Solar Desalination

The Business Opportunity

With over $1 million of support from the Department of Energy and the National Renewable Energy Laboratory, AIL Research (AILR) has developed and proven at a laboratory scale technologies that address the critical problems of (1) converting seawater, brackish water and wastewater into a potable water, and (2) converting solar energy into high quality thermal energy at a cost that is competitive with natural gas (even at today's low natural gas prices). Although not included in this white paper, the low-cost solar collectors that supply high quality thermal energy can be coupled with emerging technologies for heat-driven air cooling and dehumidification to produce air conditioners that (1) use very little electricity, (2) do not rely in refrigerants that significantly contribute to global warming, and (3) improve indoor air quality by more effectively controlling humidity.

Competing Desalination Technology

Although the very high thermal efficiency and low capital cost of AILR's thermal desalination technology could eventually supply water at a lower cost than today's large-scale thermal desalination plants (millions of gallons per day), market entry for the technology will most likely occur at a much smaller scale. Furthermore, since reverse osmosis (RO) can supply relatively inexpensive potable water when low-cost electricity is available and the feed stream of impure water is not heavily contaminated, AILR's thermal desalination technology is most likely to first enter the market as either (1) a source of very pure water, (2) a source of potable water in remote, off-grid locations, or (3) a means of treating highly challenged wastewater.

AILR's thermal desalination technology will compete directly with products now being introduced into the market by the following four start-up companies:

- Altela
- Memsys
- Solar Spring/Oryx
- Mage

The technologies behind these four companies are similar in that they all (1) rely on plastic heat exchangers to transfer heat to the impure brine stream, (2) operate at atmospheric pressure (thus avoiding the large vacuum vessels that characterize large thermal desalination plants), and (3) use the input thermal energy multiple times to produce pure water more efficiently than simply boiling the impure water and condensing the steam.

AILR's thermal desalination technology shares all three of its competitors' key characteristics. However, AILR's technology can be more than twice as efficient: whereas the competing technologies driven by the thermal energy in steam will produce between 3 to 7 pounds of water per pound of steam, AILR's technology will produce more than 15 pounds.

AILR's Diffusion-Gap Distillation Applied to Desalination

Large, commercial, thermal desalination plants achieve high efficiencies (expressed as a Gain Output Ratio [GOR] which equals the pounds of product water per pound of input steam) by reusing the heat released when water vapor condenses to evaporate additional water. In large desalination plants, the processes of evaporation→condensation→heat recovery→additional evaporation are done within vacuum vessels with heat transfer across expensive cupronickel or titanium heat exchangers. AILR's Diffusion-Gap (DG) distillation also achieves high GORs through evaporation→condensation→heat recovery→additional evaporation. However, DG distillation avoids the need for vacuum vessels and expensive metallic heat exchangers.

The novel, patent-pending design feature through which DG achieves high performance is to locate hot, evaporating surfaces that are wetted with brine very close to cooled, condensing surfaces, the gaps between the surfaces being less than 6 mm (about 1/4th inch). This close positioning of evaporating and condensing surfaces allows a high flux of water vapor to flow from the evaporating surface to the condensing surface even when the evaporating surface is only a few degrees warmer than the condensing surface. Thus, high fluxes of water vapor driven by small differences in temperature, which characterizes large commercial thermal desalination plant, are achieved without vacuum vessels or metallic heat exchangers.

