of skilled personnel for defect rectifications, repairing, high power consumption and low recovery ratio, the government could not have achieved the expected outcomes (Indika, et.al,2021).

Sri Lanka Navy (SLN) has been pioneering Reverse Osmosis operations on board naval vessels since 1992 and therefore, SLN is sufficient with expertise, modern workshop facilities, and skilled personnel to handle any situation, in BWRO techniques. Economic feasibility has been recognized as the major concern while developing improved BWRO plants for the continuous supply of clean water to rural communities with low income in CKDu-impacted areas in Sri Lanka. Hence, it is necessary to consider manufacturing costs, enhance the product water supply (recovery ratio), and ease up the existing situation. Sri Lanka lies within the equatorial belt and thus substantial solar energy can be acquired mostly throughout the year for any applications. The main aim of this research was to develop a novel design of a solar-powered efficient BWRO plant with a multistage high-pressure centrifugal pump and efficient membrane arrangement to optimize manufacturing cost, and produce more units to supply safe drinking water for the impacted communities, enhance the recovery ratio, and membrane lifetime.

2. Methodology and Experimental Design

The capacity of the BWRO plant was defined as 10 tons/day to initiate the proposed project and the most vulnerable locations of CKDu prevailing areas in the country such as Vavuniya (Irrattaperilakulam), Sri Lanka Naval Ship Pandukabaya (SLNS) (Poneewa), Madawachchiya Town (Mithreepala Senanayake Central College), Dutuwewa Village and Kadawthrabewa Village in the Madawachchiya area at Anuradpura district were targeted (Ranasinghe, et al., 2019) .

A. Water Quality Analysis

Water quality parameters of collected feed water samples from those targeted areas were tested at the Industrial Technology Institution (ITI), Sri Lanka to determine the nature of the water quality of the collected water aiming at designing suitable BWRO plants for those targeted locations. Physical water quality parameters (pH, Colour, and Turbidity) were tested through APHA 4500 - H+B, APHA 2120 B, and APHA 2130 B respectively. Then, chemical water quality parameters (hardness, alkalinity, metal cations, and anions) were tested by APHA 2340 C, APHA 2320 B, APHA 3125 B, and APHA 4500 Cl- respectively. Product water samples were tested at Sri Lanka Water Board.

B. Designing a Low-Cost BWRO Plant

1) Selection of a Feed Water Pump: The effective pre-treatment process is crucial to improve the quality of the feed water to the level that would result in the reliable operation of the BWRO filtration practice. According to the raw water quality, the pre-treatment application was designed with the following, all or some treatment steps; incorporate chlorination process, apply with lime treatment, fix with media filtration, pH adjustment, water sterilization (Ultraviolet (UV) filter) and fix with micron filters as the final step (Knops, et al., 2007).

The capacity of the feed pump was decided considering the capacity of the BWRO plant, and calculations were done as follows;

Required outlet pressure = 3 bar

Gross Feed Flow rate for filtration = 2.5 m^3/hr

Capacity = 0.7457 kW (1 HP)

2) Designing of Multimedia Filters: Gross Feed Flow rate for filtration is the most concerning factor to design vessel sizes.

$$F\_f = F\_fn/N\_f \qquad (1)$$

Where, F_f is feed flow per filter

N_f is the number of filter units

F_{fn} is feed flow to a filtration plant

$N_f = 2$

$F_{fn} = 2.5\ m^3/hr$

$F_f = 2.5m^3/2 = 1.25m^3/hr$

Required cross-sectional areas for multimedia filter vessels are as follows;

$$A\_f = F\_f/F\_sd \qquad (2)$$

Where, A_f is the cross-sectional filtration area per filter

F_f is feed flow per filter

F_{sd} is service down-flow rate

A downflow of a sand filter is one of the key factors for calculating the cross-sectional filtration area. Further, downflow sand filters are directly impacting to separate from solid to liquid at flow rates up to about 18 $m^3/h\ m^2$ of filter (Ezzeghni, 2018)[11].

