Prospects for Sustainable Energy

A Critical Assessment

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CAMBRIDGE
UNIVERSITY PRESS

PUBLISHED BY THE PRESS SYNDICATE OF THE UNIVERSITY OF CAMBRIDGE
The Pitt Building, Trumpington Street, Cambridge United Kingdom

CAMBRIDGE UNIVERSITY PRESS
The Edinburgh Building, Cambridge, CB2 2RU, UK   http://www.cup.cam.ac.uk
40 West 20th Street, New York, NY 10011–4211, USA   http://www.cup.org
10 Stamford Road, Oakleigh, Melbourne 3166, Australia
Ruiz de Alarćon 13, 28014 Madrid, Spain

First published 2000

Printed in the United Kingdom at the University Press, Cambridge

Typeset in Times 10/12pt [VN]

A catalogue record for this book is available from the British Library

Library of Congress Cataloguing in Publication data

Cassedy, Edward S.
Prospects for sustainable energy : a critical assessment / Edward S. Cassedy.
p.   cm.
Includes index.
ISBN 0–521–63120–3
1. Renewable energy sources.   2. Energy policy.   I. Title.
TJ808.C37   1999
333.79′4 – dc21   99–11969   CIP

ISBN 0 521 63120 3 hardback

Contents

Preface *page* vii

I Introduction 1

Introduction 3

II Candidate technology assessment 17

1 Solar energy sources 19
2 Biomass energy 67
3 Windpower 113
4 Hydroelectric power 136
5 Energy storage 153
6 Geothermal energy 188
7 Ocean energy 193
8 Nuclear fusion 200
9 Hydrogen fuel from renewable resources 207

III The prospects for technological change toward sustainability 223

10 Summary assessment of the technologies 225
11 Research and development 231

Appendices 259

Appendix A *Energy cost analysis* 261
Appendix B *Glossary* 264
Appendix C *The conduct and management of research and development* 269

Index 279

1 Solar energy sources

1.1 Introduction

Solar radiation as a source of energy is, of course, the epitome of the clean, sustainable energy technology. Except for residues possibly arising out of the manufacture of solar components (e.g. semiconductors), solar technologies have very low environmental impacts. The environmental impacts of solar systems in operation are very low and the source is, for us, inexhaustible.

The energy incident on the earth from the wide electromagnetic spectrum emitted by the sun may be converted to useful heat, to electricity, or used to create a fuel. The uses of converted solar heat range from domestic hot water (DHW) to industrial process heat (IPH). Electricity may be generated from solar radiation either by thermal-plant methods, using solar-heated steam, or by direct conversion to (d.c.) electricity in solar cells. Alternative fuels, such as clean-burning hydrogen, can be evolved from solar-driven chemical reactions or by electrolysis driven by solar cells. Finally, of course, biomass fuels derive their energy from the sun. Any or all of these means of converting sunlight to useful energy could supply the worlds needs, if the technologies were ready. The problem with solar technologies is not, as is sometimes asserted, that there is insufficient land area to collect all of the energy society needs; worldwide there is and in the larger countries there is. In the USA, for example, it would take less than 2% of the land area to supply *all* of the country's primary energy demand from solar sources, at current consumption levels . The problem with solar energy, as we will outline here, is its *cost*.

The various possible ways in which solar energy can be used, replacing conventional fossil-fuel energy, are at different stages in technological development. In this chapter, we will assess the status of each of five prospective solar-conversion technologies, leaving biomass fuels and other indirect schemes to other chapters. The five technologies are solar DHW (SDHW), solar–thermal steam (for electric generation or IPH), solar (active) space heating, passive solar space heating, and direct solar–electric conversion (using photovoltaic (PV) cells). The first three of these involve the use of solar-heat collectors. Solar-heat collectors actually involve several different techniques, depending on the application, ranging from flat-plate collectors heating water to focusing collectors generating steam. By contrast, passive solar heating (and cooling) is a matter of architectural design. Finally, no heat collection whatsoever is necessary in the direct conversion of sunlight to electricity by semiconductor solar cells.

