Collecting Energy from a Planetary Entropic Stirling Engine

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Abstract

We extend previous work [1, 2] on *entrochemical systems*, energetically closed systems which spontaneously create an internal thermal gradients. Like an electrical battery, these *thermal batteries* use differing chemical potentials to generate work, though thermal work from their environment. This paper introduces a 'spontaneous' methodology for recharging the system. We utilize a solar chimney to generate airflow over a draw solution, evaporating water and reconcentrating the solution. The reconcentrated solution is used to restore the original internal concentration gradient which enables the entrochemical system. We examine a device comprising three major parts: a reaction chamber, a distiller, and a solar chimney. We measure the output of our thermal battery at 129.3 ± 11.9 W/m^2 using KCl as an enabling salt and 235.3 ± 15.3 W/m^2 using NaCl as an enabling salt. We measure internal recharge rates of 55.6 ± 6.9 W/m^2 when using a KCl / NaCl salt pair and 116.4 ± 18.0 W/m^2 when using a NaCl / CaCl$_2$ salt pair. We utilize a 6.096 m tall solar chimney with a 0.74m^2 solar collector. This solar chimney enables airflow of 37.05 m^3/day. We measure a maximal evaporative performance of 1.213 L/day/m^2. This corresponds to an effective energy utilization of 75.49 W/m^2 (50.5% of maximum, given the airflow). Extrapolation using the model of [3] to model a 35°C thermal lift and a 200 m tall chimney indicates an effective energy utilization of 405.49 W/m^2. We discuss how this energy can enable water distillation. The process naturally stores entropic potential removing daily solar irradiance limitations and enabling on-demand energy. Waste products are humidified air, which may enable precipitation, and salt crystals.

1 Introduction

In 2010, Kazadi et. al. [1] coined the term entrochemical system to describe a class of systems in which the development of a thermal gradient through a spontaneous entropy transfer is possible. The devices presented in that work create a thermal gradient spontaneously as a result of the interaction between entropy and energy transfers between two water solution reservoirs of differing chemical potentials. Though the effect is predicted by thermodynamics [2], it has been largely unobserved due to the specific set of conditions required to enable it.

The systems also represent an example of what we call thermal batteries, devices that deliver a specific quantity of thermal energy, typically by using an exothermic chemical reaction. Recharging the system was not addressed in previous work. Entrochemical systems function via strictly physical changes as opposed to chemical changes. As a result, an input of heat can reverse the effect. Yet when the heat is directly applied to a closed system, this process is simple distillation of the concentrated solution, and requires more energy than one can extract from the thermal battery.

In this paper, we address a recharge method for entrochemical systems. This recharge method uses a solar chimney to enable evaporation of water from an intermediate solution used to "dry" the high concentration reservoir of the entrochemical device when it becomes diluted. This process, which is spontaneous, enables the continual use of the entrochemical system in "harvesting" atmospheric thermal energy.
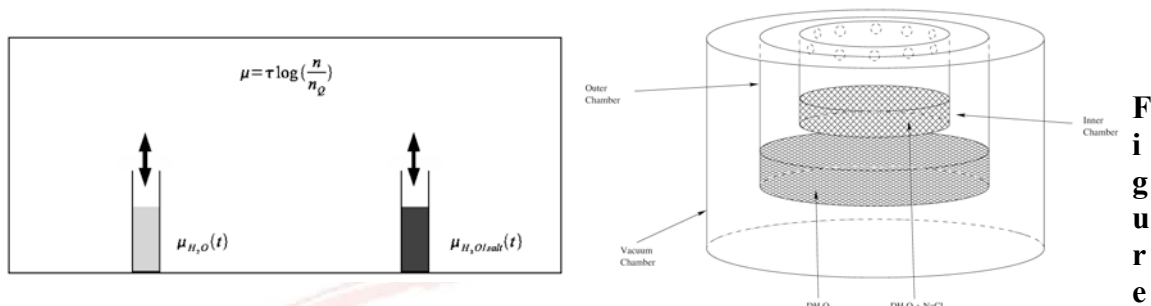
This device's continual efficacy depends on the ability to continually transfer entropy to the atmosphere through evaporation, making this energizing step spontaneous. In order to explain why this effect does not ever stop, we introduce the concept of a planetary entropic Stirling engine, powered by solar heat. This analogy to a Stirling engine explains how, through the daily heating, the atmosphere is made able to accept entropy after daily rejecting entropy to space during cooling. In effect, our entrochemical system is "plugged in" to the planetary entropic Stirling engine by the solar chimney.

Section 2 describes the entrochemical systems and their energetic, entropic, and systemic properties. Section 3 discusses the planetary entropic Stirling engine. Section 4 describes the apparati and procedures we developed to investigate this process. Section 5 provides experimental data. A discussion is given in Section 6. We conclude in Section 7.

2 Entrochemical Devices

2.1 Basic theory and experiments

The basic entrochemical system is diagrammed in Figure 2.1 below. In the basic system, two reservoirs are at least partially filled with water and enclosed in a larger chamber. One of the two reservoirs also contains salt.

F i g u r e

2.1: (A) A diagrammatic description of a basic entrochemical system. The reservoirs of water, one containing salt (or more salt than the other) must, in equilibrium, be at the same chemical potential. This is only possible if they are at different temperatures. (B) A nested version of the entrochemical system with an external insulating vacuum jacket. [1] reported a thermal gradient of 2.5∘C when used at 19∘C with saturated NaCl solutions on top and distilled water on the bottom.

As a result, the chemical potentials of the two reservoirs, μ, cannot be the same at the same temperature. I.e.,

$$\mu_{H_2O}(t) \neq \mu_{H_2O/salt}(t). \tag{1}$$

In equilibrium the chemical potentials of the two solutions must be equal to that of the vapor

$$\mu_{H_2O}(t_{H_2O}) = \mu_{vapor}(t_{vap}) = \mu_{H_2O/salt}(t_{salt}). \tag{2}$$

contained in the chamber.

In order to avoid a contradiction, we must conclude that $t_{H2O} = t_{salt}$, or that the two water reservoirs equilibrate at different temperatures. This equilibration is mediated by a vapor transfer from the water reservoir to the salt solution reservoir, increasing entropy and transferring heat (the heat of vaporization).[1]

The resulting system approaches an equilibrium with a temperature gradient that brings the chemical potentials to approximate equality. The system never completely reaches equilibrium, however, as some of the thermal energy leaks out of the system from the warmer side or into the system through the colder side. At least a small flow of vapor from the water to the salt solution continues until either the concentrations of dissolved solutes in the two reservoirs become equal or all the water in the less concentrated side evaporates.

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1   A different proof is offered in [2].