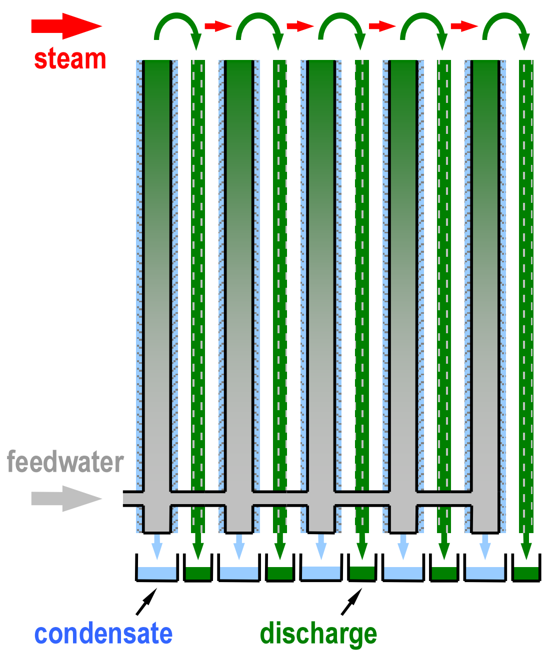

Figure 1 – Schematic of a Diffusion Gap System

The DG process is schematically represented in Figure 1. As shown in this figure, the DG system consists of a set of plates that have feedwater entering at the bottom and leaving at the top. Thin, wicking surfaces (the flat, green surfaces in Figure 1) are positioned in the gaps between these plates. The feedwater that flows up within the plates is heated as water vapor condenses on the outer surface of the plates (i.e., the thin, blue films that drain off the plates as blue arrows at the bottom). The source of this water vapor is the feedwater, which after being preheated in the plates is further heated by an external source (shown as steam in this figure) and then is delivered to the top of the wicks. The cooled feedwater flowing off the wicks (downward green arrows) and the condensate flowing off the plates are collected in separate troughs.

AILR's pending patent application describes the DG process in more detail[1].

Proof of the DG Concept

The DG process was first proven in a 15-plate small-scale prototype. When operating with low concentration brine (typical of brackish water) as the feedwater, the prototype's GOR and its conversion fraction varied with the maximum brine temperature at the top of the plates as shown in the graph in Figure 2.

Two values for COP (which is equivalent to GOR) are presented in the graph. The higher of the two is the COP corrected for the heat loss through the outer envelope of the prototype. These higher COPs are representative of the performance for a large DG plant where the heat lost through the outer envelope is a very small percentage of the thermal input to the plant.

[1] Lowenstein, "Apparatus for Diffusion-Gap Thermal Desalination," WIPO Patent Application WO2012/170900, December 2012.

As shown in Figure 2, the COP steadily increases with increasing temperature reaching a value of 17 at 97^{o}C. At this temperature, 10% of the feed stream is converted to pure product in a single pass through the system. Higher conversion fractions can be achieved with multiple passes.