$A_f = 1.25/18 = 0.0694\ m^2$

$$A_f = \pi/4\ (ID)^2 \qquad (3)$$

Where, ID is required internal diameter

ID = 0.3 m

Then, two commercially available filter vessels (12' x 52') were selected for this application and they were filled with sand and active carbon up to 50% of their capacities while keeping 50% freeboard to allow bed expansion during the backwash cycle.

3) Selection of a High-Pressure Pump: A detailed study was carried out on the operating pressures of existing imported BWRO plants that

were functioning at Naval Bases in NPC, and it was revealed that the operating pressures were always maintained below 12 bar, with half load conditions even in the driest season (Table 1). Subsequently, it was realized that there was a high routing maintenance cost and a very high monthly electrical bill during this type of BWRO operation. When the high-pressure pump of the BWRO plant was checked, it was revealed that there was a positive displacement (gear pump) with the overpressure protection. Therefore, a comparison between the Positive Displacement Pump and Centrifugal Pump was carried out to select the suitable high-pressure pump for this BWRO design (Supplementary Table 1).

Table 1. Level of Total Dissolved Solids of feed water and operating pressures of imported BWRO plants at Sri Lanka Navy Basses, North Central Province

Location	Total Dissolved Solids (TDS) mg L^{-1}	Maximum Operating Pressure (bar)
SLNS Pandukabaya	707	10
SLNS Tammanna	814	12
SLNS Shiksha	710	10
SLNS Gajaba	796	12
SLNS Buwaneka	823	12

The operating pressures of imported BWRO plants were studied to select a suitable high-pressure pump for this low-cost BWRO application (Table 1).

4) Selection of a Membrane: A spiral wound of 10.16 x 101.6 cm^2 (4 x 40 $inch^2$) membranes was matched with this new design according to the availability of membranes in the local market, productivity, feed water hardness, and TDS. Subsequently, it was decided to fix membranes in serial with each other to the BWRO plant for enabling enhanced productivity (Jayasumana, et al., 2016) (Figure 2). The membrane specifications are as follows;

i. Capacity - 250 LPH

ii. Type -10.16 x 101.6 cm^2 (4 x 40 $inch^2$) spiral wound

iii. Make -Vontron

iv. Effective Area -7.9 m^2 (85 ft^2)

v. Material -Polyethylene

vi. Model - 400

vii. Operating Pressure -200 psi

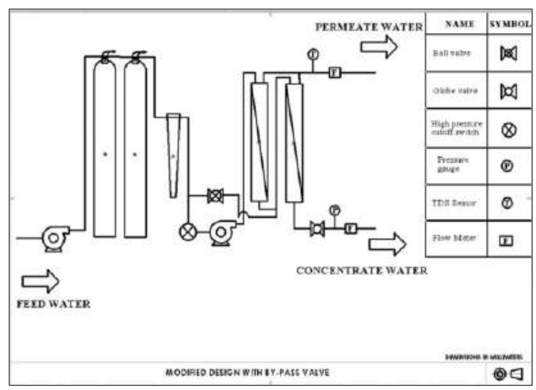

Figure 1. Modified design with by-pass valve (Ahn, et al., 2008)

C. Setting up of the BWRO Plant

The BWRO plant setup was comprised of a raw water tank, feed pump, multimedia filter, cartridge filter, high-pressure pump, RO modules, and two flow meters (McMordie, et al., 2013). The spiral wound membrane [(brand Vontron) 10.16 X 101.6 cm^2 (4 X 40 $inch^2$)] with an effective membrane area of 7.9 m^2 (85 ft^2) was installed with this BWRO Plant. The experiments were conducted at ambient temperature with a fully operational mode to get safe drinking water. The BWRO system was encompassed with Polypropylene Random Copolymer (PPR) pipes that sustain 25 bar pressure. The capacity of the feed water tank is 5000 L, and the feed pump was operating under 3 bar pressure for the pre-treatment process by an overhead tank. Then, pre-treated water was pressurized by the 15-bar multistage centrifugal high-pressure pump and the permeate was taken off from one pipe and connected to a 1000 L tank, and allowed rejection flow through another pipe to reject water collected to another 1,000 L tank. In this BWRO process, both the membranes were installed to the system in serial to each other, and then parameters were investigated (Qiu & Davies, 2012)(Figures 2&3).

