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Life cycle analysis of distributed concentrating solar combined heat and power: economics, global warming potential and water

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Abstract
We report on life cycle assessment (LCA) of the economics, global warming potential and water (both for desalination and water use in operation) for a distributed concentrating solar combined heat and power (DCS-CHP) system. Detailed simulation of system performance across 1020 sites in the US combined with a sensible cost allocation scheme informs this LCA. We forecast a levelized cost of \$0.25 kWh^{-1} electricity and \$0.03 kWh^{-1} thermal, for a system with a life cycle global warming potential of ~80 gCO_2eq kWh^{-1} of electricity and ~10 gCO_2eq kWh^{-1} thermal, sited in Oakland, California. On the basis of the economics shown for air cooling, and the fact that any combined heat and power system reduces the need for cooling while at the same time boosting the overall solar efficiency of the system, DCS-CHP compares favorably to other electric power generation systems in terms of minimization of water use in the maintenance and operation of the plant.

The outlook for water desalination coupled with distributed concentrating solar combined heat and power is less favorable. At a projected cost of \$1.40 m^{-3}, water desalination with DCS-CHP would be economical and practical only in areas where water is very scarce or moderately expensive, primarily available through the informal sector, and where contaminated or salt water is easily available as feed-water. It is also interesting to note that \$0.40–\$1.90 m^{-3} is the range of water prices in the developed world, so DCS-CHP desalination systems could also be an economical solution there under some conditions.

Keywords: desalination, solar thermal, solar CHP, combined heat and power, distributed generation, life cycle analysis, life cycle assessment

1. Introduction

Ultimately, the goal of this research project, of which this article is one part, is to develop an energy generation system that utilizes a renewable energy source (the sun) while working towards mitigation of global climate destabilization. To ensure this goal is achieved the following three steps are necessary: (1) determine and utilize appropriate metrics for solar energy technology (2) establish and utilize methods for life cycle assessment (LCA) of emerging technologies (3) optimize the system based on the chosen metrics and LCA results.

To these ends, the first part of this paper is devoted to LCA economics and global warming potential (GWP) analysis of a proposed DCS-CHP system, and the latter part explores the water use and potential for water purification/desalination using DCS-CHP. For the purposes of life cycle analysis, the problem of joint production makes it difficult to allocate the relative costs of a CHP system to electrical and heat production (Wade 1999) so costs are divided using the methodology described in (Norwood *et al* 2010).

2. Life cycle assessment of a single solar dish collector DCS-CHP system

Performing a life cycle assessment (LCA) is a useful way of comparing the environmental impacts of different power generation systems. Here, a life cycle assessment is completed on a single solar dish collector Rankine combined heat and power system using the Industry Benchmark US Department of Commerce EIO model from 1997 (Hendrickson *et al* 1997). The global warming potential (GWP) per kWh of energy, the energy payback time (EPBT), the cost per installed peak watt, and the levelized cost of electrical and thermal energy are calculated. These results show DCS-CHP generates an estimated GWP of 80 gCO_2 equivalent greenhouse gases per kWh electricity, putting it below the competitive range with photovoltaics (PV), which range from 110 to 180 $gCO_2eq\ kWh^{-1}$ according to a couple recent studies (Stoppato 2008, Lenzen 2008). The EPBT for the DCS-CHP system, estimated at 27 months, makes it competitive with PV systems. The levelized cost of energy generated by the DCS-CHP system over its lifetime is estimated to be \$0.25 kWh^{-1} electric and \$0.03 kWh^{-1} of 100 °C heat, or \$3.20 W^{-1} electric and \$0.40 W^{-1} thermal in terms of installed capital cost per peak power output. The LCA of the system affirms that small scale solar combined heat and power systems can economically compete with other renewable energy systems and have comparable environmental footprints to PV systems.

2.1. Assumptions of LCA

The Industry Benchmark US Department of Commerce EIO model from 1997 adjusted for inflation, with the breakdown of selected sectors shown in table 1, provides a basis for this LCA.

The RawSolar prototype dish collector (RawSolar 2009), with the performance parameters specified in chapter 1 of Norwood (2011) for a dish collector, provides an estimate of collector efficiency. To get a realistic prediction of system generation we use the data for the Katrix rotary lobe expander from chapter 3 of the same reference, NREL typical meteorological year solar insolation data for Oakland, CA and the collector efficiency to run the DCS-CHP modeling software.

2.2. System generation prediction through simulation of a rotary lobe expander, dish collector DCS-CHP system

Prediction of system output of DCS-CHP is challenging due to the fact that the combined performance of the collector, turbine and steam accumulator are dependent on widely varying environmental conditions. Choosing components that interact well with each other requires advanced system modeling. The DCS-CHP simulation software developed for this task is able to model the performance of each component as they interact with the system as a whole, incorporating location-based insolation and weather data. Achieving direct steam generation in the receiver with varying levels of sunlight and potentially low-flow rates of steam will require a robust control scheme. The system should be optimized for not only peak times, but must respond well to intermittent clouds, low light levels, and periods of darkness. Throughout the design process, the primary metric for optimization has been full system life cycle cost and environmental analysis, considering materials, manufacturing, installation, operation and decommissioning.