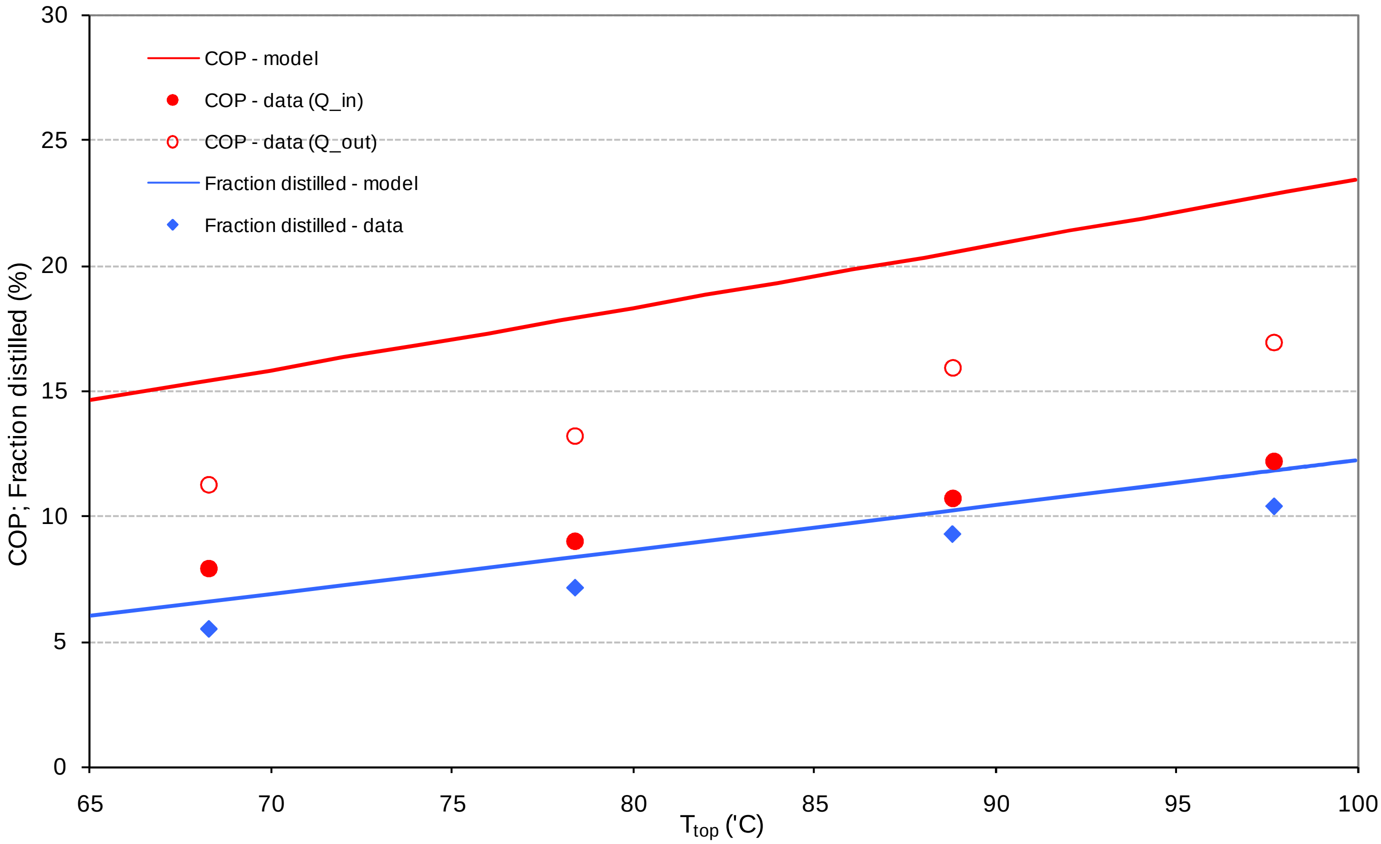

Figure 2 – Laboratory Performance of 15-Plate DG Model

DG Projected Performance

As shown in Figure 2, a computer model of the DG process predicts moderately higher efficiency than measured. Based on operating experience with the small-scale DG prototype, the most likely source of this discrepancy is flow non-uniformities both within the plates of the DG prototype and on the wicks. Current work on a second prototype will greatly reduce these non-uniformities. Assuming that second prototype operates close to the predictions of the computer model, a larger scale DG system that produced one cubic meter of product per day is projected to have the following performance characteristics for its stack of plates:

	Mature System	Early System
COP	16	12
Stack Volume (m^3)	0.42	0.62
Flux (kg/m2-day)	13.7	13.0
Stack Weight (kg)	68	83

In the preceding table, the flux is the average rate product is produced per square meter of condensing surface. The weight in the preceding table mostly consists of the plastic extrusion that forms the plates.

The Market for Desalination

The cost reductions—both capital and operating—produced by the DG technology will give it a strong competitive advantage over thermal desalination technologies now on the market. These cost reductions follow primarily from (1) the conversion of expensive metal heat exchangers to plastic heat exchangers, (2) the elimination of vacuum vessels, and (3) the increase in plant thermal efficiency. Important cost reductions will also follow from (1) the reduced use of chemical pretreatment, (2) the elimination of the need to deaerate the feed brine and (3) much lower pump powers.

Although the DG technology could eventually mature to a large-scale desalination plant that competes in the market for multi-million GPD water sources, market entry will occur in the same applications now targeted by Altela, Memsys, Solar Spring/Oryx and Mage. For these four start-up companies, targeted applications include wastewater treatment for oil/gas production sites and community-scale purification of seawater or brackish water in less developed or remote and island locations.

All four start-ups include solar desalination as an important market opportunity. The low-cost solar thermal collectors that are also described in this white paper would further expand the market for a DG desalination system in less developed and remote/island locations where electricity and fossil fuels are now very expensive.