2.2 Temperature gradients, entropy transfers, thermal work limits

We have shown elsewhere [2] that the temperature difference between two bodies of water of differing concentration is given by

$$T_1 = T_2 \frac{\mu_1 - 2\frac{\partial U_1}{\partial N_1}}{\mu_2 - 2\frac{\partial U_2}{\partial N_2}}. \tag{3}$$

which can be used to yield

$$\Delta T = T_2 \left(\frac{(\mu_2 - \mu_1) + 2\left(\frac{\partial U_1}{\partial N_1} - \frac{\partial U_2}{\partial N_2}\right)}{\mu_2 - 2\frac{\partial U_2}{\partial N_2}} \right). \tag{4}$$

$$\Delta T \simeq T_2 \left(\frac{(\mu_2 - \mu_1)}{\mu_2 - 2\frac{\partial U_2}{\partial N_2}} \right). \tag{5}$$

For solutions, where $\mu = -\ln(x)$ with x the mole ratio of water in the solution[2] (4) becomes

$$\Delta T \simeq T_2 \frac{R\left(T_2 \ln(x_2) - T_1 \ln(x_1)\right)}{RT_2 \ln(x_2) - 2\frac{\partial U_2}{\partial N_2}} \tag{6}$$

$$\Delta T \simeq \overline{T} \left(\frac{4}{R\overline{T} \ln\left(\frac{x_2}{x_1}\right)} \frac{\partial U_2}{\partial N_2} - \sqrt{4 + \frac{16}{R^2 \overline{T}^2 \left(\ln\left(\frac{x_2}{x_1}\right)\right)^2} \left(\frac{\partial U_2}{\partial N_2}\right)^2} \right) \tag{7}$$

$$\overline{T} = \frac{T_2 + T_1}{2}.$$

where $\frac{\partial U_2}{\partial N_2}$ is the molar heat of vaporization and When applied to water, this temperature multiplier has the profile given in Figure 2.2 where the horizontal axes represent the mole fraction of the solutions and the vertical axis represents the multiplier.

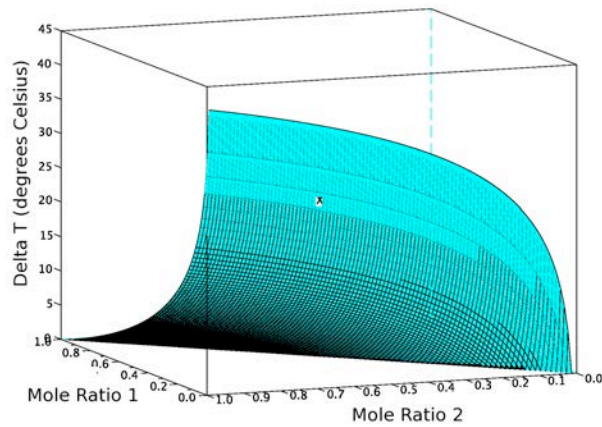2   A derivation of this chemical potential may be found in [3].

Figure 2.2: This figure illustrates the entrochemical temperature multiplier given in equation (3). The horizontal axes represent the mole fractions of the two solutions and the vertical axis represents the multiplier value.

If x_1 is 1 (or pure water), the relation becomes

$$\Delta T \simeq RT_2 \left(\frac{\ln(x_2)}{\ln(x_2) - \frac{2}{RT_2} \frac{\partial U_2}{\partial N_2}} \right). \tag{8}$$

This becomes

In this case, the curve is given by

$$\Delta T \simeq \frac{4\overline{T}}{R\overline{T}\ln(x_1)} \frac{\partial U_2}{\partial N_2} - \overline{T} \sqrt{4 + \frac{16}{R^2 \overline{T}^2 (\ln(x_1))^2} \left(\frac{\partial U_2}{\partial N_2} \right)^2}. \tag{9}$$
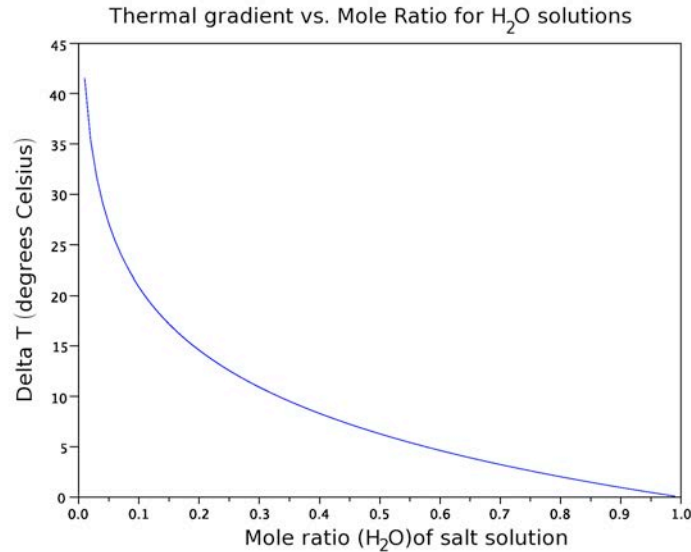
Figure 2.3: This figure illustrates the thermal gradient in a pair of water-based solutions in which one is pure and the other has the mole ratio given on the x axis (mole ratio of water in solution).

There is significant room for the development of thermal gradients when using water as a solvent.

Let there be two reservoirs containing saturated solutions of different species of salt, each with excess salt. If a quantity of water is transferred from reservoir 1 to reservoir 2, a quantity of energy equal to

$$\Delta U_1 = -\left(H_v - \Delta H_1\right)\Delta V \tag{10}$$

is extracted from reservoir 1. Likewise a quantity of energy equal to

$$\Delta U_2 = \left(H_v - \Delta H_2\right)\Delta V \tag{11}$$

is deposited in reservoir 2. $\Delta H1$ and $\Delta H2$ represent the enthalpy of dissociation of the salts within the reservoirs, and they need not be identical. In order to move ΔV from one reservoir to the next, a quantity of energy equal to $\Delta U1$ is absorbed by reservoir 1 and $\Delta U2$ is made available in reservoir 2. As a result, the efficiency is given by

$$e = \frac{\Delta U_2}{-\Delta U_1} = 1 - \frac{\Delta H_2 - \Delta H_1}{H_v - \Delta H_1}. \tag{12}$$

Note that this can be greater than 1 if $\Delta H_2 < \Delta H_1 < H_v$ or that $H_v < \Delta H_1 < \Delta H_2$.

The change in entropy is given by

$$\Delta S = \left(\frac{\Delta T}{2} ln\,(x_1 x_2) - \overline{T} ln\left(\frac{x_1}{x_2}\right) \right) \Delta V \tag{13}$$

$$\Delta S = \overline{T}\Delta V \left(\left(\frac{2}{R\overline{T} ln\left(\frac{x_1}{x_2}\right)} \frac{\partial U_2}{\partial N_2} - \sqrt{1 + \frac{4}{R^2\overline{T}^2 \left(ln\left(\frac{x_1}{x_2}\right)\right)^2} \left(\frac{\partial U_2}{\partial N_2}\right)^2} \right) ln\,(x_1 x_2) - ln\left(\frac{x_1}{x_2}\right) \right) \tag{14}$$

The system always increases in entropy when moving a quantity of water from the lower concentration solution to the higher concentration solution (ΔS is always positive). As a result, this process is spontaneous.