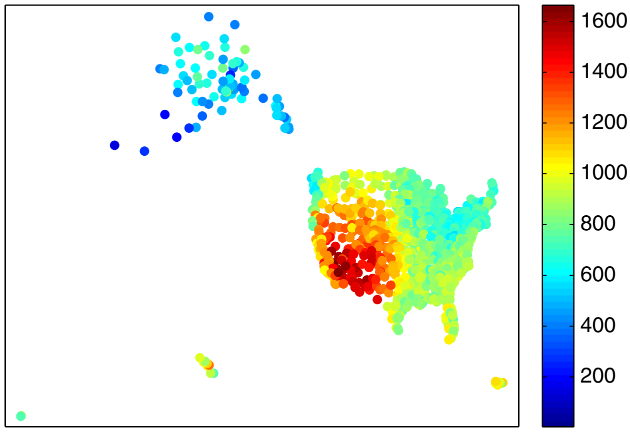

Figure 1. Katrix-Dish system yearly heat output (scale is kWh thermal per m^2 of collector aperture).

Figures 1–4 show expected output for a dish system with a steam Rankine cycle with a rotary lobe expander of 8:1 pressure ratio at all 1020 United States locations in the NREL TMY3 data. Electrical and heat data are plotted in units of kWh per square meter of collector aperture. For the purposes of performing the LCA, the specifics of this system, shown in figure 8, are chosen as realistic expectations for an actual installed system.

Simulation results of a typical meteorological year of operation in Oakland, CA are shown in table 2. Oakland was chosen because the total production is near the median of the range of locations modeled, and we had real contractor cost estimates for that location. Note that these results indicate such a system could simultaneously achieve 9% solar-electric efficiency and 58% solar-to-useful-heat efficiency at competitive costs to existing small scale dedicated solar-thermal or solar-electric systems. Because the same solar array would be used for each system, the total collector area would be reduced by about one half compared to separate PV and thermal systems providing the same output. To demonstrate this, consider that a 9% efficient solar-electric system (typical with thin-film panels currently) plus a 58% efficient solar-thermal system (flat-plate efficiency would actually be much less at the same 100 °C modeled for the DCS-CHP system) would take up exactly twice as much land area as the proposed solar CHP system. This higher land

Table 1. Cost estimates and EIO-LCA data for DCS-CHP system.

(a) Cost estimates, sector references and associated GWP (gCO2 equivalent) based on EIO-LCA for the RawSolar concentrating dish components

Dish components	Estimated price in 2009 $US	Sector/references in EIO-LCA database	GWP/component
Mirror	$254	333 314 optical instrument and lens manufacturing	8.2×10^4
Structure	$465		
Aluminum (tubing/rod)	$200	331 315 aluminum sheet, plate and foil manufacturing	3.0×10^5
Steel	$170	331111 iron and steel mills	3.5×10^5
Misc. (nuts, bolts, etc)	$35	332 722 bolt, nut screw, rivet and washer manufacturing	1.5×10^4
Paint	$60	325 510 paint and coating manufacturing	5.3×10^4
Tracking and sensing	$180		
Motors/actuators	$130	335 312 motor and generator manufacturing	6.3×10^4
Circuit board	$35	334 412 bare printed circuit board manufacturing	1.3×10^4
Sensor eyes	$15	334 513 industrial process variable instruments	3.7×10^3
Receiver piping	$60		
Receiver coating	$5	332 812 metal coating, engraving (except jewelry and silverware)	3.9×10^3
Steel coil and pipe	$25	331 210 iron and steel pipe and tube manufacturing from purchased steel	2.5×10^4
Insulation	$30	3261A0 foam product manufacturing	2.1×10^4
Manufacturing labor	$200	Weighted value	1.3×10^5
Miscellaneous parts	$100	33 291 metal valve manufacturing	3.9×10^4
Installation, labor/material	$1000	235 110 plumbing, heating and air-conditioning contractors/234 910 water, sewer and pipeline construction/235 610 roofing, siding and sheet metal contractors	5.2×10^5
Maintenance	$2500	230 340 other maintenance and repair construction	1.5×10^6
Total	$4759		3.1×10^6

(b) Cost estimates, sector references and associated GWP (gCO_2 equivalent) based on EIO-LCA for the other system components

Dish components	Estimated price in 2009 $US	Sector/references in EIO-LCA database	GWP/component
Structure	$65		
Misc (nuts, bolts, etc)	$35	332 722 bolt, nut, screw, rivet and washer manufacturing	1.5×10^4
Paint	$30	325 510 paint and coating manufacturing	2.6×10^4
System component	$1740		
Pump	$150	333 911: pump and pumping equipment manufacturing	6.3×10^4
Turbine	$990	333 611: turbine and turbine generator set units manufacturing	3.9×10^5
Alternator	$100	335 312: motor and generator manufacturing	4.8×10^4
Heat exchanger	$500	332 410: power boiler and heat exchanger manufacturing	2.6×10^5
Controllers	$100		
Pump controller	$100	333 911: pump and pumping equipment manufacturing	4.2×10^4
Piping	$150		
Steel coil and pipe	$100	331 210 iron and steel pipe and tube manufacturing from purchased steel	1.0×10^5
Insulation	$50	3261A0 foam product manufacturing	3.5×10^4
Miscellaneous parts	$100	33 291 metal valve manufacturing	3.9×10^4
Installation, labor/material	$2000	235 110 plumbing, heating and air-conditioning contractors/234 910 water, sewer and pipeline construction/235 610 roofing, siding and sheet metal contractors	1.0×10^6
Maintenance	$5000	235 110 plumbing, heating and air-conditioning contractors/234 910 water, sewer and pipeline construction/235 610 roofing, siding and sheet metal contractors	3.1×10^6
Total	$9155		5.1×10^6

