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Full-energy-chain analysis of greenhouse gas emissions for solar thermal electric power generation systems

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Abstract

Technical attributes and environmental impacts of solar thermal options for centralised electricity generation are discussed. In particular, the full-energy-chain, including embodied energy and energy production, is considered in relation to greenhouse gas emission arising from solar thermal electricity generation. Central receiver, parabolic dish, parabolic trough and solar pond systems are considered.

1. Introduction

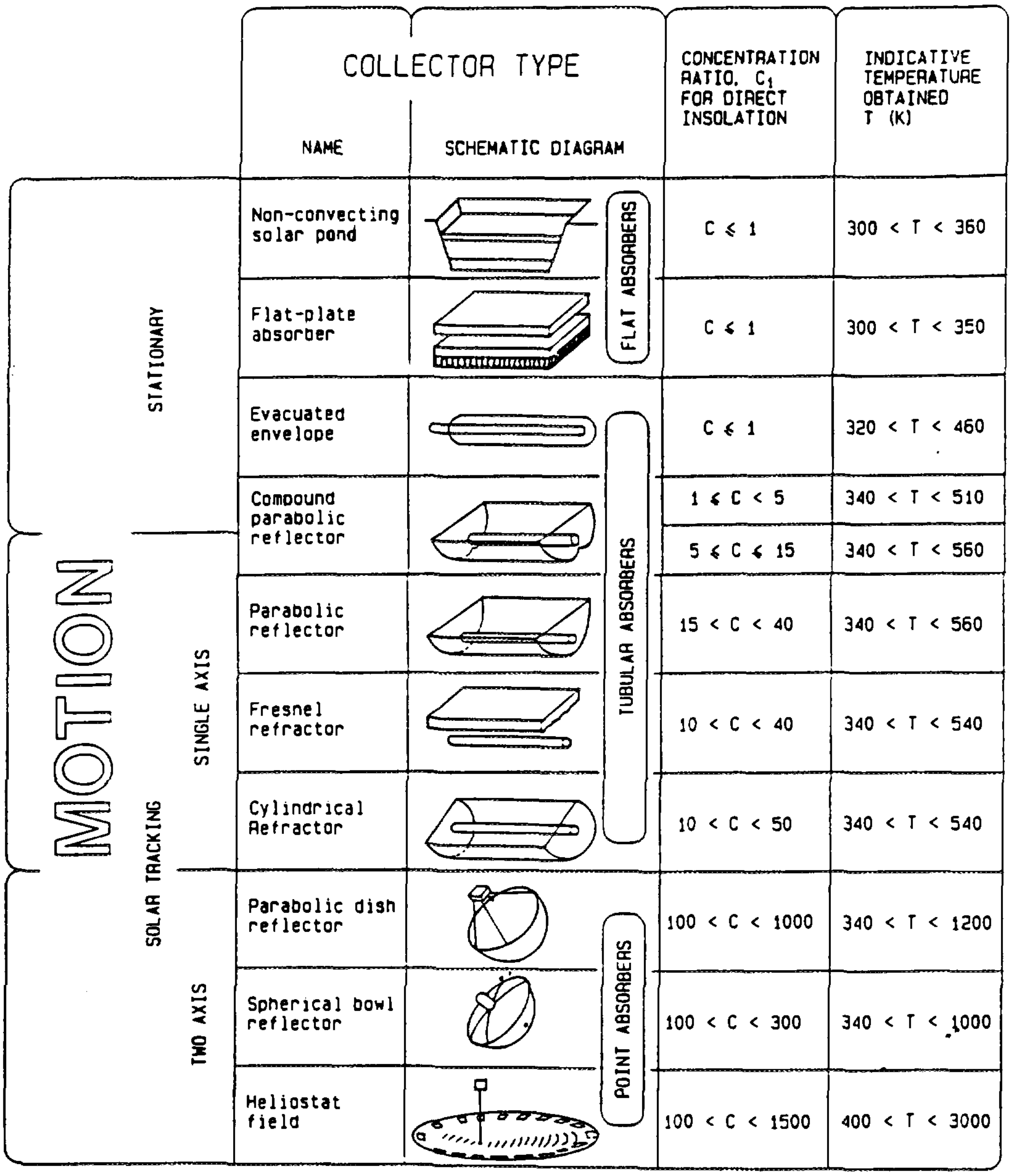
That there is discernable human influence on global climate has been accepted by governments as authoritative [IPCE, 1996] and necessitating more intensive international action to reduce greenhouse gas emissions. The competing technologies that may contribute to this goal need considered from the fullest perspective if decision makers are to be informed correctly and formal policy analysis tools [see for example Hope et al, 1993] applied validity. As a contribution to developing a sound technical base on which policy can be built, the technical attributes and environmental impacts of solar thermal options for centralised electricity generation are discussed. In particular, the full-energy-chain, including embodied energy and energy production, is considered in relation to greenhouse gas emissions arising from solar thermal electricity generation via central receiver, parabolic dish, parabolic trough and solar pond technologies.