The entrochemical device enables an entropy transfer from the lower to the higher concentration solution. The magnitude of the thermal gradient is limited by the concentration gradient between the two solutions, which is dependent on the specific solvent/solute pairs. In practice this magnitude can be quite small.

3 Plugging into the planetary entropic stirling engine

We define entropic potential as the maximum entropy a liquid can contribute to a volume of gas at a given temperature. If the water vapor in a volume V behaves like an ideal gas, then its total entropy is given by a form of the Sackur-Tetrode equation. This gives us that

$$\sigma = nV \left[ln\left(\frac{n_Q}{n}\right) + \frac{5}{2} \right] \tag{15}$$

where P is given by [3]

$$P = \frac{10^{\left(8.07131 - \frac{1730.3}{233.426 + (T - 273.15)}\right)}}{760RT} \tag{16}$$

in atmospheres and n_Q is given by

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3   This is an approximation based on Antoine's equation [6].

$$n_Q = \left(\frac{mk_BT}{2\pi\overline{h}^2}\right)^{\frac{3}{2}}$$

As a result, an amount of water equaling

$$\Delta V_w = \frac{\Delta PV_g}{RTM_m\rho_w}$$

can be evaporated into the air, where V_g is the volume of air, M_m is the molecular mass, ρ_w is the solution density, and ΔP is the pressure difference between the vapor pressures at the two temperatures. This will have a concomitant increase in entropy. Thus heating the air has the potential to draw more vapor out of solution, transferring entropy. This potential change in entropy is the entropic potential of the system and it is this we wish to take advantage of.

The increase in entropy is graphed in Figure 3.1, which illustrates the temperature dependent maximum entropy of a volume of gas.
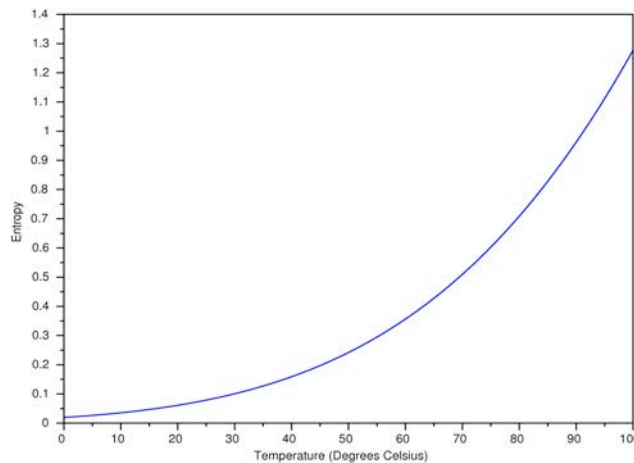

Figure 3.1: These figures give the temperature-dependent maximum entropy of a volume of gas.

The maximum entropy of the day and night environments are different, and this enables evaporative entropy transfer during the day and forces condensation-mediated nighttime entropy leakage at night.

Analogously to the Stirling engine, the daily process can be characterized as the creation of a high entropic potential atmosphere and the subsequent restoration of the previous low entropy state. What

is required to "plug in" to this Stirling engine is a method of taking advantage of the daytime expansion of entropic potential and its subsequent nightly reduction.
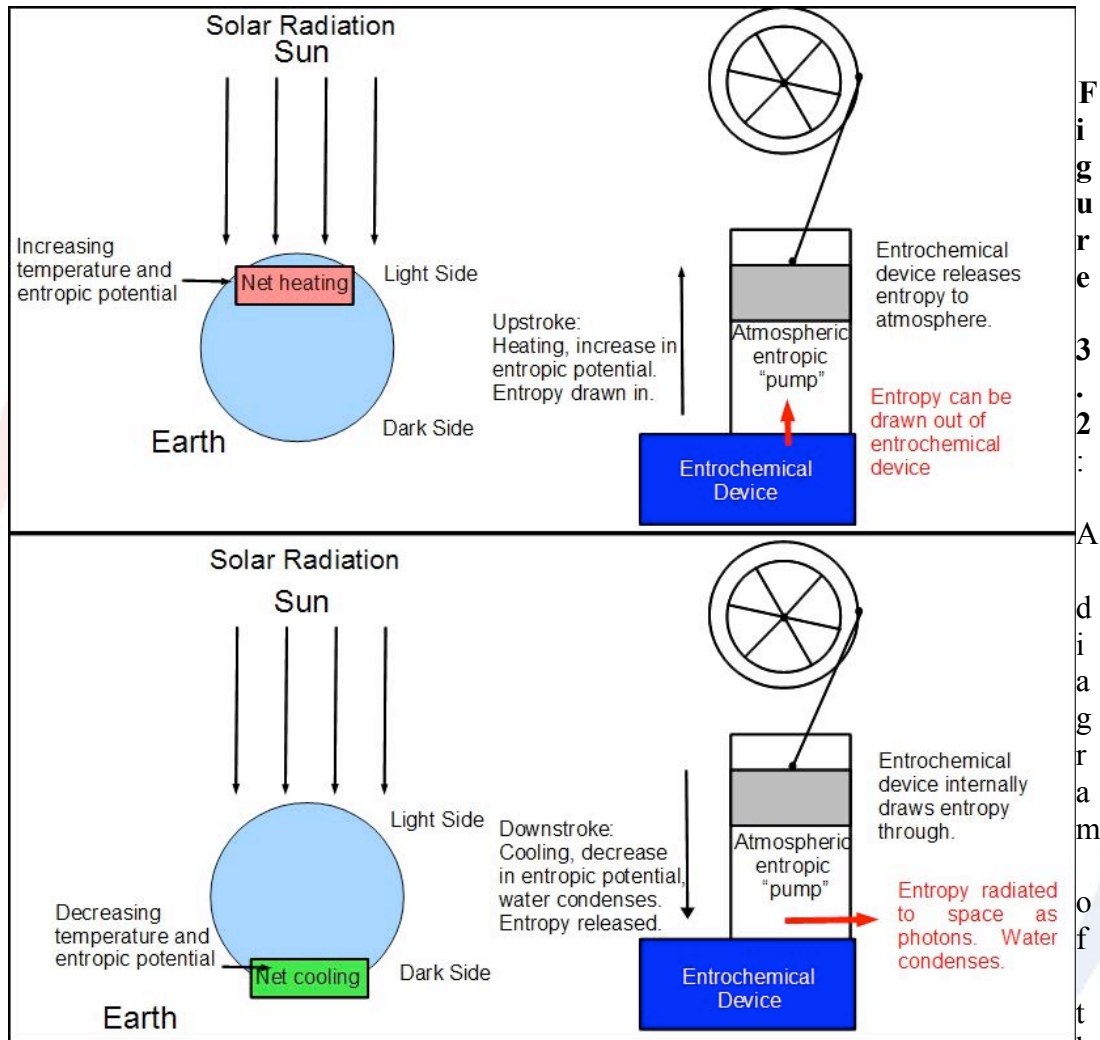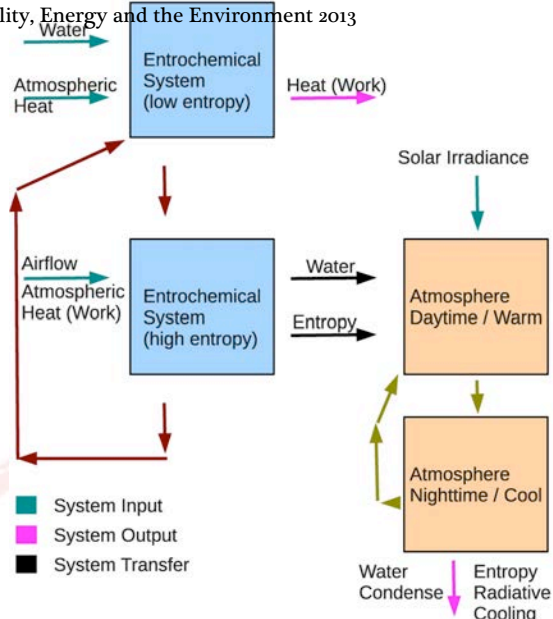