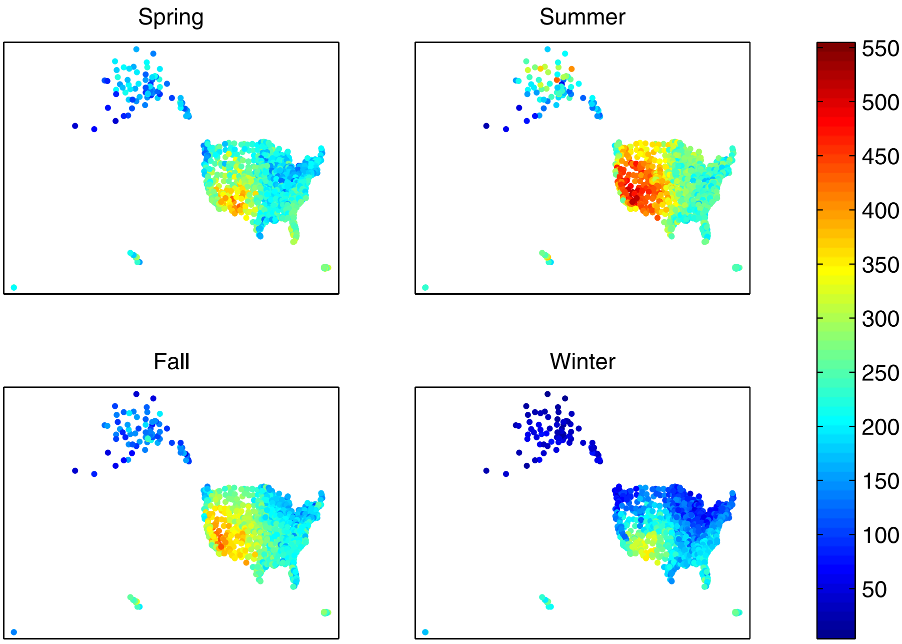

Figure 2. Katrix-Dish system seasonal heat output (scale is kWh thermal per m^2 of collector aperture).

Table 2. Results of the simulated output of the rotary lobe expander, dish collector system in Oakland, CA as used in the LCA analysis.

Parameter	Symbol	Value
Solar-heat efficiency	η_h	0.58
Solar-electric efficiency	η_e	0.09
Fraction of Carnot efficiency achieved in Rankine cycle	η_p	0.53
Total yearly heat generated (kWh m^{-2} collector aperture)	E_h	970
Total yearly electricity generated (kWh m^{-2} collector aperture)	E_e	150

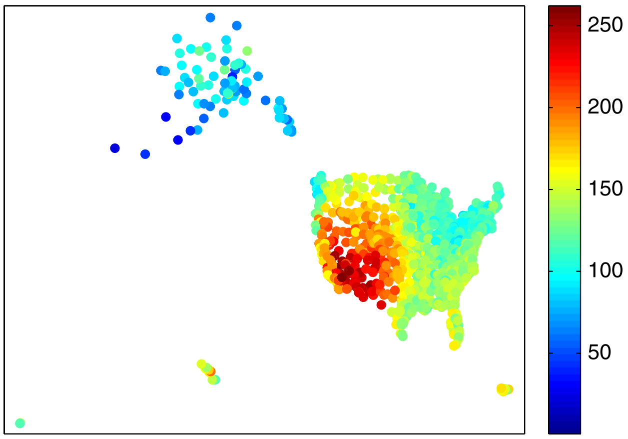

Figure 3. Katrix-Dish system yearly electrical output (scale is kWh electric per m^2 of collector aperture).

area density makes this technology suitable for urban and rural areas, especially if building integrated.

2.3. Cost allocation and levelized energy cost

Working from the cost estimate from RawSolar complete with bids for materials and labor (for installing the concentrating solar-thermal system in Richmond, CA) we add the necessary components for electricity generation to come up with a final system cost as broken down in table 1. Costs are allocated between electrical and heat generation according to the methodology described in Norwood *et al* (2010), and briefly outlined below.

The general idea of this cost allocation approach is to evaluate the output of the full solar CHP system if it was only producing heat, and compare that to how much heat is generated in CHP mode. Then, the cost of electricity generation includes the equipment specifically needed for electricity generation (Rankine expander, generator etc) and the fraction of the solar array equal to the decreased heat generation in CHP mode. The rest of the cost is assigned to heat generation.

First the dish collector efficiencies in CHP mode and heat-only mode (η_c and η_c^*, respectively) are calculated at reference solar insolation levels using the values in table 3.

$$\eta_c = E - \frac{A}{G}\left(\frac{T_{\text{inlet}} + T_{\text{outlet}}}{2} - T_a\right) - \frac{B}{G}\left(\frac{T_{\text{inlet}} + T_{\text{outlet}}}{2} - T_a\right)^2 \quad (1)$$

$$\eta_c^* = E - \frac{A}{G}\left(\frac{T_{\text{inlet}} + T^*_{\text{outlet}}}{2} - T_a\right) - \frac{B}{G}\left(\frac{T_{\text{inlet}} + T^*_{\text{outlet}}}{2} - T_a\right)^2. \quad (2)$$

Also needed is the overall Rankine cycle efficiency η_r which is a function of the Carnot efficiency η_0 (the maximum theoretical efficiency for any heat engine operating between a