2. Solar Electricity Generation Options

Demonstrated technologies for large-scale generation of electricity from solar energy are:

(i) central receivers, consisting of solar reflector heliostats that focus energy to a receiver mounted on a tower
(ii) parabolic dishes that remain focused on the sun with the aid of tracking devices. Each dish concentrates the suns rays to their central point
(iii) parabolic troughs which focus insolation onto a tubular absorber
(iv) non-convecting solar ponds which provide integral solar energy collection and medium temperature energy storage.
(v) photovoltaics which convert solar energy to electricity directly.

This paper considers issues related to the full-energy-chain analysis of greenhouse gas emissions for the first four solar thermal options listed. Their context in the broad range of solar thermal collectors is shown in Figure 1[Norton, 1992]. Solar thermal electric systems first convert solar heat energy into mechanical energy in a turbine or engine, then into electricity using a conventional generator. Solar thermal electric plants generally consist of a solar collector field, power generator and ancillary working fluid and electrical distribution systems. Since the amount of energy harnessed depends on the insolation, performance is location dependent. Broad projections of the performance of current and next generation technologies are provided in Figure 2.



Motion		Collector type: Name	Absorber	Concentration ratio, C_1 for direct insolation	Indicative temperature obtained T (K)
Stationary		Non-convecting solar pond	Flat absorbers	$C \leqslant 1$	$300 < T < 360$
Stationary		Flat-plate absorber	Flat absorbers	$C \leqslant 1$	$300 < T < 350$
Stationary		Evacuated envelope	Tubular absorbers	$C \leqslant 1$	$320 < T < 460$
Stationary		Compound parabolic reflector	Tubular absorbers	$1 \leqslant C < 5$	$340 < T < 510$
Solar tracking	Single axis	Compound parabolic reflector	Tubular absorbers	$5 \leqslant C \leqslant 15$	$340 < T < 560$
Solar tracking	Single axis	Parabolic reflector	Tubular absorbers	$15 < C < 40$	$340 < T < 560$
Solar tracking	Single axis	Fresnel refractor	Tubular absorbers	$10 < C < 40$	$340 < T < 540$
Solar tracking	Single axis	Cylindrical Refractor	Tubular absorbers	$10 < C < 50$	$340 < T < 540$
Solar tracking	Two axis	Parabolic dish reflector	Point absorbers	$100 < C < 1000$	$340 < T < 1200$
Solar tracking	Two axis	Spherical bowl reflector	Point absorbers	$100 < C < 300$	$340 < T < 1000$
Solar tracking	Two axis	Heliostat field	Point absorbers	$100 < C < 1500$	$400 < T < 3000$

