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Research article

Comparison of simple and active solar stills for freshwater recovery during lithium brine mining

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Keywords: Hydrometallurgy Sustainable mining Freshwater production Direct Solar Desalination Energy storage	Lithium mining from brines raise environmental issues due to huge volumes of both saline and freshwater being constantly pumped in desertic environments. Data indicating the slow depletion of both underground water levels and lagoon surfaces in the regions where large lithium brine mining exploitations are located have recently being disclosed. Amongst different direct lithium extraction methodologies, DLE, for more sustainable lithium recovery, a few proposals aim at the recovery of freshwater from the high salinity brines. About 900 kg of freshwater could potentially be recovered per cubic meter of processed native brine. The water evaporation and freshwater production capabilities of a simple and an active solar still are compared in this work. These are two simple and relatively low-cost technologies that could be adapted to existing solar evaporation ponds. The two systems were thermodynamically modelled. Equations were derived which were fed with real meteorological data from the Olaroz salt lake location and brine properties derived from the Pitzer model for the said brine. Analysis of the beat fluxes show that the behavior of both systems is relatively similar with large heat losses that are responsible

for neither of the systems reaching the evaporation rate of the evaporation ponds.

1. Introduction

Lithium mining from brines is constantly raising environmental controversies due to an intensive water usage in regions of extreme aridity [1,2]. The largest lithium resources in brines, and the largest facilities under exploitation at time of writing are found in a rather small region in South America called the Lithium Triangle, encompassing southwest Bolivia, northern Chile and northwest Argentina [1,3,4]. These naturally occurring brines display extremely high salinity, with no less than 180 g L⁻¹ of total dissolved solids and some of them reaching values of up to 350 g L⁻¹ [5]. Lithium cations are a very diluted species at about 1.5 g L⁻¹ in the best scenario, with sodium chloride being most often the prevalent salt in the mixture [1,5].

Briefly, the evaporitic technology currently employed for lithium carbonate production at most of the existing facilities consists in brine concentration in open air evaporation ponds. In the middle of the dessert, by the action of the strong winds and the intense solar radiation at high altitude, the brine losses by evaporation over 95 % of its original water content, while most of the salts other than lithium salts slowly crystallize in the ponds [1,6]. The evaporated water is not recovered. On average, about 383 tonnes of water are lost by evaporation for every

final tonne of pure lithium carbonate produced [1]. To make matters even worse, in the final processing of the concentrated brine leading to the production of a pure lithium product, about 50 m³ of freshwater are employed [1,5]. Brine and freshwater are found in different reservoirs [6–8]. However, both hydrogeological models and field measurements have shown that when brine pumping is intensified beyond certain levels there is a clear influx of freshwater from outside of the salt lakes or salars to try to compensate for the depletion of the saline aquifers [9–13]. Indeed, since 2018 quite a large number of research articles have effectively shown decreases of soil moisture indexes and surface area of nearby lagoons, depletion in the number of flora and fauna species whose survival depends on water, amongst other data of concern [1,7,14–16].

Beyond the environmental issues, the evaporitic technology also lags behind in competitiveness regarding techno-economic aspects. It is extremely sluggish, with brine residing in the ponds between 10 and 24 months to reach the required lithium concentration [1,6]. Thus, both industrialist and academic researchers are eagerly looking for new technologies. Amongst many different proposals, jointly known as direct lithium extraction technologies, DLE [1,17], an interesting group are those that propose to concentrate brine by some alternative method

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that does not entail water loss to the environment during open air evaporation. In simple words, the ideal scenario would be to somehow distillate the brine, while recovering the freshwater, leaving behind a hyper concentrated brine containing most of the lithium [18–23].

A simple solar still is the original solar passive desalination system developed to convert brackish water into freshwater. While being an inexpensive system to construct and maintain, requiring no particularly experienced labor, its main disadvantage, is its low output of freshwater, in comparison with other desalination systems and its large footprint [18,24,25]. In order to improve the operation of a simple solar still, there are multiple concepts that have been proposed and tested, such as to increase its operating temperature, reduce the brine depth, improve the internal transfer of heat and mass, and actively reuse the latent heat released by the steam during the condensation process [24, 26], amongst others. In this way it is possible to significantly improve the freshwater production rate of simple solar distillation systems. In a simple solar still, only the direct energy of the sun irradiating the solar still basin is used. A system where extra thermal energy is used, provided by other sources or ancillary devices is termed an active solar still [27]. Active stills are a previous step to the more complex humidification dehumidification technology [28]. There are different variants for this concept of active solar still, amongst others, some designs contemplate that the water vapor can be condensed on the surface of the glass cover partially or totally on the cooling coil in an external condenser [24,26,27]. Great improvements in the efficiency of such systems have been reported, reaching values between 45 % and 47 % [29].

An active solar still with an external condenser as depicted in Fig. 1 has three advantages over a simple system. Firstly, the latent heat of condensation of water vapor is used up to pre-heat the brine, improving the energy efficiency [24,26,30], *i.e.* energy is recovered during the condensation process and directed back to the solar still's basin for improved evaporation. The glass cover is not a condenser, it is conducive to increasing the temperature difference between the brine surface in the basin and the horizontal cover, favoring the evaporation process. Due to the implementation of the fan, the pressure inside the distiller is slightly lower than ambient atmospheric pressure, which also strengthens the evaporation of water, it is advantageous to improve the water production rate of the device [26,31].

In previous work the performance of a simple solar still was compared to open air evaporation for the concentration of brine in the lithium extraction process. Our working hypothesis was that the existing evaporation ponds could potentially be adapted to the simple solar still concept, *i.e.* using the existing ponds as the basin of the still [18]. To the best of our knowledge, that work was the first to experimentally show that freshwater could be obtained from a natural lithium rich brine. Unfortunately, the experimental results showed that the application of the solar still principle to evaporation ponds would render the brine concentration process even more sluggish than it already is under natural evaporation [18]. Despite the high levels of radiation at an existing lithium mining facility, the low average temperatures and strong winds cause important heat losses. Together with the reduction of vapor pressure due to the high salinity of the brine, our device showed lower efficiency, at about 10-30 % [18], than usual for this type of systems, at about 30-40 % [24,25]. In order to develop a real scale application, it would be desirable to match or, ideally exceed the natural evaporation rate. However, that study allowed us to obtain great practical knowledge and experience on the behavior and efficiency of this and related possible processes based on thermal solar energy under extreme weather conditions. Moreover, correlating simulations to experimental data gathered for over a year on the experimental device helped us to validate a thermal model [18]. The excellent agreement of the results of the simulations with the experimental tests allows us to rely on these models to determine evaporation rates considering design modifications to improve the solar still's performance.