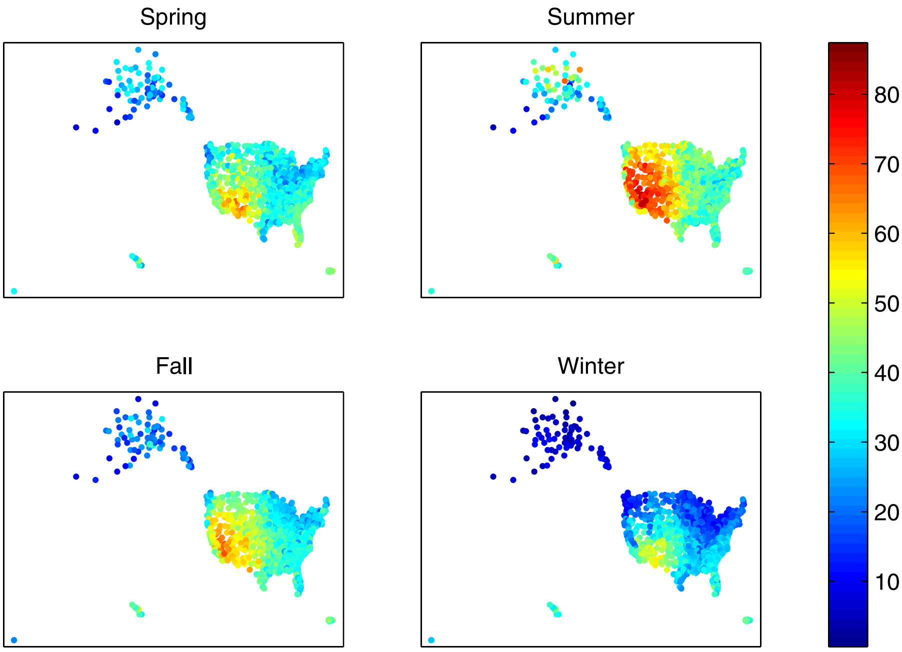

Figure 4. Katrix-Dish system seasonal electrical output (scale is kWh electric per m^2 of collector aperture).

high temperature source and low temperature sink) and the per cent of the Carnot efficiency the cycle is expected to achieve, η_p, from table 2.

$$\eta_r = \eta_p \eta_0 = \eta_p \left(1 - \frac{T_{inlet}}{T_{outlet}}\right). \quad (3)$$

From Norwood *et al* (2010) the fraction of the solar system allocated to the production of electricity F_e is then

$$F_e = 1 - \frac{P_t}{P_t^*} = \left(1 - \frac{(1-\eta_r)\,\eta_t \eta_c}{\eta_c^*}\right) \quad (4)$$

where P_t and P_t^* are the useful heat output of the system in CHP mode and heat-only mode respectively.

The result is 36% of the solar system cost allocated to electricity generation, plus the additional cost for the Rankine cycle electricity generation subsystem. A full spreadsheet with calculations for the cost allocation is downloadable at the URL in Norwood (2011).

Once the respective electrical and heat costs are disentangled, the simplified levelized energy cost LEC assuming fixed yearly operation and maintenance costs M over the lifetime of 25 years n, a 7% interest rate r, the initial capital costs I, and total energy produced per year E is (Appropedia 2011):

$$\text{LEC} = \frac{I(\frac{r}{1-(1+r)^{-n}}) + M}{E}. \quad (5)$$

2.4. LCA of economics and GWP results

The DCS-CHP system is estimated to produce ~80 gCO_2eq kWh^{-1} of electricity and ~10 gCO_2eq kWh^{-1} thermal assuming the 1997 mix of fuels reported in the US EIO database. This is much less than fossil fuel based power generation methods, which produce hundreds of gCO_2eq kWh^{-1}. In comparison to renewable energy technologies, according to Lenzen, the DCS-CHP system GWP is higher than that of wind turbines (21 gCO_2eq kWh^{-1}) and hydroelectricity (15 gCO_2eq kWh^{-1}) but lower than photovoltaics (106 gCO_2eq kWh^{-1}) (Lenzen 2008). Overall, the GWP contribution of the DCS-CHP system was split evenly between the dish components and the Rankine cycle components. Most of the GWP contribution comes from maintenance of the dish and Rankine cycle components as seen in figure 5(b). Considering the GWP of only the initial components, figure 5(a) shows that the dish structure and the Rankine expander contribute the majority of the GWP.

This analysis predicts a single dish collector system with peak capacity of ~1 kW electric would produce electricity for \$3.20 W^{-1} capital cost and a levelized cost of electricity of \$0.25 kWh^{-1}. The DCS-CHP system is additionally expected to produce useful heat energy with a peak capacity of ~5 kW (80% waste heat recovery factor) for a capital cost of \$0.40 W^{-1} or levelized cost of \$0.03 kWh^{-1}. Energy payback time (EPBT) for our system, including both electricity and heat production, is expected to be 27 months. To give some context: local residential electricity rates in the San Francisco Bay Area start at about \$0.14 kWh^{-1}, but increasing block tariffs can cause larger households to pay more than twice that rate. Heat energy is usually about one third the electricity price from fossil fuel sources.

3. Water and solar energy

The ties between water and solar energy are inextricable. The sun drives the giant distillation process called the hydrological cycle. Energy from sunlight evaporates water, 97% of which

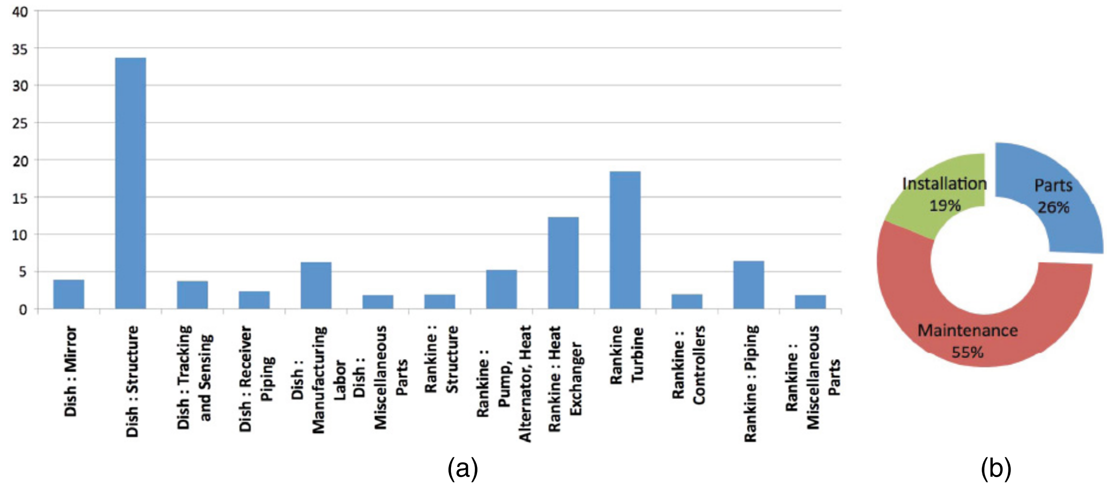

Figure 5. (a) Global warming potential of the components of a DCS-CHP system based on EIO-LCA analysis. (b) The relative GWP of the components (parts), installation and lifetime maintenance.

