Feasibility study of a solar desalination unit for small isolated communities

Daniel R. Rousse, Vincent Deblock, Misagh Irandoostshahrestani, and Patrick Turcotte

École de technologie supérieure, Université du Québec, Montréal (Canada)

Abstract

Population growth and changing consumption patterns are intensifying the use of fresh water worldwide. While large-scale, expensive desalination solutions do exist, there is still a need for low-cost solutions for populations located far from major centers and in financial need. The main objective of the project is to design a low-cost and low-environmental footprint solar-powered seawater desalination unit and to verify its performance using a custom numerical simulation tool. The second objective is to provide a summary economic analysis to target the potential cost of water production when the single-basin still is compared with a double-basin still with similar characteristics. This numerical study of two types of solar stills – without technological improvements such as fins, sponges, etc. – shows that the production per m² of the two solar stills remains relatively low. Nevertheless, when ground space is available, simple solar stills appear to be robust, resilient, and cheaper solutions as a source of drinking water.

Keywords: Feasibility study, low-cost desalination units, simple solar still.

1. Introduction

In 2015, 17 Sustainable Development Goals (SDGs) were proposed by the United Nations (UN). In particular, SDG 6 aims to "ensure access to sustainably managed water and sanitation services for all". Although fresh water is a vital element for survival, this resource represents only 2.5% of all water on Earth, compared to the 97.5% occupied by salt water, which is unsuitable for human consumption. The issues surrounding water continue to grow (WHO, 2017). On the one hand, the amount of fresh water available is decreasing, whether through global warming, which accelerates evaporation, causes glaciers to melt and raise sea levels, or through water pollution linked to human activities, mainly industrial, agricultural, and domestic discharges. On the other hand, demographic pressure leads to an increase in needs, and therefore in consumption (UN, 2020). This gap between supply and demand, known as water scarcity or water stress, poses many risks, such as the transmission of diseases like cholera, premature deaths, migratory movements or conflicts directly related to access to water (WHO, 2019). Alongside this crisis, fossil energy sources commonly used to help with water pumping, treatment, and desalination are becoming increasingly expensive and emit greenhouse gases that intensify global warming, amplifying the problem (Al-Shayji, 2018). Moreover, technologies involving processes such as osmosis (direct or reverse), electrodialysis, nanofiltration, or ion exchange, even when operated using renewable energies, are often too expensive for many communities. In this context, the solar still is an ideal source of fresh water for both drinking and agriculture in remote areas. There are many types of solar stills; the simplest and most proven is the basin type (Bloemer et al., 1961).

However, among the many variations of solar basins, several involve technologies designed to increase performance. Indeed, since the 1960s study by Bloemer et al. (1961) cited by Malik et al, (1982), which indicates that only about 31% of the incoming radiation is used to evaporate the distillate (while cover reflection (11%) and absorption (5%), ground and edge losses (2%), radiative losses from the basin water to cover (26%), internal convection (8%), re-evaporation of distillate and other losses (17%) complete the balance), researchers tried in many ways to improve this 60 years old threshold. To improve solar basins, fins, sophisticated absorbing materials, multi-basin stills, phase-change materials, storage tanks, hybridation, nanocomposites, adjacent solar pond, specific configurations, floating plates, perforated plates, cascades, glass treatments, double glass, etc. were proposed (Panchal and Mohan, 2017) (Velmurugan and Srithar, 2011).

Indeed, these improvements lead to increases in efficiency. But when space is available, is it the efficiency gains that matter?

The main objective of the project reported in this article is to design a solar-powered seawater desalination unit to

10.18086/eurosun.2024.09.09 Available at http://proceedings.ises.org

reduce costs and environmental footprint and verify its performance using a numerical simulation tool. The unit, basically designed to avoid any fancy technological improvements such as those mentioned above, will be used to produce drinking water for small, isolated communities (i.e. communities that are not connected to a reliable drinking water distribution system, and for which drinking water supply options are limited and/or expensive) located on the seafront. The sole comparison is carried out between the single- and double-basin to discuss productivity in $kg\ m^{-2}$ per unit time and unit cost in $\$CA\ m^{-3}$ per unit time

2. Brief literature review

2.1. Desalination processes

There are two main families of desalination processes: those with a phase change of the water, and those without. This review, due to limited space, can only mention a few references to available technologies and instead offers references on the state of desalination in the world. Table 1 and Table 2 list some of the studies reviewed in preparation for this article.

Tab. 1: Phase change desalination processes

Process	Reference
Multiple Effect Distillation	Guimard, 2019, Liponi et al., 2020
Flash Distillation by Successive Expansions	Nannarone et al., 2017, Darawsheh et al., 2019
Vapor Compression	Lara, 2005, Bahar et al., 2004
Freezing	Kadi & Janajreh, 2017, Mandri, 2011
Membrane Distillation	Saadat et al., 2018, Lawson & Lloyd, 1997
Direct Solar Desalination	Chauhan et al., 2021, Arunkumar et al., 2019

Tab. 2: Desalination processes without phase change

Process	Reference
Reverse osmosis	Kim et al., 2019, Shafagnat, Eslami & Baneshi. 2023
Electrodialysis	Akther, Habib & Qamar, 2018, Sedighi et al., 2023
Nanofiltration	Wafi et al., 2019, Yadav, Karki & Ingole, 2022
Direct osmosis	McCutcheon et al., 2019, Qasim et al., 2015
Ion exchange	Subban & Gadgil, 2019, Wang et al., 2020

2.2. Direct Solar Desalination

To provide an overview of the current situation of desalination in the world, a few recent studies can be recommended, including those by Eke et al. (2020), Ghazi et al., (2022), Janaireh et al., (2023), Jones et al., (2019), Li et al., (2023) and Ray et al., (2023). More specifically, Aboulfotoh et al. (2023) investigated the effectiveness of a solar still for desalination to produce fresh water for small and rural communities in Zagazig, Egypt. They studied the effect of variations in water depth, salinity, and cover angle on the still's water production. Not surprisingly, it was shown that reducing water depth and salinity, along with increasing the cover angle in winter, increased water output. Removing chloride and total dissolved solids, the still demonstrated high efficiency in producing water. The developed theoretical models predicted the still's thermal performance with good agreement compared to experimental data. Furthermore, the economic analysis showed that the solar still is more cost-effective than commercially available water. In He et al. (2024), water scarcity in rural regions was studied by introducing a solar-powered electrodialysis reversal system used for desalination. It was showed that the system can harnesses 77% of available solar energy. They evaluated this technology for a village-scale case study in India and they concluded that water production costs can decrease by 22%. The authors declared that this technology can be a reasonable alternative to fossil fuel-powered reverse osmosis systems.