In work reported here, the concept of an active solar still with an external condenser with recovery of latent heat is developed. The system was modelled using thermal networks and numerical simulations were produced to predict daily patterns of heat fluxes and water evaporation rate. The model was fed with real meteorological data, and the precise composition of a lithium rich high salinity brine was taken into consideration by including deviations from ideal solutions in the activity coefficients using the Pitzer model. The low air pressure at a precise lithium mining facility located at almost 4000 m above sea level was also included in the simulations. The results were compared to those of a simple solar still and natural evaporation in a PAN evaporimeter. The results of the simulations showed that the active solar still improves the



Fig. 1. Schematic representation of the active solar still.

water evaporation rate of the simple solar still only for the days of higher solar irradiation, and by a factor of 19 % in the best scenario. Analysis of the heat fluxes allowed us to understand that while the heat of evaporation is increased in the active system, so are the convective and radiative losses. It was found that the best alternative to improve either of the stills analyzed is to sharply reduce the brine mass contained in the basin. When the brine height is as low as 0.01 m, the evaporation rate can be as much as tripled as compared to an identical device containing 30 times that amount of brine. When operated under the extreme meteorological conditions of the Lithium Triangle, and with the aim of recovering water from highly saline brines, no scenarios were found were an active or simple solar still can match the performance of natural evaporation.

2. Materials and methods

2.1. Active solar still with external condenser

Two devices are compared in this work: a simple solar still, and an active solar still. The simple solar still has already been described in our previous work [18]. This is schematically represented in Figure S1 (Supporting Information). Very briefly, it consists of a basin, 2 m^2 surface area, 200 cm long \times 100 cm wide x 10 cm height. Two transparent covers are located on the top of the still, imitating a gable roof. The cover allows for the solar radiation to be transmitted, while serving to condensate the water vapor. The tilted geometry allows the condensed freshwater to slide along the inner cover and be collected through lateral channels that leads to an external dedicated cylindrical container [18].

The active solar still is schematically depicted in Fig. 1. It consists of a 2 m² basin-type solar still with a horizontal glass cover, which, contrary to the simple solar still, it is not titled. The other extra components, as compared to a simple solar still, are a small electric powered wind turbine, and a vapor condenser unit, comprising a brine-cooling coil, a freshwater collector, and coupling pipes. Its operating principle is similar to that of the simple solar still. The first difference is that the water vapor is extracted (or removed) from the basin by a low-power fan. Vapor is led to a cooling coil, which is in turn immersed in native brine that is used as cooling fluid. The condensed freshwater is collected at the bottom of the condenser coil. The brine used as a cooling fluid is thus pre-heated in the condenser, and it is in turn delivered to the distiller, at a temperature T' which is higher than the native brine temperature, T, thus favoring evaporation. Moreover, since fresh brine is constantly being delivered to the basin, the brine mass in the basin is constant (see brine feeding from condenser to basin in Fig. 1). Conversely, the brine mass in the simple solar still is constantly decreasing, since there is not a refilling system as water is evaporated (see figure S1, which can be considered a batch system).For comparison and to help our analysis, in Figs. 3 and 8 data is shown for open air evaporation. This is experimental data that was measured on a PAN evaporimeter (schematically shown in Figure S2, Supporting Information), for further details, see our previous publication [18].

2.2. Simulations

All the derived equations were used to model the system in SIMU-SOL®, an open-access software, which can be run both on Linux and Windows and can analyze thermal, mechanical, and electrical systems [32]. For further information, visit www.simusol.org. Table 1 lists the description and the numerical values used for all the parameters used in the simulations, including the reference from where these values were extracted, where appropriate.

All simulations were performed at the hypothetical location of Olaroz salt lake. This is in the *Lithium Triangle*, in the high Andean plateau in Jujuy province, north west Argentina, coordinates -23.554854°, -66.759093°, at 3940 m above sea level (masl). This location was chosen since we previously had performed experiments there with a simple solar still and an open air evaporator (PAN in the jargon), for which the corresponding equations had been validated when compared to experimental data. Moreover, at this specific location we had precise meteorological experimental data (recorded every 1 hour over 1 calendar year) with our own meteorological station including solar radiation, ambient temperature, relative humidity and wind velocity. These real meteorological variables were fed to the simulations of both the simple and active solar stills.

The composition of Olaroz brine, see Table 2, was also fed to the simulations. Specifically, the composition of the brine is required to estimate the vapor pressure lowering (Δp), specific heat capacity (C_p) and brine density (ρ). Those parameters are derived from the chemical potentials for electrolyte solutions, and thus we require values for activity and osmotic coefficients. The calculation of all of these follows our previous work [33]. Data shown in Figs. 3, 4, 5, 6 and 7 was simulated assuming a constant brine height in the basin of 0.07 m (both for the simple and active solar stills). In turn, data shown in Fig. 8 was simulated at varying brine height values, as specified in that figure.

3. Results and discussion

3.1. Heat transfer analysis

Fig. 2 shows the thermal networks for the simple solar still (left) and the active solar still with condenser (right) [31,34]. The heat transfer analysis for a simple solar still and an active solar still are similar, except that for the latter, in addition to the analysis of the basin, we need to consider the heat exchanges in the external condenser. The energy balance on the brine in the basin in the active solar still can be written as:

$$\alpha_{w}\tau G = q_{e,b-c} + q_{r,b-gi} + q_{c,b-gi} + q_{k} + (mC_{p})_{b} \frac{dT'_{b}}{dt}$$

$$(1)$$

where τ is the sunlight transmittance of the still cover, α_w is the sunlight absorptivity of brine, G is the solar radiation, C_p is the specific heat of the brine [18], *m* is the total brine mass in the basin and T'_{b} is its temperature. The energy of the sun, left side of Eq. (1), heats up the brine, last term in Eq. (1), and gives rise to the heat exchanges that take place between the surface of the brine and the glass cover: radiation $(q_{r,b-gi})$, convection $(q_{c,b-gi})$, and evaporation $(q_{e,b-c})$, where the subindexes b, gi, and c refer to brine, the inner surface of the glass cover, and the condenser, respectively. In the active solar still $q_{e,b-c}$ is the heat of evaporation which is not lost to the environment but saved in the condenser to preheat brine for recycling. q_k corresponds to all heat losses from the bottom and sides of the basin of the solar still to the surrounding through the insulation material. All heat fluxes are schematically represented in Fig. 1. Heat fluxes for the simple solar still and the PAN evaporimeter are shown in Figures S1 and S2, respectively, in Supporting Information.