Table 3. Solar CHP system properties for thermal-electric allocation with dish collectors.

Parameter	Symbol	Value	Source
Temperature at outlet of collector in CHP mode (Rankine cycle high temperature)	T_{outlet}	523 K	Norwood *et al* (2010)
Temperature at inlet of collector in CHP and heat-only mode (Rankine cycle low temperature)	T_{inlet}	373 K	Condensing temperature of water
Temperature at outlet of collector in heat-only mode	T^{*}_{outlet}	382 K	
Ambient temperature	T_{a}	287 K	For Oakland, CA
Rankine cycle efficiency	η_{r}	15%	Equation (3)
Fraction of waste heat recovered	η_{t}	80%	
Collector efficiency in CHP mode	η_{c}	68%	Equation (1)
Collector efficiency in heat-only mode	η^{*}_{c}	73%	Equation (2)
Fraction of solar system for production of electricity	F_{e}	36%	Equation (4)
Dish collector parameters estimated from IST trough	E	76%	Kalogirou (2004)
	A	0.21	
	B	0.0017	
Standard reference insolation level	G	1000 W m^{-2}	

is saline, covering three-quarters of the Earth's surface, and transforms it into fresh water vapor, condenses it in the atmosphere in the form of clouds, transports it via wind, and delivers much of it to the land as rain where it fills our rivers, lakes and aquifers. Humans often replicate this cycle, which has been occurring endlessly for eons, albeit on a more modest scale. As early as 400 BC Aristotle wrote of distilling impure water to create potable water (Kalogirou 2005). More recently, humans have tapped the power of sunlight to create electricity, through a variety of processes including photovoltaic, and thermodynamic cycles named Brayton, Ericsson, Rankine and Stirling. These cycles are the means by which nearly all electricity on the planet is produced, and their predominant energy source is the combustion of fossil fuels. These same heat engines can be designed to instead harness solar energy as the fuel. The need undoubtedly exists to transition away from a predominantly fossil fuel driven society, and there is urgency in the 'developing' world to move in the direction that this name implies. The question remains: will that development path allow us to stabilize at the imperative 350 ppm carbon dioxide in the atmosphere outlined by Hansen *et al* (2008)?

Compounding the problem is that approx. 0.9 billion people lack access to safe drinking water, and 2.6 billion lack basic sanitation (WHO and UNICEF 2010). This is another area where solar energy and water exhibit synergy. Because all thermodynamic cycles must have a means of rejecting heat to a lower temperature sink, there is much thermal energy to be dissipated in concentrating solar power plants. Because these facilities are usually large and located far from an area where the heat could be used, this heat is usually dissipated into a body of water or, in cases where there is a scarcity of water, into the air. If instead these facilities were small and distributed so that they could be located near the demand for energy and potable water, in populated areas, then the otherwise wasted heat could also be used for the purpose of desalination or purifying water through a distillation process. Not only that, but rejected heat could be used for cooking, space heating, domestic hot water, etc. This would decrease the cost of electricity generation by providing cooling to the heat engine while, at the same time, producing another valuable co-product, potable water, from this distributed concentrating solar combined heat and power (DCS-CHP) system.

3.1. Background of solar–water nexus

Dublin principle number 4, the last principle in the Dublin Statement on Water and Sustainable Development arising out of the 1992 Earth Summit, states:

> 'Water has an economic value in all its competing uses and should be recognized as an economic good. Within this principle, it is vital to recognize first the basic right of all human beings to have access to clean water and sanitation at an affordable price. Past failure to recognize the economic value of water has led to wasteful and environmentally damaging uses of the resource. Managing water as an economic good is an important way of achieving efficient and equitable use, and of encouraging conservation and protection of water resources.'

So, given that water has an economic value, and it is inextricably tied to solar energy, what is the value of potable water in the developing world and what would be the cost of producing water as a byproduct of DCS-CHP described above? In answer to the first part of that question, UNESCO reports (UNESCO 2010) that water for domestic use ranges from a cent to over ten dollars per cubic meter in selected developing countries depending on whether the water is provided through the water utility (generally inexpensive) or the informal private sector (more expensive). To answer the second part of that question, in the next section we delve into the details of solar desalination in an effort to estimate its cost in this application. Finally, to complete the water and DCS-CHP story we consider the consumptive use of water in the electricity generation subsystem, and review available cooling methods through an analysis of current solar power plants.