2.3. Recent reviews

However, the important thing to remember about current literature reviews is that, due to the preponderant importance of water for humanity and the growing supply difficulties discussed in the introduction, this field is experiencing exceptional research activity, as evidenced by the 46 review articles and 246 research articles reported in Solar Energy alone (with term: desalination) in 2022, 2023, and 2024 (by 2024-08-06).

3. Methodology

3.1. Location

To choose a location to simulate the desalination system among the 15 non-landlocked countries most exposed to the risk of water stress, the method used was a multi-criteria comparison of different countries according to three indicators:

1) water stress, related to freshwater withdrawals as a proportion of available resources. This is SDG 6 indicator 6.4.2 (clean water and sanitation) managed by the World Resources Institute;
2) the Human Development Index (HDI). Created by the United Nations Development Programme (UNDP), it takes into account three criteria: life expectancy at birth, GDP/capita, and level of education;
3) the mortality rate attributed to unsafe water, sanitation, or hygiene. This is SDG 3 indicator 3.9.2 (good health and well-being) managed by the WHO (WHO, 2019).

After a multi-criteria analysis (not presented here), the study showed that Eritrea obtains the highest average score, particularly due to the lowest HDI and the highest, by far, mortality rate attributed to insufficient water supply, inadequate sanitation or unsanitary hygiene. As a result, the modeling is carried out for the city of Assab, located in southern Eritrea. Its latitude is 13°01' North, its longitude is 42°44' East, while its standard meridian is 45°.

3.2. Meteorological and oceanic data

The climate in Assab is hot and dry, with average temperatures between 25 and 35°C. Four different sources of weather data were selected for comparison:

1) an EPW file provided on the Climate.OneBuilding website (Lawrie & Crawley, 2019);
2) hourly data from the European Commission's website (European Commission, 2019);
3) the SoDa website (HELIOCLIM-3 ARCHIVES *DEMO*, 2006);
4) daily data from the RETScreen tool (NRCan, 2016).

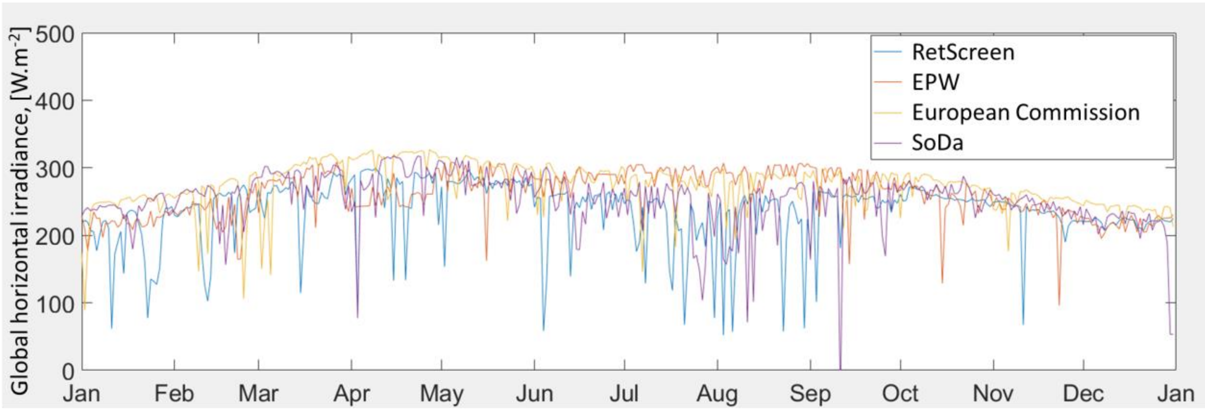

Fig.1: Yearly variations of the average daily global horizontal irradiance in Assab, Erytrea, from four different sources

The EPW has been kept for simulations, as it can easily be read by TRNSYS to obtain irradiance on an inclined plane.

To estimate the contribution that a solar still can make to the drinking water production of an isolated community, the 2020 edition of *Domestic water quantity, service level and health* was used as a reference (Howard et al., 2020). 50 litres/day/person are recommended as the minimum volume to ensure medium health risk (Optimum: 100 litres/day/day optimal low risk, Basic: 20 litres/day/person basic high risk) by Omarova et al. (2019). The basic 20 litres per person daily should be considered partly sufficient for beverages and food but not for hygiene purposes.

In desalination, it is mostly important to retrieve the characteristics of the local seawater (salinity and properties) as these will have an impact on the operation of the system. The use of the CoolProp library (Bell et al., 2014) allows quick access to these properties, which depend on salinity in addition to pressure and temperature.

3.3. Energy balance

Among the technologies previously cited, direct solar desalination in basin is the most appropriate for small, isolated communities located by the sea when cost matters. Two types of basins are studied: Figure 2 schematically illustrate the heat transfers associated with the conventional single-stage (left) and two-stage (right) basins with single glazing. In both cases, the horizontal surface area of the collector is 2m x 0.5m or 1m^2 footprint.

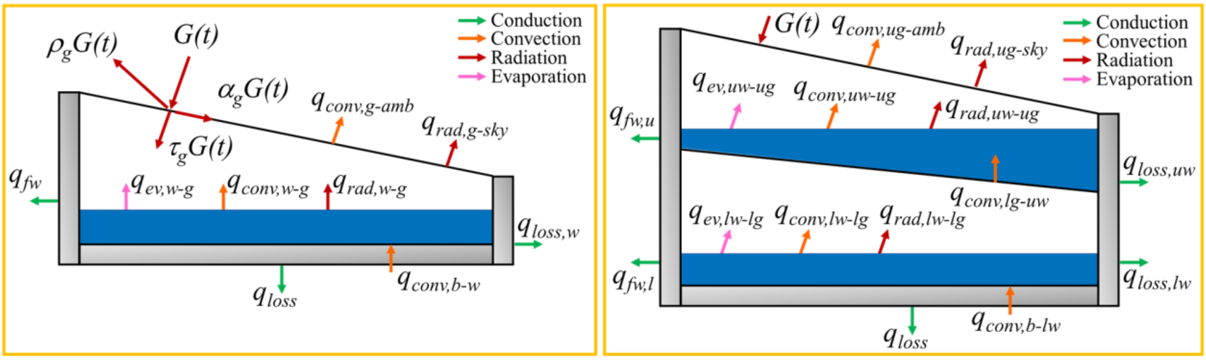

Fig.2: Energy balance on the investigated still configurations: single-basin (left); double basin (right)

The energy balance on the glazed cover (g-index) of the conventional single-basin still (Figure 2, left) is:

$$m_g cp_g \frac{dT_g}{dt} = I_T(t)\alpha_g A_g + q_{conv,w-g} + q_{ev,w-g} + q_{rad,w-g} - q_{conv,g-amb} - q_{rad,g-sky} \quad \text{(eq.1)}$$

This balance at the surface of the salt water (index w) is:

$$m_w cp_w \frac{dT_w}{dt} = I_T(t)\tau_g \alpha_w A_w + q_{conv,b-w} - q_{conv,w-g} - q_{ev,w-g} - q_{rad,w-g} - q_{fw} - q_{f,w} \quad \text{(eq.2)}$$

The balance sheet on the volume of the basin (index b) is:

$$m_b cp_b \frac{dT_b}{dt} = I_T(t)\tau_g \tau_w \alpha_b A_b - q_{conv,b-w} - q_{loss} \quad \text{(eq.3)}$$

In these equations and figures, subscripts *ev*, *conv*, and *rad* refer to evaporation, convection, and radiation while *loss*, *amb*, *g*, *sky*, *w*, *b*, and *fw*, pertain to losses to the ground and walls, ambient air, glass, surroundings, water, basin, and feed water, respectively. Subscripts *l* and *u* refer to the lower and upper basin of the double basin still.