Figure 3.2: A diagram of the planetary Stirling engine daily cycle.

The capacity of an entrochemical system is reached when either the solute concentrations of the two solutions become equal or the solvent in the one of the two solutions (that with lower solute concentration) becomes exhausted. Once this capacity is reached the solvent has been transferred to the high concentration solution. In order to restore its functionality, new solvent must be provided to the bottom reservoir and the solvent must be separated from the solute in the top reservoir. It is the latter of these two steps that requires the input of energy. When coupled to a process that induces a positive entropy change, this step is spontaneous.

The overall process, which we call the "Kazadi-cycle" or "k-cycle," is illustrated below in Figure 3.3 and involves three spontaneous steps. First, the entrochemical effect generates the movement of fluid from one reservoir to the other, producing work. Second, the entrochemical effect moves fluid from

the top reservoir into the draw solution. Third, evaporation of the solvent from the draw solution utilizes atmospheric thermal energy to transfer entropy into the atmosphere.

Figure 3.3: This process, known as the "Kazadi cycle" or "k-cycle" follows the entropic inputs to thesystem and its pathway out of the system.

The top reservoir has a T-S diagram illustrated in Figure 3.4.

Figure 3.4: The T-S diagram associated with the top reservoir in the entrochemical device. Initially, the temperature increases, followed by a leveling off and concomitant increase in entropy. An adiabatic phase ends with the maximal entropy at which point the temperature difference decreases to zero. A reversal occurs as the entropy decreases coupled with an decrease in temperature until all the water has been extracted. At that point, entropy has returned to the minimum and the system equilibrates to a common temperature (no temperature difference).

This diagram illustrates the thermodynamic cycle the top reservoir goes through. Initially, vapor movement rapidly increases the temperature gradient between the high and low temperature reservoirs. Next, the reservoir goes through an isothermal stage during which heat is drawn into the system and radiated out of the system at a constant speed while the solvent is transferred between them. The rate at which the solvent is transferred is limited by either the maximal rate of the entrochemical effect or by the rate at which heat is radiated to the environment. Once the solvent transfer has ended the system rapidly comes to thermal equilibrium. Subsequently, during the evaporative stage, the temperature of the solution drops while the entropy of the solution drops. When the evaporative stage ends, the system reaches thermal equilibrium and returns to the initial point.

This cycle enables the continued extraction of environmental thermal energy for the purpose of doing work as long as the atmosphere is capable of absorbing water vapor. Since the world is turning, this ability is restored on a daily basis (or no water would ever evaporate from the ground when there is a spill, rain, etc.). As a result this process can continue virtually indefinitely[4].

In order to tie the system's performance tightly to the environmental entropic potential, a method must be used to efficiently evaporate the water in the high concentration solution. Increasing airflow over a water body serves to increase the evaporative action. We utilize a solar chimney, which will be described in Section 4.1.2.

4 Materials and Methods

We have developed two devices capable of accomplishing together the thermal energy extraction and work production. In addition, we have developed several methods in order to achieve the experimental results of this study.

4.1 Apparati

4.1.1 Basic Entrochemical Reaction Chamber

We have developed an entrochemical reaction chamber which is diagrammatically illustrated in Figure 4.1.

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4   In our experiments, water is used as the solvent. This means that the output of the system as a result of the evaporation is water vapor, which may be expected to have a negligible environmental impact. Other solvents one might use, such as ethanol, might have significantly deleterious environmental impacts if released in large quantities, and so are not solvents of choice for this purpose.
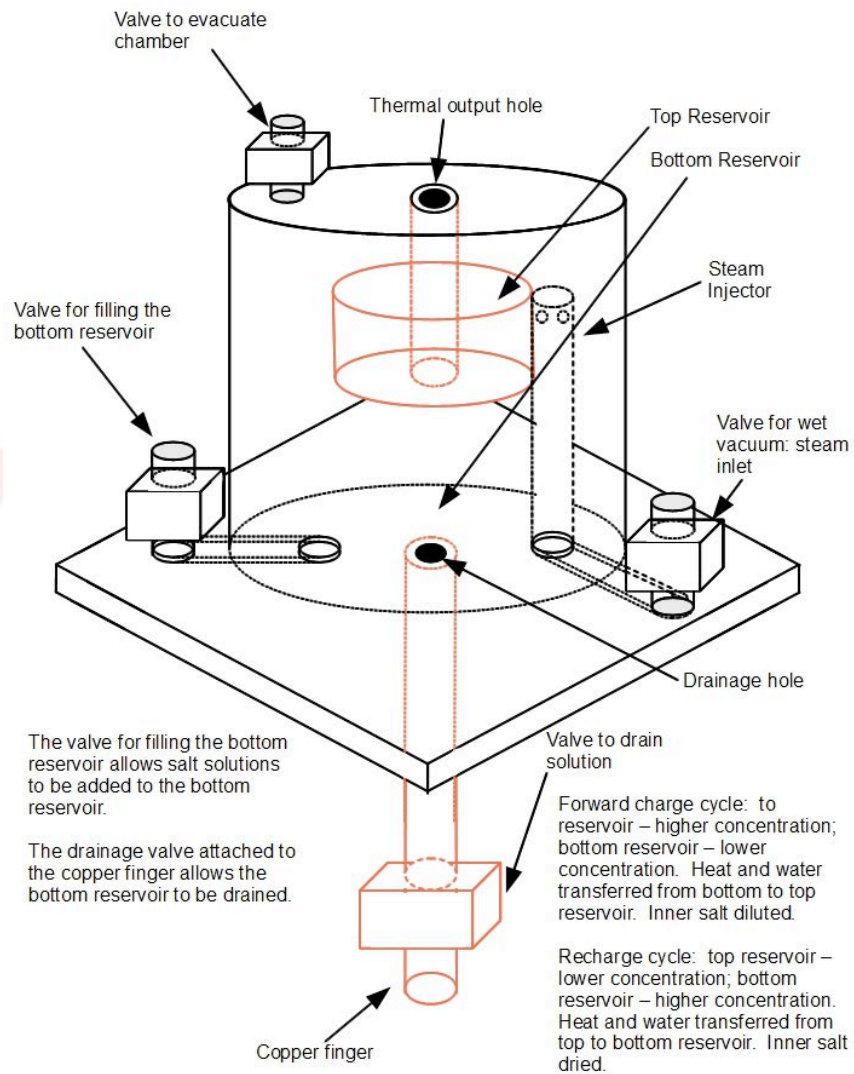
Valve to evacuate chamber