Competing Solar Thermal Collectors

Many U.S. and European companies offer solar thermal collectors that use the dewar-type evacuated tube shown in Figure 3. A typical collector would have 20 to 30 tubes mounted on a frame. In current designs for solar collectors, each dewar-type tube has an internal copper heat exchanger running the length of the tube with an aluminum fin that transfers heat from the inner wall of the tube to the copper heat exchanger. A circulating loop of water or glycol collects the thermal energy that is supplied by each collector and delivers it to the application's load.

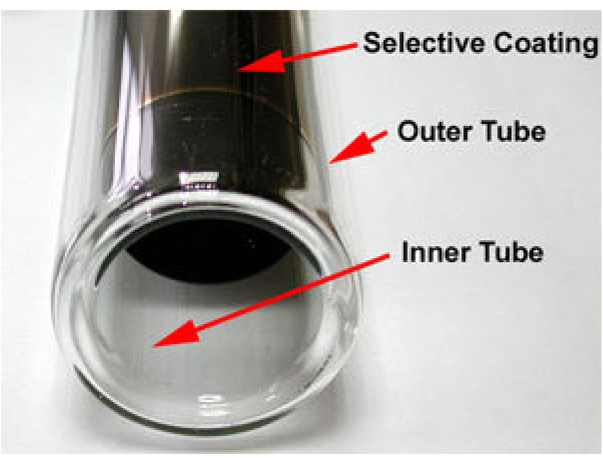

Figure 3 – Dewar-Type Solar Evacuated Tube

If one does not need SRCC certification, 30-tube solar thermal collectors can be purchased in volume from China for $398 per unit. This price is remarkably low considering that a typical installed cost for 30-tube solar thermal collectors that are part of large installations is closer to $1,800 per unit. (In this example the collectors are SRCC rated as required in most U.S. applications.)

However, despite what appear to be a very low wholesale price, the preceding solar collector captures only a minor share of the huge Chinese market for solar hot water. The dominant share of the market is controlled by a still less expensive solar thermal collector that also uses dewar-type evacuated tubes, but eliminates the internal copper/aluminum heat exchanger. As shown in Figure 4, these solar water heaters consist of an array of dewar-type evacuated tubes that are "plugged" directly into a hot-water storage tank. Water fills the central cavity of each dewar-type evacuated tube. During the day as the tubes heat up, hot water in the tube rises into the tank and is replaced by cooler water from the tank.

Figure 4 – Solar Collector with Integral Hot Water Storage Tank

In larger installation, the evacuated tubes "plug" into manifolds, 20 to 60 tubes per manifold, and water is circulated between several manifolds and a single storage tank. Since seals between the evacuated tubes and the manifolds will begin to leak at moderate pressures (i.e., above 5 psi), these solar collectors are described as "unpressurized". The manufacturer that quotes $398 for the wholesale price of a "pressurized" collector, quotes $114 for a 30-tube unpressurized solar collector.

However, the pressurized solar collectors now sold are relatively inefficient. At the end of the day, the hot water that fills the volume of each tube will cool. Even during sunny days, this loss of heat could be as large as 30% of the collected daytime solar energy.

AILR's Steam-Generating Solar Thermal Collectors

With almost no modifications to its design, the low-cost unpressurized solar collector can be converted to a collector with an efficiency equal to that of the more expensive pressurized solar collectors. The critical patented innovation[2] is to orient the tubes horizontally and then only partially fill the tubes with water. In this configuration, which is shown in Figure 5, steam quiescently evolves from the large free surface of the water within each tube when the tube is in the sun. The steam collected by several manifolds is supplied to a heat exchanger where the steam condenses providing thermal energy to the application's load. The condensed steam, which is still relatively hot, is stored in an insulated tank overnight and returned to the collector shortly before the sun begins to heat the collector the next morning. Since very little water remains in the collector at the end of the day, the nighttime heat loss is minimal. (In an alternative arrangement, all the hot water in a collector is pumped to an insulated storage tank at

[2] Lowenstein, "Solar Energy Collection," U.S. Patent No. 8,459,250, June 2013.