All of these attempts to achieve useful solar energy conversion have suffered from a lack of economic competitiveness of these new technologies and from the inherent defect of intermittency of the resource itself. Both of these deficiencies have prospects for solution in each of the approaches being studied. Technological innovations have attempted to lower construction costs of solar collectors and to provide energy storage against intermittency. Most of the five technologies appear to be evolving, albeit fitfully, toward eventual success in the markets for energy. There is still potential for new concepts to revolutionize the prospects in regard to both costs and intermittency. In any case, progress will likely only be attained in the long run with sustained support of R&D efforts, whether from direct public support or through public policies that encourage private invesment. This should become clear in the following sections as the history of these efforts is revealed.

1.2 Solar domestic hot water

Solar collectors on the roofs of homes are the most common image (Fig. 1.1) of solar technology. Such collectors have been used, for the most part, for SDHW systems to supply hot water for the house or to warm water for swimming pools. There have been over half a million such systems installed in the USA since the 1970s.

The majority of SDHW systems are termed *active* systems, meaning that it takes a circulating pump, operated from sensors and a controller unit, to make them function (Fig. 1.2). The coolant fluid must be circulated through tubes in the collector (see Fig. 1.3) and carried down to the heat exchanger in the hot-water tank in order to transfer the collected solar heat into the water. The controller causes the pump to circulate the coolant fluid from the collector through the system only when the sensors detect a temperature difference sufficient to transfer heat into the hot-water storage tank. Some designs, called “thermosiphon”, operate on the natural convection of the temperature difference without the need for a pump, but these still require an active control system to function.

The technology of solar hot-water systems is relatively simple. Apart from the collector, the system is essentially plumbing and controls. The flat-plate collector (Fig. 1.3) should have surfaces that maximize the absorption of sunlight and minimize the reradiation of heat. Absorption is easily obtained simply by the use of a dull black coating. Lowering reradiation, however, is attained only with the use of more sophisticated and, therefore, more expensive coatings. The collector must also have a transparent cover to contain the heat once it is collected. Provision must be made in cold climates against freezing of the circulating fluid, such as the use of antifreeze solutions for the coolant or a drainback provision if water is the coolant. A heat exchanger coil transfers heat from the circulating coolant into the (potable) water in the hot-water tank in most systems.

A typical home in the sunbelt region requires 100–150 ft^2 (9–14 m^2) collector area to supply most of its hot water needs, but as little as 60 ft^2 (6 m^2) can supply 50% of needs in some sunbelt locations (Hof, 1993).

Figure 1.1
A solar domestic hot water (SDHW) collector. (Courtesy of the American Solar Energy Society.)

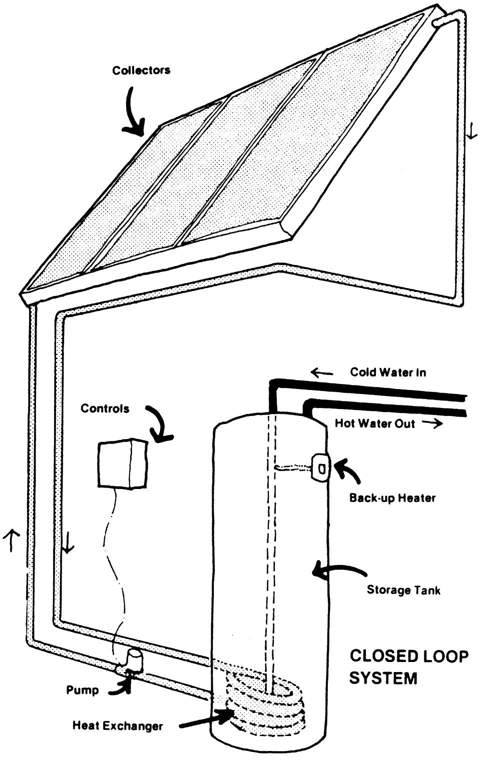

Figure 1.2
A solar domestic hot water system. (*Source*: Northeast Sustainable Energy Association.)