Figure 2. The Brackish Water Reverse Osmosis Plant with a capacity of 10 tons/ day was developed by Sri Lanka Navy.

Table 2. Cost Comparison of Locally made Brackish Water Reverse Osmosis Plant Vs Imported Brackish Water Reverse Osmosis Plant in Similar Capacity (10 tons/Day)

Description	**Qty (Nos)**	**Rate (US$)**	**Cost for Local Plant (US$)**	**Cost for Imported Plant (US$)**
Feed water pump (1HP, Single Phase)	1	195	195	2,450
Sand filter (13”X54”)	1	170	170	800
Carbon filter (13”X54”)	1	240	240	800
15 L Chemical dosing pump	1	130	130	1,250
40 L Chemical tank	1	42	42	400
Low-Pressure sensor (0-3 bar)	1	25	25	500
High-Pressure pump (0-15 bar)	1	650	650	4,500
Control panel (Locally made)	1	265	265	1,400
20" Filter Housing	1	25	25	150
20” Filter element	1	10	10	150
10" Filter Housing	1	10	10	100
10” Filter element	1	2	2	50
Membrane housing & membranes	2	240	480	8,600
PPR Pipes and joints	1	590	590	2,800
BWRO skid	1	210	210	1,100
Panel mount flow meter	2	20	40	200
Line mount flow meter	3	25	75	350
Total			**3,159**	**25,600**

D. Design of Solar-Powered Control System

In this research, BWRO plants of Vavuniya (Irrattaperilakulam) and Madawachchiya Town (Mithreepala Senanayake Central College) were connected to the Net Metering System concerning product water requirement, the electrical conductivity of feed water, and atmospheric temperature. Further, the focal point of this novel system is to achieve the correct balance between the daily requirement of electrical energy consumption by the loads and the daily production of solar-powered electrical energy (Rifai, et al., 2015). Therefore, at outset, it is very important to ascertain daily desirable solar-powered electrical energy and the total peak power of solar generators (Table 3). This net metering system is a bit different from the traditional solar powering system and is connected to the national grid and supplies power to the national ring main during the daytime and reversely operated the electricity meter which is fixed by the Sri Lanka electricity board. Then, while BWRO planting is operating, the same electricity meter is running in the correct direction and deducts the amount that was supplied to the national grid.

E. Total power requirement for BWRO plant

i. Power requirement of high-pressure pump = 2.2 kW

ii. Power requirement of feed Pump = 1.0 kW

iii. Power requirement of dosing Pump

iv. and Control Panel = 0.8 kW

v. Total Power Requirement = 4.0 kW

Considering the total power requirement of the BWRO application, a 5 kW solar panel was incorporated into the Net Metering System (Filippini, et al., 2019).

Table 3. Mean Monthly Solar Radiation in Sri Lanka [8]

Month	Mean Monthly Solar Radiation (kWh/m^2,day)
January	5.35
February	5.5
March	5.7
April	6.0
May	5.0
June	4.9
July	4.6
August	4.8
September	4.6
October	4.5
November	5.0
December	5.25

F. Test Procedure

The function of the BWRO was demarcated into two processes such as pre-treatment and reverse osmosis operations. As per the preliminary step, a pre-treatment procedure was conducted to remove turbidity, and muddiness and improve the efficiency of coagulation (McMordie, et al., 2013). Accordingly, two numbers solar-powered net metering systems were fixed with BWRO plants at Vavuniya (Irrattaperilakulam) and Madawachchiya Town (Mithreepala Senanayake Central College). The other three BWRO plants were connected to National Grid Power Supply. Subsequently, reverse osmosis operation began through a control panel. Only single-mode operation is comprised of the control panel including the operation of high-pressure and low-pressure safety cut-outs. Both the feed water pump and high-pressure pump were operated simultaneously to avoid developing a vacuum inside the PPR pipes and both sand and carbon filters. The feed water is flowing through the sand filter and the active carbon filter as a pre-treatment process (Raju & Ravinder, 2018). Then, water is flowing through the cartridge filter up to the high-pressure pump. Eventually, water is pressured up to 10 bar by a high-pressure pump and allowing water to flow through both membranes and collect the product water into a 1000 L tank and permit reject water collection to another 1,000 L tank. Then, the reject water tank is connected to feed water through a mixture, which can regulate the feedwater conductivity automatically or manually. In addition, whenever product water flow is declining badly, the cleaning cycle starts automatically and cuts off the high-pressure pump and backwashes the membranes, and cleans. Recovery ratio calculation was carried out for six months and obtained the mean value. Subsequently, daily water consumption and monthly electricity bills were checked for six months and obtained a mean value.