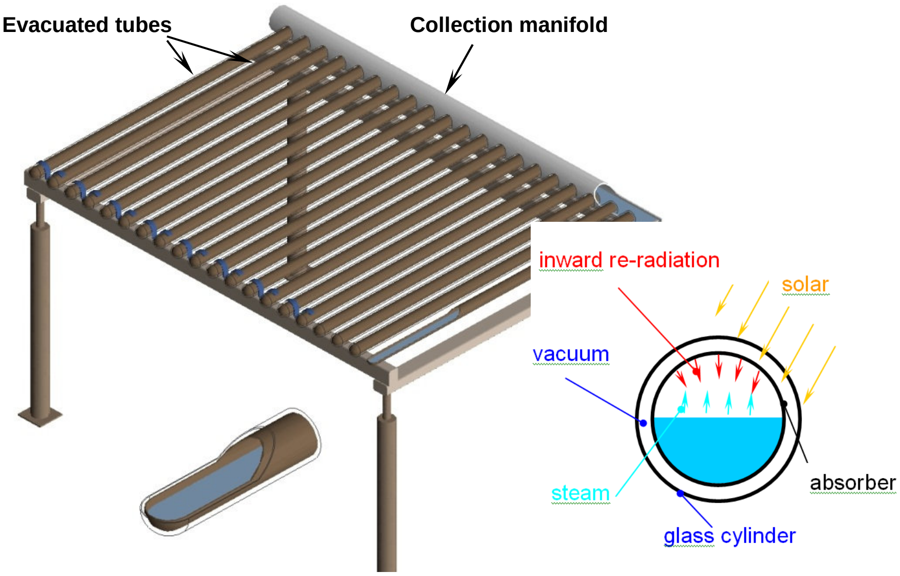

Figure 5 – A Steam-Generation Solar Collector

the end of the day, and returned to the collector the next morning. This draining of the collectors is possible because the tubes are horizontal.)

For solar thermal collectors that use dewar-type evacuated tubes, the following four factors strongly influence the efficiency for converting solar radiation into thermal energy:

- the absorptivity and emissivity of the inner cylinder (i.e., the absorber),
- the operating temperature of the inner cylinder,
- the orientation of the collector (or alternatively, the amount of solar radiation intercepted by the collector), and
- the thermal mass of the collector.

Dewar-type evacuated tubes all coat the vacuum-side of their inner cylinders with a "selective" surface that has a high absorptivity for short-wavelength radiation (i.e., the radiation that composes most of the solar spectrum) but a low emissivity for long-wavelength radiation (i.e., the infrared radiation that is emitted by hot surfaces). This coating maximizes the solar radiation that the tube absorbs while minimizing radiative heat losses. Since a steam-generating solar collector can use the same dewar-type evacuated tube as a conventional pressurized collector, the radiative properties of the absorber will not influence the comparative performance of these two types of collectors.

The dominant mechanism for heat loss from a solar thermal collector that uses dewar-type evacuated tubes is radiation from the hot inner cylinder (i.e., the tube's absorber). This radiative heat loss depends both on the radiative properties of the absorber (i.e., its "selective" surface) and temperature of the absorber. Since for a constant emissivity, radiative heat losses decrease as the fourth power of the absorber's absolute temperature, the conversion efficiency of a dewar-type evacuated tube increases as its absorber temperature decreases.

The fundamental characteristic of a steam-generating solar collector is that it supplies thermal energy at a temperature close to that of saturated steam at a pressure equal to ambient. For applications near sea level, this supply temperature is 212^{o}F. Although many applications, such as domestic hot water, do not require thermal energy at this high temperature, the need for storage will often raise the required supply temperature up towards the boiling point of water (i.e., the amount of thermal energy stored in an unpressurized tank will be at a maximum when the hot water is at 212^{o}F). Furthermore, thermally driven cooling systems such as absorption chillers and liquid-desiccant air conditioners operate more efficiently when supplied with high temperature hot water.

For heat to flow from the absorbers of the dewar-type evacuated tubes to the load, the temperature of the absorbers must be higher than the supply temperature required by the load.