FIGURE 1

SOLAR ENERGY THERMAL COLLECTORS

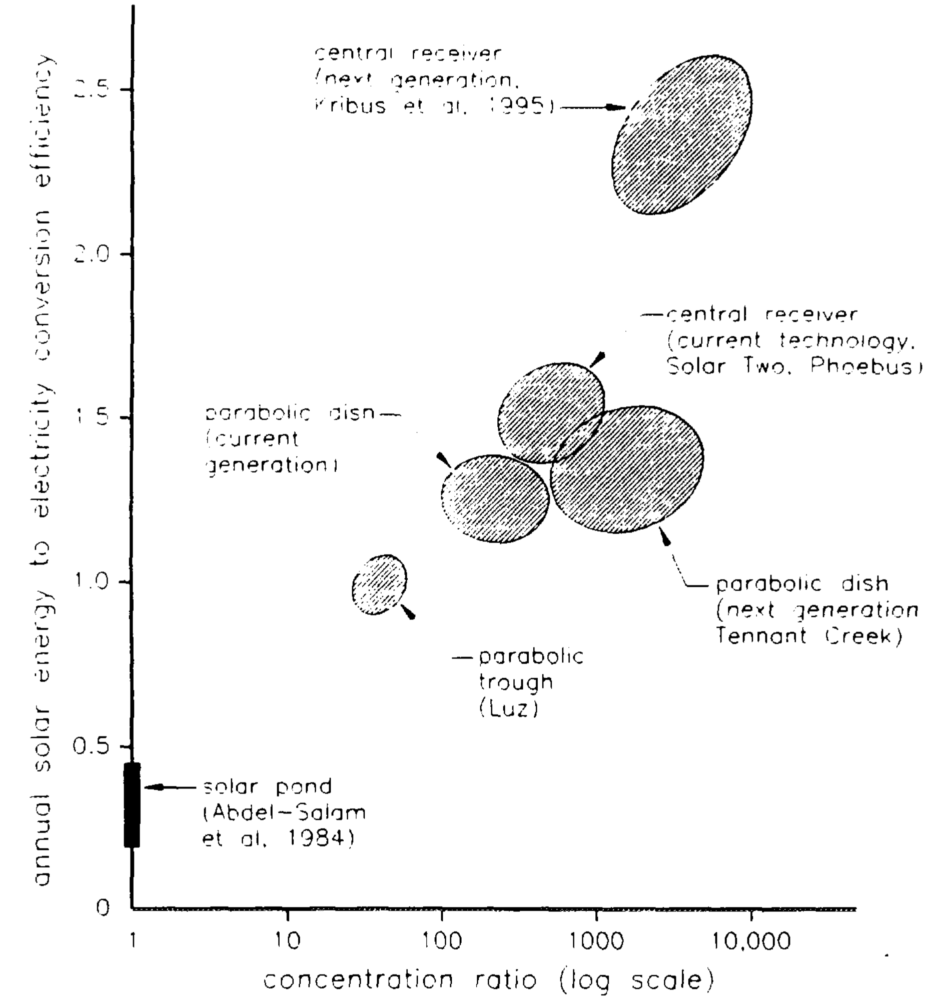


FIGURE 2

ANNUAL AVERAGE EFFICIENCY OF SOLAR THERMAL ELECTRIC OPTIONS

Previous research has compared photovoltaic with fossil fuel, nuclear, wind (see, for example, Schaefer and Hagedorn, 1992) and hydro electricity generation. Non-fossil options incur most energy and materials consumption prior to operation. For fossil fuels most energy is used in operation. Taking into account full-energy chain life-cycle analysis: coal, oil and gas systems emit respectively 270, 190 and 180 grams of carbon as carbon dioxide per kWh generated. Hydro, nuclear and photovoltaics emit respectively 5, 6 and 35 grams of carbon per kWh [Uchiyama, 1995]. However such estimates are subject to debate; for example, current carbon dioxide emissions for hydropower do not include those from rotting vegetation in dam reservoirs. It is envisaged that technical advances and process improvements will reduce greenhouse gas emissions associated with electricity generation; a gas combined cycle emits 140 grams of carbon per kWh compared to 190 g/kWh with current gas fired stations. Advanced nuclear reactors with closed fuel cycle may emit under 3 grams of carbon per kWh compared to 6 g/kWh with current nuclear technology. Photovoltaic systems, using amorphous silicon, for example, will emit 8 grams of carbon per kWh compared with the 35 g/kWh of photovoltaic power plants now [Uchiyama, 1995, Hirschberg, 1995].