The corresponding equation for the energy balance on the brine in the basin of the simple solar is conceptually the same, but the nomenclature is slightly changed. The evaporation heat exchange is denoted $q_{e,b-gi}$, since water vapor is condensed in the inner glass cover. Moreover, to mark the difference between the temperature values in the simple and active still, values in the former are signaled without the prime symbol (*i.e.* T_b and T_{gi}). The changes in nomenclature are also explicit in Fig. 2. Except for the changes in nomenclature, Eqs. (1) - (19) are the same for a simple or an active solar still. The individual heat fluxes in Eq. (1) can be mathematically expressed as:



Fig. 2. Thermal networks representing the heat fluxes in the simple (a) and active (b) solar stills.

$$q_{r, b-gi} = \epsilon_w \sigma \left(T'_b{}^4 - T'_{gi}{}^4 \right)$$

$$q_{r, b-gi} = h_{rm} = \chi \left(T'_b{}^4 - T'_{gi}{}^4 \right)$$
(2)
(3)

$$q_{c, b-gi} = n_{c,w-gi} \wedge (1 \ b - 1 \ gi)$$
 (3)

$$q_{e, b-c} = 16.2/3 \times 10^{-5} h_{c,w-gi} (p_b - p_{gi})$$
(4)

where ϵ_w is the emissivity of brine, σ is the Stefan-Boltzmann constant, T'_b and T'_{gi} are the brine and inner glass temperature values, respectively. As stated, the definitions for the heat fluxes in both stills are the same, but the temperature values should be expressed as primed in the active still. $h_{c.w-gi}$, the convection heat transfer coefficient, can be calculated as follows:

$$h_{c.w-gi} = 0.884 \left\{ \left(T'_b - T'_{gi} \right) + \frac{\left[p_b - p_{gi} \right] \left[T'_b + 273.15 \right]}{\left[169346 - p_b \right]} \right\}^{1/3}$$
(5)

Where P_b and P_{gi} are the partial pressures of water vapor, respectively at T'_b and T'_{gi} . P_b and P_{gi} are calculated according to the following equations:

$$p_b = exp^{\left(25.317 - \frac{5144}{T'_b + 273}\right)} - |\Delta p| \tag{6}$$

$$p_{gi} = exp^{\left(25.317 - \frac{5144}{T'_{gi} + 273}\right)}$$
(7)

In Eq. (6) we include the vapor pressure lowering, Δp previously calculated [18], because it relates to brine, but not in (7) because it is already pure water vapor that arrives at the inner glass cover.

The value 169,346 was calculated taking into account the reduction of atmospheric pressure due to high altitude, according to [35]

$$\frac{M_a p}{M_a - M_{H,O}} \tag{8}$$

where M_a and M_{H_2O} are the molar mass of dry air and water respectively, P is the normal atmospheric pressure value at the altitude in the location chosen for the simulations. For reference, at normal atmospheric pressure, the value reported in the literature is 268,900.

The cover dissipates heat directly into the atmosphere by convection $(q_{c,go-a})$, and radiation $(q_{r,go-a})$ after conduction through the glass:

$$q_{r,go-a} = \varepsilon_g \sigma \left[T_{go}^{4} - T_s^{4} \right] \tag{9}$$

$$q_{c,go-a} = h_{ga,c} \left(T_{go} - T_a \right) \tag{10}$$



Fig. 4. Heat fluxes calculated for the simple solar still (left) and active solar still (right). Data for the same 4 representative days shown in Fig. 3. For each raw, data on the left and right columns correspond to the same day.

Where T_{go} is the outer glass temperature, T_a the air temperature, ε_g is the glass emissivity and T_s is the temperature of the sky [36], which is an important parameter to calculate heat loss by radiation, which in a desert location and high altitude is considerable. T_s is affected by other weather variables as indicated in Eq. (11):

$$T_s = \left[T_a + 273.15\right] \left[\left(T_d + 200\right) / 250\right]^{1/4} - 273.15$$
(11)

With T_d , the temperature of the dew point, calculated as:

$$T_d = \sqrt[8]{\frac{H}{100}} \left(112 + 0.9T_a \right) + \left(0.1T_a \right) - 112$$
(12)

where *H* is the relative humidity. In Eq. (10) $h_{ga,c}$ relates to the wind velocity *v*, and can be calculated by an approximate formula:

$$h_{ga,c} = 2.8 + 3v \tag{13}$$

Heat is also lost by conduction and convection from the brine to the surroundings through the active solar still basin base and sides insulation (q_k) :

$$q_k = h_k \times (T'_b - T_a) \tag{14}$$

where the value of the heat loss coefficient h_k , includes all the factors that cause heat losses:



Fig. 5. Temperature differences between brine in the basin and the solar still cover for the simple $(T_b - T_{gl})$ and active $(T'_b - T'_{gl})$ solar stills. $T'_w - T_w$: Temperature differences for brine at the top (vapor inlet) and bottom (freshwater outlet) of the external condenser. Data for the same 4 representative days shown in Figs. 3 and 4.



Fig. 6. Heat fluxes calculated for the external condenser in the active solar still. Data for the same 4 representative days shown in Figs. 3-5.

$$h_k = \frac{K_{ins}}{L_{ins}} + h_{ga,c} \tag{15}$$

$$m_{ev} = \frac{q_{e, b-c}}{h_{fg}} \tag{16}$$

where K_{ins} and L_{ins} are the thermal conductivity and thickness of the basin insulation.

Thus, the theoretical instantaneous mass of evaporated water in the active solar still can be obtained according to the following expression.

Where h_{fg} is the latent heat of vaporization of water.

In scale of 0-1, the thermal instantaneous efficiency of the active solar still is given by:



Fig. 7. Daily patterns for produced water vapor at the simple and active solar stills and the PAN evaporimeter. Data for the same 4 representative days shown in Figs. 3–6.



Fig. 3. Experimental meteorological data for solar radiation and air temperature fed to the simulations. Simulated values for brine temperature in the basin for the active and simple solar stills, and brine temperature at the top of the external condenser of the active still. Experimental brine temperature in the PAN evaporimeter. 4 panels corresponding to representative days throughout the year as depicted in each panel.