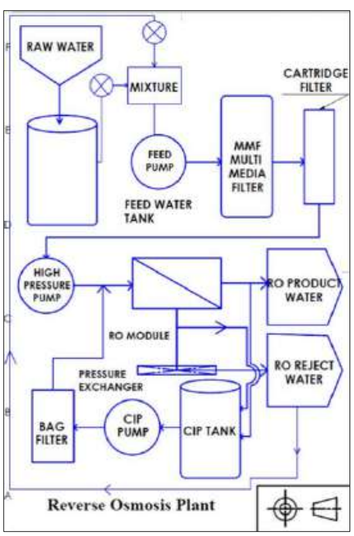

Figure 3. The Schematic of the Brackish Water Reverse Osmosis Plant was developed by Sri Lanka Navy

G. Operation and Routine Maintenance

Many BWRO plants functioning in Sri Lanka are distributed with no form of verified technical documentation, thus questioning their efficacy and efficiency for a sustainable operation (Indika, et al., 2021). Therefore, SLN introduced a trainer-trainee course for BWRO plant operators with a proper set of guidelines to avoid occurrences of regular defects and stoppages to maintain a continued supply of safe drinking water for the affected community in December 2015. Further, SLN operators are engineering mechanics in the profession and very sound in technical operations and maintenance of the BWRO plants. Moreover, SLN adopted an administrative method to gather monthly operation parameters, maintenance details, and water consumption named 'monthly return of BWRO plants' in Annex 'A' to this report. In addition, workshop facilities have been established in Welisara Navy Camp, SLNS Padukabaya, SLNS Mahanaga, and SLNS Barana to handle any emergency breakdowns without difficulties and make the BWRO plants operational to supply safe drinking water around the clock.

H. Membrane Cleaning Mechanism

This mechanism was designed and developed locally with the utilization of practical experience gathered during my BWRO research. In this design, a 4-bar pressure pump is fixed with membrane housing through a 10-bar pressure gauge, using PVC pipes, and then, fixed with a 20 L stock tank which is filled with the detergent mixture. Subsequently, a clogged membrane is installed with housing, and operate the system with 1 bar pressure then regulate pressure from time to time, at least 4 hours.

Figure 4. Membrane Cleaning Mechanism

3. Results and Discussion

Physicochemical water quality parameters of all five locations were tested through ITI and indicated (Supplementary Table 2).

Table 5. Comparison Average product water parameters in five selected locations

Location	Water Input (L)	Recovery (L)	Recovery Ratio (%)
Vavuniya	1000	756	75.6
SLNS Pandukabaya (Poneewa)	1000	751	75.1
Madawachchiya	1000	758	75.8
Dutuwewa	1000	755	75.5
Kadawathrabewa	1000	746	74.6

SLS-Sri Lanka Standard

Table 6: Recovery ratio of all five locations

Parameters	**Product water**	**SLS Requirement**
Colour Hazen units (max)	10	15
Turbidity NTU (max)	0.88	2
pH at 25^0 C	7.2	6.5 - 8.5
Electrical Conductivity S/m	163	
Chloride (as Cl) mg/l	14.5	250
Total Alkalinity (as $CaCO_3$) mg/l	50	200
Total Dissolved Solids mg/l	48	500
Nitrate (as NO_3^-) mg/l	8.1	50
Nitrite (as NO_2) mg/l	0.012	3
Fluoride (as F) mg/l	0.04	1.0
Total Phosphates (as PO_4) mg/l	0.45	2.0
Sulfate (as SO_4) mg/l	1	250
Total iron (as Fe) mg/l	0.1	0.3
Magnesium (as Mg) mg/l	0.001	0.1

