AT MICROFICHE REFERENCE LIBRARY
A project of Volunteers in Asia

Technology for Solar Energy Utilization
UNIDO Development and Transfer of Technology
Series No. 5

Published by:
United Nations Industrial Development Organization
P.O. Box 300
A-1400 Vienna
Austria

Available in English, French and Spanish. Paper copies are free to local groups in developing countries, $10 to others. Ask for document number ID/202.

Available from:
United Nations Industrial Development Organization
P.O. Box 300
A-1400 Vienna
Austria

Reproduced by permission of the Department of Public Information, United Nations Industrial Development Organizaion.

Reproduction of this microfiche document in any form is subject to the same restrictions as those of the original document.

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION

Development and Transfer of Technology Series

No. 5

TECHNOLOGY FOR SOLAR ENERGY UTILIZATION

UNITED NATIONS

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
Vienna

Development and Transfer of Technology Series No. 5

TECHNOLOGY FOR SOLAR ENERGY UTILIZATION

UNITED NATIONS
New York, 1978

The designations employed and the presentation of the material in this publication do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.

Mention of firm names and commercial products does not imply the endorsement of the United Nations Industrial Development Organization (UNIDO).

Material in this publication may be freely quoted or reprinted, but acknowledgement is requested, together with a copy of the publication containing the quotation or reprint.

Preface

As a result of the energy crisis, attention has been focused on the need, not only to conserve conventional sources of energy, but also to explore non-conventional sources of energy such as solar radiation, winds, biomass, tides, geothermal sources etc. There is no reason why these important natural resources should not be exploited for the benefit of the developing countries, particularly solar radiation, which is relatively abundant in most developing countries. Co-ordinated activity in the exploitation of non-conventional sources of energy would contribute considerably towards the developing countries' achieving their target of a 25 per cent share in world industrial production by 2000. The role of the United Nations Industrial Development Organization (UNIDO) would be, in keeping with a recommendation of the Round Table Ministerial Meeting on Industrial and Technological Co-operation among Developing Countries, held at New Delhi in January 1977, to launch programmes of co-operation in applied research and development activities in the energy sector of industry, drawing upon the machinery and capabilities already available in the developing countries.

This volume deals with the technology of exploitation of solar energy for the benefit of the developing countries. It is hoped that with the further improvements in this technology, solar energy will supply not only the certain needs of industry but also the everyday needs of the population in the rural and remote areas of those countries. The text of the volume is primarily based on the contributions made to the Expert Group Meeting on the Existing Solar Technology and the Possibilities of Manufacturing Solar Equipment in Developing Countries, organized by UNIDO in co-operation with the Austrian Solar and Space Agency (ASSA) and held at Vienna, 14-18 February 1977.[1] In addition, it incorporates information obtained by UNIDO as a result of its field contacts in many developing, as well as industrialized, countries. Because of the complexity of solar energy technology and the accelerated research and development taking place in solar energy in many parts of the world, this treatment of the subject cannot be exhaustive. Nevertheless, as a first step by UNIDO in this field, it should be an important aid to interested Governments of developing countries in acquiring the latest trends in the area of solar technology and in providing a basis of national action.

The first part of this volume contains two papers: a recommended programme for solar utilization in developing countries, prepared by the Senior Interregional Adviser on Engineering Industries at UNIDO, and a background document on the utilization of solar energy in developing countries, prepared for UNIDO by a consultant. The second part consists of summaries of work being done in some countries and institutions, and the third of 17 technical papers dealing with the conversion of solar energy into mechanical or electrical energy, the design of solar collectors, the utilization of solar energy in heating, cooling, distillation, drying and cooking, and the transfer of technology.

Throughout the volume, the views expressed are those of the contributors and do not necessarily reflect the views of the secretariat of UNIDO.

In the context of the forthcoming United Nations Conference on Science and Technology for Development, to be held at Vienna in August and September 1979, several developing countries are devoting attention to the application of technology for meeting some of their energy needs. This study, along with others to be prepared by UNIDO, is intended as a contribution to the conference and its preparatory activities.

[1] The recommendations of the Meeting are in annex I on page 147.

CONTENTS

Part one

Utilization of solar energy in developing countries

Page

Solar energy: A recommended programme of action for developing countries
Secretariat of UNIDO 3

Development of solar energy utilization in developing countries
Assad Takla 7

Part two

Summaries of country and institutional programmes on solar energy

Country programmes 41

Institutional programmes 48

Part three

Selection of technical papers on the utilization of solar energy

A 10-kW solar electric power plant
Hans Kleinrath 53

Conversion of solar into mechanical or electrical energy: Indian experience
V. G. Bhide 55

Utilization of solar energy in the development of arid zones: Solar water pumps
Jean Paul Durand, Max G. Clemot, J. Pierre Girardier and Marc Y. Vergnet 62

Theoretical conditions for maximum power from the sun
Kamal-Edin Hassan 65

Solar flat-plate collectors
A. A. M. Sayigh 66

Aspects of solar-heated swimming-pools
Gangolf Bräunlich 72

A solar energy system for greenhouses
M. Posnansky 75

Solar timber kilns: Their suitability for developing countries
R. A. Plumptre 78

Solar refrigeration and cooling
Erich A. Farber 89

Solar space heating and cooling and solar water heaters
V. G. Bhide 92

Page

Preliminary design data for a solar house in Riyadh
A. A. M. Sayigh and E. M. A. El-Salam 101

Solar refrigeration in developing countries
A. Eggers-Lura 107

Solar distillation: The state of the art
B. W. Tleimat 113

Solar water distillation
Carlo Mustacchi and Vincenzo Cena 119

The potential of solar agricultural driers in developing areas
T. A. Lawand 125

The potential of solar cooking in developing areas
T. A. Lawand 133

Assessment of solar applications for technology transfer
Jyoti K. Parikh 137

Annexes

I. Recommendations of the Expert Group Meeting on the Existing Solar Technology and the Possibilities of Manufacturing Solar Equipment in Developing Countries 147

II. Current IEA projects in solar energy 150

III. Solar energy information systems 152

IV. Institutions involved in solar energy development 155

EXPLANATORY NOTES

References to dollars ($) are to United States dollars, unless otherwise stated.

A slash between dates (e.g., 1970/71) indicates a crop year, financial year or academic year.

Use of a hyphen between dates (e.g., 1960-1965) indicates the full period involved, including the beginning and end years.

A full stop (.) is used to indicate decimals. Thousands, millions etc. are separated by spaces unless a symbol for a monetary unit precedes the number.

References to tons are to metric tons (tonnes), unless otherwise specified.

The following notes apply to tables:

Three dots (. . .) indicate that data are not available or are not separately reported

A dash (–) indicates that the amount is nil or negligible

A blank indicates that the item is not applicable

Totals may not add precisely because of rounding

Besides the common abbreviations, symbols and terms and those accepted by the International System of Units (SI), the following have been used:

Technical abbreviations and symbols
(with approximate equivalents)

mil	one thousandth of an inch
in.	inch (1 in. = 2.54 cm)
rpm	revolution per minute
hp	horsepower (1 hp = 746 W)
atm	atmosphere (1 atm = 1.013 bar)
bd ft	board foot (1 bd ft = 2 360 cm^3)
gpm	gallon (US) per minute (1 gpm = 0.063 l/s)
psi	pound per square inch (1 psi = 0.069 bar)
psia	pound per square inch (absolute)
psig	pound per square inch (gauge)
gal (US)	United States gallon (1 gal (US) = 3.785 l)
gal (Imp)	British Imperial gallon (1 gal (Imp) = 4.546 l)
ft	foot (1 ft = 30.5 cm)
Btu	British thermal unit (1 Btu = 1.055 kJ)
cal	calorie (1 cal = 4.186 J)
wt%	weight per cent
PVC	polyvinyl chloride
PVF	polyvinyl fluoride
PTFE	polytetrafluoroethylene
ABS	acrylonitrile-butadiene-styrene
R and D	research and development

Organizations

United Nations bodies

FAO	Food and Agriculture Organization of the United Nations
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNICEF	United Nations International Children's Emergency Fund

Other

ERDA	Energy and Research Development Administration
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis

Part one

UTILIZATION OF SOLAR ENERGY IN DEVELOPING COUNTRIES

Solar energy: A recommended programme of action for developing countries

Secretariat of UNIDO

As will be seen in the next article in this volume, there are definite possibilities of solar technology application for water distillation, water heating, drying, cooking, refrigeration and air-conditioning, and the conversion of solar radiation into mechanical and electrical energy. The essential need is for the development of a programme for applied research and development and eventual manufacturing activity, with emphasis on technology transfer from industrialized countries, domestic promotion of research and development capabilities and co-operation among developing countries, in the field of solar technology. Although the basic concepts in solar technology are centuries old, their industrial and commercial application have only recently received any significant amount of interest in industrialized and developing countries.

The economic analysis of solar technology and equipment requires a different philosophy and approach. As commercial manufacture is still in the early stages and not at all widespread, the optimum economic level of production cannot be established. Certainly, the initial cost of solar equipment is higher than that of similar, conventional products. However, the operating cost of solar equipment is far less.

The major problems in solar technology development, product design and product manufacture are:

(a) The technology is new and there is a lack of knowledge on what it can do and how it can be used;

(b) Solar products and equipment are not yet readily available on a commercial basis on an extensive scale; and

(c) The equipment initial cost is high, probably because the technologies are still mainly experimental and no economy of scale can be realized.

A limited number of solar products are commercially manufactured, and these in only industrialized and a few developing countries. There is a need for more information, evaluation of performance on site in interested developing countries, and, eventually, investment promotion. In addition, there are a number of institutions in both developing and industrialized countries that have engaged in applied research, developed sound technological concepts, and tested and transformed them into manufacturing prototypes, with significant emphasis on the needs of developing countries. Therefore there is a need for twinning these research and development institutions in selected industrial and developing countries in the field of solar technology. Thirdly, there is a need to develop integrated programmes of action within the framework of co-operation among developing countries. In this connection, certain institutions in developing countries should be selected for strengthening and transformation into "centres of excellence" that can provide assistance to other developing countries.

In connection with the need to develop a programme of information extension and popularization of solar technology in the developing countries, the Governments of the developing countries might take the necessary steps to initiate and support a modest programme in solar technology in a local institution, with a view towards launching an effective research and development programme with co-operation from other institutions and appropriate developing countries, as well as from bodies of the United Nations.

Any programmes that are so established should suit the needs of the individual developing countries and promote regional and interregional co-operation in the field of solar technology. That applies to information collection and analysis, information extension, applied research and development, evaluation and manufacturing promotion.

The prerequisites

Although there is an awareness in the developing countries of the need to develop alternative sources of energy, there appears to be an absence of integrated policies and work programmes directed towards that end. It seems that in most developing countries research and development in this area is carried out on an *ad hoc* basis.

In most developing countries, the major problems in the utilization of non-conventional sources of energy fall into three groups: One is the lack of information on the state of the art; the second relates to the appropriateness of the methods used to apply those sources of energy in the conditions that prevail in the developing countries; and the third concerns the reliability of the technology that the developing countries would have to import. In addition, the formulation by developing countries of integrated practical policies for these alternative sources of energy has to cover the establishment of appropriate institutional facilities for applied research and development and the promotion of local manufacture, with due emphasis on techno-economic analysis, field testing and extension services.

UNIDO, in consultation with experts in this field, has identified these areas about which developing countries lack adequate information:

(a) The criteria on which policy should be based, particularly in regard to energy utilization in rural areas;

(b) The appropriate governmental structure and machinery for development planning with respect to non-conventional sources of energy;

(c) Indigenous technology relating to the application of non-conventional sources of energy;

(d) Local potential for engineering development and manufacture of production equipment, as well as product demand analysis;

(e) Appropriate institutional facilities, work programmes and technical manpower for *(c)* and *(d)*.

Special equipment to harness solar radiation must be made available. As with other products, the equipment may be obtained by importation or local production. However, solar energy exploitation provides a unique opportunity for co-operative programmes between industrialized and developing countries, as well as among developing countries.

Therefore, if eventual local manufacture of solar energy equipment is the ultimate goal of developing countries, then applied research and development is an important integral element in eventual local manufacture, operating in two ways, by local design and development and by adaptation of imported technology. In either, co-operation among developing countries and technology transfer from industrialized countries to developing countries plays an important part. In addition, international assistance is required.

There are many prerequisites for international co-operation in solar energy research and development. Three require action by the Governments of developing countries themselves:

Elaboration of a national energy policy

Evaluation of the role to be played by non-conventional sources of energy

Realistic analysis of the contribution of solar energy to that role

As the next step, a national institution should be designated for carrying out the applied research and development, technology transfer, extension and manufacturing promotion activities. Such a programme should consist of not only technical evaluation of imported technology and hardware products but also local development of domestic technology and products. Such an integrated activity should concentrate on adaptation, prototype fabrication, testing, techno-economic analysis, and eventual local manufacture of appropriate products. The programme should also include technical manpower development, technology transfer, co-operation among developing countries, and the physical facilities should include technological research, engineering design and development, laboratory and field-testing facilities, prototype manufacturing facilities and a manufacturing extension programme.