Thermal output hole

Top Reservoir

Bottom Reservoir

Steam Injector

Valve for filling the bottom reservoir

Valve for wet vacuum: steam inlet

Drainage hole

The valve for filling the bottom reservoir allows salt solutions to be added to the bottom reservoir.

The drainage valve attached to the copper finger allows the bottom reservoir to be drained.

Valve to drain solution

Forward charge cycle: to reservoir – higher concentration; bottom reservoir – lower concentration. Heat and water transferred from bottom to top reservoir. Inner salt diluted.

Recharge cycle: top reservoir – lower concentration; bottom reservoir – higher concentration. Heat and water transferred from top to bottom reservoir. Inner salt dried.

Copper finger

Figure 4.1: The entrochemical reaction chamber contains two reservoirs of salt at different concentrations. The resulting flow of fluid from one reservoir to another serves to alternately draw water into the top reservoir or draw it out of the top reservoir, depending on the relative osmolarities of the solutions.

The chamber is made from 4" OD cast acrylic tubing approximately 4" long and sealed on each end by 1/4" to 1/2" thick acrylic sheet. Channels in the acrylic approximately 1/8" deep and 3/8" wide connect the interior of the chamber to valves which seal off the chamber from its exterior. The chamber contains two reservoirs spatially separated from one another. The bottom reservoir can be alternately filled and drained by opening valves on the side or bottom of the chamber. The top reservoir contains a static salt supply which is alternately diluted as a result of the absorption of water vapor or concentrated as a result of evaporating water into the chamber. The chamber contains a steam injector through which steam can be injected. At the top of the reaction chamber is a valve through which a vacuum is applied. Underneath the reaction chamber is a copper tube and a valve. The valve enables the draining of the chamber while the copper tube enables the absorption of thermal energy. The top reservoir is made of copper. A copper tube is soldered into the center of the reservoir, sealing the tube's interior on the reservoir. The top of the tube is connected to the top of the chamber, and its interior is topologically connected to the exterior of the chamber through a hole in the top of the chamber.

4.1.2 Solar Chimney

Our solar chimney [4,5,6,10] comprises three principle parts: a solar collector, a dessicator, and a chimney. The parts are connected via ducting or direct contact as illustrated in Figure 4.2.
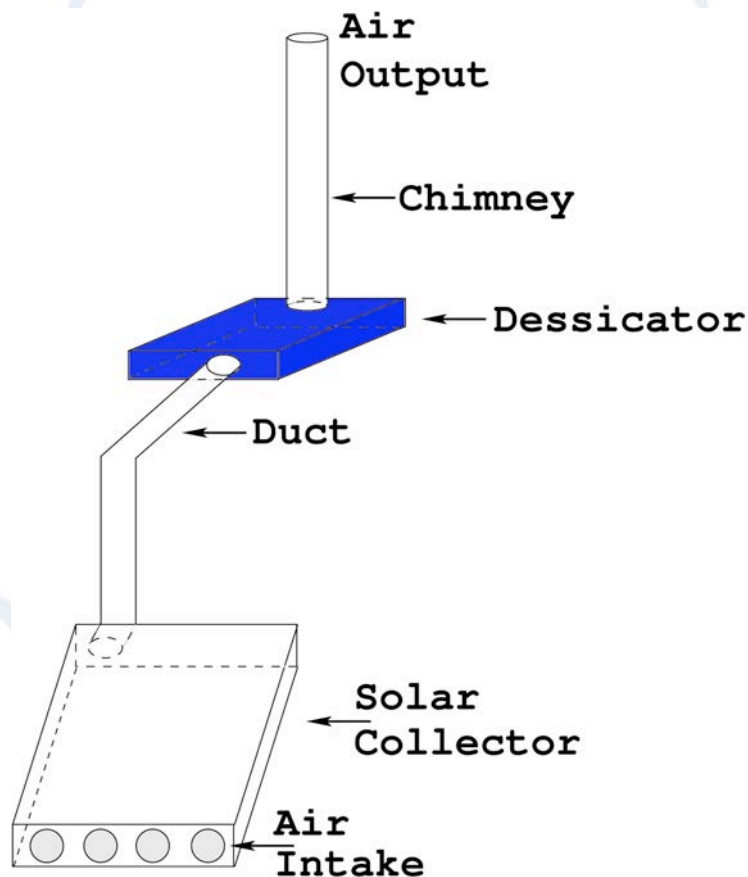
Figure 4.2: The solar distiller comprises three principle parts: a solar collector, a dessicator, and a chimney. These parts are connected with ducting and enable airflow through the system when exposed to sunlight.

Our solar collector has an approximate surface area of 8 ft^2 (or 0.74 m^2). It has a simple "box" design with a transparent top panel, transparent side panels, and a black bottom panel.

Ducting connects the solar collector to the dessicator. The ducting is heavily outfitted with insulation. The dessicator is a plastic square approximately 2 f t (or 0.61 m) in side length made of 7.62 cm inner diameter ABS plastic tubing, two mating t-connectors, and four mating 90◦ connectors. It is connected to the ducting at the middle of one side of the square and the tower on the opposite side using the t-connectors. One t-connector is angled at 90◦ from the plane of the square and the other at 45◦ from the plane on the same side. The 90◦ connector is coupled to the tower while the 45◦ connector is coupled to the solar collector. This enables pooling of liquid to be dessicated, enabling approximately 2.5 cm deep liquid to be retained within.