BWRO design was purely dependent on the following Feedwater parameters such as TDS, Total Hardness, Calcium, Magnesium, Arsenic, and Cadmium are critical factors that are considered during the designing of a suitable BWRO plant. The permissible levels of TDS, Total Hardness, Calcium, Magnesium, Arsenic, and Cadmium contents offered water as per SLS 614 and exiting levels of those feed water quality parameters in five selected locations (Vauniya

(Irrattaperilakulam), Sri Lanka Naval Ship Pandukabaya (SLNS) (Poneewa), Madawachchiya Town (Mithreepala Central College), Dutuwewa village and Kadawthrabewa village were shown in figure 6.

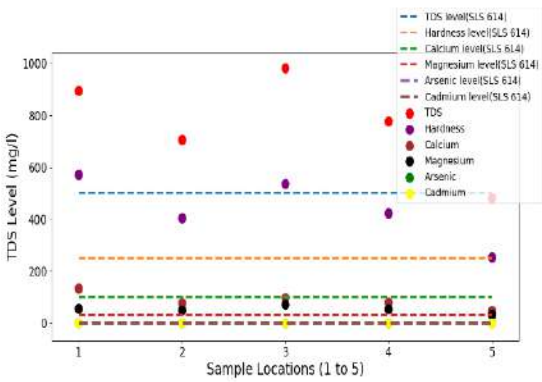

Figure 6. Feedwater quality parameters (solid lines) of BWRO plant operated in Vavuniya (Irrattaperilakulam), Sri Lanka Naval Ship Pandukabaya (SLNS) (Poneewa), Madawachchiya town (Mithreepala Central College), Dutuwewa village, and Kadawthrabewa village. Values of Total Dissolved Solids (TDS) and level of magnesium in product water were shown in red and black lines. Dash lines indicate the permissible levels as per the Sri Lankan standard 614 (SLS 614).

More importantly, analysis of feed water quality revealed that the values of TDS at locations 1 and 4 were above the permissible limit except at location 5. Further, the value of total hardness at all five locations (locations 1-5) was above the permissible limit. The calcium content of feed water at Vavuniya (Irrattaperilakulam) is higher than the permissible value but the Calcium content of feed water in other four locations (Sri Lanka Naval Ship Pandukabaya (Poneewa), Madawachchiya Town (Mithreepala Senanayake Central College), Dutuwewa Village, and Kadawthrabewa Village) are below the permissible value of SLS 614. The magnesium content of feed water in all five locations is greater than the permissible value of SLS 614. The level of Arsenic and Cadmium was not detected in all samples except location 4. Though the amount of Arsenic level in location 4 was within the limits of SLS 614, however Cadmium level was not detected in this sample.

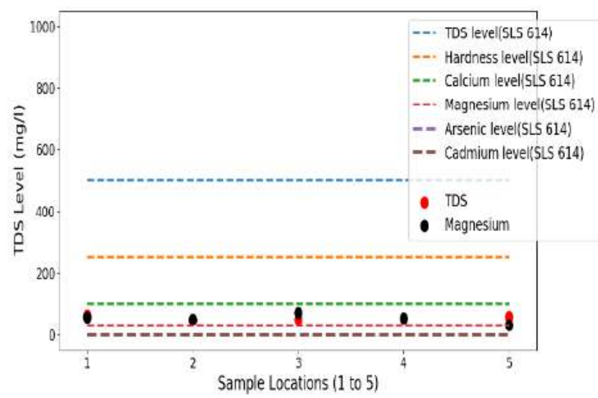

Figure 7. Product Water Parameters (solid lines) in Vavuniya (Irrattaperilakulam), Sri Lanka Naval Ship Pandukabaya (SLNS) (Poneewa), Madawachchiya Town (Mithreepala Central College), Dutuwewa village, and Kadawthrabewa village. Values of Total Dissolved Solids (TDS) and level of Magnesium in product water were shown in red and black lines. Dash lines indicate the permissible levels as per the Sri Lankan Standard 614 (SLS 614).