3. Environmental Impact

Hazards from hot viscous fluids, focussed insolation and pollution of water resources are associated with solar thermal electric plants. Normally air pollution is minimal. There is little waste to be disposed of, however inadvertant discharge of hydrocarbons, oils, corrosion inhibitors, bactericides and glycols could threaten health (via ingestion or skin contact) and water resources. The land area, about 0.4 ha/MW, required for a solar thermal electric plant is similar to conventionally-fuelled electricity generaton due to the large area associated with collector systems and associated generating plant, ancillary and office buildings, through landscaping and siting away from residential areas may relieve visual impact. Ecological impacts can include loss of and/or changes to natural habitats and, for very large systems, microclimatic changes due to local heat balance changes [OECD, 1988]. Most sites considered currently for solar thermal electric systems are located in arid deserts. Though there is little human habitation, there exist fragile ecologies which require assessment to ensure siting minimizes impact. Planning, construction and operation must be cognizant of the high soil erosion and habitat loss potential. Disruption due to construction traffic is less than for fossil fuel or nuclear plants as construction is more rapid. As light accidentally focussed off-axis may cause eyesight injuries, insolation must not be reflected at houses, offices and roads and those nearby must wear appropriate eye protection. Secondary uses for land, however, such as cattle, sheep or goats grazing where grass can grow between the collectors remains practicable. Noise associated with solar thermal facilities from fans, pumps, turbines and cooling towers is similar to that of a steam generating plant. However, with the exception of heat-storing solar ponds and, to a certain extent, molten salt storage systems, noise would only be generated during the day because at night the plant will be unable to operate. Solar thermal electric generation options do not pose radioactive waste materials disposal problems nor the major ecological and social impacts of the valley-flooding associated with hydropower.

The evaluation of solar energy technologies from an ecological point of view requires assessment of the full-energy chain arising from the entire manufacturing process [Baechler and Lee, 1991]. However, due to the wide variety of solar systems and the methodological complications of the assessment procedure, there is considerable divergence of opinion as to the level of environmental damage caused by solar technologies. Some estimates indicate that the environmental impact afforded by solar systems is far greater than the one attributed to technologies using fossil or nuclear fuels [Bezdek, 1993]. Ecological evaluations are also broader than consideration of energy and CO_2 emissions and may include qualitative as well as quantitative components which cannot be readily summed. In general, solar energy technologies require larger areas of land on which the environmental impacts are less intensive compared to that required for conventional fossil or nuclear energy technologies. The nature of the impacts may be visual rather than physical and not insignificantly, they may be much more readily reversed if necessary in the future.

The four fundamental principles underlying sustainable development, futurity, equity, public participation and environment [Mitchell et al 1995] may be more readily achieved with solar energy technologies than technologies using fossil or nuclear fuels.

The fuel cycles of conventional energy production (eg coal, nuclear) incur significant environmental impacts apart from the emission of CO_2. For example, a 1000 MW nuclear power plant consumes only 36 tonnes of processed and enriched uranium fuel, but this necessitates the minimum of $85.5x10^3$ tonnes of ore per year which produces toxic tailings containing arsenic, cadmium and mercury as well as radionuclides. Conversion to enriched uranium fuel necessitates processing with fluorides, again generating large quantities of toxic wastes [Masters, 1991]. For coal powered plant approximately one hundred times as much coal ($94.5x10^5$ tonnes per year) is required to produce the same quantity of electricity. The mining and processing of this fuel has impacts which will differ depending on the type of mining employed. Underground mines may have relatively low visual impact but lasting effects on ground stability and water tables, while open cut mines have severe visual impact as well as other lasting environmental impacts. Clearly, with solar energy technologies such fuel cycles are eliminated as well as the associated environmental impacts.

4. Technologies

The operation and efficiency of a solar thermal electric system depends upon:

- details of the technical specification and mode of operation;
- the materials used for the system (eg quality and durability of reflectors [Jorgenson, 1993]); and
- the incident insolation

When compared to fossil electricity generation systems, solar thermal electric is characterised by a greater share of total environmental impact attributable to fabrication and installation compared to the operation phase.