For the steam-generating solar collector, the wetted surface of the inner cylinder has a wick that draws water up onto the entire surface. This keeps the absorber very close to the temperature of the supplied steam (i.e., 212^{o}F). For a conventional pressurized solar collector that uses dewar-type evacuated tubes, the absorber must be significantly hotter than the temperature of the supplied hot water so that heat is driven from the absorber, across an aluminum fin that contacts the absorber, across either a heat pipe or a pumped liquid loop, and into the supply hot water. As discussed in the following section, performance tests of the steam-generation solar collector at full sun indicated that the absorbers for the steam-generating solar collector are operating 40^{o}F cooler than a conventional solar thermal collector with dewar-type evacuated tubes that supplies hot water at 212^{o}F. The lower absorber temperature for the steam-generating solar collector reduces radiative heat loss and increases the collector's collection efficiency.

The amount of thermal energy supplied by a conventional solar thermal collector depends upon its orientation. If the collector is stationary, its orientation is typically fixed so that the amount of solar radiation that falls on the collector is maximum when the thermal energy is most needed (i.e., for a solar collector that provides thermal energy for space heating, the collector would be mounted at fairly steep angle so that it intercepted more solar radiation when the winter sun was low in the sky). However, the steam-generating solar collector must be mounted with the tubes horizontal. This horizontal orientation is close to ideal for applications that are either (1) in low latitude locations where the sun is high in the sky 365 days per year, or (2) where thermal energy is used to drive a cooling or dehumidification system during the summer when the sun is high in the sky even in mid-latitude locations. However, in mid-latitude locations that require heating in the cooler months of the year, the horizontal orientation of the steam-generating collector will penalize its performance.

The last of the four factors affecting the efficiency of a solar collector is its thermal mass. All collectors will cool towards the ambient temperature at night (or lower than ambient temperature if night skies are clear). In the early morning, the solar radiation falling on the collector must first heat the collector before the collector can deliver thermal energy at a useful temperature.

As previously noted, solar collectors with dewar-type evacuated tubes that are completely filled with water are severely penalized by the nighttime heat loss from the tubes. The heat-loss penalty for the steam-generating collector is greatly reduced by only partially filling the tubes with water and storing the condensed steam from the collector in an insulated tank overnight. Depending on the amount of water in the tubes at the end of the day (which could be close to zero if hot water is pumped out of the tubes before night), the steam-generating collector may have a larger or smaller nighttime heat loss than a conventional evacuated-tube collector.

Proof of the Steam-Generating Solar Collector

Steam-generating solar collectors were operated during the summers of 2009, 2010 and 2011 under R&D contracts from both the National Renewable Energy Laboratory and DOE's SBIR program. The largest array that was tested consisted of the four 20-tube panels shown in Figure 6.

Figure 6 – A Four Panel Array of Steam Generating Collectors

The field operation of the steam-generating solar collector over three years proved the efficient operation of the concept. Under all levels of solar insolation, the collectors operated as designed with steam quiescently evolving at the water free surface.

The measured performance of the steam-generating solar collector during field operation also confirmed that its performance could be predicted using an industry-accepted computer model (TRNSYS) by defining the steam-generating collector as a conventional evacuated-tube collector that operates with a lower temperature absorber. Figure 8 compares the measured performance of the steam-generating collector with the predictions of the TRNSYS model for a conventional evacuated-tube collector with an absorber temperature that has been reduced by 40^{o}F during full-sun conditions.