Recommended programme

Taking into account the world-wide state of the art and the capabilities of the developing countries, there is a need for developing countries to draw up a three-phase programme for the immediate (1980-1990), intermediate (1999-2000) and long (2000 and beyond) term.

To elaborate the programme the developing countries need the answers to two questions:

What is the state of the art in solar energy in industrialized countries? What may be achieved, and when?

Which technologies could be applied to the immediate needs of developing countries and which require more time for effective realization, commercial exploitation and utilization?

Based on the analysis of the available information, it is recommended that the programme of applied research and development and manufacture in developing countries in the three phases be as follows:

1980-1990. Programmes for immediate local commercial exploitation and local manufacture of solar energy equipment based on well known and accepted low-temperature technology. This may be flat-plate collectors and solar equipment such as solar water heaters, grain driers, space heaters, cookers and water stills. These are the only products that can be considered for local manufacture. The applied research and development programme in this case would involve production of commercial manufacturing prototypes and manufacturing promotion. The international assistance in applied research and development may be information dissemination, prototype exchange, assisting applied research and development institutions, and manufacturing promotion, with emphasis on cost, realizability and acceptability.

1991-1999. To be ready for possible commercial exploitation of solar energy by 1990-2000, the developing countries may have to start applied research and development programmes on medium- and high-temperature technology now. This will be primarily based on concentrating parabolic collectors with or without a tracking system. The solar products may be solar coolers, refrigerators, water pumps and small electric generating plants. Although the principles are known, the work is still in the experimental and prototype stages even in industrialized countries. The solar pump and generating systems that have been installed in a few developing countries by industrialized countries are still prototypes, and the exact commercial opportunity with special reference to local manufacturing potential in developing countries is yet to be assessed. Therefore, the applied research and development programmes of developing countries will have to be carefully evaluated. They will have to concentrate on keeping track of research and development work being done in industrialized countries; evaluation, adaptation and absorption of imported technology; and regional co-operation among developing countries. In this connection an effort should be made to prevent duplication of work, and a mechanism will have to be established to develop exchange of research and development information among developing countries. As research and development is expensive, the developing countries should be selective, within the framework of national requirements and priorities. It may be worthwhile to consider co-operative research and development programmes with emphasis on effective prototype fabrication at selected regional centres of selected developing countries. In addition, such results may be made available free to other developing countries through a network system. That could result in local product performance evaluation and possibly commercial manufacturing promotion.

2000 and beyond. In order to be ready to effectively utilize the commercial opportunities that may arrive in the "solar era" of 2000 and beyond, the developing countries should establish a judicious research and development programme now. However, it must be understood that it is industrialized countries that are engaged in this sophisticated high-temperature technology. The eventual products are optical transmission technology, solar power towers and complex technology involving solar cells, semiconductors, photovoltaic conversion and material science. This research and development is expensive. The industrialized countries themselves do not know the answers, although the direction is known. The role of developing countries is therefore complex. However, this field has a great potential for international co-operation, especially between industrialized and developing countries. There is a need for sharing of efforts and results; twinning of research and development institutes in industrialized and developing countries on specific applied research programmes should be established. The prerequisites for such a programme in developing countries are:

(a) Identification of local institutions that have the potential for undertaking such a co-operative research and development programme under a twinning of institutions scheme. Existing institutions may have to be strengthened and personnel trained;

(b) Exchange of information, initiation of fellowships and organization of seminars and training programmes.

Integrated action in the United Nations system

Taking into account the three-phase programme detailed above, the most important aspect for initiation of applied research and development programmes is to establish realistic targets based on the present and probable future state of art. There is a need to be selective in applied research and development programmes. The eventual aim is to promote local manufacture. But that requires various prerequisites; international co-operation in this field will be in the strengthening of existing institutions, promotion of technology transfer, training and promotion of co-operation among developing countries.

In principle, the integrated programme of action in the United Nations system incorporates the following two areas:

(a) Evaluation of the existing technology in the field of solar energy in order to define the appropriate technology for the developing countries;

(b) Elaboration of a programme of technical assistance aiming at developing the utilization of solar energy, intensifying research and development, initiating the manufacture of equipment and strengthening the transfer of technology among developing countries.

The programme will require the following steps:

Identification of institutions in developing and developed countries

Practical research and development programmes

Development of prototypes, specifications and standards

Manufacturing promotion

Technology transfer from developed countries to developing countries

Co-operation among developing countries

UNIDO activities in non-conventional sources of energy

The UNIDO programme in non-conventional sources of energy is in the areas of solar, wind, pyrolysis, biomass energy now and may incorporate micro-hydropower, geothermal energy and photosynthesis later. The emphasis in assisting the

developing countries is on the adaptation and extension of imported technology, the promotion of applied research and development, and the extension of domestic technology with special reference to promotion of eventual local manufacture of equipment together with development of the necessary infrastructure. In this connection, significant emphasis is given to the promotion of co-operation among developing countries.

In early 1977, UNIDO organized, in co-operation with the Austrian Solar and Space Agency, an expert group meeting on the existing solar technology and the possibilities of manufacturing solar equipment in developing countries. (See preface and annex I.) The conclusions and recommendations of this expert group may be regarded as the basis of the UNIDO programme of action and technical assistance activities in the field of solar technology.

Possible UNIDO assistance to developing countries

UNIDO, at the request of the Governments of developing countries, is prepared to assist them in the promotion, development and utilization of solar energy along the lines recommended above. The components of UNIDO technical assistance may be experts, equipment or fellowships for specific, approved projects. Normally, these components are financed by funds allocated by the United Nations Development Programme (UNDP) according to the Indicative Planning Figure (IPF) for each developing country for a given programme cycle. (The next cycle is 1978-1982.) Therefore it is recommended that the Governments of the developing countries allocate a priority for UNDP-IPF technical assistance projects in the field of solar energy. In addition, UNIDO has modest funds available for direct assistance.

Development of solar energy utilization in developing countries

Assad Takla

Afamia Consulting Engineers, Abu Dhabi, United Arab Emirates

Introduction

History shows that solar energy has been utilized for a long time, but it was only in the last century that such equipment as boilers fitted with mirrors, steam engines, hot-air engines and cookers came into being. The intensive development of thermal and electrical engines and the extremely low cost of energy, especially that imported from the third world, discouraged research in the field of solar energy to some extent. Now that the cost of energy is reaching a normal level and the discovery of new oil resources is becoming rare, industrialized countries are launching intensive research programmes in solar energy. For example, the Energy and Research Development Administration (ERDA) in the United States of America had a budget of $115 million for the fiscal year 1976. The projects in this field of the International Energy Agency (IEA), whose member States are all industrialized countries, are described in annex II on page 150.

Some methods of utilizing solar energy have reached a stage of development where they can compete economically with methods of using conventional energy sources. Since developing countries are often situated in sunny regions, it is in their own interest that they should develop the utilization of solar energy, which is free, inexhaustible, omnipresent (no transport or distribution problems) and non-polluting. This energy could be converted into mechanical, electrical or chemical energy to be used in various fields, such as the production of electricity, desalination of water, irrigation, cooking, food preservation by means of refrigeration, drying of fishery products, fruit and vegetables, space heating, and air-conditioning.

The purpose of this study is to give an account of the development of research on solar energy and its utilization from the techno-economic point of view. It aims mainly to throw light on the principal issues related to the utilization of solar energy by developing countries, and it is hoped that it could serve as a first guideline for technicians, economists and policy makers in those countries.

There has been a proliferation of commercial companies in the field of solar energy. Unfortunately, some of them have asked extremely high prices for the transfer of solar technology of doubtful value. Most developing countries therefore need a tool that can help them to improve their position in negotiating the transfer of solar technology for R and D purposes. This study is the first attempt at providing such a tool. For more details concerning one aspect or another of the study, more specialized references should be consulted. An annotated bibliography of important sources of information is provided. Annex III, on page 152, which describes information systems, and annex IV, on page 155, a list of institutions involved with solar energy, should also be consulted.

Attention has here been focused on the short- and medium-term prospects because available data are not good enough to serve as a basis for valid long-term projections. However, because of the accelerated change in technology, it is also felt that a study of this nature should be repeated periodically and that the specific field of utilization of solar energy in developing countries should be discussed periodically in expert group meetings.

This study is neither a manual nor an extensive and detailed survey of all aspects related to solar energy utilization. Its chapters are not balanced; in general more importance has been given to fields which have not yet been popularized.

Chapter I describes the general applications of existing technology and includes information gleaned by the author in visits to R and D centres and at international meetings. In the second chapter some general techno-economic comparisons are made to show which solar equipment could be economically utilized in the short- and medium-term in developing countries. General equations for the comparison are introduced and an example of their use is elaborated.

The author has visited some important centres of solar and wind energy research in developed countries (Canada, France, Germany, Federal Republic of, Netherlands, United States of America) and developing countries (Greece, India, Mexico, Trinidad and

Tobago). Some findings and evaluations based on these visits constitute chapter III. Problems and possible solutions and the general trend for co-operation between developing and developed countries and among developing countries are discussed.

Except for the original work and the personal appraisals, the author does not claim credit for the information included in this study. Such information is based on available technical literature, brochures or statements by manufacturers and on direct contacts and discussions held in specialized institutions.

I. DEVELOPMENT AND STATE OF THE ART

Conversion of solar energy into mechanical energy

General considerations

The term "solar engine" designates an engine operated by solar energy. The thermodynamic cycle of such an engine may be as follows: Vapour is obtained when a liquid working fluid is heated by solar radiation. This vapour expands in a reciprocating or rotating engine, doing work. From the engine it flows to a heat exchanger, in which it condenses. The condensate is reinjected by a pump (usually operated by the solar engine itself) to another heat exchanger, in which it evaporates, closing the cycle.

The efficiency of the engine depends first on its Carnot efficiency:

$$\eta_C = \frac{T_1 - T_2}{T_1}$$

where T_1 is the thermodynamic temperature of the hot source (the evaporating heat exchanger in the example) and T_2 the thermodynamic temperature of the cold source (the condensing heat exchanger).

It appears from this equation that, theoretically, one should use the highest temperature possible for the hot source and the lowest temperature possible for the cold source. In a practical sense, however, T_1 depends on the performance of the solar collectors and on how high a pressure the materials of which the engine is made can withstand; for example, the pressure of Freon 22 is already 20 bar at only 50°C. And, T_2 cannot be lower than the temperature of the fluid used for cooling—water or air with natural or forced convection.

No standards defining the range of low, medium and high temperatures exist. In this study, however, "flow temperature" means a temperature below 100°C. Flat-plate solar collectors capturing direct and diffuse solar radiation operate in this range. "Medium" and "high" temperatures will therefore refer to temperatures above 100°C; in this case, focusing solar collectors, which track the sun and trap only direct solar radiation, are used.

Air can be heated to a relatively high temperature by solar energy and used as the working fluid in a solar engine. Two cycles can be used:

(a) *Closed (Stirling).* The air is compressed in a cold space. Then it is put into contact with a hot source, where its pressure increases and expands in a power cylinder. From there it flows to the cold space and the cycle is closed;

(b) *Open (Ericson).* Compressed air is introduced into a hot space. It then expands and exhausts into the atmosphere.

Low-temperature solar engines

Practically speaking, the low-temperature solar engine is restricted to temperatures lower than 80°C. A working fluid (Freon 22, Freon 12, Freon 11, Freon 114 or butane) is evaporated directly in flat-plate solar collectors or by hot water obtained from solar collectors and circulating in a heat exchanger (evaporator). (See figure 1.) In its gaseous phase, the working fluid flows to and expands into a reciprocating or rotating engine. From the engine it flows to an air- or water-cooled condenser, from which the working fluid, now a liquid, is reinjected into the evaporator by a pump operated by the solar engine itself. In some applications, when hot water is used to evaporate the working fluid, a circulating pump also operated by the solar engine is used to accelerate the circulation of the hot water and improve the heat transfer in the evaporator. In this case, manual starting is necessary.

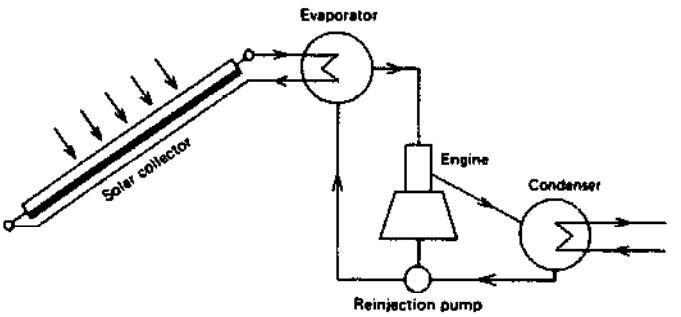


Figure 1. Low-temperature solar engine with working fluid evaporating in an evaporator heated with hot water from the solar collector

Direct evaporation of the working fluid in the solar collectors can be economical in small installations, but it would be very difficult to use the method in large solar collectors because of the difficulty of maintaining trouble-free circulation of the working fluid in large installations.