Most of the imported BWRO plants have been encompassed with positive displacement high-pressure pumps, and they can be pressurized up to 25 bar. Further, the flow rate remains constant with a variation in pressure (Purcell & Silvaggio, 1997). Though, their operating pressure of them was always maintained at less than 12 bar at Naval Bases, NPC due to good quality feed water inputs. Considering the above facts, 15 bars multistage centrifugal high-pressure pump was chosen in this novel BWRO application to bring down the manufacturing cost [Supplementary Table 1].

In this study, different configurations of electrically driven BWRO systems have been tested however, it was realized that the recovery can be improved by up to 75% but with high electrical energy consumption (Qiu & Davies, 2012). In the global context, brackish water desalination plants are powered by solar with battery banks and are a bit expensive affaire (Mahmoud, 2003). Therefore, to make the process economically feasible, a solar-powered net metering system was incorporated into this novel design. Further, a cost comparison between SLN the novel design of a solar-powered BWRO plant, and an imported electrically driven BWRO plant with a similar capacity revealed that the SLN-manufactured novel design of solar-powered BWRO plant was 7-fold cheaper over the use of electrically driven imported BWRO plants. Application of the novel design of solar-powered BWRO operation in Vavuniya (Irrattaperilakulam) and Madawachchiya Town (Mithreepala Central College) in Sri Lanka, a drastic reduction in the cost of electricity was achieved compared to the other three locations were electrically driven BWRO plants operated [Supplementary Table 3]. Further, the production cost of purified water was reduced and the payback period for the net metering system was approximately 7 years and six months. In addition, product water recovery is improved by up to 75% [Table 6].

However, in the Sri Lankan context, it has been recognized that most of the BWRO plants contained membranes in parallel to the applications and the recovery ratio is an average of 39% and membrane lifetime is limited to one year or a little more as per the operator's skill (Indika, et al., 2021). Therefore, this novel BWRO plant has been configured with the automated mixture (sets of valves) which facilitates the measurement of conductivity and TDS of reject water, then induct as feed water into the pre-treatment process. Subsequently, the stage array membrane fixing method was incorporated with a novel application and enhanced the product water recovery up to 75% and meets the mandatory requirement of the United States Environmental Protection Agency. In addition, it shows that the membrane lifetime is enhanced to 2 years and a little more.

SLN operators are manning BWRO plants around the clock and are ready to supply safe drinking water for consumers at any given time. Further, they are providing 20 L for family and maintaining records daily basis. Subsequently, SLN BWRO operators are carrying out daily backwashing 100% and ensuring all the operating parameters are within specified limits. Therefore, regular defects and membrane clogging are not taking place compared to CBO-operated BWRO plants (Indika, et al., 2021). In addition, monthly returns are evident that the maintenance cost of these BWRO plants is very minimal (annually 135 USD), and issuing more than 5,000 L per day of safe drinking water to the CKDu-impacted community. Generally, membranes were replaced after 2 -3 years due to the fouling and scaling leading to low recovery. Then, the replacement of membranes was depending on feed water quality, the efficiency of the pre-treatment process, and best practices such as avoiding lower pressure operation below standard value by operators. Further, an improvised membrane cleaning method is adopted by SLN experts and enhances the lifetime by one year. Cartridge filters were replaced once every six months. However, it was experienced that the cartridge filters were become dark brown colour after operating the BWRO plant for a few days especially in the dry season due to inorganic precipitants and clogging sediments such as manganese and oxides of iron in the feed water and then, washed by the operator and reused it. Though, regular cleaning of filters becomes vain after a few cleaning cycles and shows the requirement for replacement. Usually, the replacement period of the cartridge filter was depending on the efficacy of the sand filter, Carbone filter, and feed water quality. Consequently, skilled SLN operators adopted one method to wash sand and active Carbone and reused them, and enhanced the life of sand and Carbone filters [Table 5].

The operating pressure of the BWRO plant is one of the main and critical parameters which specify the existing condition of the membrane. The chemistry of the feed water is the key factor that fluctuates the pressure inside the membrane and also, and maintaining proper and standard pressure is somewhat challenging (Ahn, et al., 2008). Normally, all five BWRO plants were operated at 8 to 12 bar even in the direst season.