Cotton strips approximately 2.5 cm in width are hung from the ceilings of the dessicator on the sides not containing the t-connectors so as to increase the evaporative surface area. The cotton strips are staggered with approximately 2.5 cm separating subsequent strips. The staggering allows airflow to be directed from one strip into the next strip, ostensibly increasing the overall evaporative capacity of the airflow.

The tower is constructed of 7.62 cm inner diameter ABS plastic tubing coupled by an ABS pipe fitting. It is 6.096 meters tall.

4.2 Wet vacuum

A wet vacuum is a vacuum in which all gasses have been removed excepting the solvent used in the experiment. We establish wet vacuums by injecting steam produced by applying vacuum to a warm water body into one part of the cavity while a vacuum is applied to another distal part of the cavity.

In our studies, we use 500 mL of water prepared by heating to approximately 76◦C. Steam is injected into our chambers as outlined above. The vacuum is maintained for a period of at least one minute to ensure that most of the air that is not water vapor is removed from the chamber.

4.3 Salt production

It is necessary to utilize salt crystals that do not have air pockets contained within. Three methods of obtaining these crystals are described below.

4.3.1 Salt Drying Method 1

A quantity of water with an excess of salt is heated to boiling. This solution is decanted from the remaining salt into a pre-heated container. The container is then placed into a vacuum chamber and subjected to a mild vacuum. Boiling of the water in the container generates steam. Steam moving out from the container sweeps out unwanted air. The container is then sealed under vacuum and allowed to cool. Crystals precipitate out of the cooling solution in an air-free environment.

4.3.2 Salt Drying Method 2

Two chambers are connected to one another so that vapor can pass freely between them. A saturated salt solution is placed into one chamber. Both chambers are sealed and a wet vacuum is established

within. The saturated salt solution is heated, driving water from the solution into the other, colder chamber; salt crystals without enclosed air are thereby formed.

4.3.3 Salt Drying Method 3

One chamber is prepared with a quantity of a saturated solution prepared with a salt with a high osmolarity within. A thermally conducting container is placed within so that it is in contact with the surface of the water, but water cannot pass into the container. A second saturated salt solution prepared with a salt with a lower osmolarity is placed inside the container. The container is sealed with a wet vacuum. Salt crystals of the second salt form as the first salt solution absorbs the water from the second.

4.4 Forward Direction

The forward direction is that use of the system which enables thermal work. The forward direction is measured in terms of its maximal ability to move energy through the system. This is achieved by maintaining both the energy input and output surfaces at the same temperature via a water bath. The salts utilized in the forward direction are KCl and NaCl.

Referring to Figure 4.1, we place 20 g of prepared salt and 10 mL of H_2O in the top reservoir. We place 150 mL of water in the bottom reservoir, making sure that this water is not in physical contact with the top reservoir. A wet vacuum is established in the reaction chamber and the entire reaction chamber is placed into a water bath. The water is circulated around the thermal input of the reaction chamber and into the tube thermally connecting the top reservoir to the exterior. After a period of between 12 and 72 hours (varied so as to eliminate transient effects), the amount of water transferred between the two reservoirs is measured.

4.5 Recharge Procedure

Once the salt in the top reservoir has been fully dissolved, it is necessary to dry it, regenerating the salt crystals. This procedure consists of two different processes. In one, the salt in the top reservoir is directly dried. In the second process, the higher osmolarity solution used to dry the salt is itself dried. The salt pairs used in this study are KCl/NaCl and NaCl/CaCl$_2$.

4.5.1 Recharging the salt reservoir

Thirty grams of saturated KCl or fifty grams of saturated NaCl salt solution are put into the top reservoir. Approximately 450 mL of saturated high osmolarity salt solution is placed in the lower reservoir chamber – enough to bring the solution's surface into contact with the top reservoir. A wet vacuum is established in the reaction chamber. After a period of time, varying from 12 to 72 hours, the reaction chamber is emptied of the high osmolarity solution having regenerated the salt crystals. The amount of solution remaining in the top reservoir is measured; the amount of water moved is the difference between the initial amount and this measurement.

4.5.2 Recharging the high osmolarity solution

This procedure involves utilizing the solar chimney described in Section 4.1.2. A quantity of the high osmolarity solution, ranging from two to three liters, is placed in the dessicator device of the solar chimney. This solution is removed from the solar chimney between 5 and 24 hours later. The salt solutions used as high osmolarity draw solutions are NaCl and CaCl$_2$.

5 Data

We collected data on several different kinds of experiments. The first set of experiments validated those salt pairs that might be used in a system which enabled the full charge/recharge cycle of the thermal battery. These data are summarized in Table 5.1.

Charge Salt	Recharge Salt
KCl	NaCl
KCl	$CaCl_2$
KCl	$ZnCl_2$
NaCl	$CaCl_2$
NaCl	$ZnCl_2$
$CaCl_2$	$ZnCl_2$

Table 5.1: These charge/recharge salt pairs enable the full cycle entrochemical system.

These data are obtained by utilizing the reaction chamber to enable the forward direction of the reaction. In this case, the charge salt and a quantity of water are used for the forward direction. Subsequently, the water is replaced with a saturated solution of the recharge salt. The experiment initially evaluated whether the pair of solutions would yield a set of crystals in the charge salt solution as it was dessicated by the recharge solution. The pairs given in Table 5.1 are those tested that produced crystals at the conclusion of the cycle.

As $ZnCl_2$ cannot be dried via airflow of air through a solar chimney in most natural environments, we limit our examinations of the system to the salt pairs: KCl/NaCl and NaCl/$CaCl_2$.

We collected data regarding the maximal rate of movement of liquid and energy in the forward direction using distilled water in the bottom reservoir of the reaction chamber and saturated saline solutions with excess salt crystals in the top reservoir of the reaction chamber using the process described in Section 4.4.1. These data provide the maximal energy transfer rates possible for our thermal batteries.

Saline Solution	Volumetric Rate $(L/day/m^2)$	Energetic Rate (W/m^2)
KCl	4.99 ± 0.46	129.3 ± 11.9
NaCl	9.08 ± 0.59	235.3 ± 15.3

Table 5.2: These are the measured rates of water throughput and their corresponding energetic rates.

We collected data regarding the rate of recharge – movement of liquid from the top reservoir to the bottom reservoir during which the salt crystals in the top reservoir are regenerated. This provides information about how quickly the devices can be restored to functionality. This process, as desribed in Section 4.5.1, negates the need for thermal energy input, as energy is repeatedly transferred to and from each of the solutions during the process. The data are given in Table 5.3.

Saline Solution	Recharge solution	Volumetric Rate($L/day/m^2$)	Energetic Rate (W/m^2)
KCl	NaCl	2.14 ± 0.27	55.6 ± 6.9
NaCl	$CaCl_2$	4.49 ± 0.69	116.4 ± 18.0

Table 5.3: These are the measured rates of saline solution recharge and their corresponding energetic rates.