SOFRETES engine

The Société française d'études thermiques et d'énergie solaire (SOFRETES), has already installed or is installing about 50 solar pumps, most of which are rated at 1 kW.

The technology, however, is not yet fully developed. SOFRETES has tried butane and many kinds of Freon, especially Freon 12 and 11, and now seems to be changing to Freon 114. Their technology with respect to heat exchangers has changed. Shell-and-tube condensers and evaporators were used first, then tube-in-tube (coaxial) condensers, and now plate heat exchangers similar to those used in the food industry.

In one of the 1-kW solar-pump installations using butane as the working fluid and 60-m^2 flat-plate solar collectors, the water outlet temperature of the solar collectors is about 70°C. The temperature at the outlet of the evaporator and at the entrance of the solar reciprocating engine is about 67°C, and the outlet temperature of the engine is about 50°C. The condensing temperature in the condenser, cooled by the pumped water, is about 30°C. In a good solar radiation regime, such an engine could function about 6 h a day without solar storage, but it would not give full power all this time. In another 1-kW solar-pump installation, the engine entrance temperature is 55°C, the engine outlet temperature, 40°C and the condenser outlet temperature, 30°C.

SOFRETES, in collaboration with the Government of Mexico, has installed a 25-kW solar power plant in San Luis de la Paz. The electric generator is operated by a turbine of 7 200 rpm driven by the evaporated Freon 11 at a pressure of about 3 bar. The working fluid entrance temperature is 57°C and the outlet temperature is about 30°C. The Freon 11 is evaporated in an aluminium evaporator with an exchange surface of about 350 m^2 and rate of 1 740 MJ/h with a water entrance temperature of 62°C and a water exit temperature of 58°C.

The evaporator is fed with hot water coming from solar collectors with a net effective surface of 1 200 m^2. The gas is condensed in a stainless steel condenser exchanging 1 590 MJ/h with an exchange surface of about 100 m^2. The condensed Freon is reinjected into the evaporator by a 3-kW reinjection pump driven by electrical energy from the electric generator.

The installation has been in operation for about one year and does not present serious technological problems, but the control system is very sophisticated.

V-2 solar vapour engine

Erich A. Farber of the Solar Energy and Energy Conversion Laboratory of the University of Florida (United States of America) has developed the V-2 solar vapour engine, which uses Freon evaporating directly in the solar collectors. It consists of two cylinders at right angles to each other, each having a bore of 51 mm and a stroke of 39 mm. Slide valves control the vapour flow in and out of the cylinders admitting vapour for 90° of the flywheel rotation and exhausting it for 140°. The engine, 25 cm high, 35 cm wide and 23 cm deep, is mounted in a housing 40 cm in diameter and 25 cm deep. The total displacement of the engine is 305 cm^3 per revolution.

The vapour is fed to the engine through the housing and, after it has produced work, is exhausted into the housing surrounding the engine. Thus any leaks that may be present are not critical, since the housing catches all exhausted and escaping vapours. From the housing, the vapour flows to the condenser.

The speed of the engine is controlled by an adjustable centrifugal flywheel governor, which regulates the vapour flow to the engine.

The water-cooled condenser used in connection with this engine is a cylinder 76 cm in diameter and 61 cm long containing seven coils of 3.5-cm pipe, giving a total length of 13.5 m. The vapour is condensed in this pipe.

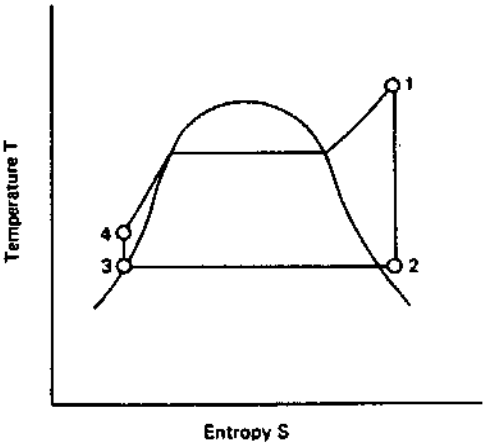


Figure 2. Ideal temperature-entropy diagram of the V-2 solar vapour engine

The operating conditions and the ideal temperature-entropy *(T-S)* diagram for the system are shown in figure 2. Path 1-2 represents the expansion of vapour through the engine, which converts some of the thermal energy into mechanical work, path 2-3, the changes of state that occur in the fluid when it is moving through the condenser, path 3-4, the pump action raising the pressure to that of the solar vapour generators, and path 4-1, the changes that occur in the evaporator, completing the cycle. This same cycle is presented for Freon 11 as the working fluid on the pressure-enthalpy *(p-H)* diagram in figure 3. Conservative operating conditions that can readily be obtained by such systems were selected. Vapour at a temperature of 72°C is delivered by the flat-plate solar collectors; the liquid from the condenser has a temperature of 28°C. The pressures corresponding to these temperatures are moderate and do not require special design.

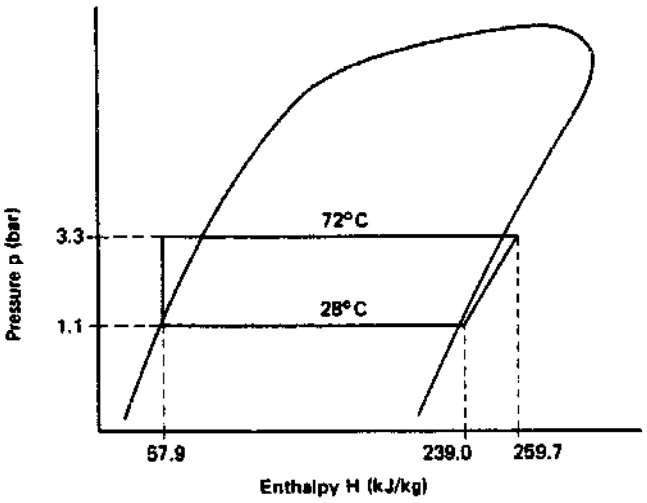


Figure 3. Pressure-enthalpy diagram of the V-2 solar vapour engine using Freon 11 as the working fluid (not to scale)

The changes of state of the air inside the engine cylinders, on one side of the piston, are indicated in the idealized pressure-volume *(p-V)* diagram of figure 4. (In reality, the corners are rounded.)

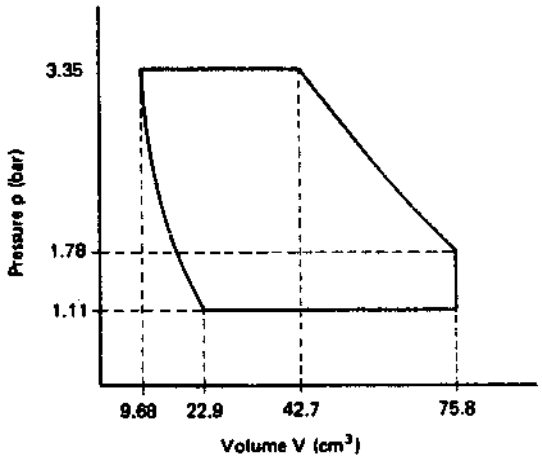


Figure 4. Pressure-volume diagram of the air inside the cylinders of the V-2 solar vapour engine

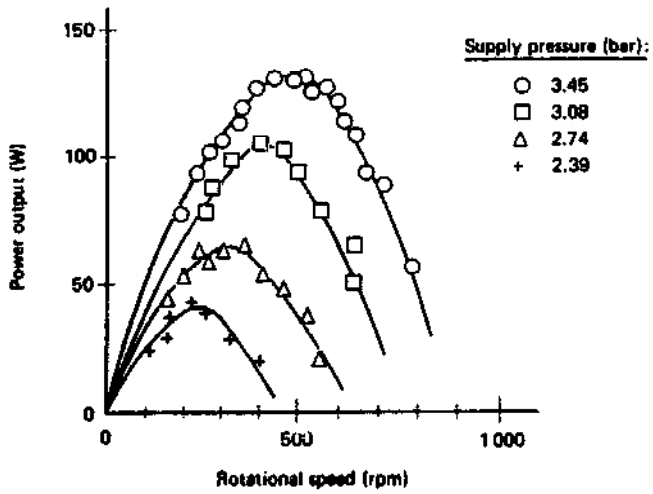


Figure 5. Power-speed curves for the V-2 solar vapour engine

Figure 5 shows the actual performance of the engine with supply pressures held constant at 2.39, 2.74, 3.08 and 3.45 bar, pressures corresponding to temperatures of 51°, 56°, 60° and 65°C, respectively, for Freon 11. The curves are typical of engine performance. Maximum speed is reached at no load, and as the load is increased the speed drops. If the power output is plotted against rotational speed, each curve exhibits a maximum. Temperatures and pressures higher than those shown can be obtained, but only for a very short part of the day.

The combination of two cylinders in a compact V arrangement makes this engine self-starting, which is a distinct advantage when cloud cover is intermittent.

Sun Power Systems engine

Sun Power Systems has developed a rotating engine designed mainly to use industrial waste energy. However, the working fluid, namely, Freon, could be evaporated by hot water obtained from flat-plate solar collectors. The engine is based on the Rankine cycle. A 10-kW power generation plant was tested at Albuquerque, New Mexico (United States), by a team of consultants working for the United Nations Environment Programme (UNEP), before being sent to a project executed by UNEP in Sri Lanka. This unit is now operating at full power with 12 m^3 of water at 90°C entering the Freon evaporator hourly. It is expected that a 276-m^2 net effective surface of solar collectors would provide the energy necessary to heat the water. In this plant two standard heat exchangers manufactured by a refrigeration and air-conditioning firm are used, one, with a 23-m^2 heat-exchange surface, as evaporator and the other, with a 35.2-m^2 heat-exchange surface, as condenser. The engine runs at 1 800 rpm and its weight is about 80 kg. It drives a 60-Hz electric generator. The engine, including the heat exchangers, the reinjection pump and the electric generator, is quite compact.

The 10-kW power is for a 55°C difference between the evaporating and the condensing temperatures, but in practice such a difference cannot be obtained with a flat-plate solar collector; only a difference of about 40°C can be expected with the usual collectors of this type. The maximum expected power will then be about 7 kW. As in the case of the SOFRETES engines, lubrication is ensured by a lubricant dissolved in the Freon. The actual surface of the evaporator seems to be insufficient, particularly when the temperature of the hot water entering the evaporator is about 70°C. According to the manufacturer, one of his small prototypes has been tested for 10^4 h without significant problems. However, the test was undertaken near the factory and not in the field.

Gironnet-ENSAM engine

The Ecole nationale supérieure des arts et métiers (ENSAM) has developed a prototype low-speed

reciprocating engine delivering less than 1 kW and is now negotiating with an industrial firm to undertake the manufacture of a 2-kW prototype. The only technical problem that has not yet been resolved is lubrication. The same system of lubrication as that used by the SOFRETES engine or the Sun Power Systems engine could be used, but an attempt is being made to develop a dry lubricating system, which is believed would be better.

The cost of construction of the 2-kW prototypes is estimated at $4,000, not including the solar collectors, of which the required surface is estimated at 50-60 m^2 in a favourable solar radiation regime.

The first prototype is being tested with compressed air. Such a test will not permit a valid evaluation. However, the design of the engine is simple and its expected cost is relatively low.

Messerschmidt-Bölkow-Blohm (MBB) engine

Messerschmidt-Bölkow-Blohm GmbH, Ottobrunn, Federal Republic of Germany, is working on a 10-kW solar electric power plant. (See figure 6.) This plant is to be an independent power station for remote rural communities. Besides the required peak electrical power of 10 kW, an energy reserve for night operation is planned that has been specified to be 12 kWh at the rate of 1 kW. This requirement implies an optimal energy storage system. The flat-plate collectors used for about two years by MBB in preliminary work on solar space heating will be used as solar collectors. To achieve the desired peak power, a total collector surface of approximately 700 m^2 is required. MBB expects to be able to reduce the net effective surface of the solar collectors to about 350 m^2. However, the final specification of the required surface depends strongly on the climatic conditions and consumer requirements at the place of installation and must be harmonized with the required storage capacity over the 24-h working cycle taking into consideration the partial-load behaviour of all the plant components. A screw motor developed by the Linde company, using R114 as the working fluid, will be used because of its expected high efficiency in the partial-load range. Other advantages are low specific weight (weight-to-power ratio), small bulk and absence of valves.

The MBB flat-plate collector is a two-glass collector of modular design. The outer dimensions of the absorption surface of each module are 60 cm X 180 cm ≈ 1 m^2. The absorber is made of roll-bond aluminium and is protected against corrosion by an inhibitor. The outer absorber layer is a thermal paint with a high absorption factor (0.96). (The paint was developed for space applications.) The rear heat insulation consists of a protected polyurethane-foam cover. The temperature of the hot water could be as high as 95°C.

MBB has already assembled a prototype, which has been given several short tests with hot water supplied by an electric boiler. Some modifications are now under consideration. The engine itself is very compact and is used in the air-conditioning of trains. (It has been modified to be included in this plant.) To reach the evaporating temperature of R114 with conventional flat-plate solar collectors would be very difficult. Sophisticated technology, including the use of selective surfaces in the collectors, would have to be used, and it has not yet been proved that such collectors can be manufactured easily at a reasonable cost. However, MBB is open-minded about all possible changes regarding temperatures used or modifications in the design of the plant.