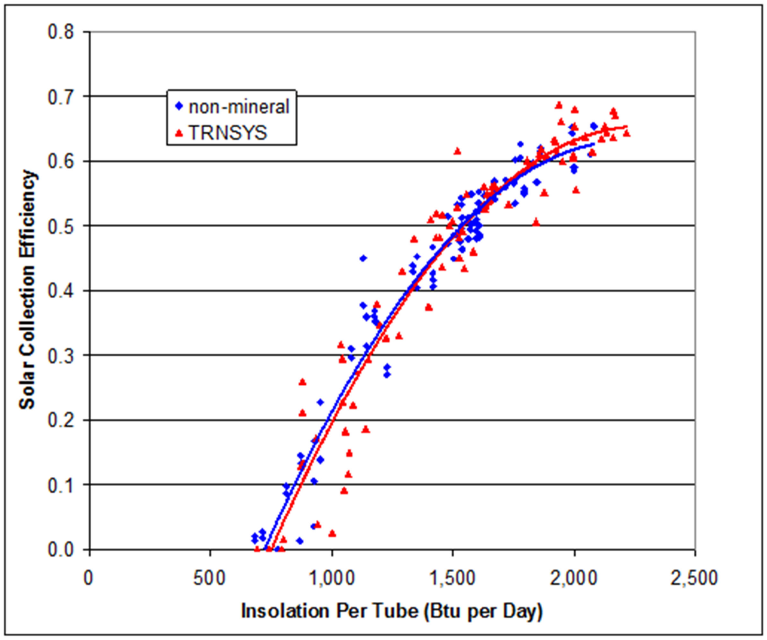

Figure 8 – Comparison of the Measured Performance of a Steam-Generating Collector and Computer Modeled Performance

The Market for Steam-Generating Solar Collectors

The thermal energies provided by arrays of steam-generating collectors and a conventional evacuated-tube collectors (115 panels each with 30 tubes) are compared in Table 1 for nine locations with latitudes that range from 13.55 degrees north to 43.87 degrees north. For this comparison, the tubes in both arrays are oriented north/south and the collectors in the conventional array are inclined at an angle that equals the latitude angle of their location.

Table 1

		Full Year (MMBtu)		Cooling Season (MMBtu)	
Location	Latitude	ET	SG	ET	SG
Guam	13.55	951	917		
San Juan	18.43	1,077	1,020		
Honolulu	21.33	1,124	1,039		
San Antonio	29.53	1,002	788	766	755
Houston	29.57	856	678	641	599
Atlanta	33.65	908	716	706	671
LaCrosse	43.87	646	461	432	426
Islip	40.78	710	508	586	503
Miami	25.80	985	761	710	709

Cooling season defined as March through October for all cities except LaCrosse where it is April through September

Both arrays provide thermal energy at 212^{o}F.

As shown in Table 1, in locations with a latitude less than 22 degrees, the array of steam-generating collectors supplies essentially the same amount of thermal energy as the array of conventional collectors. In higher latitude locations, the array of steam-generating collectors also comes close to supply the same amount of thermal energy as the array of conventional collectors if operation is limited to the cooling season.

In addition to its significantly lower capital cost, the steam-generating solar collector will be less expensive to install and operate because it does not require a pump to circulate hot water through the array.

Early entry markets for the steam-generating solar collector will be locations with good solar resources and high costs for fossil fuels and electricity. Using Honolulu as an example, an array of 115 steam-generating solar collectors each with 30 tubes provides 1,039 MMBtu of thermal energy per year. At $28.50 per MMBtu for propane in Hawaii and an 80% efficient water heater that converts the fossil energy into hot water, the array of steam-generating collectors is displacing propane that has a value of $37,000 per year. Assuming that purchasing decisions are made based on a three-year payback, the cost to the customer for the array of steam-generating collectors should be no more than $111,043.

A large array of steam-generating collectors installed on a flat roof can meet the three-year payback target (assuming a high utilization of the supplied thermal energy). For the preceding Honolulu example with an array of 115 collectors each with 30 tubes, the wholesale price from China for the collectors would be $13,110 (assuming the previously quoted price of $114 per collector). Allowing 20% for shipping from China, $100 per collector for frame and material required for installation, a 100% retail/installer combined mark-up on material, and two man-hours for installing each collector at $30 per hour produces an installed cost of $61,365. Depending on the application, a completed installation will have additional costs for storage, pumps, controls and system commissioning, but the total cost for the installation should still meet the three-year payback requirement.

Conclusion

The Diffusion-Gap Distillation System and the Steam-Generating Solar Collector are technologies that have the potential to meet pressing needs for thermal desalination and renewable energy far more competitively than the leading technologies now in the market. Both technologies have successfully passed critical proof-of-concept tests, but require more extensive field operation so that possible life-limiting effects can be uncovered. The fundamental simplicity and high performance of both technologies greatly increases the probability that they will meet the demanding cost constraints imposed on any new energy product that is to be broadly applied.