In this context, it is revealed that the essential minerals were rejected during this BWRO operation and become a major drawback of this application (Indika, et al., 2021). Therefore, the automated mixture is incorporated with this novel system, and the percentage of rejected water mixed up with product water and remineralization was adopted and then, avoid taking place any health-related issues among CKDu impacted community. In addition, SLN operators and repair teams are regularly carrying out water quality tests in both feed water and product water and maintaining the standards specified by SLS.

The novel design of the solar-powered BWRO plant can be manufactured locally at a low cost, and hence it would be the ideal replacement for imported BWRO plants to access high-quality drinking water for the farming community who could not have sufficient wealth to obtain safe drinking water on a payment basis (Dissanayake, et al., 2021). Subsequently, it is making the pathway to access safe drinking water for the impacted communities, which makes a huge impact on the prevention of prevailing CKDu among rural populations living in CKDu-impacted areas.

4. Conclusion

The solar-powered BWRO plant considerably reduced the government overheads to subsidize the water purification cost by up to 90% of the existing expenses with minimal GHG emissions. Further, introducing 15 bars multistage centrifugal high-pressure pump is a viable solution to bring down the manufacturing cost with moderate power consumption. Moreover, the recovery ratio is enhanced up to 75%. In addition, using skilled operators and best practices would minimize defect occurrences and enhance the lifetime of the BWRO plant. Therefore, recommend integrating a net metering system for all BWRO plants to bring down government expenses. Further, PVC pipes with gauge 10^3 instead of PPR pipes in the BWRO system can be recommended to bring down the manufacturing cost.

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Author Biography

Cmde (E) MCP Dissanayake, CEng (India) is currently performing as the Head of Department (MarineEngineering) and holds 2 patents for his research papers published so far. He is an inventor and published 06 No's publications on Brackish Water Reverse Osmosis application, Fan Boat Building and Oscillation Water Column, Ocean Wave Energy Converter. He was the Director in Research & Development at Sri Lanka Navy and has received commendations on number of occasions from the Commander of the Navy, HE the President of Sri Lanka for his innovation. Further, he was awarded with prestigious, Japanese, Sri Lanka Technical Award for his own developed low-cost Reverse Osmosis Plant, to eliminate Chronic Kidney Disease from Sri Lanka. Moreover, he has vast exposure on marine diesel engines and possesses a Master's degree in Marine Engineering from Australian Maritime College, University of Tasmania, Australia.

Supplementary Table 1. Comparison of Positive Displacement Pump Vs Centrifugal Pump

Feature	Positive Displacement Pump	Centrifugal Pump
Mechanism	Develop pressure by generating flow	Develop flow by generating pressure
Performance	Flow rate remains constant with a variation in pressure	Flow rate contrasts with a variation in pressure
Viscosity	Flow rate quickly inclines with an increment of viscosity	Flow rate quickly decline with an incline of viscosity
Efficiency	Efficiency is very minimally affected by pressure (High)	Optimum efficiency at a specific pressure and decreased efficiency as per variation of pressure (low to moderate)
Power Consumption	High	Moderate
Cost	High	Low

Supplementary Table 2. Physicochemical water quality parameters of feed water in five villages

Test	Requirement (Maximum)	Method	Results					L.O.D.	E.U.% (k=2)
			Vauniyawa	SLNS Pandukabaya	Madawchchiya Twon	Dutuwewa	Kadawathrebewa		
Colour	15 Hazen units (max)	APHA 2120 B	ND	ND	ND	ND	ND	5	
Odor	Unobjectionable	CML 1	UnOb:	UnOb:	UnOb:	UnOb:	UnOb:		
Turbidity	2 NTU (max)	APHA 2130 B	ND	ND	ND	ND	ND	1.0	
pH at 25^0 C	6.5 - 8.5	APHA 4500 - H^+B	7.33	7.48	7.27	7.47	7.95		
Chloride (as CI)	250 mg/l	APHA 4500 CI^- B	104	71	138	89	36		4
Total Alkalinity (as $CaCO_3$)	200 mg/l	APHA 2320 B	510	403	498	438	358		4
Free Ammonia (as NH_3)	0.06 mg/l	SLS 614:2013,	ND	ND	ND	ND	ND	0.02	