High-temperature engines

To obtain steam or vapour is the main problem with the high-temperature solar engine. The Carnot efficiency η_C is relatively high, but other efficiencies

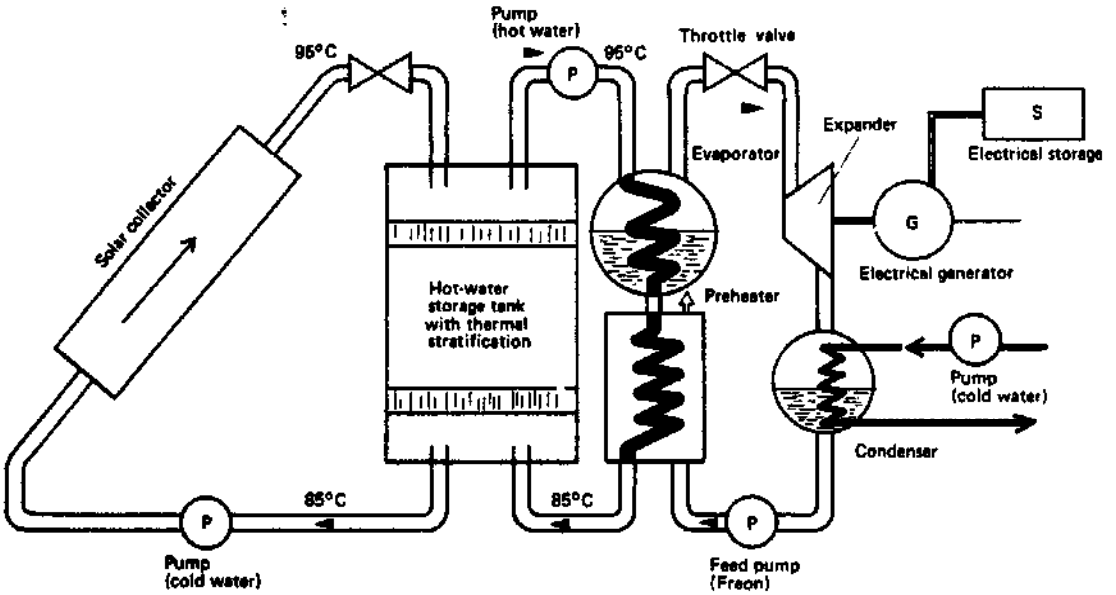


Figure 6. Schematic diagram of the MBB solar electric power plant

should be taken into consideration. In the case of the heliostat, for example, the overall efficiency is

$$\eta = \eta_C \eta_d \eta_r \eta_s \eta_a \eta_l \eta_h \eta_t \eta_m$$

the individual efficiencies other than η_C, which depends on T_1 and T_2 (see above), having the following typical values:

η_d	diffuse-direct solar radiation factor	0.80
η_r	reflectivity of mirror	0.80
η_s	sunset-sunrise factor	0.70
η_a	focal absorption and geometrical losses	0.70
η_l	heat losses	0.70
η_h	transient clouds factor	0.80
η_t	heliostat spacing factor	0.6
η_m	mechanical efficiency ratio	0.5-0.8

It can be seen from those figures that the overall efficiency cannot be more than 5%-8% of the Carnot efficiency. For example, if the steam temperature is 200°C (T_1 = 473 K) and the condensing temperature is 30°C (T_2 = 303 K) the Carnot efficiency is about 36% and the overall efficiency of the system is 1.9%-3.0%. In a favourable solar radiation regime about 40 m² of heliostat will be needed to obtain an average power output of 1 kW during the daytime. Some firms seek to obtain an area per unit output of 10-15 m²/kW but this generally refers to peak, not average, power. (Peak power is the power delivered by the engine when solar radiation is maximal.)

Many institutes are working on very large thermal power plants. For example, the Centre national de la recherche scientifique (CNRS), in collaboration with Electricité de France, is working on a high-temperature power station of 10 MW in which the pressure could reach 80 bar. A 100-kW boiler being developed jointly by CNRS, Babcock-Wilcox, Heurtey, St. Gobain and Renault (SERI) and using heliostats was to have begun operation at Odeillo in early 1977.

Among the firms which have already realized a prototype of a small steam engine is Maschinenfabrik Augsburg-Nürnberg AG (MAN) in the Federal Republic of Germany, which, in collaboration with the Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt, Stuttgart, is constructing a plant consisting of 12 collector rows that track the sun with 6 parabolic trough collectors (concentrating factor, 30) in each row. The length of a collector is 2.5 m, the aperture 1 m². The collectors are arranged on a platform inclined at an angle corresponding to the latitude. The total effective mirror area of the prototype is about 180 m², the working temperature is 200°C and the mean thermal energy output per day is about 700 kWh (working time from 7 a.m. to 5 p.m.). With a steam motor and electric generator (10 kW peak), the electric power output is about 70 kWh/d (overall efficiency about 6%). The condensed water has a temperature of 95°C, and it is planned to use it for hot-water supplies, space heating or air-conditioning. To increase the electrical output while decreasing the effective collector surface, higher working temperatures are envisaged. Table 1 shows the specifications planned for different stages of development of the plant.

TABLE 1. SPECIFICATIONS OF THE MAN SOLAR POWER PLANT AT DIFFERENT STAGES OF DEVELOPMENT

Specification	*Prototype*	*Improved type*	*Optimized series type*
Effective area (m²)	180	130	100
Working temperature (°C)	200	250	300
Thermal capacity (kWh/d)	700	480	390
Electrical capacity (kWh/d)	70	69	68
Efficiencies (%)			
Collector	58	54	59
Cycle	20	24	28
Motor/generator	50	60	63
Overall	6	8	10

According to the design, this plant could be extended in modular construction to larger plants having electrical power outputs up to several hundreds of kilowatts.

MAN is also working on a screw motor, and it is planned that this unit will work with superheated Freon 114 vapour.

The following quotation is taken from a MAN report.

> "The chance of success with a low-temperature solar engine is very small. Contrary to concentrating collectors conventional flat-plate collectors utilise partly the diffuse radiation. This part however, is on the average lower than 10 per cent for the regions considered and plays therefore a minor role. Flat-plate collectors have the crucial disadvantage of strongly decreasing efficiency with increasing collector temperature. Furthermore, the insolation on fix tilted collectors is smaller in the morning and afternoon. Thus the value of efficiency decreases still more. An additional disadvantage is that a low-boiling working fluid such as Freon must be used. This demands expensive heat exchangers.
>
> "The thermal efficiency increases correspondingly for higher collector temperatures. However, sufficiently high efficiencies can be achieved only if envelopes reflecting the infrared radiation are used (which are expensive) or selective coatings are applied (which show degradation).
>
> "Focusing collectors consist for instance of a parabolic trough or a Fresnel lens concentrating the direct solar radiation on an absorber pipe mounted in the focus line. These collectors have very high efficiencies—about 50 per cent—already for low concentrating factors between 20 and 30.

"Focusing collectors must track the sun. Thus the high efficiency remains nearly constant in the morning and afternoon. A further crucial advantage—contrary to flat-plate collectors—is that conventional, available steam engines can be used because of the higher working temperatures."

The steam engine used in the MAN plant is a conventional one that was manufactured in the 1960s. Its power capacity is greater than that which the available set of solar collectors can give.

The expected breakdown of the cost (1976) of the plant per unit of electrical power output is ($/kW):

Steam engine and generator, including frames and controls	810
Condenser	140
Pumps, pipelines, insulation and cycle controls	200
Storage, insulation and storage-water container	530
Collector	1 110
Total	2 790

In the United States, many small companies have emerged whose aim it is to construct focusing solar collectors that track the sun automatically. One of them, Sun Power Systems Corporation in Tempe, Arizona, has developed cylindro-parabolic solar collectors. One of these has the following performance data and specifications:

Description: Aluminium parabolic troughs are arranged in series; the number of troughs needed per specific installation is determined by energy requirements. Troughs are kept constantly focused on the sun by an electronic device that incorporates a high-temperature defocusing capability, low-temperature freeze protection, and a temperature comparator that guarantees that the unit will only heat water in the storage facility

Trough dimensions—standard: 4 ft X 10 ft (1.22 m X 3.05 m; effective area 3.41 m^2)

Trough surface: anodized aluminium, guaranteed for over five years. Dust has no significant effect on efficiency

Energy produced daily (assuming latitude N 32° and 100 % sunshine):

	Per unit area		*Per trough*	
	(MJ/m²)	*(Btu/ft²)*	*(MJ)*	*(Btu)*
21 June	21.41	1 885	73.0	69 190
21 December	13.05	1 149	44.5	42 170
Average	17.23	1 517	58.7	55 680

Concentration ratio: 44 to 1

Absorber fluid: water

Absorber fluid flow rate: 0.3 l/s (5 gpm), although the system works equally well with faster or slower flows

Water temperature: 177°C (350°F) (closed-loop system circulating water from eight collectors through a 150-l (40-gal), insulated storage tank)

Maximum operating pressure: 20 bar (300 psi)

Collector weight: specific, 7.3 kg/m^2 (1.5 lb/ft^2); per trough, 27.2 kg (55.1 lb) (includes all framing, components, water)

Absorber material: 1-in. hard copper pipe with selective black coating

Framing material: tubular steel (rectangular), 0.065-in. (1.65-mm) wall

Tracking motor: 2.8 rpm; gear ratio, 1 780 to 1; current load, 1 A; accurate within 10 min of sun time

Collector end-fittings: adaptable

Recommended storage per unit area of collector: 60 l/m^2 (1.5 gal/ft^2)

Orientation: north-south orientation is preferred, but not necessary

A flat roof is preferred, but not necessary

Aesthetics: system is very low profile; it can easily be placed behind a parapet wall and thus be unobtrusive

Adaptability: system can be fitted to any existing structure and can be expanded by adding extra troughs should energy demands increase

Maintenance: None required. Collectors may be washed occasionally, but it is not necessary

Storm-damage susceptibility: in overcast conditions troughs are automatically returned to nighttime position to minimize storm damage

Warranty: one year on all materials and components except those under warranty limitations imposed by other manufacturers

The problem with these simple focusing collectors, which certainly work, is that the short duration of experience is insufficient to evaluate their lifetime, their performance and the effects of climatic conditions and dust. The present (1976) unit cost of such simple solar collectors is about 100 $/$m^2$.

Summary

Medium- and high-temperature solar engines can use conventional steam engines and steam turbines. (That is nothing new; in the early years of this century, a successful solar steam engine was installed in Egypt). However, small turbines do not yet exist on the market.

The thermal efficiency of these engines is better than that of the low-temperature engines because the Carnot efficiency is higher.

The engines require direct solar radiation, which is not always available.

Focusing solar collectors should track the sun; the tracking problem can be technologically solved at

a reasonable cost. (However, no systems of this kind have yet been tested over a long period.)

Medium- and high-temperature solar energy plants are expected to be more successful in large rather than small installations.

The problem of energy storage is still the most important problem; it must be satisfactorily solved before many of the other problems can be overcome.

Hot-air engines

The Stirling engine

In a conventional combustion engine, heat is supplied by burning a quantity of fuel inside the working chamber of the engine. In the Stirling engine, heat is added to the working gas inside the engine by an external flame and a heat exchanger (heater head).

First, a volume of cool gas, entrapped in a cylinder by a piston, is compressed (figure 7a) and then heated by an external heat source (figure 7b). As the gas is heated, its pressure increases and the piston is driven downward, turning the crankshaft. After expansion (figure 7c), the gas is cooled by an external cooling source (figure 7d). Its pressure decreases, and the gas is once again compressed (figure 7a). Since the pressure during the hot expansion is much higher than during the cool compression, there is a net output of work from the engine. The complete cycle takes place in one revolution of the crankshaft instead of in two revolutions as in conventional engines.