3.2. Solar desalination and purification

Of the 3% of water on the planet that is fresh water, only 1/1000 of that is produced from desalination plants. Desalination systems are many and varied, however, numbering over 13 000 worldwide, most in the US and Middle East (El-Dessouky *et al* 2000, Gleick 1994). Although many types exist, distillation systems are generally divided into two categories: membrane systems and phase change systems (Kalogirou 2005). Of the membrane systems, reverse osmosis (RO) garners the most worldwide popularity, and multiple stage flash (MSF) distillation is the most common of the phase change processes followed by multiple effect boiling (MEB). Solar stills have historically been a popular system on the village and small scale, and are usually single-stage distillation where the energy from the evaporated water is typically not recovered thus leading to lower overall system efficiency. MSF systems tend to be larger (on the scale of 1000–100 000 m^3/day), but MEB systems have been designed in rugged varieties suitable to deployment in small villages under less controlled and less skilled operation (Kalogirou 1997, Thomas 1997). Looking at the energy required for each type of plant can help guide the selection of the technologically and economically optimum desalination system to run off the waste heat of a distributed concentrating

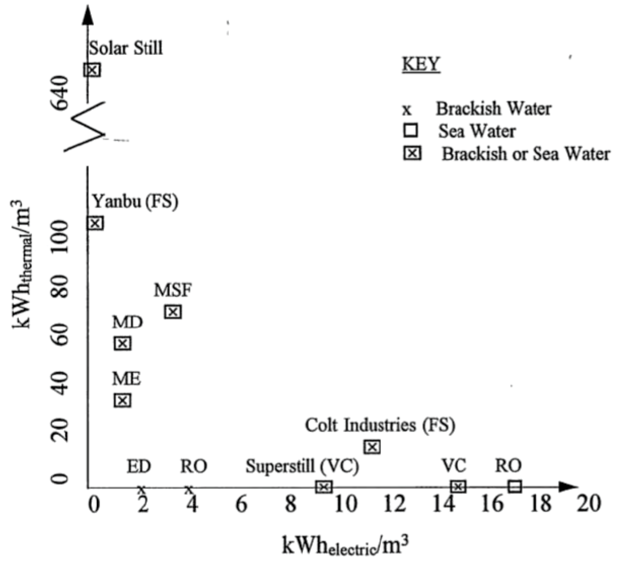

Figure 6. Thermal versus electrical energy demands of select desalination systems: freeze separation (FS), multiple effect boiling (ME), reverse osmosis (RO), vapor compression (VC), multiple stage flash distillation (MSF), electrodialysis (ED), membrane distillation (MD), and solar stills. This image has been reprinted with permission from National Renewable Energy Laboratory, 'Overview of village scale, renewable energy powered desalination', Karen E Thomas, April 1997, NREL/TP-440-22083, www.osti.gov/bridge/servlets/purl/463614-TjQD5Z/webviewable/463614.pdf.

solar combined heat and power system (DCS-CHP). Figure 6 shows the required energy for different desalination systems, and table 4 shows their comparative equipment costs.

It is interesting to note that membrane systems consume the least energy, yet all that energy must be mechanical work, making them an inappropriate technology to use with a system like DCS-CHP where thermal energy is abundant and thermal to electrical/mechanical energy conversion efficiency is low. The fact that the most abundant energy available from a DCS-CHP system is moderate grade heat (at around 370 K), rules out the use of vapor compression, reverse osmosis, and electrodialysis as the optimum choice for desalination. Of the remaining choices, it is important to look at the method of operation of the system to further narrow down the selection. Kalogirou has published several papers on the selection of optimal desalination systems for solar (Kalogirou 1997, 2005). He concludes that the MEB process with a multiple effect stacked (MES) evaporator is the most appropriate for solar, a schematic of which is shown in figure 7. An MES with a DCS-CHP system would function like this:

(i) Low pressure steam (generated from the condenser of the Rankine cycle) will enter into a tube array in the first effect as the feed-water is sprayed down from above.

(ii) The steam will condense while causing the feed-water (at lower pressure) to evaporate on the outside of the tubes. The condensate that forms inside the tubes will become part of the product water while the evaporate from the outside of the tubes will flow into the next effect.

(iii) The feed-water that does not evaporate drips down into a pool in the first effect and goes through a nozzle dropping

Table 4. Comparison of desalination plants; price is reported in capacity per day (Kalogirou 2005). (Note: low figures in equipment price refer to bigger size in the range indicated and vice versa.)

Item	MSF	MEB	VC	RO	Solar still
Scale of application	Medium-large	Small-medium	Small	Small-large	Small
Seawater treatment	Scale inhibitor antifoam chemical	Scale inhibitor	Scale inhibitor	Sterilize coagulant acid deoxidizer	—
Equipment price (Euro m^{-3})	950–1900	900–1700	1500–2500	900–2500 membrane replacement every 4–5 yr	800–1000

the pressure and falling onto the tubes of the second effect where the steam inside the tubes (the evaporate from the first effect) again causes vaporization of the now slightly more saturated feed-water solution.

(iv) This effect continues and at each stage the condensate coming from the tubes becomes part of the product until the last stage where the unheated feed-water loop condenses the last evaporate to add to the final product while the brine from the last stage is removed.

(v) At the same time steps 1–4 are occurring the feed-water is being heated sequentially, as it is piped up from the fourth effect to the first, gradually warming as it goes until it is sprayed onto the tubes of the first effect as described in step 1.

The choice of a MEB distillation system is synergistic with the DCS-CHP concept because the temperatures needed for a MEB are in the 340–370 K range, which exactly matches the condensation temperature for the steam Rankine system. Because MEB is an indirect solar distillation process (i.e. the sunlight would not be directly evaporating the water to be purified) the condenser will effectively act to transfer energy from the condensing working fluid of the Rankine subsystem to the feed-water of the desalination/purification system as illustrated in the system schematic of figure 8. Kalogirou surveyed dozens of solar MEB systems installed worldwide (Kalogirou 2005) and concluded the following benefits of MEB systems for solar desalination:

- Like any boiling process, MEB inherently removes salinity, manganese, fluoride, heavy metals, microbiological contamination and pesticide/herbicide residues.
- MEB is the least expensive of all indirect collection systems.
- MEB is robust in that it does not require highly trained operators to keep it running safely. There are no complicated additives to use, nor, as in RO, can misoperation cause damage to the membrane allowing contaminated water to be passed through.
- MEB is stable for varying energy supply from 0 to 100% of capacity, so it is uniquely suited for fluctuating solar insolation levels.
- Very small amounts of descaling agent can be used in seawater desalination as the system is effectively a once-through process, and the feed-water is at its lowest impurity concentrations at the highest temperature.
- The total cost of MEB with solar thermal is less than RO with photovoltaics because of the high cost of photovoltaic electricity.