Each of the terms is familiar to the heat transfer analyst and the reader wishing to obtain the entire mathematical model involving 49 equations is invited to contact the authors. A similar balance can be explained for the two-stage basin shown in Figure 1, right.

3.4. Production and efficiency

The average annual daily productivity results of the desalination system are obtained in kg.m^{-2}.d^{-1}, which then makes it possible to determine the floor area needed to support an entire community.

Equations (4) and (5) provide the hourly productivity, in kg.m^{-2}.h^{-1}, for the single- and double-basin stills, respectively.

$$\dot{m}''_h = 3600 \times \frac{q_{ev,w\text{-}g}}{A_w h_{fg}} \quad \text{(eq.4)}$$

$$\dot{m}''_h = 3600 \times \left(\frac{q_{ev,lw-lg}}{A_{lw} h_{fg}} + \frac{q_{ev,uw-ug}}{A_{uw} h_{fg}}\right) \quad \text{(eq.5)}$$

The daily unit production, in kg.m^{-2}, is simply the cumulative sum of equation (4) or (5) over 24 hours. The daily recovery efficiency of the ponds is defined for the two types of ponds such as:

$$\eta_d = 100 \times \frac{\sum_1^{24} \dot{m}''_h h_{fg}}{\sum_1^{24} I_T(t)\Delta t} \quad \text{(eq.6)}$$

3.5. Simplifying assumptions

In addition, it is important to specify the assumptions made during the implementation for the two types of basins (Fig.2):

- There are no air leaks and the stills are waterproof.
- The window is supposed to be clean.
- Water vapor and dry air act as ideal gases.
- There are no temperature gradients along the vertical axis, the temperature is considered uniform in the chamber and initially the temperatures of all surfaces are equal to the ambient temperature.
- The surfaces of the water and the basin are of equal dimensions.

- Conduction is neglected in the glass and in the absorbent plate, due to their low thicknesses, and condensation only takes place on the inner surface of the glass.
- For a deep basin, the reduction in water mass due to evaporation is negligible. However, in a shallow basin, the effect of the mass of evaporated water on performance is significant. It is therefore assumed that the evaporated mass is continuously replaced and that the volume of water in the basin is thus constant. The water replaced is assumed at atmospheric temperature and it exchanges heat with the water in the basin.

These assumptions are appropriate for this feasibility study and also allow for consistency with the literature, so that different studies can be compared with each other more rigorously. Nevertheless, the impact and actual accuracy of these simplifying assumptions should be reassessed in future studies.

3.6. Implementation details

For each still, the mathematical model was developed and then implemented in MATLAB. This model makes it possible to solve the systems of ordinary differential equations partially presented above, to obtain the temperatures of the different components of the solar still (glass-g, water-w, and the absorbent plate of the basin-b) and to deduce its instantaneous and cumulative productivity as well as its efficiency as a function of time.

Usually, it is advisable to use the *ode45 solver*, based on an explicit Runge-Kutta formula (of order 4 and 5), more specifically the Dormand-Prince method. This method uses six function evaluations to compute precise fourth- and fifth-order solutions. The difference between these solutions is then considered the error of the solution. However, this solver is not recommended in the case of a so-called "stiff" system of differential equations. This is more of a qualitative notion than a quantitative one, and it means that sensitivity to the parameters of the equations makes it difficult to solve by explicit numerical methods. This is due to the fact that the *ode45s solver* would need a very small time step to ensure the stability of the solution, but over a high time interval, which would result in a long computation time. It is then recommended to use the *ode15s solver*, which also integrates the system of differential equations according to a given time interval and initial conditions. But this solver is implicit, usually based on a variable-order numerical differentiation formula, or on an inverse differentiation formula. This solver calculates the solution at time t + Δt taking into account the value of the function in t and t + Δt. This method also uses a variable time step, which therefore makes it possible to reduce computation times (Shampine & Reichelt, 1997).

3.7. Irradiance calculation

The driving force behind the system is the irradiance, G_T in W.m^{-2}, which hits the sloping glass surface. The classical equations of radiative transfer are implemented in TRNSYS. This software is used to feed the MATLAB code. The theory and equations for radiation models are not reproduced here since they are standard. However, it is important to note that the data extracted from TRNSYS show that the Perez, Reidl, and Hay Davis models differ by up to 3.8% from the isotropic model (overshoot). Since the sunshine data values predicted with the latter are lower, the sizing will be conservative regardless of the type of desalination unit simulated.

3.8. Cost evaluation

For a community with limited financial means, it is also important to study the economic viability of a solar still throughout its lifespan to justify the interest in this potential solution. The cost of water produced in a solar still depends on several parameters, mainly the initial investment (CAPEX), the costs of operation (OPEX), maintenance, storage and repair, the lifespan of the still, and its freshwater production capacity. Usually, seawater desalination involves high operating costs due to a large energy cost. However, in the case of the solar stills, the energy is drawn directly from solar radiation. The operation and maintenance (O&M) costs of the solar stills must be as low as possible to meet the objectives set at the beginning of the study. It is interesting to compare the cost of the solar still with other approaches, to estimate its possible economic interest. Other possible options include the delivery of fresh water from a conventional source, or the use of another desalination technique.

The specific cost of freshwater production, CPL in \$.litres^{-1}, can be found with equation (7).

$$CPL = \frac{CAPEX \times \left[\frac{i(1+i)^N}{(1+i)^N - 1}\right](1 + x_{\%}) - y_{\%} \times CAPEX \times \frac{i}{(1+i)^N - 1}}{1000 \times \frac{\dot{M}''_a}{\rho_w} \times A} \quad \text{(eq. 7)}$$

The denominator of equation (7) denotes the average annual production, in litres.y^{-1}, which can be expressed as a function of the annual mass production per unit area, $\dot{M}''_a$, the density of the water, ρ_w, as well as the surface area of the solar basin studied, A.