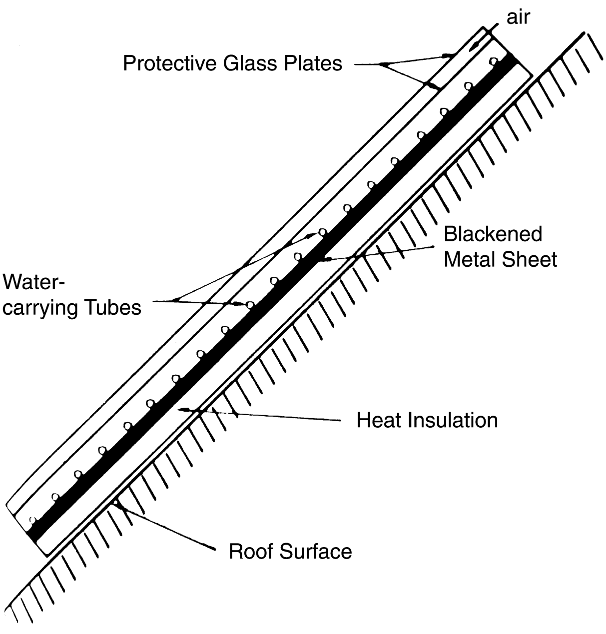

Figure 1.3
A flat-plate solar collector.
(*Source*: Penner & Icerman, *Energy*, vol. II, © 1975, Addison-Wesley Publishing Co., Inc., Reading, MA. Reprinted with permission.)

Household hot water typically runs 50–100 gallons daily, requiring around 50 000 BTU (53 000 GJ) heat. An auxiliary (back-up) heater is required in most sections of the country to meet the needs during cloudy periods. Generally, it is uneconomical to attempt to store hot-water heat to cover such periods and SDHW designs look for the least-cost "solar fraction" trade off between the solar system and its back-up (Beckman *et al.*, 1977). This fraction, based on annual operation, typically runs 60–90% in the sunbelt and 40–60% elsewhere in the lower 48 states of the USA. Similar comparisons hold for northern versus southern (sunbelt) regions elsewhere. Hot-water storage equivalent to about 1 day's usage is recommended both to carry over the evening and early-morning needs and to smooth supply on days of intermittent sunshine.

If storage is attempted to achieve a high solar fraction approaching totally-solar operation, hot-water storage capacities equivalent to 2–3 days of use will be required in sunbelt sections and more in other regions. Increases in storage capacities above this level yield ever diminishing returns. An attempted totally solar system (i.e., no back-up heater), besides being uneconomical, will most probably leave the household with insufficient hot water for some weather sequences. The larger the storage and collection capacity, the smaller the probability of insufficiency, but it is impractical to try for total coverage. An account of possible modes of solar operation with storage is given in Winter, *et al.* (1991). A more detailed discussion of the economics of hot-water storage is given here in Chapter 5.

The challenge for solar manufacturers has been to fabricate systems that are reliable and durable, yet cheap enough to compete against conventional (fossil-fueled) systems. For example, multilayer wavelength-selective coatings or (low heat loss) evacuated tubes to improve the efficiencies of collectors have generally resulted in costs too high for the DHW market. Correspondingly, it is prohibitively expensive for SDHW to have the collectors track the sun – collectors are simply oriented south facing (in the northern hemisphere) with a fixed elevation tilt that optimizes annual collection over the seasons. Collector frames are typically made of inexpensive extruded aluminum and insulated with cheaper forms of fiberglass or plastic foams. At the same time, however, performance requirements, such as collection efficiency, low heat loss, and durability against high temperatures and ultraviolet radiation, must compete against the cost factors for an overall product competitiveness.

The history of SDHW shows wide variations in its use (Hof, 1993). Solar hot-water systems, using simple roof-mounted tanks, were installed in Southern California early in the 20th century, but their use declined after 1920. Florida residents also utilized solar hot water, with some 50 000 units being sold in the decades 1920–50. Use declined in both sunbelt states with the advent of cheap oil for heating. Even wider use of solar hot-water collectors was made in Japan and Australia prior to the 1970s but also declined with the availability of low-priced fuel oil. With the arrival of the oil crisis of the 1970s, interest revived worldwide in various alternatives such as solar heat.

With the revival of SDHW in the 1970s, its path to adoption in the market has been checkered in the USA (Frankel, 1986; Larson & West, 1996). Low-quality products and fly-by-night marketers, in the midst of an industry otherwise trying to gain experience with the peculiar requirements of the new technology, created a wariness in the buying public (FSEC, 1979). Attempts by the fledgling industry to establish standards and warranties, which would have put DSHW systems on an acceptance basis comparable to that of conventional boilers and hot-water tanks, were slow in the making. Such uncertainties for the solar consumer, together with the inevitable barrier of the newness of the technology, made for few adoptions in the potential market even without considering the costs (Vories & Strong, 1988). Even though testing procedures and standards (SRRC, 1993–4; Larson & West, 1996) have subsequently been developed and industry certification now exists for SDHW systems, the opportunity of the 1970s was largely lost.