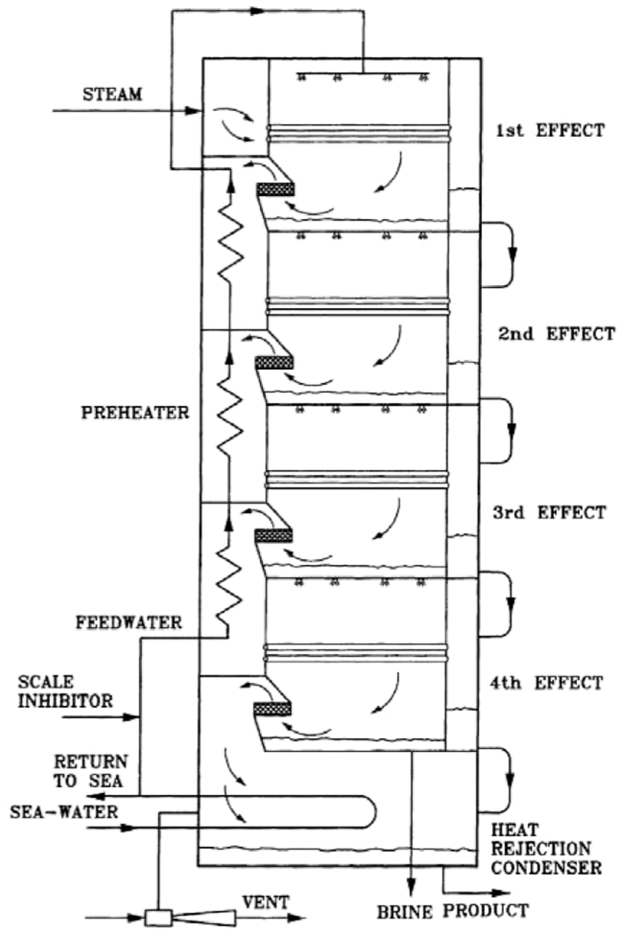

Figure 7. Schematic of MES evaporator. Reprinted from Kalogirou S A 2005 Seawater desalination using renewable energy sources *Prog. Energy Combust. Sci.* **31** 242–81, Copyright 2005, with permission from Elsevier.

- Improved energy efficiency is possible because the brine is not heated above its boiling point, leading to less irreversibility (i.e. less entropy generation).
- There is low electrical demand compared to other desalination technologies: no high pressure pumping losses as in RO, no MSF recirculation pumps, nor vapor compression, etc (see figure 6).
- Plant simplicity is promoted because fewer effects are needed for a given performance ratio.

Perhaps most importantly to the DCS-CHP desalination concept, Kalogirou agrees with Thomas in concluding that MEB is better suited for small applications than the other indirect solar distillation techniques (Kalogirou 2005, Thomas 1997).

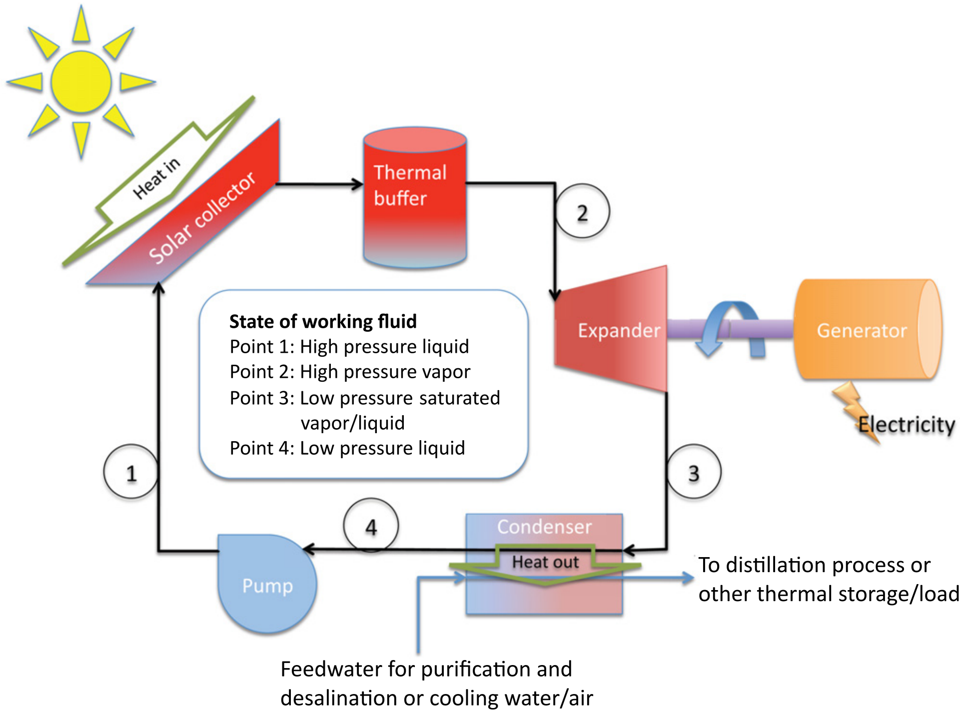

Figure 8. Distributed concentrating solar combined heat and power with desalination.