Fig. 8. Amount of evaporated water produced per 24 hour periods in the PAN evaporimeter, and for the simple and active solar stills as the brine height is varied in the stills' basin. Data for the same 4 representative days shown in Figs. 3–7.

Table 1

Literature parameters used in the simualtions.

Parameter	Description / units	Value	Reference	
α_w	Absorptivity of water	0.95	[36,46]	
τ	Transmittance of glass	0.95	[35,36]	
C_p	Specific heat of the brine $[Jg^{-1}K^{-1}]$	3.4	[18,36]	
ϵ_w	Pure water emissivity	0.95	[36]	
σ	Stefan-Boltzmann constant [$W = m^{-2}K^{-4}$]	5.6697x10 ⁻⁸	[36]	
M_a	Molar mass of air vapour [gmol ⁻¹]	28.96	[36]	
M_{H_2O}	Molar mass of water [gmol ⁻¹]	18.0153	[47]	
р	Normal atmospheric pressure [<i>Pa</i>] at 3940 masl	64000*		
ϵ_g	Glass emissivity	0.94	[36]	
K _{ins,SS}	Thermal conductivity of solar still insulation $[Wm^{-1}K^{-1}]$	0.04	[36]	
Lins,SS	Insulation thickness of the solar still [m]	0.08		
$K_{ins,ASS}$	Thermal conductivity of active solar still insulation $[Wm^{-1}K^{-1}]$	0.028	[36]	
$L_{ins,ASS}$	Insulation thickness of the solar still [m]	0.1		
L_{PAN}	PAN evaporimeter thickness [m]	0.002	[48]	
K_{PAN}	Thermal conductivity of the PAN evaporimeter $[Wm^{-1}K^{-1}]$	55	[49]	
h_{fg}	Latent heat of vaporization for pure water $[kJkg^{-1}]$	2453.55*	[50]	
T'_w	Brine temperature at the top of the condenser $[°C]$	60		
T_w	Brine temperature entering the condenser [$^{\circ}C$]	25		
ρ_1	Density of saturated water vapour at temperature T'_{w}	130.41	[50]	
ρ_2	Density of saturated water vapour at temperature T_w	23.07	[50]	
ρ_b	Brine density [kgl ⁻¹]	1.23	[18,36]	
h_{fg}	latent heat of condensation of water vapour $[kJ\!kg^{-1}]$ at T_w	2441.71	[50]	

* These parameters are temperature dependent. Values listed are those corresponding to 293 K. Values at different temperatures were extracted from the same cited references in the last column of the table.

$$\eta_{iG} = \frac{q_{e,b-c}}{G} \tag{17}$$

The average efficiency calculated from simulations is:

$$\bar{\eta} = \frac{\int q_{e, b-c} dt}{\int G dt}$$
(18)

Where both integrals are over the same time-period (e.g. 24 h, 1 months, etc.).

Overall, the key parameter here is $q_{e, b-c}$ (or $q_{e, b-gi}$ in the simple still), we recall the heat employed to evaporate a given amount of water. The larger $q_{e, b-c}$ at a given incoming solar radiation, the larger the amount of evaporated water and the energy efficiency of a given system.

Re-arranging (4) and (5), we obtain:

$$q_{e, b-c} = 0.01439 \left\{ \left(T'_{b} - T'_{gl} \right) + \frac{\left[p_{b} - p_{gl} \right] \left[T'_{b} + 273.15 \right]}{\left[169346 - p_{b} \right]} \right\}^{1/3}$$

Where p_b and p_{gi} are still the magnitudes defined in (6) and (7). Thus, it should be possible to increase $q_{e,b-c}$ by designing the still such that a large temperature difference between brine and the inner cover, $T'_b - T'_{gi}$ is achieved. This temperature difference is explicit in Eq. (5) and the larger T'_b as compared to T'_{gi} , then the larger will be the difference between p_b and p_{gi} . In an active solar still, as compared to the simple solar still, by allowing water vapor to condense in a separate condenser, the inner surface of the glass cover T'_{gi} remains at a much lower temperature, resulting in a larger temperature difference $(T'_b - T'_{gi})$.

We now proceed with the energy balance in the condenser, which is only applicable to the active solar still. In this case only $q_{c,b-gi}$ and $q_{r,b-gi}$ are lost through the glass cover while the evaporation heat $q_{e,b-c}$ is partially recovered in the condenser [24]. In the simple still, all three heat

(

Table 2

Composition of Olaroz brine. TDS = total dissolved solids.

$Na^+mg L^{-1}$	$K^+mg L^{-1}$	${\rm Mg}^{2+}{\rm mg}~{\rm L}^{-1}$	$Li^+mg L^{-1}$	$Ca^{2+}mg L^{-1}$	$SO_4^{2-}mg L^{-1}$	$Clmg L^{-1}$	B mg L^{-1}	HCO ₃ ⁻¹ mg L ⁻¹	TDS / g L^{-1}	Density Kg L^{-1}
93,300	4200	1450	510	330	15,700	148,600	1120	670	265.88	1.23

fluxes are lost through the glass cover. Thus, the energy balance in the condenser, following Fig. 2, can be written as,

$$q_{e,b-c} = q_s + q'_k + q_{c-b} + \left(M_c C_{p_c}\right)_c \frac{dT'_w}{dt}$$
(20)

 q'_k is the heat energy lost from the condenser due to conduction and convection to the surroundings. q_s is the heat of condensation lost due to the fact that some water vapor escapes from the condensing coil without condensing. q_s depends on the temperature of the incoming native brine at the bottom of the condenser, T_w . q_{c-b} is the recycled heat of condensation. M_c and C_{p_c} are the mass and the specific heat of brine in the condenser respectively. In the setup proposed here, brine in the condenser used as a refrigerating fluid has exactly the same composition as brine in the basin, as explained above. Thus $C_{p_c} = C_p$, *i.e.* the same magnitude defined in Eq. (1). T'_w is the brine temperature at the top of the condenser. The last term in Eq. (20) is the heat used to raise the temperature of brine in the condenser. The term q'_k can be small in a well-designed and sufficiently insulated condenser, and q_s and q_{c-b} can be calculated from the following equations [24]:

$$q_{s} = \dot{m}_{v} \left(\frac{\rho_{2}}{\rho_{1}}\right) h_{fg}$$

$$q_{c-b} = \dot{m} \left(T'_{w} - T_{w}\right) C_{\rho_{c}}$$

$$(21)$$

where \dot{m}_{v} is the hypothetical mass of water vapor produced per second in the basin at temperature T'_{w} , T_{w} is the temperature of brine entering the condenser, ρ_{1} and ρ_{2} are the densities of saturated water vapor at temperatures T'_{w} and T_{w} respectively, \dot{m} is the mass of water transferred per second from the condenser to the basin. h_{fg} is the latent heat of condensation of water vapor (i.e. numerically the same value as the latent heat of vaporization of water).