4.1 Parabolic Trough

Parabolic troughs have found application in a full range of solar heating and cooling applications (see, for example, Eames & Norton 1993a, 1993b and Prapas et al 1987). Solar thermal electricity generation relies on the collection of solar heat at temperatures sufficiently high to produce electricity generation using a heat engine. Although small plants appeared early in the 20th century in the USA and Egypt, the use of these on a large scale was delayed until the last decade by inexpensive fossil fuel generation. Reliable solar thermal electricity generation using parabolic troughs has been demonstrated commercially. The world's largest solar power plant, the Luz Solar Electric Generating System has operated in California. About 2,500,000 m^2 collectors generated 354 MW of electricity. Once accounting for more than 95% of the world's solar power production, this group of installations was larger than the 1990 global installed photovoltaic electricity generation. The cost of electricity produced, at $US0.08 per kWh(e), was also lower than photovoltaics. It has been anticipated that the next major improvement in this technology would result in electricity generation costs of 5.5 cents per kilowatt-hour in areas of high solar insolation. This is less than both the projected cost of electricity generated from "clean coal" technology and the 8 kWh US Department of Energy threshold for likely growth in the use of solar photovoltaic technology. Current commercial solar thermal electricity generation uses collectors which comprise an evacuated-annulus receiver consisting of an inner stainless steel tube mounted in a concentric evacuated cylindrical glass envelope, which serves to minimize convective and conductive losses. Relatively large-diameter absorber tubes are necessary to facilitate adequate flow rates and pressures for the heat transfer fluid. To limit radiative losses, the outer surface of the inner steel tube is coated with selective surface with an emittance of about 0.17. High concentration ratios of more than 25 remain necessary, which requires reflector apertures about 80 times the tubular absorber diameter. For a representative example of current technology each collector has an aperture area of 545 square metres and uses 224 glass mirror segments. An 80 MW(e) plant utilizes nearly 900 such collectors.

A north-south axis orientation has been used in Californian installations to give the summer bias to annual electricity production which is needed by a summer-peaking electricity utilities. On an annual basis, north-south tracking delivers less solar radiation than a two-axis tracking configuration so the reflector is large to compensate for this.

4.2 Central Receiver

Central receiver technology, such as the Solar One 10 MW(e) station in the United States, and the more recent Solar Two and Phoebus plants use a distributed field of planar reflectors called heliostats to reflect solar radiation at high concentration upon a central receiver. With molten salt energy storage, as in Solar Two, it potentially it offers high levels of availability at night. The 10 MW Solar Two molten salt storage power tower effort will demonstrate the technical and economic performance of this technology from 1996-1998.

A 3MW heat central receiver facility has been operating at the Weizmann Institute in Israel for research purposes since 1988. An heliostat field provides a primary concentration ratio of 1000-2000.

4.3 Parabolic Dish

Two-axis tracking collectors such as point focus paraboloidal dishes achieve much higher solar radiation concentration than single-axis troughs, exhibit low heat losses and face incident insolation directly at all times [Noyes, 1990]. They can collect over 25% more energy per unit of collector area than parabolic troughs.

At Tennant Creek in Australia, parabolic dish technology provides 2 MW electric input from solar thermal. If the plant proves successful in its demonstration phase, there are plans to build a series of prototype installations to demonstrate the commercial viability of high temperature solar thermal power generation technology. Though have been reasonably large scale solar thermal projects using both heliostats and parabolic trough technology, there have not been any significant attempts to build a plant of any reasonable size utilising parabolic dishes before the Tennant Creek solar thermal project. The plant will utilise a steam turbine with a net electrical output of 4 MW, with 2 MW of solar contribution. The parabolic dish to be used has a nominal 25 metre diameter. The main benefits of the parabolic dish to be used for the project are space frame construction giving low cost per square metre mirror area compared with central receivers and troughs and the direct production at the dish of superheated steam.

TABLE 1
TENNANT CREEK DEMONSTRATION PLANT OUTLINE TECHNICAL SPECIFICATIONS

Parabolic Dish	
Area:	400 m^2
Diameter:	25 metres
Energy rating:	approximately 300 kW thermal at 1000 W/m^2 insolation
Steam Turbine	
Gross electrical output:	4.4 MW
Net electrical output	4MW
Solar contribution:	approx 2 MW
Steam inlet conditions:	42.4 bar abs, 454 °C
Steam flow at rated output:	18930 kg/hour
Generator:	11 kV at 0.8 power factor, 3 phase

Much research is underway, in the USA and Germany in particular on dish technology. This work aims to reduce cost and materials content and improve overall efficiency. Stretched-membrane concentrators could cost as much as 40% less than today's solar concentrator designs based on glass mirrors. A stretched-membrane dish concentrator [Mancini, 1991] uses an optical surface of aluminized polyester film. Such a concentrator can produce a concentration ratio of about 5,200. Research has also quantified the effect of operation and maintenance on the life-cycle costs of the Stirling Engines employed in dish systems [Stone et al, 1994].