The first term (on the left-hand side) of the numerator refers to the fixed annual costs or FAC, in $.y^{-1}, which is expressed as a function of the CAPEX of the solar basin studied, in $, the interest rate i and the estimated lifetime of the system, N, in years. That is $FAC = CAPEX \times [f(i, N)]$. The term $x_{\%}$ indicates that the annual operation and maintenance costs or $O\&M$, in $.y^{-1}, are expressed as a percentage of the annual fixed costs. $O\&M = x_{\%} \times CAPEX \times [f(i, N)]$

The last term (on the right-hand side) of the numerator refers to the annual residual value or ARV of the solar still studied, expressed in terms of RV, the residual value of the solar still at the end of its lifetime, in $, and a sinking fund factor. Here, RV is expressed as a percentage of the CAPEX of the solar still studied, i.e. $RV = y_{\%} \times CAPEX$.

This concludes the partial presentation of the methodology used in this study. The following section presents selected results obtained from the simulations carried out on the two solar stills.

4. Selected results

As part of this project, the solar basin will be south oriented, towards the equator. The azimuth angle γ is equal to the magnetic declination δmag, in the opposite sign. As the latter is close to zero, a zero azimuth is chosen. Since the drinking water requirements are assumed to be constant throughout the year, and because we are close to the equator, the value of the slope β angle is equal to the value of the latitude φ to induce optimal irradiance throughout the year. The inclination must also be large enough to allow the condensed water to flow, which is the case here. September 20 and December 21 were selected for the simulations, as these days respectively provide strong and low sunlight on the inclined plane of the simulated solar stills. With these parameters chosen, TRNSYS can then extract and read the supplied .EPW file and output the irradiance on the inclined plane for the two selected typical days and according to five different models. For example, on September 20, a maximum at 11:00 is observed between 1020 W.m^{-2} (isotropic model) and 1035 W.m^{-2} (Perez 1999 model). On December 21, a maximum at 12:00 was observed between 790 W.m^{-2} (isotropic model) and 820 W.m^{-2} (Perez 1999 model).

4.1. Validation of the formulation and implementation

Before looking at the results obtained from the use of the implemented MATLAB models, it is worth comparing the results of the numerical simulations with a few references, when possible. Here, validation is carried out using experimental data (Table 3) from a paper published in 2021 (Raj Kamal et al., 2021) as well as theoretical data (Table 4) from a paper published in 2009 (El-Sebaii et al., 2009). These two papers deal in particular with a conventional single-glazed solar still (Figure 2), the first being tested from 9:30 to 16:00, in Tamil Nadu, India, and the second being simulated over 24 hours with meteorological data from the city of Jeddah, Saudi Arabia.

The relative difference E, in %, between the external data X and the calculated data Y is estimated using equation (8), where the two variables X and Y can designate the temperature of the still, T_b, the water, T_w, the glass, T_g, or the instantaneous and cumulative daily productivity, $\dot{M}''_d$.

$$E_t = |X_t - Y_t| \,/\, \left[\frac{X_{max}+Y_{max}}{2}\right] \times 100 \qquad \text{(eq.8)}$$

The relative difference was computed every 30 minutes from 9h30 to 16h00 for comparison with experimental data from (Raj Kamal et al., 2021) and from 7h00 to 18h30 for comparison with the theoretical calculations of (El-Sebaii et al., 2009).

Tab.3: Comparison with experimental and theoretical data from Raj Kamal et al., 2021 and El-Sebaii et al., 2009, respectively.

Source	Relative difference	T_g [°C]	T_w [°C]	T_b [°C]	$\dot{M}''_d$ [kg m^{-2} h^{-1}]
		E [%]	E [%]	E [%]	E [%]
Raj Kamal et al., 2021	Average	7.77	11.05	10.37	10.25
	Standard deviation	5.14	8.86	8.47	10.32
El-Sebaii et al., 2009	Average	1.47	1.82	2.15	1.65
	Standard deviation	0.77	1.65	2.09	1.90

The adequacy with the first study is correct with maximum deviations of 10%, while this maximum does not exceed 2% in the case of the results proposed in El-Sebaii et al. (2009). The values for the 4 variables were always higher in the morning and lower in the afternoon when compared to the experimental data. This could suggest a different weather on those days in Tamil Nadu, India than that embedded in the data file and a relative inertia of the still structure to heat up. The discrepancies with the experimental study by Raj Kamal et al. (2021) could also be explained in different ways: 1) some values are collected from graphical readings, which leads to an error in the result; 2) information was omitted from the article, such as the depth of the basin (which has an influence) or whether the irradiance provided is on a horizontal or inclined plane; 3) the properties of materials such as insulation have also been estimated due to the lack of full citation in the article; 4) the reality on the real site may compromise some assumptions made for the simulation, such as the absence of leaks or the absence of conduction in the glass or the absorbent plate.

Nevertheless, these results validate the correct formulation and implementation of the model.

4.2. Some results for Assab, Erytrea

Table 5 provides a summary of the data required to conduct the simulations and for the reader who would like to benchmark their own method relative to this one.

Tab 5: Main technical characteristics of the simulated stills

System	Parameter	Value	System	Parameter	Value
Location	φ	13.00°	**Still water**	e_w	0.02 m
	L_{loc}	42.74°		α_w	0.05
	L_{st}	45°		τ_w	0.9
	ρ_g	0.2		ε_w	0.95
Global	L	2 m		x	0.035
	l	0.5 m	**Absorbing plate**	cp_b	871 J kg^{-1}K^{-1}
	H	0.20 m		e_b	0.0015 m
	γ	0°		α_b	0.9
Glass	β	13°		ρ_b	2719 kg m^{-3}
	cp_g	840 J kg^{-1}K^{-1}	**Insulation**	L_{is}	0.08 m
	e_g	0.003 m		k_{is}	0.04 W m^{-1}K^{-1}
	α_g	0.05	**Other**	P_{ref}	101325 Pa
	τ_g	0.88		g	9.81 m s^{-2}
	ε_g	0.90		σ	5.67e-08 W m^{-2} K^{-4}

4.3. Daily production and conversion efficiency

Figure 3 and Figure 4 present the daily evolution of the instantaneous and cumulative productivity of the two types of solar stills for the two days that were studied. Concerning the conventional basin, its maximum productivity is 0.89 kg.h^{-1}.m^{-2} around noon on 20 September, with a total daily production of 6 kg.m^{-2}, compared to 3.8 kg.m^{-2} for 21 December. On September 20, its production began between 6:30 and 7:00 and ended around 19:45. As for the double-stage still, its maximum productivity is 0.93 kg h^{-1} m^{-2} around 1:30 p.m. on September 20, with a total daily production of 7.9 kg.m^{-2}, compared to 4.7 kg.m^{-2} for December 21. On September 20, its production begins between 6:30 and 7:00 and ends around 20:00. for the lower basin, and from 9:00 to 21:00. for the upper basin. Basin 2 shows an increase in daily production of 31.7% compared to Basin 1 for 20 September and 23.7% for 21 December.