It can be seen that unlike the simple solar still, the expressions for the heat flows $q_{c,b-gi}$, $q_{r,b-gi}$ and $q_{e,b-c}$ in the active solar still depend on the new temperatures T'_b and T'_{gi} of the brine in the basin and inner surface of the glass cover, respectively, as can be seen in Fig. 2. Other changes in these heat transfer equations with respect to the simple solar still are not taken into account here. The changes in convection heat transfer coefficient and internal pressure are neglected.

In order to estimate the required size for the condenser to effectively condense the largest possible amount of water vapor, we resort to Eq. (23) [24,31]:

$$M_{c} (T'_{w} - T_{w}) C_{p_{c}} = M_{v} \frac{(\rho_{1} - \rho_{2})}{\rho_{1}} \left[I_{v} + C_{p_{c}} (T'_{w} - T_{w}) \right] - M_{v} \left(\frac{\rho_{2}}{\rho_{1}} \right) (T'_{w} - T_{w}) C_{v}$$
(23)

Where M_{ν} is the daily production of water vapor given in kg. The last term on the right side of Eq. (23) represents the heat given out by water vapor that escapes uncondensed when it cools down from T'_{w} to T_{w} and C_{ν} is the specific heat of water vapor. It is small compared to the other two terms and can be neglected. In Eq. (23) it is assumed that the condensation of steam takes place at T'_{w} whereas actually it condenses as it goes down the condenser coil from temperature T'_{w} to T_{w} [24].

One important simplification is included in the models for all three systems. Mathematically, the brine composition is not modified, *i.e.* it is

considered constant and equal to that shown in Table 2. This simplification renders easier the implementation of the model and the computing requirement for the calculations are thus much less demanding and can therefore be run on a desktop computer. This assumption is physically not precise. As water evaporates, the different brine components become more concentrated in both the simple solar still and PAN evaporimeter. In the case of active solar still, fresh brine is continuously fed to the basin. Another assumption is made here: mass of incoming fresh brine equals mass of evaporated water. In this case, brine in the basin still becomes more concentrated than fresh brine.

The original model, developed for the simple solar still was validated by comparing simulation results with experimental data [18]. In those experiments, the basin was refilled with freshwater every (24 \pm 1) hours. Considering the basin dimensions, right after refilling, it contained 172.2 kg brine. On the day with largest register, 5.32 kg m^{-2} day⁻¹ water were evaporated. Thus, considering the 2 m² of basin area, the brine mass variation was never larger than 6.2 % during a 24 h period (the time frame for which the simulations are run and compared to the experimental data). Precise calculations for the osmotic and activity coefficients for this system as water is removed [33], showed that for concentration variations not larger than 6.2%, neither the activity, nor the osmotic coefficients change by amounts larger than 10 % (much less for some species). Moreover, osmotic and activity coefficients are used to calculate brine vapor pressure lowering, heat capacity and density, and while all of these show changes with concentration, these changes are not abrupt either [18].

Overall, while there are differences between the two solar stills and associated thermal networks we still consider that the two systems share sufficient similarities and therefore the previously validated model can be used to predict heat exchanges in the active solar still. The most important assumption, brine composition being kept constant, is the same for both systems. In the case of the active solar still, and in the time frame of the simulations, changes to brine composition are never larger than 6.2 %. The validity of these assumptions will not hold any longer for the simulations with much more shallow brine depths, see discussion in Section 3.6.

3.2. Dimensioning of the external condenser

Dimensioning of the condenser is crucial firstly to maximize the amount of freshwater to be recovered. Secondly, because we are recovering the heat of condensation to pre-heat the native brine, so that it enters the basin at the highest possible temperature. Thus, undersizing the condenser would result in loss of freshwater, while oversizing will result in the brine entering the basin at a lower temperature, in addition to a higher capital cost in its construction and higher footprint. We must consider seasonal variability and daily peak values in temperatures and the daily production of water vapor to accurately size the mass of brine in the condenser. Taking into account our previous work [18], the approximate design values will correspond to the day with the measured highest daily production of water vapor in the simple solar still. This was a day in November.

With the values listed in Eq. 1, Eq. (23) reduces to $M_c = 17, 7M_v$. Thus considering the peak daily production of water vapor $M_v = 5.34 kgm^{-2}$, in the month of November, the mass of brine in the condenser should be $M_c = 232$ kg for an active solar still with a surface area of 2 m^2 . It is interesting to see that in order to maximize the amount of condensate water vapor, the mass of brine in the condenser is actually 34.7 % larger than the mass of brine in the basin. This is relevant regarding a potential scaling up of the system. Such a large condenser would both increase the capital costs and the footprint of the installation.

3.3. Temperature values

Fig. 3 shows for 4 representative days in February, May, August, and November, the daily patterns of real meteorological data for solar radiation and air temperature values. These values will be fed to the models that follow the thermal networks presented in Fig. 2. As expected, both the solar radiation, and the air temperature values are higher in February and November (location in the southern hemisphere). Year-round colder temperatures are observed during the night. Moreover, Fig. 3 shows simulated values of daily patterns for brine temperature in the two solar stills and for comparison, in a PAN evaporimeter, $T_{b,SS simul}$, $T_{b,ASS simul}$, and $T_{b,PAN simul}$, respectively. In the case of the active solar still, the temperature of the brine at the top of the condenser T'_w is also shown.

On days with larger solar radiation (February and November), the simulations show that the brine temperature peaks in the active solar still $T_{b,ASS simul}$ reach lower values as compared to the simple solar still $T_{b,SS simul}$. This is explained because on days with greater solar radiation the heat fluxes between the brine and the cover in the active solar still are greater than in the simple solar still due to a greater temperature difference between brine and inner cover, see Figs. 4 and 5, and discussion below. Let us recall that in the active solar still there is a fan which is responsible for the water vapor being constantly removed from the basin and driven to the external condenser. In this way the inner cover temperature (T'_{gi}) reaches lower values, increasing the temperature difference with the brine (T'_b) , and the heat fluxes between them $(q_{r,b-gi}$ and $q_{c,b-gi}$). In this way the brine temperature $T_{b,ASS simul}$ reaches lower peak values. On days with lower radiation there is hardly any difference between $T_{b,SS simul}$ and $T_{b,ASS simul}$. In turn, the temperature of the brine in the condenser T'_{w} presents greater variability on days with greater radiation. This is directly related to a higher recycled heat of condensation (q_{c-b} , Eq. 22). In order to understand the trends in these temperature daily patterns, the different heat transfers within the solar stills and the condenser will be analyzed in more detail.