4.4 Solar Ponds

Solar ponds have a one to two metre salinity gradient which stops the process of water convecting when heated. Large quantities of salt dissolved in the hot lower layer of the pond render it too dense to rise to the surface and cool. There are three main layers; the top layer is cold and has relatively little salt content, the bottom layer is hot - up to 100°C and has a 20% salt concentration, there are separated by a non-convecting layer of increasing salt concentration. During the winter of 1987 the surface of the El Paso, USA, Solar Pond was frozen while 2.3m below the ice the temperature remained at 70°C - hot enough to generate electricity with an organic Rankine cycle engine.

The upper-convecting zone (UCZ), of almost constant low salinity at close to ambient temperature is typically 0.3m thick results from evaporation; wind-induced mixing and surface flushing. Wave-suppressing surface meshes and placing windbreaks near the pond keep the UCZ as thin as possible. The non-convecting zone (NCZ), in which both salinity and temperature increase with depth inhibits convection and thus provides the thermal insulation. The lower-convecting zone (LCZ), of almost constant, relatively high salinity (typically 20% by weight) at a high temperature. Heat is stored in the LCZ which is sized either to supply energy continuously throughout the year for power generation or provide interseasonal heat storage for space heating. As the depth increases, the thermal capacity increases and annual variations of temperature decreases. However, large depths increase the initial capital outlay and require longer start-up times.

Salt gradient lakes, which exhibit an increase in temperature with depth have occurred naturally in Transylvania, in California and Washington State, USA, in the Arctic, Venesuela, western Uganda, and on the east coast of the Sinai Peninsula. If the eight largest natural saline lakes were converted to salinity gradient solar lakes for electric power production, the output would be approximately 100,000 MWof base-load capacity. The technology is, however, not ready for implementation on this scale. Barriers to the implementation of solar ponds include the lack of demonstration of reliable and easy-to-use solar pond lining and operating systems and a mismatch between suitable sites and either local loads or ready access to grid distribution. For areas (such as the southwest USA) with salt resources, brackish water, and natural salt lakes, solar ponds are a significant potential resource.

The application of solar ponds for electric-power production usually employs an organic vapour Rankine cycle engine to convert solar-pond heat to mechanical work, and then into electricity. To obtain a low cost per unit generated power, solar ponds of several square kilometres are required. Significant economies of scale are associated with salinity-gradient solar ponds arising from savings in excavation, lining, salt and power generation equipment costs. Low-cost ponds of $10^4 m^2$ or larger have been estimated to produce medium-grade, thermal energy at costs competitive with the current price of delivered heat from natural gas and significantly below that for oil. The site for a solar pond should be near a cheap source of salt, an adequate source of water, incur low land costs, and experience an all-year solar exposure. The pond must not pollute aquifers nor lose heat via underground water streams passing through an aquifer. Any continuous drain of heat will lower the pond's storage capability and effectiveness. Stormy regions should be avoided in order to limit wind surface mixing effects.

Species of freshwater and saltwater algae grow under the conditions of temperature and salt concentration that exist in a stratified solar pond. Algae and cyanobacteria growth will inhibit solar transmittance and, for the latter, possibly, be toxic too. Different algae and cyanobacteria species are introduced by rain water and airborne dust. To prevent algae formation, copper sulphate has been added at a concentration of about 1.5 mg l^{-1} [Abdel-Salam et al, 1984].

A solar pond will cease to function without maintenance of the vertical salt gradient stratification. The stability of the salt gradient is maintained by controlling the overall salinity difference between the two convecting layers inhibiting internal convection currents if they tend to form in the NCZ and limiting the growth of the UCZ.