The cumbersome exchange of the heating and cooling sources shown in the simple representation of figure 7 is, of course, impractical. Stirling's key invention was to achieve the exchange by adding a mechanism called a displacer piston, which serves to move the gas between a stationary hot chamber and a stationary cold chamber (figure 8). These chambers (represented by coils in figure 9) are connected to opposite ends of the displacer section of the cylinder. When the displacer piston moves upwards (figure 9a),

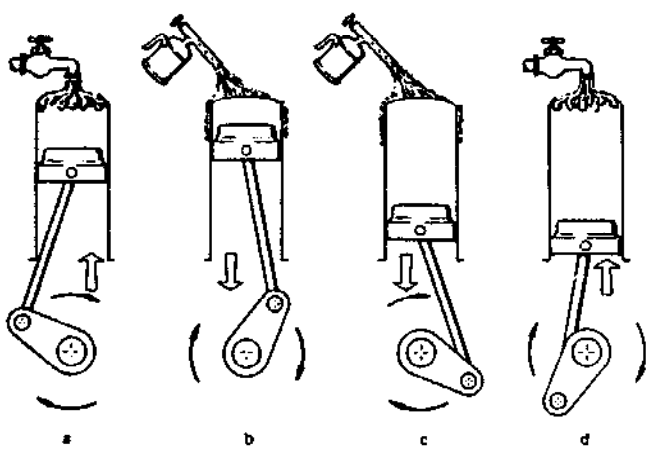


Figure 7. Simple representation of the operating principles of the Stirling cycle

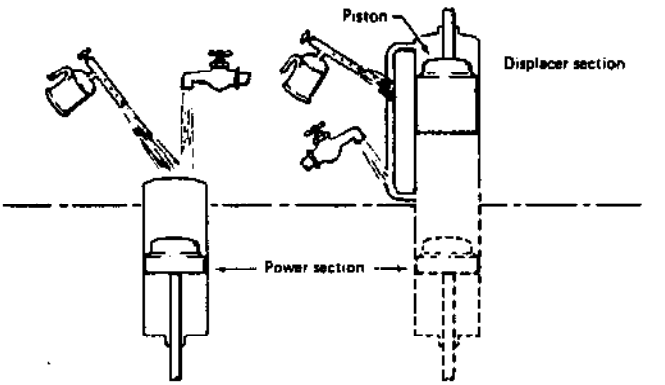


Figure 8. Simple representation of the displacer piston

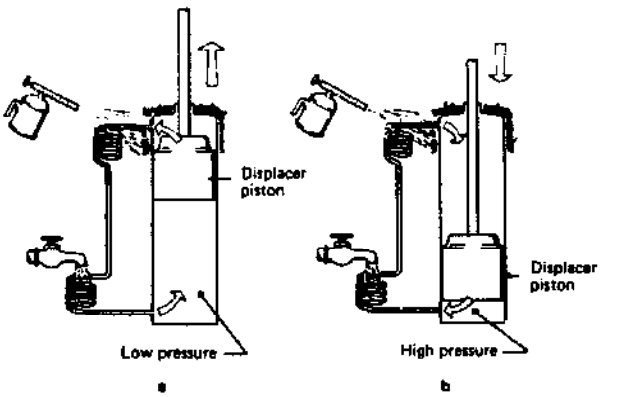


Figure 9. Action of displacer piston

the hot working gas from the upper portion of the cylinder is first moved through the heating coil. The gas then flows through the cooling coil, where it is cooled until most of the working gas is in the cold section below the displacer piston. Because the gas is cool, its pressure is low. Moving the piston downward (figure 9b) forces the working gas back through the cooling coils and into the heater tubes, where it is heated and forced into the hot section above the displacer piston. Since the gas is hot, its pressure is high. There are no valves in the flow path, so that when the upper chamber is at high pressure, the lower chamber is also at high pressure.

One more addition is required to make the Stirling engine practical: the regenerator (figure 10). Located between the fixed heating and cooling sources, it stores otherwise wasted heat during the cooling process and permits recovery of that heat during the heating phase. The amount of this stored heat is actually equal to several times the amount of heat added from the external heat source.

Figure 11 shows the regenerator and the displacer section combined with the power section to form the basic Stirling cycle power unit. (Not shown is the mechanical linkage between the pistons that maintains the proper phase relationship between them.) Figure 11a shows the cooled gas being compressed by the power piston as in a conventional internal combustion engine. In figure 11b, the

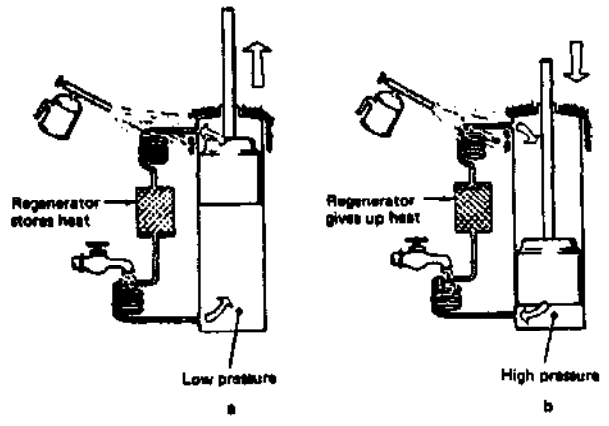


Figure 10. Action of regenerator

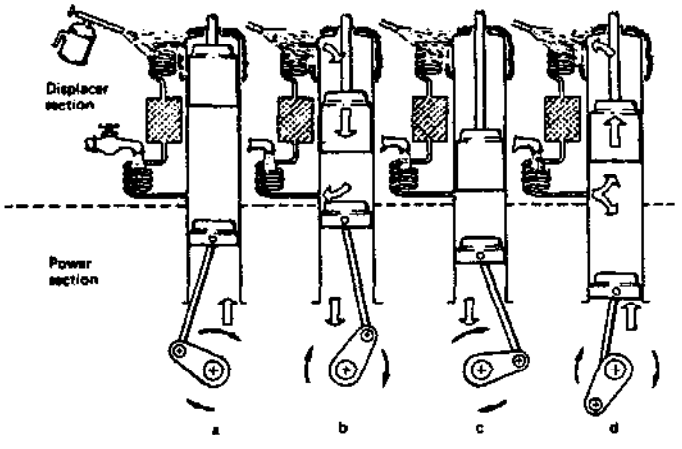


Figure 11. Stirling cycle complete with displacer section and regenerator

compressed gas is being heated and its pressure is being increased because the displacer piston is moving a portion of the gas into the upper (hot) part of the displacer section. The pressure increase is felt on the lower piston, driving it downwards. In figure 11c the hot, high-pressure gas has completed its heating cycle through the action of the descending displacer piston, and the power piston has completed its power stroke. Figure 11d shows the displacer piston moving upward to force the working gas into the cooling chamber, thus decreasing its pressure. The power piston is now ready to repeat the compression stroke of figure 11a, and the cycle is completed.

Closed-cycle hot-air engine

Philips engine

Philips has developed small hot-air engines in the past; one engine of 750 W (1 hp) at 1 500 rpm has been modified by KHANA in India for experimentation with solar energy. The heating system, in the form of a cylindrical head 6 cm in diameter and designed to burn kerosene oil, was removed and concentrated solar energy used to heat the engine. A set of mirror reflectors with a surface of 8 m^2 was used; the engine was able to operate a 200-W electric generator, but the theoretical efficiency of the Stirling cycle could not be reached.

Farber engine

Several prototypes of the closed-cycle, hot-air engine type have been developed by the Solar Energy and Energy Conversion Laboratory of the University of Florida (United States). One interesting prototype is a supercharged, water-injected solar hot-air engine in which an adjustable check-valve allows the engine to supercharge itself by drawing in fresh air or water during the part of the cycle that is below atmospheric pressure.

The engine can be "fuelled" with solar energy or used directly without modification to burn wood, coal or liquid fuels. If used with solar energy it is only necessary to concentrate the solar energy upon the end of the displacer cylinder inside the furnace box. The engine can be built with very simple machine tools.

A displacer cylinder with a bore of 70 mm and an internal length of 257 mm is mounted at the top of the engine. Inside this cyliner moves a displacer with an outside diameter of 68 mm and a length of 203 mm. The displacer, with a stroke of 50 mm has enough end and side clearance to move freely in the cylinder.

The displacer cylinder is designed so that it can be heated at one end by gas, oil or solar energy and cooled at the other end by air or water (closed or open circuit). The displacer is moved by a 12-mm rod entering through a sleeve bushing.

The displacer cylinder is connected by a 3/4-in. pipe nipple to the power cylinder, which has a piston 60 mm in diameter and a stroke of 38 mm.

The linkage between the displacer and the power piston allows timing of the engine. For normal operation the displacer leads the power piston by about 100°. Regeneration occurs along the displacer and the displacer cylinder walls. Heat is stored in those walls during part of the cycle, to be released and used during another. The working fluid, streaming back and forth, alternately giving off this heat and then absorbing it later and thus preventing it from leaving the system, provides internal regeneration.

The engine is started when the pressure inside is equal to atmospheric pressure. Thus, during operation, the internal pressure will dip below atmospheric pressure for part of the cycle. During the operation of the engine under normal conditions this dipping is enhanced by leakage of the working fluid (air) through the displacer-rod bushing, out during the high-pressure part of the cycle and in during the low-pressure part.

It has been found quite difficult to prevent or minimize this leakage without increasing the friction losses considerably. Two methods of solving the problem have been developed:

(a) Air injection. A small, adjustable ball-check valve, installed as shown in figure 12, makes it easy for fresh air to enter the system quickly during the

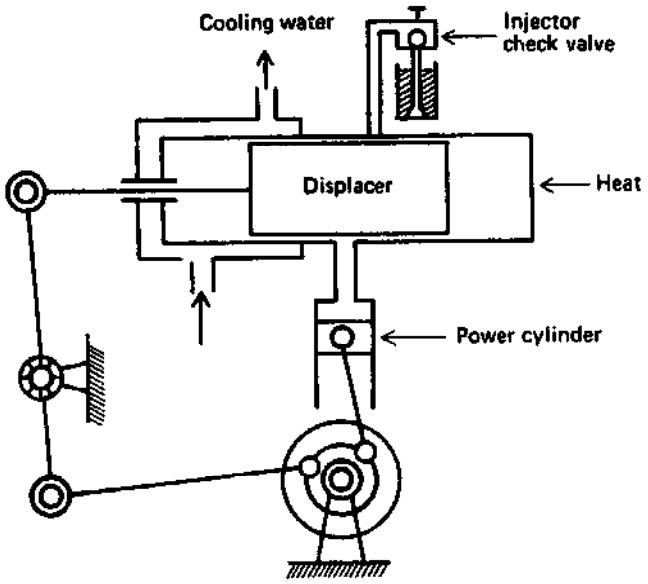


Figure 12. The Farber engine with air and water injection

below-atmospheric-pressure part of the cycle. This very simple addition allows the engine to operate with a larger average amount of working fluid, resulting in higher power output.

(b) Water injection. If the inlet to the check valve is dipped in water, water is injected into the system rather than air. This procedure allows even larger amounts of fluid to be added to the system, since it is added in the liquid phase, resulting in even greater increases in power output. Another advantage of injecting water (or other liquids) is that it greatly enhances the heat transfer at the hot end.

Thus, self-acting air or water injection can considerably improve the performance of the simple closed-cycle hot-air engine. (See figure 13.)

Engines of the type described here can be classified as "hybrid", since they combine the advantages of the Stirling cycle with those of others.

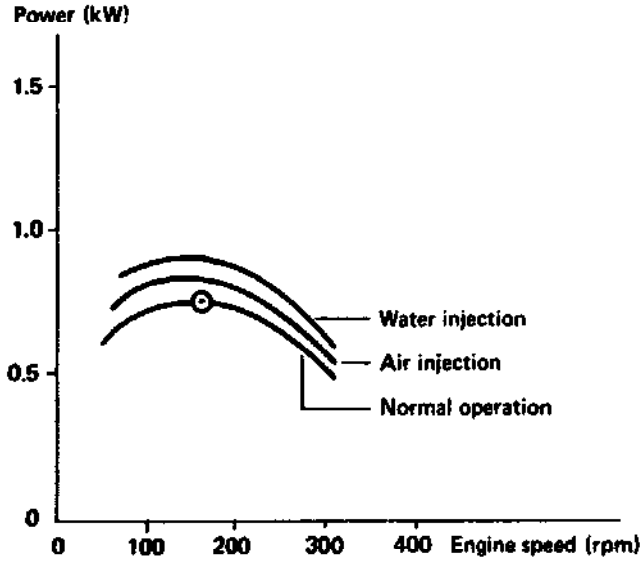


Figure 13. Power-speed curves of the Farber engine, showing the increase in performance obtained with injection

Open-cycle hot-air engine

The open-cycle hot-air engine takes atmospheric air, compresses it, then heats it by solar energy; the compressed air expands and exhausts into the atmosphere. A compressor is combined with the engine (which can also be a turbine). The advantage of this system is that the speed of the engine is independent of the air-heating cycle.

KHANA engine

A small open-cycle hot-air engine taken from an old kerosene-operated fan was overhauled. Its worn-out parts were replaced and it was suitably modified before use. It operated at an average speed of 250 rpm. Heat at the cold end was dissipated through large, thick fins cast along with the body of the engine. To give smooth and continuous running a 38-mm thick hollow disc, which formed the false bottom, was slipped over the bottom of the expander cylinder. The disc was made of copper sheet and the empty space was filled with dry sand. It formed a perfect fit and ensured complete contact between the metal surfaces. The entire cylinder length (216 mm), including the false bottom, was enclosed in a Pyrex glass tube of slightly larger diameter and closed at one end. Both these arrangements helped to raise the temperature of the hot end and to achieve uninterrupted and steady running of the engine.

Coupled to a small reciprocating water pump, this engine was suitably mounted with the three metal reflectors described above and used for experiments on pumping water from different depths. The coupled unit developed only about 45 W, half of the power expected.

Later, another hot-air engine of nearly double the capacity of the one used earlier was procured, modified and mounted in the vertical position on an iron tripod. It was used with plane-mirror concentrators. Coupled to the water pump, the engine developed about 95 W. A small parabolic cylindrical metal reflector was placed behind the cylinder to help heat the hot end of the engine uniformly and thereby ensure its smooth running.