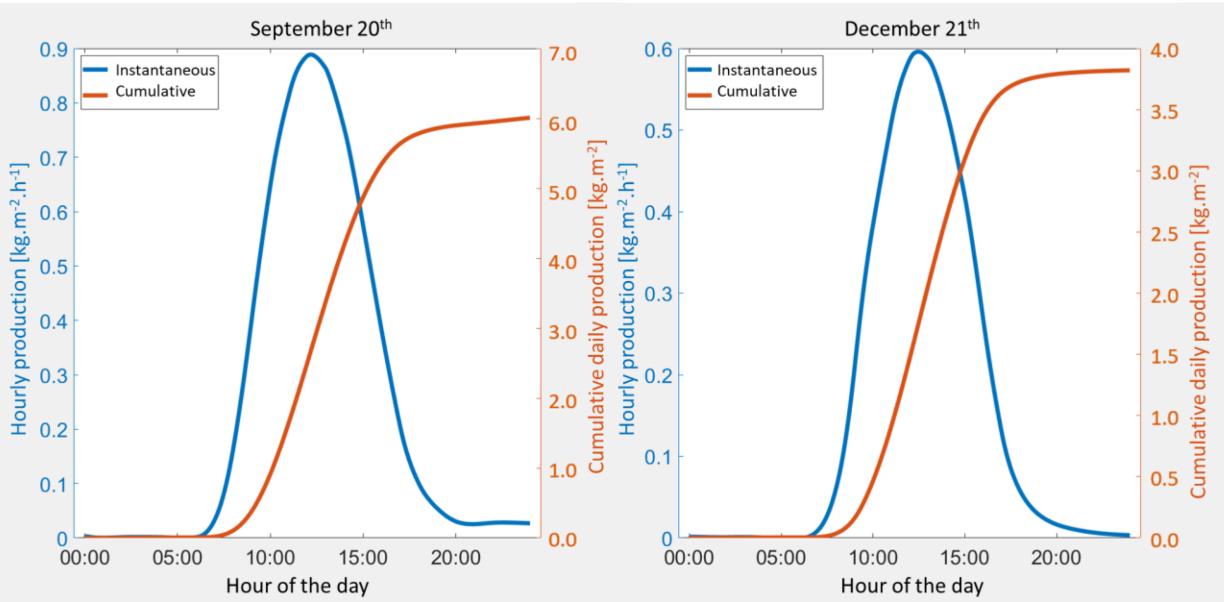

Fig.3: Daily evolution of productivity for the conventional still

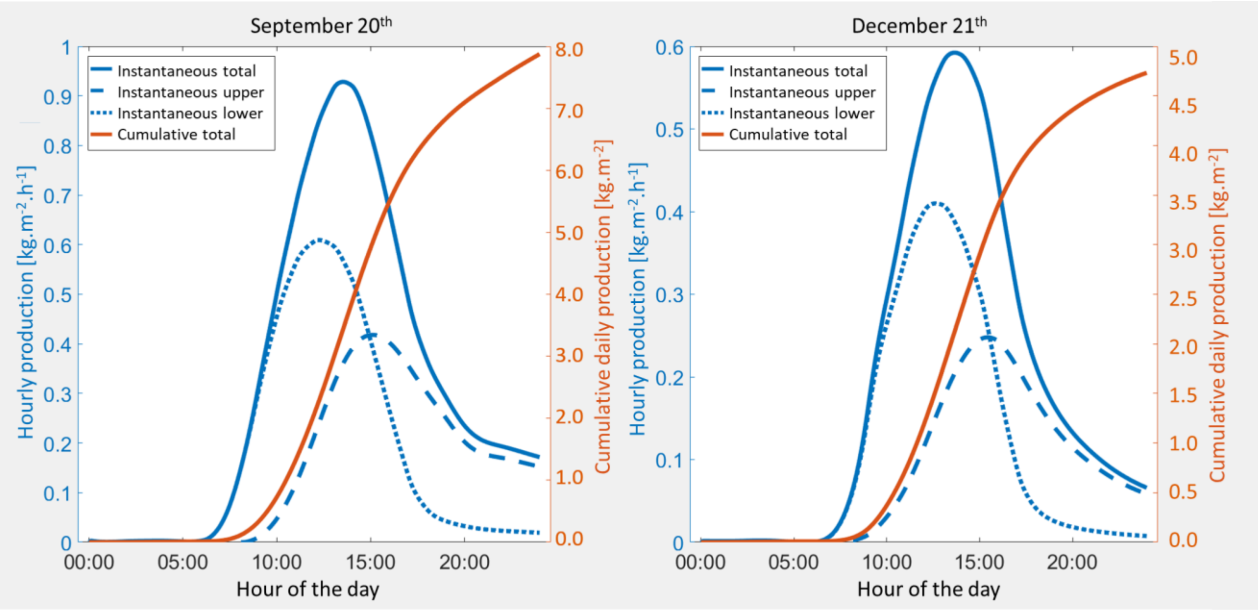

Fig.4: Daily evolution of productivity for the two-stage still

Variations in the conversion efficiency of the two stills were also determined (Figure 5). The conventional single-basin still shows a yearly average value of 49%, while the double-basin counterpart has an average efficiency of 61%. In both cases, the maximum values are observed during the late summer and early fall periods. The peaks observed at the end of June can be explained by abnormally high ambient temperatures for these days, sometimes approaching 50°C. This consequently promotes the heat exchange of the upper basin of the double-basin still with the upper glass cover. This results in a considerable production surplus compared to the standard basin which loses more of this energy to the environment.