It is interesting to observe as well that the brine temperature values $(T_{b,PAN simul})$ in the open system, the PAN evaporimeter, are the lowest amongst the three systems. Year round, brine temperature in the open system is around 25 °C during the peak radiation hours. Even at dawn, when brine in the three systems consistently cools down brine in the open system is between 6 and 10 °C colder than in both solar stills. We have already stablished that at equal solar radiation levels, it is not the brine temperature that determines the evaporation rate, but the percentage of solar radiation that is used up in brine evaporation, *i.e.* the thermal efficiency in the use of solar radiation (η_{iG} , Eq. 17). This is better understood when the detailed heat transfer processes are studies (see Fig. 4 and discussion below). In the discussion of the heat transfer, the determining parameter will be the minimal temperature difference between brine and air. Brine in the open system is only just above air temperature (see Fig. 3), never reaching differences higher than 1 °C.

3.4. Heat transfer simulations

Fig. 4 is a plot of the daily patterns for the different heat exchanges for both the simple solar still (left) and the active solar still (right) for 4 representative days in February, May, August, and November. We firstly observe that the heat flows between the surface of the brine and the glass cover, convection $q_{c, b-gi}$ and radiation $q_{r, b-gi}$ reach higher values for the active solar still compared to the simple solar still. The same observation applies to the heat of evaporation (exchanged between brine and the inner cover, for the simple still, and brine and the condenser, for the active solar still, $q_{e,b-gi}$ and $q_{e,b-c}$, respectively). In absolute terms, the increases in heat fluxes are much more marked for the days with the highest radiation corresponding to the months of February and November, while the difference for the days of lower solar radiation in May and August is much smaller. However, in relative terms, the percentual increase is similar throughout the year. For example, the peak values of the heat of evaporation are 16 %, 19 %, 13 %, and 12 % higher in the active solar still for February, May, August, and November, respectively.

In this type of still, losses from bottom and sides of the basin, q_k , are rather large, as observed both in Fig. 4 and in our previous work [18]. In this work, we purposely improved the thermal insulation parameters in the active solar still vs. those of the simple solar still, to reduce these heat losses. This was possible because this work did not contain comparison with a real device that forced us to use the construction parameters. The thickness of the insulation layer was increased by 25 % (from 0.08 m to 0.10 m), while the thermal conductivity was reduced by 30 % (from 0.04 to 0.028 W m^{-1} K⁻¹). Despite this improvement, the heat losses from bottom and sides were the highest heat fluxes during May and August, almost doubling the heat of evaporation during the hours the still is subjected to solar irradiation. Even in the months with higher solar radiations, February and November, the heat losses were close to the heat of evaporation in the simple solar still. In the active solar still, the heat losses in months with higher solar radiations were higher than the heat fluxes due to convection and radiation although lower peak values are observed compared to the simple solar still. This is explained by the lower peak temperature of the brine (See Fig. 3, in months with lower radiation this difference is practically negligible). Heat losses also are affected by the wind velocity, that causes anomalies in the shape of the curve.

Following Eq. (16) we would like to maximize the heat of evaporation, so that we can maximize the amount of evaporated water. Thus, the brine will become concentrated faster, and potentially reach the same rate of evaporation as in the solar ponds, albeit with concomitant water recovered. If we come back to the energy balance in the basin, Eq. (1), the incoming energy of the sun is divided between all heat fluxes plotted in Fig. 4, and brine heating. Analyzing Eqs. (4)-(7) it is evident that an increase in the temperature difference between glass and inner cover will have a beneficial effect on the heat of evaporation. Unfortunately, the increase in the difference between these two temperatures will also increase the convective and radiative heat exchanges between brine and glass cover. This is particularly evident, see Fig. 4, for the convective heat, which is increased by almost 50 % in the months with higher solar radiation (higher brine temperature, see below).

We have previously calculated [18] that in the open system the heat of evaporation is highest due to a combination of factors, including low air temperature, relative humidity and atmospheric pressure along with strong winds. Moreover, the convective heat fluxes are most often smaller in the open system, except at moments of very high wind velocity [18]. Most importantly, heat losses to the surroundings are minimal, because the temperature difference between brine and air is never higher than 1 °C.

Fig. 5 shows the simulated temperature differences between brine and the glass inner cover, both for the simple and active solar stills. It can be observed that year-round, brine and inner cover are roughly at the same temperature over the night in both the simple and active stills. Conversely, the temperature difference increases during the day and becomes maximal at around 4–5 pm. When comparing Figs. 5 and 3, it is observed that there is a certain thermal inertia, brine temperature only shows a considerably increase after about 1.5 hour the solar irradiation starts. Year-round larger temperature differences are observed in the active solar still, as compared to the simple solar still, with these differences being more marked in the months with larger solar irradiation. It is interesting to recall that in Fig. 3 we observed that the brine temperature values reached in the active solar still were smaller than in the simple solar still, *i.e.* $T'_b < T_b$. Thus, the fact that $T'_b - T'_{gi}$ is higher in the active solar still is because the inner glass cover is colder in the active solar still, as compared to the simple solar still, *i.e.* $T'_{gi} < T_{gi}$. This difference is due to the fact that the evaporation heat $q_{e,b-c}$ is directed to the condenser instead of the glass cover. Fig. 5 also shows the simulated temperature differences between brine at the top of the condenser, T'_w , and at the bottom, T_w . It is interesting to observe that $T'_w - T_w$ shows a behaviour that is almost the opposite of $T'_b - T'_{gi}$, which is explained by thermal inertia, see below.