A Solar Pond Power Plant (up to 5 MW in 1984) was built in Beit Ha' Arava at the northern end of the Dead Sea in Israel. The low temperature heat from the solar pond operated on Organic Rankine Cycle vapour turbine. The plant is not in operation, as the running cost made the electricity higher than the prevailing electricity price.

5. Material requirements

The material requirements of the typical system presented in Table 2, refer to the materials used for mirror construction essentially of aluminium and small quantities of coating and welding materials. As a reference point, an example of full energy chain emissions calculated for solar domestic hot water systems in terms of materials content (rather than energy production) [CEC, 1995] are provided in Table 3. As with many such inventories, their present status is more a position in an on-going debate rather than a definitive statement. For example the figure for copper SO_2 emissions in Table 3 may be too low; copper ones are sulphides, of which a large amount has to be processed to their 0.5-2% copper.

TABLE 2

TOTAL MATERIAL REQUIREMENTS OF A TYPICAL ALUMINIUM REFLECTOR

Material	Weight (kg m^{-2})
Aluminium	3.2
Welding material	0.4

TABLE 3

EMISSION RATES OF THE PROCESSING ACTIVITIES INVOLVED IN THE MANUFACTURE OF DOMESTIC SOLAR WATER HEATERS SYSTEMS [CEC, 1995]

Material processing	CO_2	SO_2	NO_x
	(in kg of pollutant per tonne of material)		
Aluminium	21,458	105.4	44.7
Steel	2,225	17.6	8.2
Copper	2,683	31.3	12.2
Insulating materials	2,437	16.9	20.6
	(in kg of pollutant per m^2 of collectors)		
System construction	20.7	0.11	0.0478

Variations in the fuels used in the extraction and processing of materials will obviously alter figures for associated emissions. This is particularly trace of aluminium but also applies to other materials, for example because New South Wales coal has a low sulphur content, the SO_2 emissions associated with Australian steel are lower see Table 4. Aluminium also produces fully fluorinated compounds which, though emitted in small quantities, are much more powerful greenhouse gases than CO_2 [Cork, 1995].

TABLE 4

EMISSION FIGURES FOR AUSTRALIAN CAST STEEL

	CO_2	SO_2	NO_x
	(kg of pollutant per tonne of steel)		
Steel	2200	2.5	2.2

6. Greenhouse gas emissions associated with materials

In this evaluation only CO_2 emissions are considered in detail as they are much larger in magnitude than other emissions. However a fuller analysis could include the effect of NO_x and CH_4 using the formula [Anon, 1990];

$$Greenhouse\ Gas\ Index\ (kg) = CO_2\ (kg) + \left[\frac{CO(g)x3 + NO_x(g)x150 + CH_4(g)x63}{1000}\right]$$

TABLE 5

CO_2 EMISSIONS ASSOCIATED WITH MATERIALS EXTRACTION AND PROCESSING

Material	kg of CO_2/kg of Material	
	Energy Efficient Process	Typical Process
Steel	2.2	4.3
Aluminium	21.4	45.0
Copper	2.2	7.2
Plastics		4.9
Glass	0.6 (using gas, this is equivalent to 9 kg CO_2 per m^2 of 6mm glass)	2.0
Sand, Gravel, Salt		0.009
Cement	0.8 (dry process)	1.8

The CO_2 emission factors used herein are given in Table 5. This table arises largely from available literature and communications with suppliers. These figures are multiplied by the mass of each material inherent to each system. The material masses were obtained from scrutiny of such detailed specifications as are available. Commercially confidential information not in the public domain was employed. This data was subject to large project-specific variability. The results are shown in Table 6. These are compared with non-solar thermal options in Table 7 which also includes estimates for "next generation" technologies.