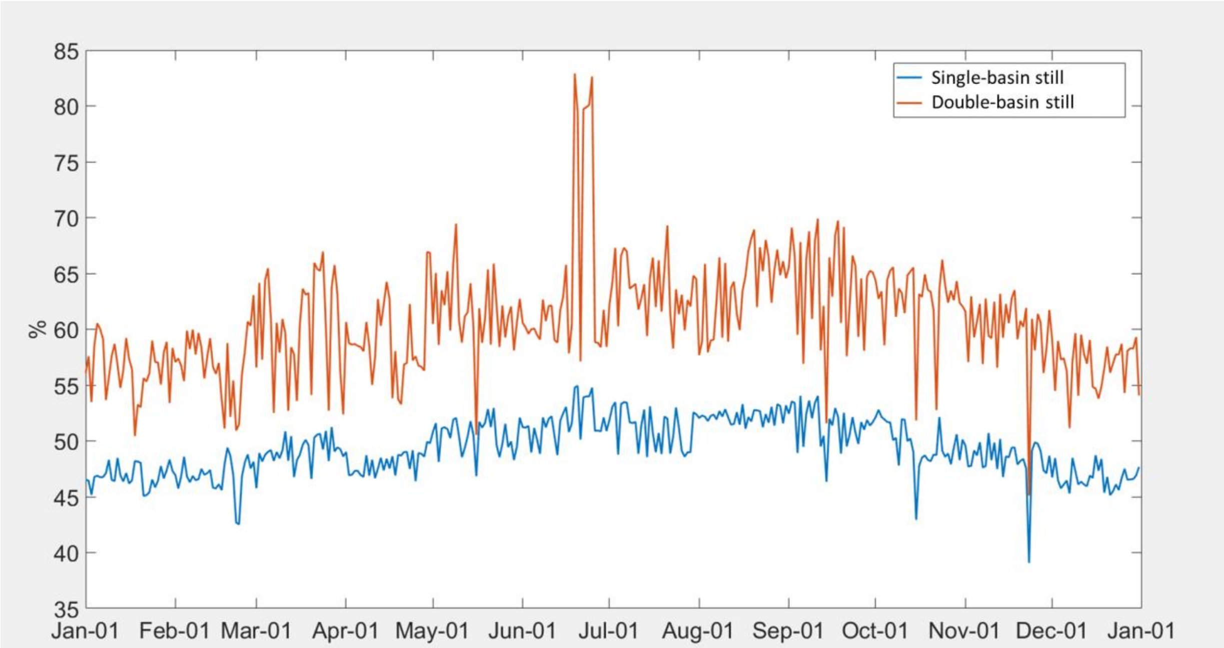

Fig 5: Variations in daily efficiencies during the year: blue – single-basin still; orange – double-basin still.

4.4. Brief parametric study

The graphs presented here concern the conventional basin (Figure 2, left) for a variation in the thickness of the insulation and the depth of the water admitted to the latter. Figure 6 shows the evolution of daily freshwater productivity for the day of September 20 as a function of the thickness of the insulation (left) and the depth of the basin (right). It can be seen that production increases significantly when the insulation thickness is increased by up to 4 cm. Beyond that, the increase continues, but less markedly, and it ends up being negligible when this thickness is greater than 6 cm. This suggests that care must be taken to avoid making the still too expensive with respect to the water production gain. On the left-hand side of Figure 6, when the depth of the water increases in the basin, the daily production decreases significantly almost linearly. For example, a 33% drop is observed when the depth increases from 2 to 10 cm. It is probably this parameter that explains the predictions lower than the measurements in Table 3 (Raj Kamal et al. 2021) as the authors do not specify this parameter.

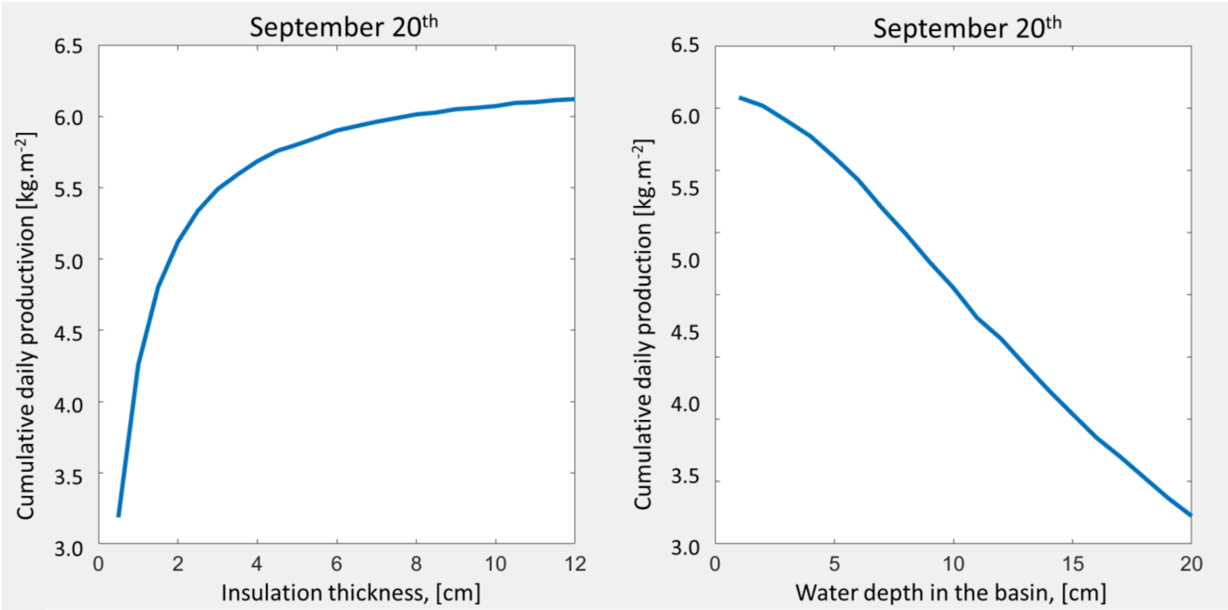

Fig. 1 : Variation in daily production as a function of insulation thickness (left) and water depth (right) in the single-basin still.

4.5. Economic results

The estimated material (glass, absorbing plate, insulation, ply-wood, structure, paint, tank, sealant, pipes, gutters, hardware) and labor costs for the simulated basins are CA$200 for the conventional still and CA$295 for the two-stage still. These benchmark costs were obtained by consulting with suppliers in Montreal, Canada and assuming very low production. Thus, unit costs could decrease with greater production and design optimization, for both types of stills. With an estimated lifespan of 10 years and a residual value of 20% of CAPEX for both types of basins, a specific cost of 21.2 $\$CA.m^{-3}$ for the conventional solar basin is obtained compared to 25.5 $\$CA.m^{-3}$ for the two-stage solar basin. Table 6 summarizes the results.

Tab 6: Annual economic results for the two simulated stills

Item (for a 1 m^2 still)	Single-basin still	Double-basin still
Annual fixed costs, [$]	35.41	52.3
Annual O&M costs, [$]	5.30	7.80
Annual residual value, [$]	2.28	3.37
Annual water production, [m^3]	1.80	2.22
Specific costs, [$\$.m^{-3}$]	21.20	25.50

To validate the results, an equation-solving package originally proposed with the 4th edition of the classic heat transfer textbook *Fundamentals of Heat and Mass Transfer* (Incropera and Dewitt, 1996) (Interactive Heat Transfer, IHT 4.0) was used. The software has been used to estimate the annual water production based upon the global cumulated average daily radiative energy over a square meter from the EPW database, the yearly average conversion efficiency calculated with the MATALB model for the single-basin still (49%), and the water properties functions embedded within IHT. The annual amount of water calculated is 3.3% lower (1.743 m^3 vs 1.796 m^3) than the above result (Table 6).