The principal determinant for the low market penetration of DSHW systems, however, has been price. Even when oil and other energy prices were at their highest in the 1970s, exceeding (wholesale) price levels of \$5/MBTU, solar hot water was competitive only in the sunbelt. In general, it took incentives in the form of investment tax credits to promote sales of DSHW systems. A growing industry, selling annually tens of millions of square feet (collector area, a measure of system size) of systems, existed into the 1980s when the federal tax credit had been set at 40% (Andrejko, 1989) and states, such as California and New York, had added credits of their own up to 55% for domestic systems and up to 25% for commercial buildings. Perhaps no better indication of the necessity of the incentives was the collapse of the DSHW market after the expiration of the federal tax credits in 1985. Up to that point, in the previous decade, over 100 million square feet of collectors (9 million square meters), with systems, had been sold benefiting from the subsidies. While this failure was deplored by solar advocates and many others, the 40% measure of price competitiveness, at least for the sunbelt market, was a demonstrated indication of the market status of the technology in the absence of aid to early adopters.

Progress has taken place in the technology since the mid-1980s, some changes improving operational efficiencies and durability, and several innovations have led to reduced fabrication and installation costs (Andrejko, 1989). Operational modes, involving slower circulation of the coolant and improved heat exchanges, have improved system efficiencies. The use of improved absorbing coatings and foam insulation has improved collector efficiencies by 15–20%. The lighter weights of the insulation and use of aluminum frames have resulted in easier and less costly installation. New materials, such as unbreakable (tempered) glass on collectors and more durable absorbing coatings, have extended the working lives of collectors. New "brushless" electric motors for circulation pumps have improved system performance and reliability. Finally, the innovative use of photovoltaic cells as combined solar sensors and electricity suppliers for the controllers of the circulation systems has resulted in reduced cost and in operational enhancements.

Technical progress alone, however, is not likely to be the key to market penetration for DSHW. Technical improvements are likely to continue incrementally only, given the relatively "low-tech" nature of these systems (Katzman, 1984). It continues to be apparent that the major determinant of market competitiveness of DSHW heat will be its price compared with those of conventional fuels (oil and natural gas). That price comparison for the DHW market can be made on a unit energy basis, such as \$/MBTU. The unit cost of the SDHW energy is determined strictly by the pay off of the capital investment over the life-time energy output of the equipment, plus (small) operating costs.

As an illustration, consider a hot-water system in the sunbelt, where there is 680 000 BTU/ft^2 (7722 MJ/m^2) of annual insolation (250 W/m^2, average), a 50% collector efficiency, a system unit cost of \$50/ft^2 (\$538/m^2) collector, and a 25-year depreciation lifetime. This system would yield unit energy costs of \$17 per MBTU (\$16.1/GJ), including 10% interest charges and small operating costs levelized over the life of the system (see Appendix A for the cost of energy methodology). This cost might be compared with \$9/MBTU for heating oil at \$1.25 per gallon or \$7/MBTU (\$6.60/GJ) for natural gas at 70¢ per therm (0.1 MBTU), which a home owner in the USA might be faced with in the 1990s. Clearly, this is not a competitive cost of energy in the market for the commodity of heat energy with the current level of energy prices.

The average homeowner, however, is more likely to look at the fuel savings on the solar hot water to pay back the initial purchase price of the system and not explicitly consider interest costs (Cassedy & Grossman, 1990, 1998). In this simplified view, the homeowner considers every solar-produced BTU as a saving on a BTU produced by the auxiliary (back-up) fuel-burning heater. By this simplified view of life-cycle costs (see Appendix A), the homeowner could calculate that 340 000 BTU/ft^2 (3860 MJ/m^2) annually collected solar heat (i.e. sunbelt insolation, with a 50% collector efficiency) would pay off the investment in 16 years, if oil is the alternative fuel, or 20 years, if the alternative is natural gas. If interest was included, it would take over 35 years to show a life-cycle payback, and then only for a very low interest rate. A consumer attitude survey (Stobaugh & Yergin, 1979) has found that a payback time less than 5 years is commonly necessary to attract serious consideration of purchase by the public. In a few cases, utility customers have been lured into attractively financed purchases of SDHW systems, subsidized by the utility as part of their demand-side management (DSM) programs (Carlisle & Christiansen, 1993), but otherwise no financing schemes have been devised that would be attractive to the public when the basic cost of energy is in the range that includes solar domestic heat.