We measured the rate at which the recharge solutions used can be regenerated in the process described in Section 4.5.2. These data were obtained at 34°4′55′′N 118°8′6′′W at times during spring and summer months, with average irradiance as indicated in Table 5.4. The solar chimney's throughput was measured at

We measured the rate of wind flow in the solar chimney as 1.30 m/s. This corresponded to a total volume of 37.05 m^3 /day[5]. We also measured the thermal lift at an average of 13.87∘C. Given these data, we calculate the maximum daily evaporative capacity of this volume as 1.778 liters. Therefore the evaporative efficiencies of the solar chimney dessicating the NaCl and CaCl2 solutions, respectively, were 50.5% and 5.62%.

6 Discussion

We are in search of an energy source that provides at least parity for solar irradiance at the surface of the earth but is capable of achieving this whilst

- generating little or no waste materials,
- being constructed of materials that can easily be built by virtually any society on

    earth,

- providing environmental remediation when used in the proper environments,
- and can be built in virtually any size and integrated into virtually any structure.

Saline Solution	Average Solar Irradiance	Volumetric Rate ($L/day/m^2$)	Energetic Rate (W/m^2)
NaCl	900	1.213 ± 0.145	75.49 ± 9.04
$CaCl_2$	913.44	0.338	26.27

Table 5.4: These are the measured rates of saline solution drying in our solar chimney at conditions water throughput and their corresponding energetic rates.

The technology described in this work is a promising candidate for an energy system that achieves these goals.

6.1 Energy potential

We have demonstrated that the use of our solar chimney can enable 1.213 L/m^2 /day of evaporation when used with NaCl and 0.338 L/m2 /day of evaporation when used with $CaCl_2$. This means that the solar chimney is doing an amount of work on the solutions equivalent to the input of 2.717 MJ/m^2

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[5]   We assume a 10 hour day of significant solar irradiance.

/day or 0.757 MJ/m^2 /day. As the movement of air is achieved by the solar chimney but the evaporation is largely enabled by the ambient thermal energy of the external air, most of this work can be viewed as having been done by the air on the liquid with a concomitant transfer of entropy to the air.

We have also demonstrated that when used in the recharge mode, these solutions enable 2.14 L/m^2/day (KCl/NaCl) and 4.49 L/m^2/day (NaCl/CaCl2) of regeneration. This is equivalent to the effect of driving off water from the solutions using 4.8 MJ/m^2/day (KCl/NaCl) and 10.1 MJ/m^2/day (NaCl/CaCl$_2$). As a result, the ability of the NaCl and the CaCl$_2$ solutions to absorb liquid from the KCl and NaCl solutions, respectively, represents the equivalent of an energetic input. Yet, though it is mediated by a thermal transfer and a subsequent reverse thermal transfer through the reservoir material, it is accomplished without significant external energetic input, though some small environmental energy will be absorbed to compensate for the increase in entropy.

Finally, we have demonstrated the maximal energetic transfers possible in the forward direction using the basic entrochemical system. We have shown that a maximum of 4.99 L/m^2/day (KCl) or 9.07 L/m^2/day (NaCl) are transferred in the forward direction, and that this yields an energetic throughput of 11.17 MJ/m^2/day (KCl) or 20.33 MJ/m^2/day (NaCl).

Together, these indicate that the throughput of the device is limited by the performance of the solar chimney in our model. Extrapolating to much larger solar chimneys in hotter climes transfers the limiting factor to the recharge performance. However, as the units can be stacked to improve the overall performance given a specific footprint, it is likely that a facility employing this technology would still be primarily limited by the performance of the solar chimney. As a result, the power equivalent of the solar chimney is likely to be the limiting factor determining the energy potential of the technology.

We can evaluate the performance of larger solar chimneys in different climes using the model of Schlaige et. al. [3] If we extrapolate to a larger solar chimney with a height of 200 m and with a thermal lift of 35∘C, the throughput and therefore energetic potential is 0.405 kW/m^2 or 6.52 L/day/m^2.

6.2 Water and electrical energy production

We have already seen that the entrochemical effect generates a significant energy yield and that this energy is provided in the form of thermal energy drawn through the thermal battery. It makes sense, then, that this energy could be used for a variety of thermal processes, though these processes must be enabled. At energetic outputs described in Section 6.1, this process can enable the production of 1.214 L/m^2/day of water when using the solar chimney used in this study. Projected production for a larger chimney is bounded above at 6.52 L/day/m[26]. In order to determine the actual output of this method, we propose the entrochemical distiller design given below. These experiments, though under way, will have their outcomes reported in an upcoming publication.

The entrochemical distiller comprises of a two parts: a basic entrochemcial reaction chamber and a thermal distiller (Figure 6.1). Heat collected in the top reservoir passes naturally into the distillation water reservoir through the copper pipe connected to the top reservoir. The water in the distillation water reservoir is warmed by the heat, generating vapor which is warmer than the outside world. This
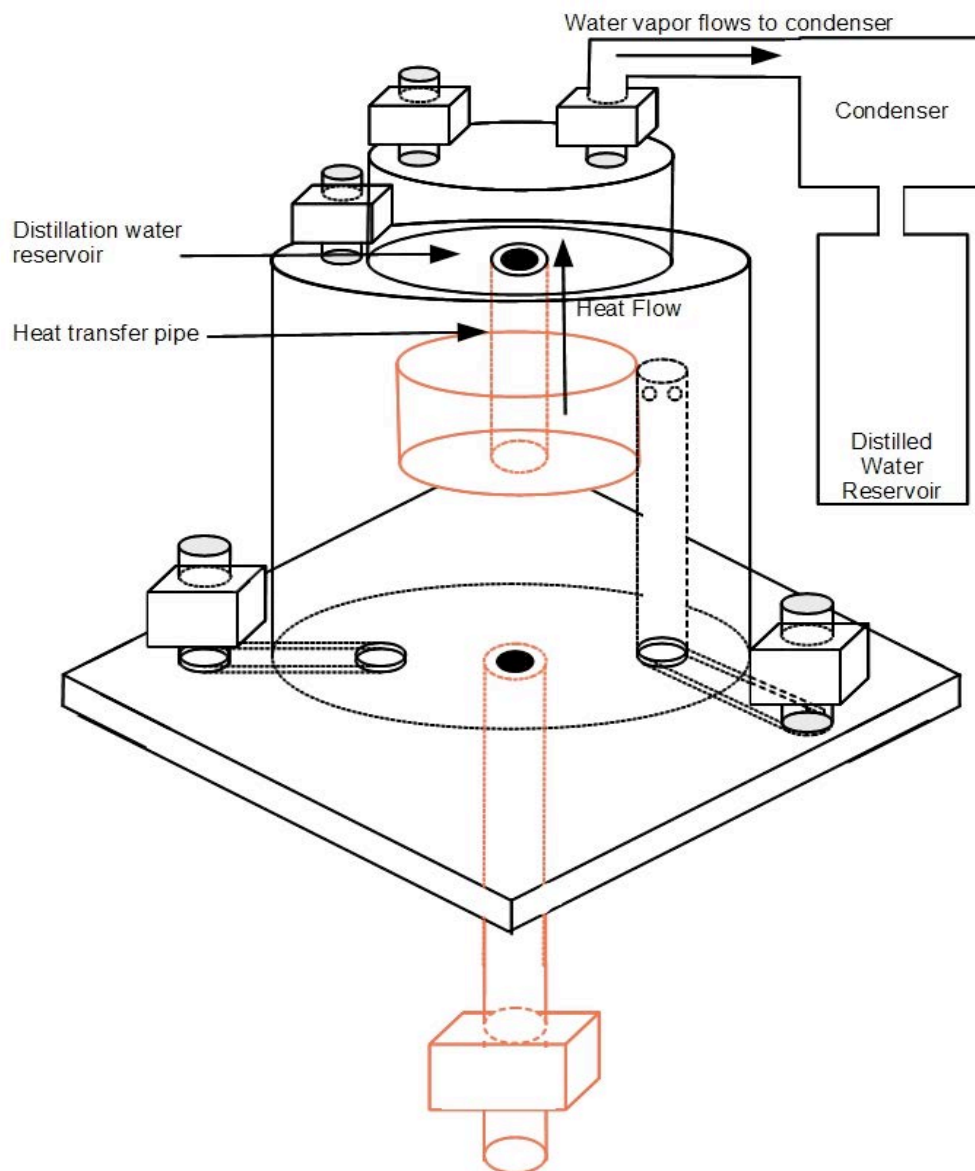
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6   This amount is enough to supply the City of Los Angeles, California, assuming 100% efficiency and a 25,000 acre
    facility – the same size as that planned by the company Enviromission.