TABLE 6

CO_2 EMISSIONS PER UNIT POWER OUTPUT FOR CURRENT SOLAR THERMAL ELECTRICITY TECHNOLOGIES

	Emissions per unit output (g CO_2/kWh)	
	Energy efficient processing of constituent materials	Typical processing of constituent materials
Central receiver	21.11	48.43
Parabolic dish	24.01	50.92
Parabolic trough	30.03	80.21
Solar pond	5.05	6.44

TABLE 7

CARBON EMISSION STATUS AND PROJECTS

Carbon Emissions g CO_2/kWh

	Coal	Oil	Gas	Hydro	Nuclear	Photo-voltaic	Solar thermal			
							Central Receiver	Parabolic Dish	Parabolic Trough	Solar Pond
Current Technology	270	180	180	5	6	35	21.22	24	30	5
Next Generation Technology	80	140	140	5	3	8	10	15	20	4

(Solar thermal values: assumes energy efficient processing of constituent materials)

7. Conclusion

Medium concentration ratio systems emit the most CO_2 per kWh generated. The reasons for this are the low embodied energy of a solar pond at the low concentration extreme and the opportunities to improve optical performance at the high concentration extreme with little increase in overall material content [Kribus et al, 1995]. An indicative relationship similar to that shown in Figure 3 may be shown to prevail, though further work is required to address this.

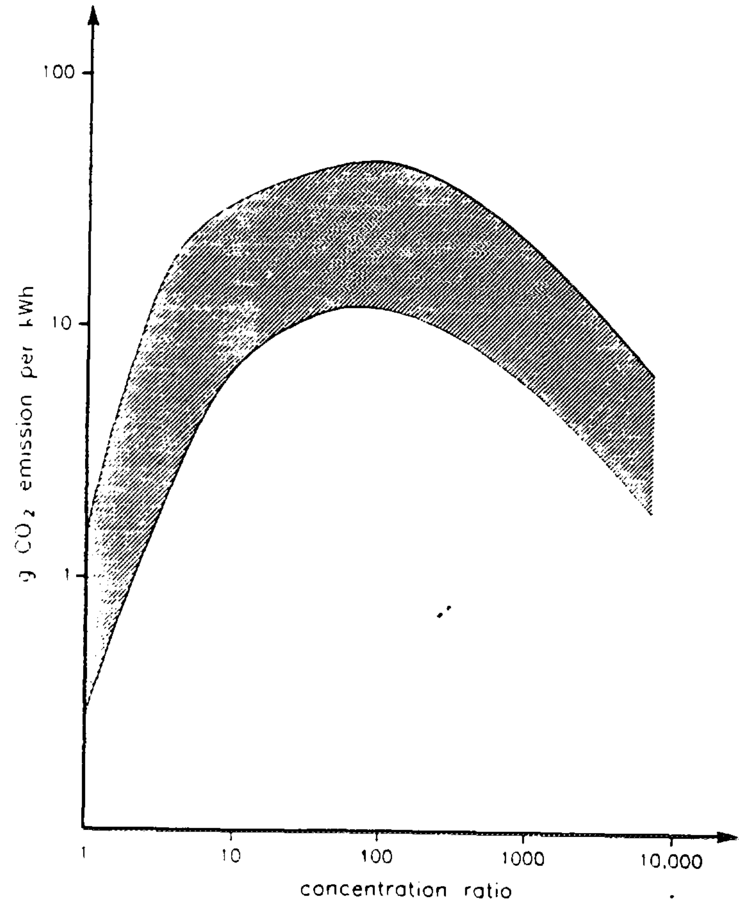


FIGURE 3
POSSIBLE RELATIONSHIP BETWEEN EMBODIED CO_2 PER UNIT OUTPUT AND CONCENTRATION RATIO FOR SOLAR THERMAL ELECTRIC GENERATION IN AREAS OF HIGH DIRECT COMPONENT OF INSOLATION

There remain large uncertainties in the carbon dioxide emissions associated with materials. This is due to (i) lack of agreement as to the boundaries of assessment and (ii) genuine differences arising from variations in fuel use and process efficiencies. Intercomparison with other studies is also hampered by non-citation of prime sources of data. Solar thermal electric generation is barely leaving the demonstration phase of development. It is reasonable to see substantial improvements to the technology that will improve efficiency and reduce materials content. The comparative ranking of solar thermal electric generation in terms of full-energy-chain analysis should thus improve. Central receiver and solar pond technologies have had limited research and development investment in comparison with competing options. The benefits of an increase in such research and development may lead to improvements in their full energy chain carbon emissions performance.

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