The inescapable conclusion is that, in the absence of financial incentives and with prevailing fossil-fuel prices, domestic solar hot-water systems are not economic, even in the heart of the sunbelt. In other parts of the country, the annual solar production would be half or less that of the sunbelt and the unit energy costs or payback times twice or more. This situation could only be changed by a jump in fuel prices over twice the present levels or by tax incentives of more than 50% for the sunbelt (more elsewhere), or some combination of the two. The first possibility has a historic precedent in the 1970s but is very ulikely to be repeated in the first part of the 21st century. Second, the prospects of government policy in the USA returning to subsidizing solar commercialization are problematic in the absence of another world oil crisis or other widely accepted contingency, such as slowing climate change. In other OECD countries, the prospects for solar domestic price supports might be somewhat better. Subsidization of a new technology is likely to be accepted as sound policy in some of these countries only if that technology appears to need just temporary assistance in becoming competitive in the market. In the author's estimation, with small prospects for dramatic reductions in SDHW costs through technical breakthroughs, this lack of cost competitiveness does not seem to be temporary.

The only other argument that could be mustered in support of temporary tax subsidies would be that mass production would lower present unit investment costs of DSHW systems to a fraction of the present \$50/ft^2 level. While such arguments seem plausible for other technologies, such as photovoltaics, they do not seem appropriate for these comparatively rudimentary systems, where dramatic technological advances seem unlikely. If that is the case, then there would have to be a rationale for subsidization of an indefinite duration, such as being part of a broad policy of reduction of fossil-fuel use. The current lack of interest, at the political level, in energy policy and the general turn to *laissez faire* politics make any such policy quite unlikely.

As of 1991, there were about 1.25 million SDHW systems installed in homes in the USA, representing only about 1% of its market potential (Golob & Bus, 1993), and these mostly as a result of the tax credit program of 1977–85. In Israel, 65% market penetration exists, partly because of the insolation level giving high solar-fraction operation and partly because SDHW systems are required by the government in all new homes and (small) apartment buildings (Shea, 1988). This regulation is based on a national policy to reduce dependency on imported oil. Much the same motivation exists in Japan, where over 5 million solar hot-water heaters are already installed and more are installed each year. The sense of urgency for the USA to adopt a national policy to reduce oil imports has long since passed. It is possible, however, that environmental policy, such as that enacted in California against air pollution, could become the rationale for solar subsidies.

1.3 Solar (active) space heating and cooling

Active space heating

Space heating using solar collectors and *active* transfer of the heat is the same concept as (active) solar hot water but on a larger scale. It takes considerably more collected energy, and a proportionally larger collector (Fig. 1.4), to keep an entire house heated on a winter's day than it does to supply just the household hot-water needs. As a result, the commitment by a home owner to a solar space-heating system is much larger than that for only hot water. For example, requirements run up to 100 ft^2 (9.3 m^2) collector per room to be heated, with each square foot of collector costing in the vicinity of $50 (system cost) (Hof, 1993). Solar space-heating systems have also been installed in commercial buildings, with very similar design and cost considerations as domestic systems but on a larger scale.

Solar space-heating systems can be based on either hot water or hot air. The hot-water installations are larger versions of SDHW circulating systems, delivering their heat to radiators just as conventional fuel-fired furnaces do. Hot-air systems (Fig. 1.5) by comparison, circulate air through a solar collector (with air ducts) and into the rooms of the home or building. Whereas some heat storage had been thought necessary in space-heating systems to smooth the heat supply, some newer hot-air, space-heating systems do not have it. These systems operate on ambient fresh air (Andrejko, 1989) and are found satisfactory for commercial buildings in daytime use only. Where heat storage is necessary for hot-air systems, large porous beds of pebbles through which the air is forced by fans serve as inexpensive storage media.

Where heat storage – either hot water or hot air – is necessary to maintain round-the-clock space heating, it must be used in conjunction with auxiliary heating for an economic system in temperate climates. Attempts to increase the solar fraction for space-heating systems by increasing storage capacity and/or collector area is even more a matter of diminishing returns (Beckman *et al.*, 1977; Hof, 1993) for space-heating

Figure 1.4
A domestic space heating collector. (Courtesy of the National Renewable Energy Laboratory, Boulder, CO.)