vapor travels to the condenser where it condenses and falls into the collector. This is a single effect distiller, so the heat passes naturally back into the environment.

> **Figure 6.1**: The entrochemical distiller has the basic entrochemical reaction chamber embedded and adds to the simple system a thermal distiller which utilizes the heat of the entrochemical effect to heat and vaporize water which condenses and is collected.

This device is currently under investigation; results will be reported in an upcoming publication.

We also intend to investigate the use of the process in generating electrical power using a process of forward osmosis [9], enabled by our distilled water production. This work is underway and will be reported in an upcoming publication.

6.3 Energy storage

One of the important aspects of future renewable energy systems is their ability to, either independently or in concert with supporting technologies, store energy. We have shown that the method of drawing in energetic potential in the thermal battery technology is in restoring the properly generated crystals in the top reservoir of the reaction chamber through the recharge process. This process can easily be decoupled from the forward (work mode) process, and the crystals therefore represent stored energetic potential. The crystals, once created, can be physically removed from the systems and stored virtually indefinitely without degradation of their potential for future energetic activity. As a result, the system automatically stores the energetic potential it extracts from the air during the evaporative process.

6.4 Environmental Remediation

A current and urgent problem around the world is the availability of water and the lack of rainfall. It has been noted elsewhere[4] that the use of solar chimneys can enable cloud formation both outside of and within solar chimneys. The reason for this is that updrafts can yield humid air that cools as it rises. If the cooling proceeds beyond the point where the air's dew point is higher than the current temperature, water vapor can condense immediately. This process generates condensation which can grow into clouds and, eventually, into rain.

Even in the case that the solar chimney does not generate clouds, it will generate humidified air. If the air is in sufficient volume, it can generate localized condensation at night as it cools. Such condensation could generate rainfall affecting drought prone regions. This effect requires significant additional research, and remains as an interesting potential effect of this energy-generating modality. If this effect is observed, it would provide water that would, in turn, generate increased growth of local vegetation. The environmental remediation due to such growth could include carbon sequestration, if sufficiently large devices are deployed or if sufficiently many devices are used.

Though other technologies are known which change ambient heat into work [8] and others are, aside from producing heat, potentially environmentally neutral [7], no other renewable power source is known to the authors with the potential for generating environmental remediation.

7 Concluding Remarks

This paper centers the observation that the temperatures of two solutions with different osmolarities are necessarily different at equilibrium and that the entropic potential of the earth's atmosphere varies daily, enabling the absorption of additional entropy during the day and the rejection of entropy during the night. The combination of these two things enables the creation of the Kazadi cycle during which thermal energy can be extracted from the environment and made available to do work; additional thermal energy from the environment can enable the transfer of water and associated entropy to the atmosphere. As the process is enabled by the planetary entropic Stirling engine, it can be expected to continue indefinitely.

In thermodynamic terms, we have demonstrated that the process of transferring water from a low concentration solution to a high concentration solution is spontaneous, as is transferring water to the environment through evaporation. We have demonstrated that the atmosphere has a positive entropic potential change through the daily heating and a subsequent reduction in entropic potential through a rejection of heat during the night. As a result, the processes that enable these entropy transfers are spontaneous and indefinite, powered by thermal energy from the sun, its absorption in our atmosphere daily, and its subsequent rejection.

We developed a set of apparati and processes to examine this effect and measure the forward (work-enabling) modality and the reverse (regenerating) modality. We find that when these two modalities are implemented using the salt pairs KCl/NaCl and NaCl/CaCl$_2$ the maximum forward liquid transfer is 4.98 and 9.02 L/m^2/day, respectively, and the maximum recharge rate is 2.19 and 4.49 L/day/m^2. These are equivalent to a forward energy production of 129.3 W/m^2 or 235.3W/m^2, respectively. We have also examined the use of a small solar chimney as a means of restoring the high osmolarity solution and found that the NaCl and CaCl$_2$ solutions may be restored at a rate of 1.213 L/day/m^2 and 0.338 L/day/m^2 respectively. We estimate that solar chimneys similar to that deployed during the early 1980's in Manzanares Spain by the American company Enviromission can extend this capacity beyond the maximum single chamber recharge rate, with estimates as high as 6.52 L/day/m^2 .

This process and these apparati provide a significant step toward a fully renewable power source. The energy derived from this process may be delivered in the form of heat and subsequently transformed to any number of alternative forms. We have already outlined a process by which this can be applied to water distillation – a process that we are currently investigating and will report in an upcoming paper. The apparti described and processes developed are such that they may be implemented by virtually any society on the planet using indigenous materials and processes. As a result, it represents a promising potential form of power generation that can be adopted virtually anywhere.

Future work will focus on the development of fully integrated (charge/recharge) systems for the purpose of generating sustained heating/cooling, water distillation, and electrical power generation.

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