5. Discussion

5.1. Technical and economic feasibility

For either solar still model investigated here, this type of approach seems technically viable to provide a solution for producing drinking water for remote communities by the sea. It is suitable for an isolated area, as there is usually no running water distribution system, or even any other option to get water, other than the use of unhealthy and/or remote sources, or the purchase of bottles at high prices. However, the production per m^2 of the two types of solar basins remains relatively low, and this could represent a significant area when considering meeting the needs of a family. Large open spaces are needed, since in Assab the production of 1795 litres.m^{-2} of surface per year (approximatively 4.91 litres daily on average) by the conventional still unit means that at least 4 m^2 of surface is required to satisfy basic needs and 10 m^2 for intermediate needs of one person (Omarova et al., 2019). This may call for efficiency improvements. The double-basin model was compared with the single-basin model; the average conversion efficiency increased from 49% to 61%. However, the specific cost for each cubic meter of fresh water rose from 21.20 $CA to 25.50 $CA. Therefore, is it worth injecting technologies to improve the yield?

The answer seems to be no. However, to confirm it, we need to consider the premises of this article. The technological and financial resources of the target communities are limited. Furthermore, it is assumed that there is sufficient space to install several collectors close to each other or even per house. While this could be possible in Assab, where the solar resource is abundant, particular care should be taken in extrapolating this study to other locations.

Nevertheless, even if it were possible to increase the conversion efficiency to 100% by technological means, i.e. all available solar energy would be used (without loss) to evaporate the water from the brine and no water loss would occur, the surface area required could not be divided by a factor greater than 2 as the efficiency is very near 50% with the prescribed characteristics of the still.

Consequently, if ground space is available, the simplest solar basin appears to be a robust and resilient solution as a source of drinking water, if only in addition to another main source. It would then free up some of the time spent by people fetching and transporting clean water in many communities, especially by women and children.

6. Conclusion

Given that 97.5% of all water on earth is salty, that freshwater resources are under increasing pressure, that water is becoming increasingly polluted, that the world's population is growing, and that financial disparities are exacerbating, we need to find cheap, resilient, robust, and reliable solutions to produce drinking water for the world's remote and poorest populations. In this context, several areas of the world rely on high-tech solutions such as osmosis (direct or reverse), electrodialysis, nanofiltration, or ion exchange, to produce water for villages and cities. However, these technologies are often too expensive for many remote and poor communities. In this context, the solar still could be considered as a solution for the production of fresh water. But as these low-tech solutions basically have low yields, is it worth trying to improve them with sophisticated technologies?

This study attempted to answer that question. First, it simulates a single-basin still unit and compares its production with that of a double-basin still unit involving the same thermo-mechanical characteristics and properties. The article shows that while the double-basin still unit offers better productivity than the conventional one, it nevertheless involves a higher specific cost due to the increase in its manufacturing cost.

In general, the conversion efficiency ratio of a solar basin remains relatively low (here 49% for the basic single-basin) and the technology therefore requires large areas to fully meet the needs of a community. In addition, it has a high specific cost compared to other technologies. But, the isolation and size of the communities are often obstacles to other options that require significant production to be profitable, making the solar basin a possible solution for isolated communities of small sizes.

7. Acknowledgments

The authors thank Mr. Michel Trottier for his unwavering financial support of the research group's activities and the FRQ-NT and NSERC organizations for the public funding granted to the t3e research group.

8. References

Aboulfotoh, A., et al., 2023, Optimizing solar distillation to meet water demand for small and rural communities, Desalination and Water Treatment, 292, 10-22.

Akhter, M., Habib, G., & Qamar, S. U., 2018. Application of Electrodialysis in Waste Water Treatment and Impact of Fouling on Process Performance. Journal of Membrane Science & Technology, 08(02). https://doi.org/10.4172/2155-9589.1000182

Al-Shayji, K., & Aleisa, E., 2018. Characterizing the fossil fuel impacts in water desalination plants in Kuwait: A Life Cycle Assessment approach. Energy, 158, 681-692.

Arunkumar, T., Raj, K., Dsilva Winfred Rufuss, D., Denkenberger, D., Tingting, G., Xuan, L., & Velraj, R., 2019, A review of efficient high productivity solar stills. Renewable and Sustainable Energy Reviews, 101, 197-220. https://doi.org/10.1016/j.rser.2018.11.013

Bahar, R., Hawlader, M. N. A., & Woei, L. S., 2004, Performance evaluation of a mechanical vapor compression desalination system. Desalination, 166, 123-127. https://doi.org/10.1016/j.desal.2004.06.066

Bell, I. H., Wronski, J., Quoilin, S., & Lemort, V., 2014, Pure and Pseudo-pure Fluid Thermophysical Property Evaluation and the Open-Source Thermophysical Property Library CoolProp. Industrial & Engineering Chemistry Research, 53(6), 2498-2508. https://doi.org/10.1021/ie4033999

Bloemer, J. W., Collins, R. A., & Eibling, J. A., 1961, Study and evaluation of solar seawater stills, OSW Report No.60 PB111934

Chauhan, V. K., Shukla, S. K., Tirkey, J. V., & Singh Rathore, P. K., 2021, A comprehensive review of direct solar desalination techniques and its advancements. Journal of Cleaner Production, 284, 124719. https://doi.org/10.1016/j.jclepro.2020.124719

Darawsheh, I., Islam, Md., & Banat, F., 2019, Experimental characterization of a solar powered MSF desalination process performance. Thermal Science and Engineering Progress, 10, 154-162. https://doi.org/10.1016/j.tsep.2019.01.018

Duffie, J. A., & Beckman, W. A., 2013, Solar Engineering of Thermal Processes. 4th edition, Wiley, 928 p.

Eke, J., Yusuf, A., Giwa, A., & Sodiq, A., 2020, The global status of desalination: An assessment of current desalination technologies, plants and capacity. Desalination, 495 (2020) 114633

El-Sebaii, A. A., Al-Ghamdi, F.S., Al-Hazmi, A. S. Faidah, A. S., 2009, Thermal performance of a single basin solar still with PCM as a storage medium. Applied Energy, 86 7 1187-1195

European Commission., 2019, JRC Photovoltaic Geographical Information System (PVGIS, https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html#PVP

Ghazi Z.M., Rizvi, S.W.F., Shahid, W.M., Abdulhameed, A.M., Saleem, H., Zaida, S.J., 2022, An overview of water desalination systems integrated with renewable energy sources, Desalination, 542 116063

Guimard, L., 2019, Étude du comportement et modélisation d'une installation de dessalement d'eau de mer par distillation soumise à des régimes transitoires [Université de Lyon]. https://tel.archives-ouvertes.fr/tel-02091474/document

He, W., et al., 2024, Flexible batch electrodialysis for low-cost solar-powered brackish water desalination, Nature Water volume, 2, 370–379.