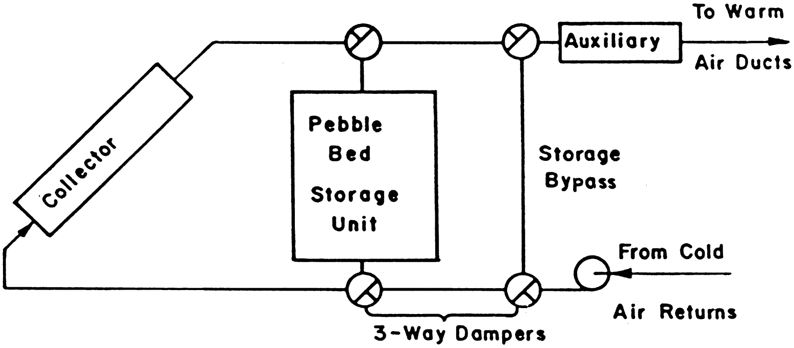

Figure 1.5
Hot-air space heating system. (Courtesy of the US Department of Energy.)

systems compared with hot-water systems. (This may be recognized as simply a consequence of the seasonal mismatch of solar availability with space-heating needs.) Nonetheless, a totally solar-heated house has been constructed and operated in the sunbelt, although it was not deemed optimum on a cost basis. Optimum (annual) solar fractions appear to be in the range of 75% in the sunbelt and down to the 40–50% range in northern climates of the U.S.

The recent history of active solar space heating parallels that of SDHW. During the energy-crisis period, with tax credits, there were over 25000 systems sold (Andrejko, 1989). For the most part, these were retrofits of existing homes. The manufacturers and distributors were generally from the same group as suppliers of SDHW and suffered from the same deficiencies of standards and quality (Hof, 1993). Federally sponsored demonstration programs were introduced early in the period (mid-1970s) but did little to assure industry standards and reliability of the equipment sold when the tax-credit program was initiated. Later, the industry was able to improve on quality and institute a certification system for collectors. Nonetheless, the public image of solar systems, space heating as well as hot water, suffered. Furthermore, sales collapsed, as they did for solar hot water, with the end of tax credits for solar home use in 1985.

Active solar cooling

Active solar cooling is a seemingly self-contradictory term that is used in space-cooling technology, such as absorptive refrigeration, which can use collected solar heat rather than fuel-fired heat to drive a thermodynamic cooling cycle (Duffie & Beckman, 1974; Hof, 1993). In such operation, the solar collector system supplies the absorptive refrigerator with the hot working fluid, which is the energy input needed to drive the cooling cycle. The principle of operation of solar-driven absorptive cooling is the same as that when natural gas is used to supply the heat for the thermodynamic cycle.

A solar cooling system, for summer use, can be combined with a solar, space-heating system for winter use. Flat-plate collectors, of the type described earlier, can be used if the cooling cycle uses a lower temperature coolant, such as lithium bromide. The joint-purpose system (Fig. 1.6) can then be adjusted for either season's space-conditioning needs by use of the right-hand valve shown in Fig. 1.6 (the valve is used to bypass the solar subsystem only). For winter's heat, the valve is set to let the hot water flow through the heating coil, while the valve set for summer cooling allows flow through the (absorption) air-conditioning unit. Room air is forced through the joint unit for either operation. The unit can also supply domestic hot water the year round.

The joint use makes for a better payback on the investment in both the collector and its subsidary equipment, with a much improved capacity-factor utilization of the solar source. Summer solar cooling, in particular, is a good match of the load demand to the source, in contrast to that of winter solar heating. However, the principle barrier to market adoption has been, as with solar in general, the initial cost. The current installation costs for solar cooling, with solar-system costs allocated just to cooling, are three to eight times those of conventional cooling systems (Andrejko, 1989). Even with solar-system costs allocated to both cooling and heating, however, there would be no savings on energy costs over conventional fuels, such as natural gas, for the technology in its present state.

Not surprisingly, solar cooling had a history in the "energy crisis" period paralleling that of solar heating and hot water. The sales of solar cooling units grew with the help of tax credits but dropped abruptly with their demise in 1985. In the 5 years the credits were given, nearly 10000 solar cooling units were sold. This was after government-sponsored prototypes had demonstrated operating feasibility. At the end of the 1990s commercial heat-driven cooling systems are marketed with natural gas burners as the heat source, not solar collectors.

It is worth noting, however, that the potential market for solar cooling is