Fig. 6 shows the recovered heat flux, q_{c-b} , and the heat loss due to water vapor that is not recovered as freshwater in the condenser, q_s . These two heat fluxes are also higher on days with greater solar radiation. According to Eq. (22), q_{c-b} is proportional to \dot{m} , the mass of brine transferred per second from the condenser to the basin, and the temperature difference between top and bottom of the condenser, $(T'_w - T_w)$, *i.e.* the temperature gain between incoming brine, and brine transferred to the active solar still basin. Here we have assumed that \dot{m} is equal to the mass of evaporated water per second in the basin at temperature T'_{b} , in order to maintain a constant brine volume in the basin, and for simplicity in the simulations. It was also assumed that the temperature T_w is equal to brine temperature in the PAN evaporimeter (which as already discussed is close to air temperature). An initial value of T'_w greater than T_w is considered. It is also important to note that the T'_w depends on the mass of brine in the condenser M_c according to Eq. 20. Fig. 6 shows that the recovered heat flux density reaches its peak value approximately one hour after the peak in $q_{e,b-c}$ is reached, i.e. one hour after the peak of water vapor production is reached, and while the temperature difference $(T'_w - T_w)$ continues to increase.

Regarding the heat lost by non-condensed vapor q_s , the highest values are observed also on the days of greatest radiation. Moreover, the daily pattern of q_s is opposite to the recovered heat q_{c-b} , that is, the maximum values of this lost heat occur in the hours without solar radiation. This is because according to Eq. (20), this heat flux is proportional to the theoretical value of the mass of water vapor produced per second that would be obtained in the active solar still at temperature T'_w . This temperature corresponds to the brine in the condenser, which varies slowly due to $q_{e,b-c}$, the heat transferred by condensation. Therefore, due to this thermal inertia, T'_w , contrary to T'_b , reaches its highest values only when night falls, and then begins to decrease to a reach a minimum value the following morning, and only starts to increase again after midday. Taking this into account, variations in T'_w throughout the day, determines the maximum and minimum values of q_s observed in Fig. 6.

3.5. Evaporated water

Fig. 7 shows the daily patterns for the amounts of evaporated water in the open PAN evaporimeter, and the simple and active solar stills. The figure also shows the average wind values. The amount of evaporated water is larger year-round in the open system. Moreover, in the PAN evaporimeter even if the rate of evaporation considerably decreases during the night, it is never zero [18]. The active solar still shows larger amounts of evaporated water than the simple solar still, but these are still clearly below those of the open system. Results shown in Fig. 7 agree with the heat fluxes observed in Fig. 4. The amount of evaporated water is proportional to the heat of evaporation, Eq. (16), and thus from Fig. 4 we could already forecast that the improvement in the active still would be of 16 %, 19 %, 13 %, and 12 % for February, May, August, and November, respectively, when the comparison is for the daily peak values. If we analyze water produc-

tion over a 24 h period, the improvements will be lower. It can be seen that the advantage observed in the peak hours is lost at sunset when the simple solar still shows higher values. Considering the total amount of evaporated water, over a 24 h period, the active solar still has an advantage of about 0.5 L m⁻² only on the days with largest radiation, in agreement with the analysis on the heat fluxes carried out up to this point. Correspondingly, increases in thermal efficiency ranging from 6.3 % to 12.5 % are also observed (e.g. efficiency increases from 0.31 to 0.34 in November).

Overall, the analysis of the simulations predicts that the construction of an active solar still with characteristics as discussed up to this point will present a slightly better performance than the conventional simple solar still, with better improvements in the days of greatest radiation. The effect of low temperatures during the autumn and winter months, with large losses through the bottom and sides of the basin, continues to be a determining factor on the low performance, even though the insulation parameters were improved in the simulations carried out in this work.

3.6. Further improvements

Re-arranging Eq. (1) we obtain:

$$q_{e,b-c} = \alpha_w \tau G - q_{r,b-gi} - q_{c,b-gi} - q_k - (mC_p)_b \frac{d'T_b}{dt}$$
(24)

where it is mathematically observed that the decrease in efficiency is due to heat losses by radiation, convection, dissipation via the bottom and side of the basin and heating a large amount of brine. Therefore, taken inspiration from recent work on interfacial solar vapor generation [37], we explored the possibility of changing the amount of brine contained in the basin. In all results previously shown, the brine mass in the basin was considered constant at 0.07 m, which, considering a brine density of 1.23 kg L⁻¹ and 2 m² of basin surface amounted for a total of 172.2 kg brine.

Fig. 8 shows results for water evaporation rate for both the simple and active solar stills for varying brine depths, ranging from 0.005 to 0.30 m. Evidently, an increase water evaporation rate translates into larger amounts of freshwater production. It is observed that the rate of water evaporation decreases with increasing brine depth both for the simple and active solar stills. Interestingly, the difference between water evaporation rates for the simple and active stills becomes more marked the larger the amount of brine contained in the basin. In turn, for brine depths of 0.01 and 0.005 m, the differences are almost imperceptible. Upon decreasing the brine depths from 0.30 to 0.01 m, the rate of water evaporation is doubled for the days of higher solar radiation, and it is almost tripled in the days of lower solar radiation. Even for the shallowest brine depth, the rate of water evaporation does not reach the values calculated for the PAN evaporator. Indeed, in the days of highest solar radiation, under the best scenario water evaporation rate in either of the stills is only 69 % of that in the open system, whereas for the days of lower solar radiation, water evaporation rates in the still merely reaches 50 % of that in the open system. The improvements observed upon decreasing brine depths are attributed to a lesser amount of heat being used in brine heating. The heat transfer process is more concentrated in the brine-air interface.

At this point, we should recall one important simplification made in the modelling. We assumed that the brine concentration was constant (Section 3.2). This simplification was justified when the starting brine depth was 0.07 m, since brine concentration changes would never be larger than 6.2 %. However, we now see that upon decreasing brine depths the water evaporation rate increases. At the same time, the removal of a maximum of $5.32 \text{ kg m}^{-2} \text{ day}^{-1}$ of water from a basin containing 0.07 m of brine produced a brine concentration of 6.2 % in a 24 h period. Conversely, for the shallower simulation (0.005 m brine),

the basin could become complete dry in under 24 h. On a first approach, this means that the concentrated brine should be removed on a daily basis, otherwise valuable Li cations would end up trapped in the solid at the bottom of the basin. Moreover, the simulation was produced assuming negligible variations in brine concentration, which is clearly no longer the case. Overall, the two shallower calculations in Fig. 8 only hold assuming that brine is re-fed to the system every few hours. If brine is not re-fed to the system, then the concentration will increase in appreciable proportion. At higher concentrations, the vapor pressure will be even lower, and hence the rate of water evaporation will decrease.