HELIOCLIM-3 ARCHIVES *DEMO*., 2006, SoDa - Solar radiation Data. http://www.soda-pro.com/web-services/radiation/helioclim-3-archives-for-free

Howard, G., Bartram, J., Williams, A., Overbo, A., Fuente, D., & Geere, J.-A., 2020, Domestic water quantity, service level and health (p. 76, World Health Organization. https://www.globalwaters.org/sites/default/files/domestic_water_quantity.pdf

Janajreh, I., Zhang, H., El Kadi, K., Ghaffour, N., 2023, Freeze desalination: Current research development and future prospects, Water Research 229 119389

Jones, E., Qadir, M., van Vliet, M.T.H., Smakhtin, V., Kang, S., 2019 The state of desalination and brine production: A global outlook. Science of The Total Environment, 657 (2019) 1343-1356.

Kadi, K. E., Janajreh, I., 2017, Desalination by Freeze Crystallization : An Overview. Environmental Engineering, 8.

Kim, J., Park, K, Yang, D.R., Hong, S., 2019, A comprehensive review of energy consumption of seawater reverse osmosis desalination plants. Applied Energy, 16.

Lara, Jorge R., 2005, An advanced vapor-compression desalination system, Ph.D. thesis, Texas A&M University

Lawrie, L. K., & Crawley, D. B., 2019, Development of Global Typical Meteorological Years (TMYx, http://climate.onebuilding.org/default.html

Lawson, K. W., & Lloyd, D. R., 1997, Membrane distillation. Journal of Membrane Science, 124(1), 1-25. https://doi.org/10.1016/S0376-7388(96)00236-0

Li, Y. and 6 other authors, 2023, Desalination by membrane pervaporation: A review, Desalination, 547 116223

Liponi, A., Wieland, C., & Baccioli, 2020, A. Multi-effect distillation plants for small-scale seawater desalination : Thermodynamic and economic improvement. Energy Conversion and Management 205 112337

Malik, M.A.S., Tiwari, G.N., Kumar, A. and Sodha, M.S., 1982, Solar Distillation: A Practical Study of a Wide

Range of Stills and Their Optimum Design, Construction and Performance. Pergamon Press, Oxford.

Mandri. Y., 2011, Étude paramétrique du procédé de dessalement de l'eau de mer par congélation sur paroi froide [Université Claude Bernard - Lyon I]. https://tel.archives-ouvertes.fr/tel-00831277/document

McCutcheon, J., Xia, L., Bui, N.-N., 2019, Forward Osmosis. In J. Kucera (Éd.), Desalination (p. 209-243, John Wiley & Sons, Inc. https://doi.org/10.1002/9781119407874.ch5

Nannarone, A., Toro, C., Sciubba, E., 2017, Multi-Stage Flash Desalination Process : Modeling and Simulation. SAN DIEGO, 13.

Omarova, A., Tussupova, K., Hjorth, P., Kalishev, M., & Dosmagambetova, R., 2019, Water supply challenges in rural areas: a case study from Central Kazakhstan. International journal of environmental research and public health, 16(5), 688.

Panchal, H., Mohan. I., 2017, Various methods applied to solar still for enhancement of distillate output, Desalination, 415 76-89.

Qasim, M., Darwish, N.A., Sarp, S., Hilal, N., 2015, Water desalination by forward (direct) osmosis phenomenon: A comprehensive review, Desalination 374 47-69.

Raj Kamal, M. D., Parandhaman, B., Madhu, B., Magesh Babu, D., Sathyamurthy, R., 2021, Experimental analysis on single and double basin single slope solar still with energy storage material and external heater. Materials Today: Proceedings, S2214785320401610

RNCan, 2022, RETScreen Expert (8.1.0.44) [Computer software]. Ressources Naturelles Canada.

Saadat, A. H. M., Islam, M. S., Islam, M. S., Parvin, F., & Sultana, A., 2018, Desalination Technologies for Developing Countries: A Review. Journal of Scientifc Researh, 10 (1) DOI:10.3329/jsr.v10i1.33179.

Sedighi, M., Mahdi Behvand Usefi, M. Fauzi Ismail, A., Mostafa G. 2023. Environmental sustainability and ions removal through electrodialysis desalination: Operating conditions and process parameters, Desalination 549 (2023) 116319

Shafagnat, A.H., Eslami, M. Baneshi, M., (2023) Techno-enviro-economic study of a reverse osmosis desalination system equipped with photovoltaic-thermal collectors, ATE 218(2023) 119289

Shampine, L. F., Reichelt, M. W., 1997, The MATLAB ODE Suite. SIAM Journal on Scientific Computing, 18(1), 1-22. https://doi.org/10.1137/S1064827594276424

Ray, S.S., Verma, R.K., Singh, A., Ganesaoillais, M., Kwon, Y.N., 2023, A holistic review on how artificial intelligence has redefined water treatment and seawater desalination processes, Desalination, 547 (2023) 116221.

Subban, C. V. Gadgil, A.J., 2019, Electrically regenerated ion-exchange technology for desalination of low-salinity water sources. Desalination 465 (2019) 38-43.

UN, World Water Development Report., 2020, World Water Development Report (UN WWDR 2020): Water and Climate Change https://www.unwater.org/publications/world-water-development-report-2020/

Velmurugan, V., Srithar, K., 2011, Performance analysis of solar stills based on various factors affecting the productivity—A review, RSER 15 1294-1304

WHO, World Health Organization., 2017, Guidelines for drinking-water quality. https://www.who.int/publications/i/item/9789241549950

WHO, World Health Organization., 2019) GHO | By category | Burden of disease—SDG 3.9.2—Mortality rate attributed to unsafe water, unsafe sanitation and lack of hygiene (exposure to unsafe Water, Sanitation and Hygiene for All (WASH), WHO; World Health Organization. Updated 2022-11-07 https://apps.who.int/gho/data/node.main.INADEQUATEWSH?lang=en

Yadav, D., Karki, S., Ingole, P. G., 2022) Current advances and opportunities in the development of nanofiltration (NF) membranes in the area of wastewater treatment, water desalination, biotechnological and pharmaceutical applications, Journal of Environmental Chemical Engineering, 10 (2022) 108109

Wafi, M. K., Hussain, N., El-Sharief Abdalla, O., Al-Far, M. D., Al-Hajaj, N. A., & Alzonnikah, K. F. 2019. Nanofiltration as a cost-saving desalination process. SN Applied Sciences, 1(7), 751. https://doi.org/10.1007/s42452-019-0775-y

Wang, Z., Tain, S., Niu J., Kong, W., Lin, J., Hao, X., Guian, G., 2020) An electrochemically switched ion exchange process with self-electrical-energy recuperation for desalination, Separation and Purification Technology 239 116521.