Solar pumps

Conventional pumps can be operated by solar engines; however, prototypes of installations for pumping water without moving parts are being developed by the Birla Institute of Technology and Science, at Pilani, India. The principle is described below.

A mixture of petroleum liquids with a boiling temperature range of 35°-40°C is evaporated in flat-plate solar collectors and then flows to a closed tank full of water situated in a well. The pressure of the working fluid permits the water to rise to an upper level, depending on the pressure of the mixture. The vapour condenses during the night in the solar collectors. This discontinuous mode of

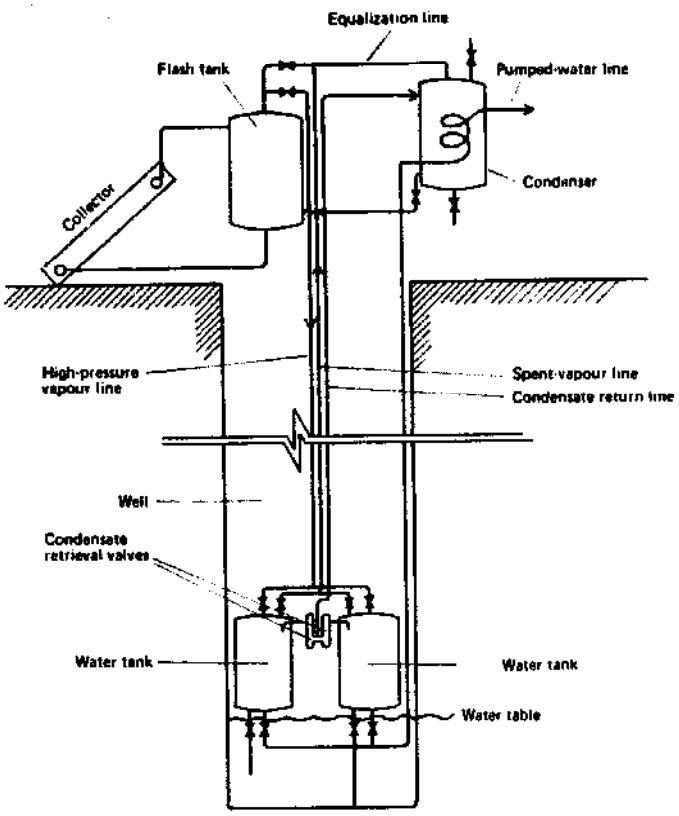


Figure 14. Solar water pump

pumping is very simple, but only a small quantity of pumped water is obtained. The vapour can also be condensed by allowing it to flow to a condenser cooled by the pumped water. By using two water tanks and a set of control valves, semi-continuous pumping is possible. Besides the collector and the flash tank, there are two water tanks located close to the water source and a condenser at ground level. The pipe network interconnecting the tanks is shown in figure 14.

The working fluid drawn into the collector is vapourized and returned to the flash tank. The vapour from the flash tank is let into one of the water tanks, displacing the water. (It is assumed that the water tanks are full of water.) The displaced water condenses the vapour in the shell side as it goes through the condenser coils. After the first tank is emptied, the vapour is switched over to the second tank. Simultaneously, the first tank is condensed by the water being pumped from the second tank. As condensation proceeds, the pressure in the first tanks is reduced and water enters through the non-return valve. Thus, as the second tank is emptying the first one is being filled. On reversing the cycle, by manipulation of the valves, the first tank will pump while the second one draws water. In this way, water can be pumped continuously.

To prevent working fluid from going into the water line, a water seal is always maintained inside the water tanks. The working fluid that is condensed in the water tank can be pumped to the condenser at the start of each cycle. The condensate is pumped by the condensate retrieval valve, which is similar in principle to a steam trap. Further, the condensate can be transferred to the flash tank, periodically or at the end of the day, by pressure equalization.

The capacity of the pump can be increased by the addition of more collectors, which affects only the cycle time.

The working fluid should be immiscible with water; have a normal boiling point slightly higher than the atmospheric temperature; and be non-toxic, non-flammable, cheap and readily available. Pentane fulfils all the requirements except for its flammability.

A petroleum fraction having a close boiling range with properties similar to that of pentane would be cheaper and more readily available than pentane. The petroleum fraction, a mixture of hydrocarbons, offers an additional advantage. It can be tailor-made to suit the atmospheric conditions of a particular region. For example, in a region where the night temperature is around 2°C and the day temperature is 15°C, by choosing a mixture having more light hydrocarbons with a boiling range of 15°-20°C, water can be pumped to a considerable height even at very low collector temperatures. In regions like Pilani (located at the edge of the Thar Desert) where extreme climatic conditions occur, the working fluid properties can be modified to suit seasonal variations by adding small amounts of light or heavy hydrocarbons to obtain high pump performance.

Practically speaking, any two fluids are always at least slightly soluble in each other; hence continuous contact of the working fluid with fresh water in each cycle will result in some loss of working fluid. Fortunately, the working conditions in the pump are such that the mass transfer rates close to interface are extremely low most of the time. As a consequence, the loss of working fluid will be negligible.

The following is a proposed specification for a solar water pump of the type described above:

Flat-plate collector area	100 m^2
Pumping rate	150 m^3/d
Head	18 m
Water tank dimensions	150 cm high X 90 cm diameter

The cost of the installation, assuming a collector unit cost of 35 $/$m^2$, would be $6,000.

In developing prototypes many technological problems remain to be solved, in particular the control of the system of valves. The present proposed electrical control does not meet the requirements of a rural solar pump, which should be independent of any external source of power.

Direct conversion of solar energy into electrical energy

Photovoltaic cells produce an electric potential when they are illuminated by solar radiation. Those utilizing the semiconductors Si and CdS are the best

known on the market, those utilizing Si having the longer lifetime. Important R and D programmes are being undertaken to improve the performance, simplify the technology and reduce the cost. In 1976, the cost per unit of power was about 15 000 $/kW (peak). Research programmes seek to reduce this cost to 8 000 $/kW in 1980 and to some hundred dollars per kilowatt in 1985.

At present, the available technology seems still too sophisticated for most developing countries, and manufacture even of a small series of cells cannot be planned for the medium term. For these reasons this subject will not be discussed further in this study in spite of its very promising future.

Solar refrigeration and air-conditioning

Air-conditioning means the treatment and handling of air to obtain well-defined values of temperature, humidity, velocity and purity of the air in a given space. Only the cooling aspect will be considered here, so that solar refrigeration and space air-conditioning can be associated. The temperature is generally lower in the case of refrigeration, especially if one is speaking of ice production or most cases of food preservation. Well-defined values of temperature and humidity could not be obtained in the case of air-conditioning without an external source of energy to operate fans, pumps and control systems.

Solar refrigeration can be achieved through a solar engine operating a conventional compressor, but in this report only absorption machines heated by solar energy will be discussed. This kind of machine can function either continuously or intermittently. In the continuous regime an external source of power is necessary, at least to operate the pumps and control system. The best known fluids used are aqueous solutions of ammonia and of lithium bromide. The first is more suitable for use with flat-plate solar collectors.

Principle of operation (figure 15)

The ammonia-water mixture is heated directly by solar energy in the generator (boiler) or indirectly by water heated by solar energy. When the temperature of the mixture rises, the ammonia begins to evaporate because its solubility in the water decreases with increasing temperature. The vapour flows to a condenser, which is water- or air-cooled, where it condenses. The operation now becomes similar to that in a conventional refrigeration system with compressor. A subcooled liquid is available at the outlet of the condenser. The pressure of the ammonia, which increases when the temperature increases, is controlled by the condensing temperature. The liquid expands through the expansion valve and begins to evaporate; its temperature and pressure decrease. The cold, low-pressure vapour reaches the evaporator, in which it absorbs the heat of the material being cooled (e.g., chilled water for air-conditioning purposes and brine for ice production). The temperature of the vapour increases and it flows to an absorber where it meets a spray of a weak solution of ammonia in water and is absorbed. The

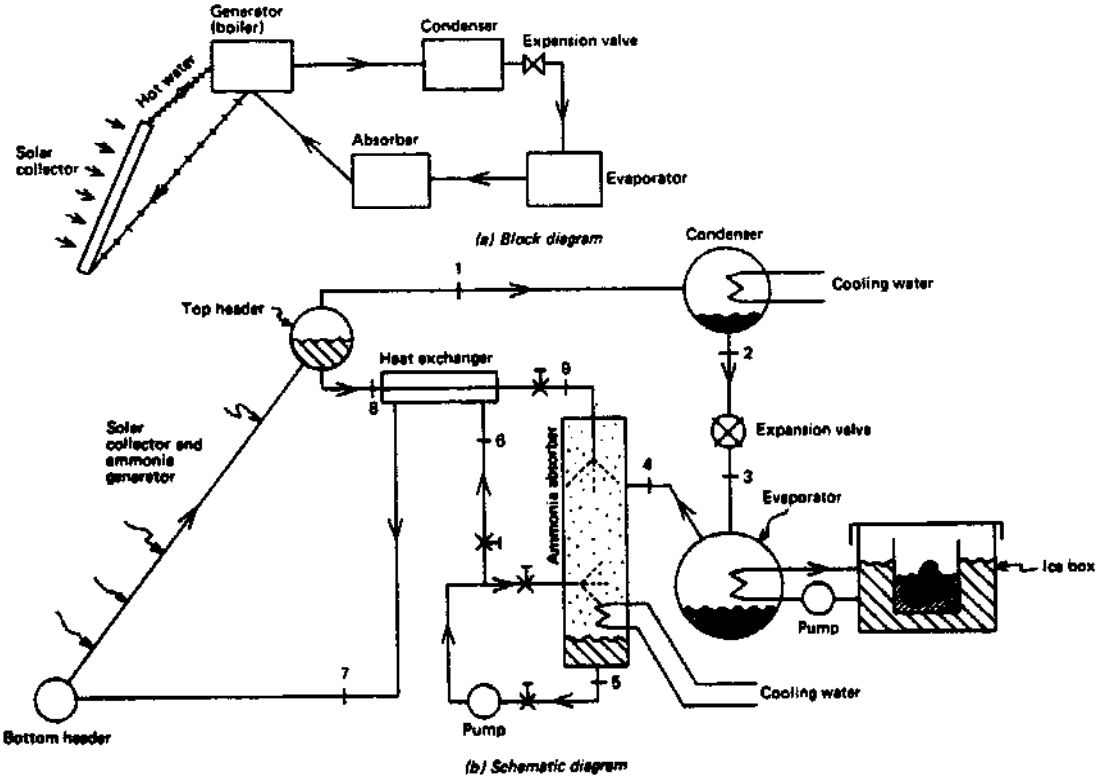


Figure 15. Ammonia-water refrigeration cycle

absorption is exothermic, and to keep the temperature of the mixture in the absorber within the limits permitting the desired concentration to be obtained, the absorber should be cooled. The concentration of the mixture increases, it is pumped to the generator and the cycle is closed.

Hence:

(a) Cooling is necessary in the condenser and in the absorber; if the cooling is by natural convection, the heat exchangers must have quite large surface areas;

(b) Powered pumps are necessary, at least to pump the mixture from the absorber to the generator; a thermosyphon, if applicable, would greatly decrease the productivity;

(c) Operation should be continuous in solar air-conditioning;

(d) A heat exchanger between the condenser and the absorber can improve the productivity.

Some experiments are taking place (for example at the Refrigeration Institute of the Technical University at Delft, the Netherlands) for producing 4 kg of ice per day with 2 m^2 of flat-plate solar collector, with an intermittent ammonia-water absorption machine independent of any external source of power. Condensation of the ammonia vapour is obtained during the night by sky radiation through the flat-plate solar collector.

First case study: *An ammonia-water solar refrigeration system, Solar Energy and Energy Conversion Laboratory, University of Florida*

A 1.2 m (4 ft) square flat-plate solar collector acts as generator. It consists of 1-in. steel pipe running from a 1.25-in. bottom header to a 2.5-in. top header. The steel pipes are spaced on 100-mm (4-in.) centres and soldered to a 20-gauge galvanized-iron sheet. This element is then placed into a galvanized sheet-metal box between a single glass cover and 25 mm (1 in.) of styrofoam insulation.

The whole unit is inclined 30° with respect to the horizontal; the angle is a compromise to provide both good solar collection and good two-phase flow and heat-transfer characteristics in the inclined tubes running from bottom to top. Since the unit is stationary it is faced south to give the best average orientation for the whole day.

The condenser consists of a 3-in. pipe shell containing four standard ½-in. black-iron pipes, 1.2 m (48 in.) long providing a heat-transfer surface of 0.325 m^2 (3.5 ft^2).

The evaporator is made from a 4-in. pipe shell containing seven standard ½-in. black-iron pipes, 1.2 m (48 in.) long providing a heat-transfer surface of 0.572 m^2 (6.15 ft^2).