In recent years, several clever strategies for more effectively utilizing wind energy and reducing heat losses have been proposed. Astounding freshwater production rates have recently been reported [38–43]. This work is aimed at the detailed comparison of a simple and an active solar still, and a detailed comparison with said systems is beyond our scope. As commented above, one of the advantages of these systems is that they would be readily adaptable to the existing evaporation ponds in existing lithium mining facilities. A key point that should not be forgotten here is that it is equally important to recover freshwater and the hyper concentrated brine. Freshwater is key from both industrial and environmental perspectives. The hyper concentrated brine is paramount since the concentrated lithium cations remain in said brine. Thus, a careful analysis of new designs of advanced solar stills (or similar distillation systems) should be made so as to figure out how that hyper concentrated brine can be recovered.

Moreover, avoidance of brine entrapment in the crystallized salts should be targeted. Because the initial brine is so concentrated (see Table 2, close to 265.88 g L^{-1} of total dissolved solids, with a large majority of NaCl), different salt mixtures (NaCl, KCl, CaSO₄, borates, mixed salts) will readily crystallize soon after water starts evaporating from the initial brine [5,33]. This is a key aspect of any desalination system were water is removed to reach higher concentration brines, regardless of freshwater being recovered, such as proposed here, or not, e.g. evaporation ponds. Crystal harvesting at regular intervals will be necessary, as is the case today in evaporation ponds. The amount of mixed salts to be collected is huge, in the example proposed here, in the order of 250 kg per m³ of brine fed to the evaporation ponds or any desalination system. From this perspective, any of the two systems discussed in this work would be easy to adapt to facilitate the removal of crystals. It would only be required to temporary removed the cover of either of the solar stills.

Finally, it is interesting to compare the performance of the systems under study here with other systems proposed for freshwater recovery lithium rich brines. To the best of our knowledge, only two alternative technologies have been proposed. Membrane distillation[19-22,44], coupled and uncoupled from crystallization units has been reported to produce different water recovery rates, ranging from 22.5 kg m⁻² h⁻¹ [21] to 2.3 kg m⁻² h⁻¹ [44]. Cyclopentane hydrate formation was shown to recover up to 70 % of the original water content from a LiCl solution in 24 h [45]. In the case of membrane distillation, the performance is indeed astonishing, reaching much higher brine concentration rates than both reported here and open air evaporation (and consequently, higher freshwater recovery rates). While we consider membrane distillation a technology for which new reports should be followed with attention, it should be highlighted that it is high energy consuming. Membrane distillation requires to heat brines to about 50-60 °C, and brine volumes to be processed are huge, in the order of 21,000 m³ per day [1]. The second alternative also produced very promising results [45]. However, those experiments were produced in pure LiCl solutions, i.e. no other salts were present. While future reports on the technology are also worth being followed, we wonder how the efficiency will change at 20 times higher salinity, and whether salts crystallization will affect the performance.

4. Conclusions

Recovering at least a fraction of the water that is currently evaporated and lost during lithium rich brine concentration is of paramount importance. Extremely large volumes of water being lost are still at the center of controversy in lithium brine mining. Freshwater recovery might be the key to social licensing for lithium mining in the near future [1,23]. Beyond environmental aspects, freshwater pumping from dedicated underground reservoirs entails high operational costs. Moreover, process water required during lithium carbonate purification needs to meet certain purity standards, and thus the pumped freshwater needs to be further purified (*e.g.* reverse osmosis) in order to reach such standards [5]. Conversely, freshwater produced via solar stills is distilled water quality and would thus meet the required standards.

The heat of evaporation increases in the active solar still, reaching higher peak values, but so do the heat fluxes of convection and radiation. Therefore, the average thermal efficiency in an active solar still only increases slightly compared to the simple solar still on the days with the highest radiation. On these days, a greater temperature difference $(T'_b - T'_{gi})$ is achieved due to the reduction of T'_{gi} . However, the brine temperature T'_b reaches a lower peak value and a lower minimum value compared to the simple solar still due to the greater heat transfer from the brine surface. The heat recovered q_{c-b} is significant also only in the same days.

The active solar still shows larger amounts of evaporated water than the simple solar still. During the peak hours of freshwater production, the active solar still produces 16 %, 19 %, 13 %, and 12 % more freshwater in February, May, August, and November, respectively. However, over a 24 h period, and for a brine depth in the basin of 7 cm, the active solar still has an advantage of about 0.5 L m^{-2} only on the days with largest radiation (spring and summer). The difference in evaporated water amounts when comparing the simple and active devices are strongly dependent on the brine depth in the basin. The larger the brine depth, the larger the difference in the amount of produced freshwater. In November, 0.9 L m⁻² day⁻¹ extra freshwater are produced in the active solar still when the brine reaches a depths of 0.3 m, as compared to the simple solar still with the same brine amount. Conversely, and for the same month, there is hardly any difference in the freshwater production of both stills when the brine depths fall below 0.01 m. Much more freshwater can be produced in solar stills with very shallow brine depths. Year round, the amount of freshwater produced is roughly tripled when decreasing the brine depths from 0.3 m to 0.005 m. Overall, it would be best to work with shallow brine depths, provided that technical means are found so that the hyper concentrated brine can be rapidly removed from the basin when appropriate lithium cations concentrations are reached for successful lithium carbonate crystallization.

For all the different simulated conditions, the daily amount of water evaporated in the open air system is higher compared to the active solar still. Neither the changes in design, nor the improvements in thermal isolation in the construction materials, or the reduction in brine mass in the basin were sufficient to match the amount of evaporated water in the open system. The comparison yields even worse performance indicators for days with the lower solar radiation, which is attributed to the wind velocity having greater influence on natural evaporation than the thermal effect, which can be observed in hours with low or nil solar radiation. The stronger winds usually come along with days and hours of lower solar radiation values. Precisely in those months and times of day, the highest wind speeds are observed, which obey a local wind pattern. The heat recovered through an external condenser in the active solar still only implied a minimum benefit which is completely lost when the mass and depth of brine considered in the still is reduced to a minimum.

Natural evaporation of highly concentrated brines is already sluggish. Thus, while freshwater recovery is of outmost importance during lithium mining, the process cannot be rendered slower than it already is. If the objective is to match, or ideally exceed, the natural evaporation rate, direct solar thermal systems within the low temperature range present clear limits. This work shows that it is necessary to move to more complex designs than the simple or active solar stills. Taking advantage of wind energy along with solar energy through the humidification-dehumidification of an air flow could be the key to achieving the aforementioned objective by increasing the evaporation rate and maintaining a relatively simple off-grid/autonomous and low-cost system that would allow for simultaneous brine concentration and partial freshwater recovery.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.nxsust.2024.100055.

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