Albuminoidal Ammonia (as NH_3)	1.15 mg/l	Appendix A	0.06	0.08	0.08	0.1	0.16		
Nitrate (as NO_3^-)	50 mg/l	APHA 4500-NO_3^- B	13.1	19.0	18.6	8.7	11.6		
		CML/MM/02/02/019/V1.2							
Nitrite (as NO_2)	3 mg/l	APHA 4500 - NO_2^- B	ND	0.05	0.03	ND	ND	0.03	14
Fluoride (as F)	1.0 mg/l	APHA 4500 - FC	0.8	1.2	0.97	0.87	1.1	0.10	6
Total Phosphates (as PO_4)	2.0 mg/l	APHA 4500 - P B & C	ND	ND	ND	ND	ND	1	
Total Dissolved Solids	500 mg/l	APHA 2540 C	896	707	981	777	481		
Total Hardness (as $CaCO_3$)	250 mg/l	APHA 2340 C	572	403	537	423	253		4
Sulfate (as SO_4)	250 mg/l	Modified APHA 4500 SO_4^{2}E	60	45	75	50	25		
Calcium (as Ca)	100 mg/l	APHA 3500 Ca - B	133	78	96	80	47		
Magnesium (as Mg)	30 mg/l	APHA 3500 Mg - B	57	50.0	72	54	32		
Cyanide (as CN)	0.5 mg/l	CML 18	ND	ND	ND	ND	ND	0.05	
Sodium (as Na)	200 mg/l	APHA 3125 B	59.3	63.3	87.4	60.0	75.9		
Total Iron (as Fe)	0.3 mg/l		ND	ND	ND	ND	ND	0.01	
Copper (as Cu)	1.0 mg/l		ND	ND	ND	ND	ND	0.01	
Manganese (as Mn)	0.1 mg/l		0.003	0.003	0.14	0.002	0.006		

Zinc (as Zn)	3.0 mg/l		0.03	ND	ND	ND	ND	0.01	6.3
Aluminum (as Al)	2.0 mg/l		ND	0.01	ND	ND	ND	0.01	
Chromium (as Cr)	0.05 mg/l		ND	ND	ND	ND	ND	0.01	
Nickel (as Ni)	0.02 mg/l		ND	ND	ND	ND	ND	0.001	
Arsenic (as As)	0.01 mg/l		ND	ND	ND	0.002	ND	0.001	2.6
Cadmium (as Cd)	0.003 mg/l		ND	ND	ND	ND	ND	0.001	
Lead (as Pb)	0.01 mg/l		ND	ND	ND	0.002	0.002	0.001	
Selenium (as Se)	0.01 mg/l		ND	ND	ND	ND	ND	0.001	
Mercury (as Hg)	0.001 mg/l		ND	ND	ND	ND	ND	0.001	
Chemical Oxygen Demand (COD)	10 mg/l	APHA 5220 D	ND	ND	ND	ND	ND	5	4
Phenolic compounds (as C_6H_50H)	0.001 mg/l	APHA 5530 B & D	ND	ND	ND	ND	ND	0.5	
Oil & Grease	0.2 mg/l	APHA 5520 B	ND	ND	ND	ND	ND	2	

Supplementary Table 3. Cost comparison of the monthly electrical bill among five locations

Srl. No	Location	Plant Cost (US$)	Solar Powering Cost (US$)	Total Cost (US$)	Daily Water Consumption (L),	Monthly Electrical Bill (US$)
1	Vavuniya (Irrat-taperilakulam)	3,169	4,850	8,019	2,660	1
2	Madawachchiya Town (Mithreepala Senanayake Central College)	3,169	4,850	8,019	2,800	1
3	Sri Lanka Naval Ship Pandukabaya (SLNS) (Poneewa)	3,169		3,169	2,600	55
4	Dutuwewa Village	3,169		3,169	2,500	52