The absorber is fabricated from a 6-in. pipe shell containing eleven standard ½-in. black-iron pipes, 0.9 m (36 in.) long, providing 0.573 m^2 (6.16 ft^2) of heat-transfer surface, which in addition serves as support for the liquid film in which part of the ammonia vapour is reabsorbed.

The ice production and storage unit is a cubical galvanized sheet-metal box 46 cm (1.5 ft) on an edge with 100 mm (4 in.) of styrofoam insulation around it, protected by a thin plywood outer layer.

The heat exchanger is a simple, single-pass, counter-flow, double-tube type.

The circulating pump for the water anti-freeze solution is of the standard centrifugal type, while the ammonia-water solution circulating pump is of the rotary, nylon-roller type. A bypass loop on the pump permits control of the amount of solution distributed to the various parts.

Four valves in the system in addition to the expansion valve permit control of the flow rates in different sections of the system. Numerous pressure gauges, thermometers, thermocouples and liquid-level sight-glasses permit constant monitoring of the conditions. The ammonia concentration in the solution varies from 48 to 60 wt%.

The system has been hydrostatically tested to a pressure of 20 bar and is considered safe for operation at 13-15 bar. This corresponds to a temperature in the generator of about 66°C (150°F).

To freeze the water in the metal container in the ice box, the design temperature of the evaporator is −6° to −9°C, corresponding to a pressure of about 3 bar.

Figure 16 presents the data of a test run on 6 July 1968. It was a perfectly clear day, although a considerable amount of solar energy arrived as diffuse radiation owing to the relatively high humidity. An indication of this was the slight temperature increase of the absorber-generator even before the direct sunshine hit the front surface of the unit.

At the start of the day the expansion valve was closed and the system was allowed to warm up. (The heat capacity of the combination solar absorber and ammonia generator was about 1.9 kJ/°C (46 Btu/°F).) Part of the energy used for warm-up was returned to the system in the late afternoon hours when the stored heat was released owing to the drop in temperature.

The pressures and temperatures in the solar refrigeration system were effectively controlled by varying the flow rates in the different parts of the system by adjusting the various valves. About 41 MJ (39×10^3 Btu) fell upon the absorber-generator during that day, and 18.6 kg (41 lb) of ice were produced (from 24°C (75°F) water), a rate per unit area of collector surface of 12.5 kg/m^2 (2.56 lb/ft^2).

The following comments may be made:

(a) A compact solar refrigeration unit that will give satisfactory performance can be designed and constructed;

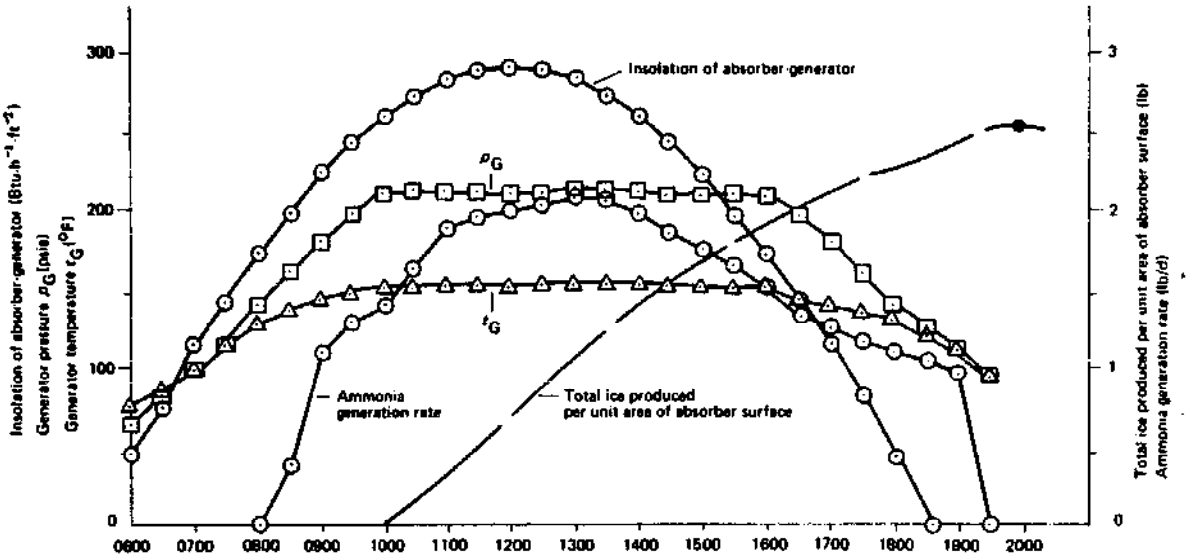


Figure 16. Data from a test run of a solar refrigerator performed on 6 July 1968

(b) A considerable amount of solar energy can be collected even on cloudy days by the flat-plate solar collector; operation of a solar refrigeration system is possible at solar absorber temperatures as low as 43°C (110°F);

(c) Utilizing solar energy to produce ice solves the problem of storage;

(d) Combining the solar collector and the ammonia generator into one unit eliminates the rather large heat losses between the solar absorber and the ammonia generator observed in previous systems. However, the advantage is realized only when small units are involved; in large units, problems of circulation of the two-phase fluid and of tightness could arise;

(e) The extensive theoretical analysis of the system, especially for the combined absorber-generator reported elsewhere, has shown that the design can be theoretically determined and the desired performance obtained;

(f) Since the maximum production rate of ice is about 20 kg/d for a system including two pumps operated by external sources of power and a water-cooling condenser and absorber, the system delivers only about 10.5 MJ (2.4 Mcal) of cooling per day.

Second case study: *An air-cooled ammonia-water absorption air-conditioner with new generator temperatures, Energy and Environment Division, Lawrence Berkeley Laboratory, University of California (1976)*

Part of an ERDA-supported project, the system is designed to operate at generator temperatures of 80°-99°C (175°-210°F), compatible with the temperature range of flat-plate solar collectors.

The air-conditioner uses as a base the condenser, absorber, pre-cooler evaporator and solution pump from an Arkla Model ACB-60-00 gas-fired ammonia-water absorption water chiller, which has a nominal cooling capacity of 3.5 kW (5 tons of refrigeration). The total power of the pumps and fan is 1.6 kW. The following components were added: generator, pre-heater, rectifier, storage tanks, adjustable expansion valves and measurement instruments (6 pressure gauges, 25 thermocouples, 2 rotameters and 2 sampling tubes for concentration measurement).

The generator is a packed-tower, counter-flow heat exchanger. The strong solution drips down through the steel pall-ring packing, making contact with four hot-water coils in parallel. The total outside surface area of the water coils is 3.3 m^2 (36 ft^2). The condenser and absorber are air-cooled, finned-tube, cross-flow heat exchangers with a total outside tube area of 1.3 m^2 (14 ft^2) and 2.0 m^2 (22 ft^2), respectively. The fins were 0.01 in. (0.25 mm) thick aluminium sheets spaced at 14 fins per inch (1.55 mm) apart.

The unit is started by pumping hot water at constant inlet temperature through the generator coils. The condenser-absorber fan and the solution pumps are turned on when the generator pressure reaches about 10 bar (150 psig). It takes about 15 min to warm up the system to approach running conditions (with a charge of solution in the system of about 29 kg (65 lb) at 55% ammonia concentration). The flow rates of ammonia and of the weak solution are then readjusted, by means of expansion valves, to the desired values.

All runs made during the initial testing stage served to confirm cycle calculations based on the

assumption of equilibrium states. That is, given the measured mass-flow rates and the measured pressures and temperatures, the energy balances between the components can be satisfied within experimental error (about ±5%) by using the thermodynamic equilibrium enthalpies. The mass balances can be satisfied by using the equilibrium concentrations.

The system operation is very stable. No appreciable changes are observed after hours of operation. The stability of operation extends a circulation ratio (mass of absorbent per unit mass of refrigerant) as high as 27.

Operating the system at near cut-off conditions (i.e., Δx close to zero, where x is the mass concentration of ammonia in the solution) demands more power and a larger pump to circulate the solution. Therefore, imposing a limit on the pumping power to say 48 mW per watt of cooling load constrains Δx to values above 0.03, or the circulation ratio to values of less than 16 (assuming a pump efficiency of 40%). Figure 17 shows graphs that serve to summarize the possible operating temperatures for an ammonia-water absorption air-conditioner operating under these conditions.

For acceptable cooling and dehumidification using reasonably sized chilled water coils, t_E is limited to $t_E < 8°C$ (47°F). Inexpensive flat-plate collectors may reasonably limit the generating temperature to $t_G < 90°C$ (195°F).

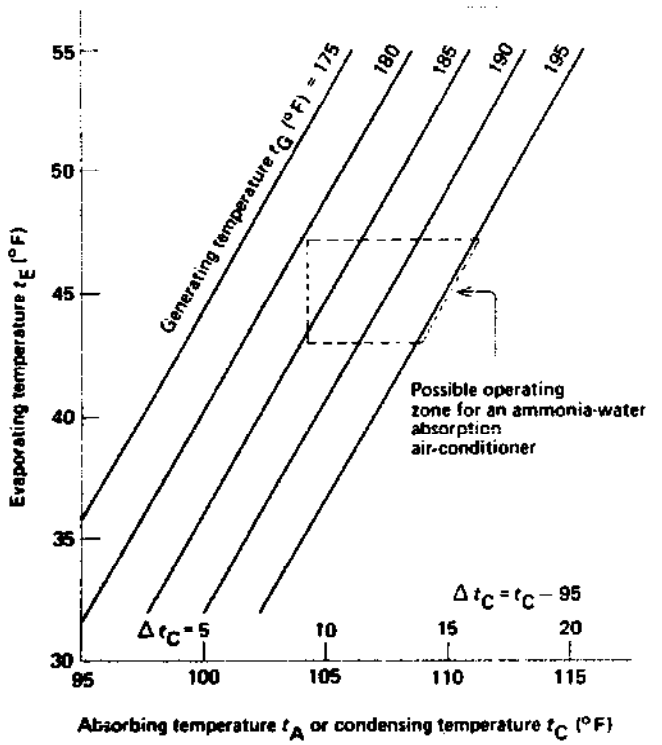


Figure 17. Evaporating temperature t_E of an ammonia-water absorption air-conditioner as a function of the absorbing, condensing and generating temperature t_A, t_C and t_G for the following conditions:

pressure drop across absorber p = 0.2 bar (3 psi), concentration difference Δx = 0.03, and $t_A = t_C$

The above practical constraints combine to require condensing and absorbing temperatures below 43°C (110°F). This constraint can be met by doubling both the cooling-air flow rates and the size of the condenser-absorber, compared with those used in conventional gas-fired systems using a finned-tube condenser and absorber. (These conditions are essentially satisfied already since the condenser, absorber, and fan are over-sized.)

Doubling the cooling-air flow rates is essential, but new designs of more efficient condenser-absorbers may reduce the requirement of doubling the size (and cost) of these heat exchangers. Doubling the cooling-air flow rates typically increases the power of the fan from 24 mW to 48 mW per watt of cooling, giving an overall performance of 10 W of cooling per watt of electrical power input (as compared with a rating of about 2 W per watt for a mechanical compressor unit).

The coefficient of performance (COP) depends strongly on the pre-heater efficiency η_{PH} and Δx and is quite insensitive to the values of the remaining parameters. To have COP > 0.65 with $\Delta x = 0.03$, η_{PH} must be at least 90%. This value of η_{PH} is not expensive to achieve, since there is sufficient pressure in the weak solution to promote high heat-transfer coefficients. A high value of η_{PH} is essential to avoid dumping the heat contained in the weak solution into the absorber.

The experience with the air-conditioner described above shows that it is technically feasible to use the ammonia-water absorption cycle for cooling, with a heat-source temperature below 93°C (200°F) and a heat-sink temperature (using air cooling) below 43°C (110°F).

Third case study: *Lithium bromide solar absorption air-conditioning system, Ohio State University (1975)*

The system was designed to provide air-conditioning for a single-storey laboratory with a floor area of 204 m² (2 200 ft²) built over a 1.2-m (4-ft) deep crawl space. In addition, there are three enclosed, but unconditioned, courtyards. The perimeter window area of the building is limited to six vision strips, or 1.7 m² (18 ft²) of glass area. Natural lighting orginates primarily from the courtyards. The building wall and flat-roof framing members are steel and support, in addition to the conventional building loads, over 1 500 kg (3 300 lb) of collector, framing and piping load. The walls and roof are insulated with 50 mm (2 in.) and 75 mm (3 in.) of calked-joint styrofoam to minimize infiltration and heat transfer with the outside. The U values for the composite wall and roof sections are 0.07 and 0.05 Btu h^{-1} ft^{-2} °F^{-1} (0.40 and 0.28 W m^{-2} °C^{-1}) respectively.

The roof-mounted collectors are oriented due south and are tilted up 45° from the horizontal. The collector array consists of 37 baseline collectors

connected in parallel (total area: 61 m^2 (660 ft^2)). The collectors are constructed with two sheets of 1/8-in. (3-mm) thick tempered glass over a flat black aluminium roll-bonded absorber. Heat loss from the back of the collector is controlled with 3½ in. (90 mm) of fibreglass insulation. The plumbing in the system is copper with dielectric unions at each of the two connections per solar collector. Great care was taken at start-up to flush the system and fill it with distilled water. The system was operated this way for one year, then modified to accommodate a glycol-water mixture as the collector working fluid.