Table 5. Comparison of consumptive use of various power plant technologies using various cooling methods: *—annual energy output loss is relative to the most efficient cooling technique. **—added cost to produce the electricity. ***—majority of this amount is returned to the source but at an elevated temperature (USDOE 2009) .

Technology	Cooling	Gallons (MWh)	Perform penalty*	Cost penalty**
Coal/nuclear	Once-through	23 000–27 000***		
	Recirculating	400–750		
	Air cooling	50–65		
Natural gas	Recirculating	200		
Power tower	Recirculating	500–750		
	Combination hybrid parallel	90–250	1–3%	5%
	Air cooling	90	1.3%	
Parabolic trough	Combination hybrid parallel	100–450	1–4%	8%
	Air cooling	78	4.5–5%	2–9%
Dish/engine	Mirror washing	20		
Fresnel	Recirculating	1000		

3.3. Utilization of water in power system operation

In addition to the potential benefit of potable water as a co-product, a DCS-CHP system consumes (i.e. not returned to source) water in cleaning the concentrating collectors, for make-up water to replace water lost due to leaks, and in some cases for water cooling. To fully understand the relationship between water and solar energy this water needs to be considered. Table 5 shows the relative consumptive use of various power plant technologies. For a DCS-CHP system we assume water use comparable to a parabolic trough with air cooling since the optimal high temperature of the working fluid in parabolic trough collectors is in the right range (Kalogirou 2004), at approximately 500 K, and the thermal load effectively acts as a water cooling loop without the water consumption. In the case when there is no desalination or thermal loads to dissipate heat from the condenser an air cooling system is shown to have just a 2–9% cost penalty, but water consumption of just 0.3 m^3 MWh^{-1} as compared to recirculating water cooling of 3 m^3 MWh^{-1} (USDOE 2009). Of course, operating a DCS-CHP system with air or water cooling implies that there is not sufficient thermal load to absorb the energy rejected from the electric power generation subsystem. This in turn would lead to a higher cost of electric generation, and would decrease the economic value of the system. The least expensive energy produced by these small scale concentrating solar systems is indeed thermal energy. There is no question, as compared to coal, nuclear and natural gas, that even water-cooled concentrating solar power water consumption is on par with the best available technologies in the electric power sector.

3.4. Solar desalination economics

Thomas reviewed the costs of various desalination systems for the village scale and states that solar thermal MEB has a levelized cost of \$0.70–\$4.00 m^{-3} with the low end referenced to a capital cost of \$1000 m^{-3} of capacity on a daily basis (Thomas 1997). We would expect system cost to be in this range for a DCS-CHP system where the solar field cost is split between the electrical generation and the solar-thermal generation as described by Norwood *et al* (2010). With a predicted levelized solar-thermal cost of \$0.03 kWh^{-1}, this leads to a limiting estimate of the cost of a solar still at \$21 m^{-3} (based on the thermodynamic minimum energy, 2800 J g^{-1}, to evaporate water from ambient temperature). Since the multiple effect evaporator has about 1/15th the energy use of a solar still we would predict a cost of \$1.40 m^{-3} for an indirect solar MEB as described in this paper, which falls right in the range of Thomas. El-Dessouky cites the cost of a low temperature MEB at \$0.45 m^{-3} from fossil fuel sources (El-Dessouky *et al* 2000), or about one third the predicted cost from DCS-CHP with desalination of \$1.40 m^{-3}. This DCS-CHP desalination cost is only a rough first-order estimate, and would be at the high end of the household cost of water for selected Asian developing countries as presented by UNESCO (2010), but is competitive with the informal sector for about half of those countries.

4. Conclusions

The life cycle analysis presented in the first part of this paper affirms that a solar Rankine CHP system can be cost effective and directly competitive with other fossil and renewable energy production methods in small scale. The cost and environmental benefits of this system could be improved by further refinements in both trough and dish collector systems, and by continued development of a low-cost expander like the Katrix rotary lobe expander for use with steam as the working fluid. The results presented here predict levelized costs of \$0.25 kWh^{-1} electricity and \$0.03 kWh^{-1} thermal, for a system with a life cycle global warming potential of $\sim$80 $gCO_2eq\ kWh^{-1}$ of electricity and $\sim$10 $gCO_2eq\ kWh^{-1}$ thermal, sited in Oakland, California.

Based on the reasonable economics shown for air cooling, and the fact that any combined heat and power system reduces the need for cooling while at the same time boosting the overall solar efficiency of the system, DCS-CHP does rate among the best electric power generation systems in terms of minimization of water use in the maintenance and operation of the plant. Additionally, the LCA of the embodied water in the manufacture of a concentrating solar system, which uses primarily common metals and glass in simple manufacturing processes, promises to be insignificant, (on the order of 0.03 m^3 MWh^{-1}) even as compared to the modest water use in operation (Montgomery 2009).

The outlook for water desalination coupled with distributed concentrating solar combined heat and power is less favorable. Based on the economics described in the last section, water desalination with DCS-CHP would be economical and practical only in areas where water is very scarce or moderately expensive, primarily available through the informal sector, and where contaminated, or salt water is easily available as feed-water. Additionally, the cost of fossil fuels would have to be greater than DCS-CHP solar energy for the economics to favor solar desalination. It is also interesting to note that \$0.40–\$1.90 m^{-3} is the range of water prices in the developed world (UNESCO 2010), so DCS-CHP desalination systems, at a predicted cost \$1.40 m^{-3}, would be an economical solution there under some conditions. Of course, in most developed countries the most cost effective option to meet water scarcity problems is to increase water end-use efficiency and forgo energy-intensive supply side augmentation such as desalination.

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