The thermal-energy storage system consists of two steel storage tanks each 1.5 m (5 ft) in diameter and 3.7 m (12 ft) long and lined with a Tinkolite coating. The horizontally mounted tanks are in the crawl space under one of the courtyards. The entire crawl-space volume around the tanks was filled with a foam-in-place polyurethane to minimize energy losses.

An Arkla 3-ton (10.5 kW) lithium-bromide/water absorption direct-expansion machine, modified by Arkla Industries to operate on hot water, is the solar cooling machine. Circulation within the machine occurs as a result of the thermal syphon pump effect, which requires a generator inlet temperature of 88°C (190°F) or higher to start circulation. In addition to the hot-water heat source, the cooling machine requires a cool-water heat sink. The heat rejection is accomplished with a 7.5-ton (26-kW) Marley cooling tower. The presence of this unit adds two energy-consuming motors to the operation, a ½-hp (375-W) cooling-water pump and a ⅓-hp (250 W) cooling-tower fan.

Figure 18 gives the collector efficiency as a function of the ratio Δt/HR, where $\Delta t = t_{in} - t_a$ is the difference between the inlet and ambient temperatures and HR is the insolation. The absorption

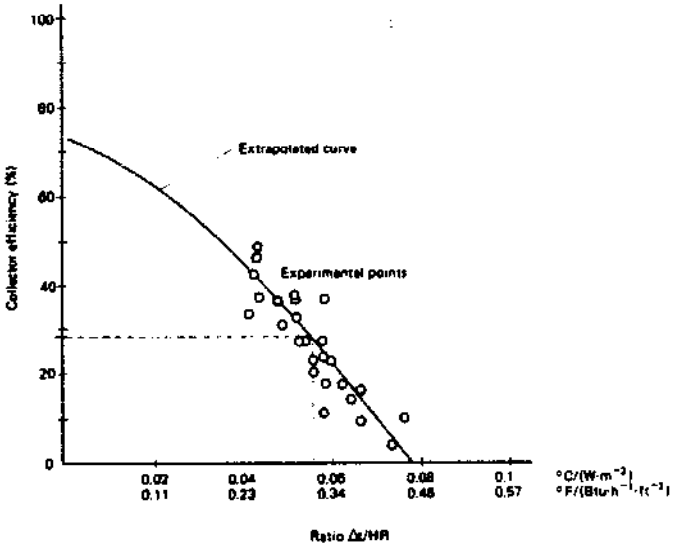


Figure 18. Collector efficiency as a function of the ratio of the difference between the inlet and ambient temperatures and the insolation

cooling machine requires a steady heat input at the rate of 16 kW (55 X 10^3 Btu/h) to cool at the rate of 10.6 kW (36 X 10^3 Btu/h). To achieve that, the collector array must collect energy at the rate of 262 W per square meter (83 Btu/h per square foot). If the ambient temperature is 32°C (90°F) and the collector inlet fluid temperature is 85°C (185°F), we have Δt = 53°C (96°F), and from figure 18 we find that HR must be 946 W m^{-2} (300 Btu h^{-1} ft^{-2}) and the collector efficiency 28%, which clearly pushes the array to its limit.

The storage-tank temperatures in the early summer of 1975 never exceeded 71°C (160°F) and consequently no solar cooling was done. A check revealed that there were serious heat losses from the storage tank. With an adequate system of control, it was possible to obtain a water temperature of 93°C (200°F) periodically; however, the system was extremely sensitive to passing clouds. A passing cloud would cause the flux to drop radically, and the collector losses caused the loop temperature to drop rapidly. The motor-operated control valves were unable to respond to such operating conditions; therefore this mode of operation was abandoned.

The comparison below between the energy required with a conventional vapour-compression machine and with a solar absorption machine shows that absorption cooling requires three times as much power as cooling by vapour compression.

Solar absorption		*Conventional vapour compression*	
Power input (W)			
Electrical			
Collector pump	560	Compressor	5 400
Mechanical room pump	125	Blower	640
Generator pump	350	Condenser fan	620
Arkla blower	560		
Cooling-water pump	350		
Cooling-tower blower	250		
Subtotal	2 195		6 660
Solar	16 100		
Total	18 295		6 660
Cooling output (W)	10 560		11 720
COP (output/input)	0.58		1.76

A significant advantage of the solar absorption machine can be seen from the above comparison: its six electric motors require only one third as much power as the three motors of the conventional vapour-compression machine. That is important when it is necessary to conserve electrical energy.

These are the disadvantages of the system described:

(a) Lithium bromide requires a minimum temperature of about 90°C, which is very difficult to obtain with flat-plate solar collectors, unless very expensive selective material is used;

(b) The system is bulky;

(c) With six independent motors, the system is complicated; it requires a control system just as complicated as that of the conventional machine.

Solar space heating

Many studies have been made on the economics of solar space heating. The energy saving varies from 30% to 80% of the total consumed heat. It depends on, among other things, climatic conditions; building shape, location and orientation; number of floors; area of glass in the external walls; materials used in construction; kind and method of insulation; and mode of utilization of the premises.

Much development work on solar heating has been undertaken in both developed and developing countries, for example France, the Federal Republic of Germany, India, the Netherlands and the United States. From the technological point of view, solar space heating is already operational. Nevertheless, R and D programmes are being undertaken to improve the performance, find better architectural solutions, and reduce the cost. In many cases, as in conventional heating systems, domestic hot water can be obtained from the solar space heater.

Two modes of heating are usually employed when solar energy is used to heat space, passive and active.

Passive system

The principle of the passive system is shown in figure 19. Solar radiation heats the absorbing surface, the dark outer surface of the wall which is oriented towards the south (in the northern hemisphere). The distance between this absorbing surface and the double sheet glass constitutes a duct in which air warms up and rises by the thermosyphon effect and then enters the space to be heated by an aperture in the upper part of the wall. As the warm air heats the space, it cools, descends and returns to the duct by an aperture at the bottom of the wall.

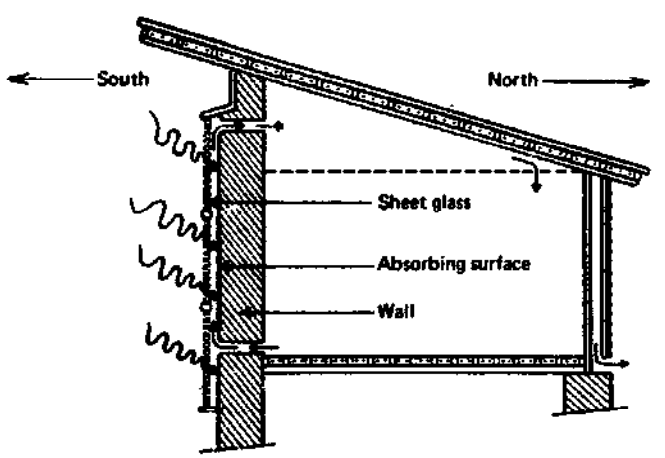


Figure 19. Passive solar space heating system

Such a simple design is easy to construct. The walls constitute the storage system. At Odeillo in the south of France, such systems have supplied 60%-70% of the total energy necessary for heating purposes.

Active system

Water is heated in flat solar collectors and is circulated through a storage tank into radiators or convectors located in the space to be heated. Hot water can also feed coils, on which air is blown; thus the space is heated by hot air. In normal climatic conditions an auxiliary source of heat may be used (figure 20).

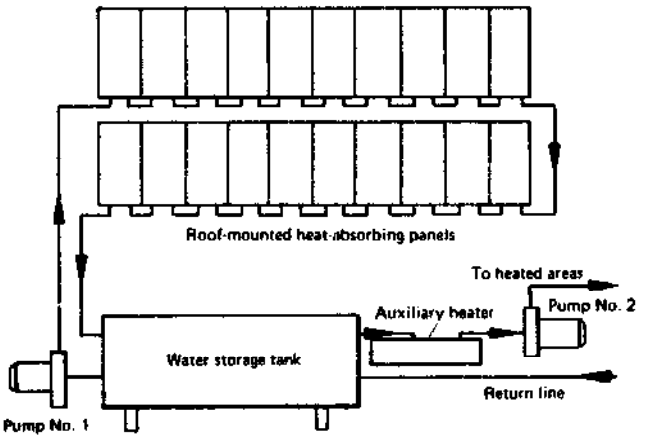


Figure 20. Active solar space heating system with auxiliary heater

Solar water heating

Solar water heaters are already used on a relatively large scale in Australia, Cyprus, Japan and the United States. They have already passed the phase of R and D and pilot projects, and the technology is reliable and well known. Several models exist on the international market. The most common has a 2-m^2 flat-plate solar collector and a 200-l storage tank.

In many countries solar water heaters could supply all the hot water necessary for domestic purposes all year round. In other countries with a less favourable solar radiation regime, a conventional auxiliary heater is necessary.

The development of solar water heaters depends on the development of flat-plate solar collectors for other purposes, such as solar space heating or solar engines.

The solar water heater developed by the Brace Research Institute of McGill University, Canada, could be used in a wide range of developing countries. A diagram of this heater is given in figure 21.

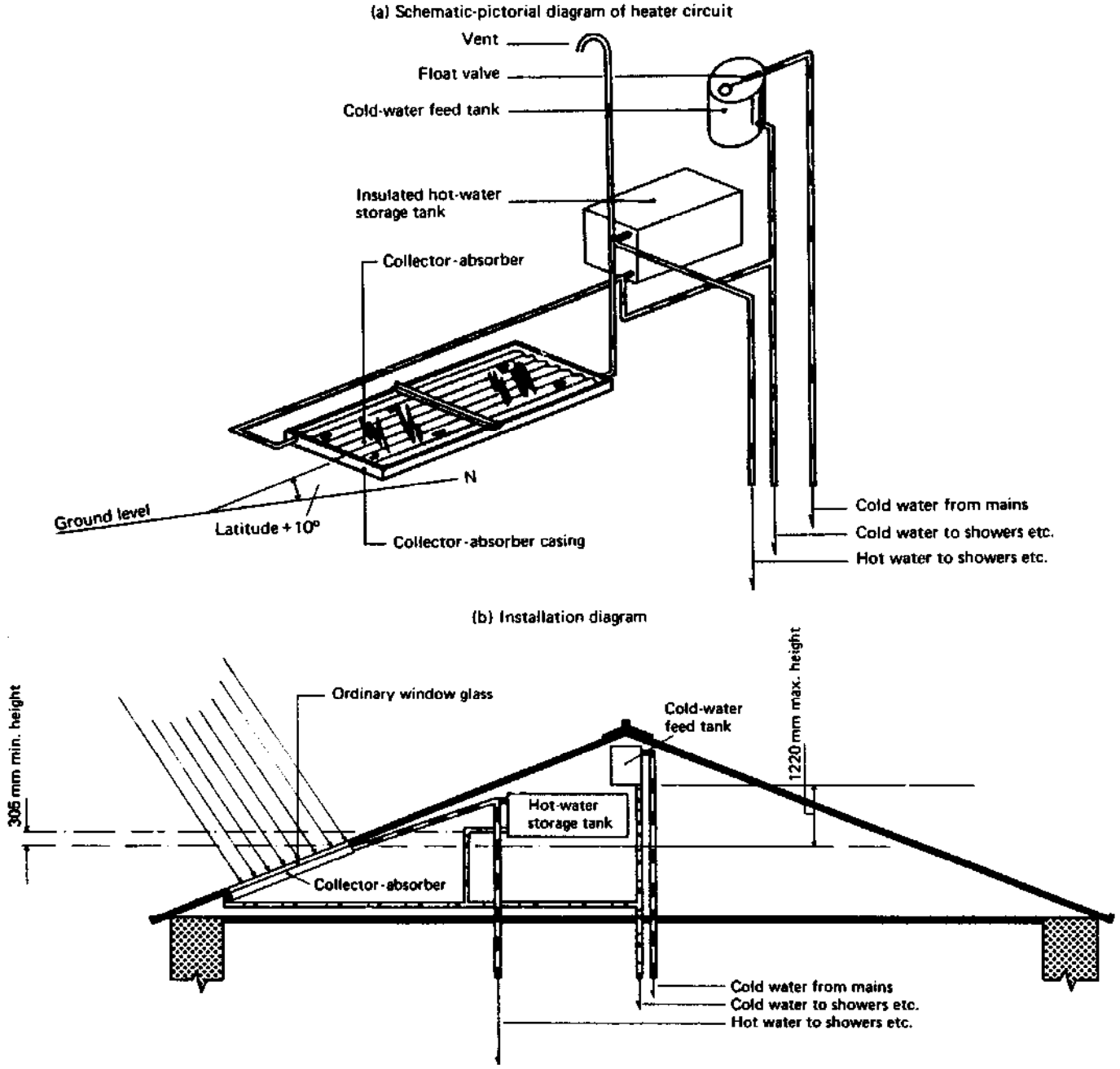


Figure 21. Solar water heater developed by the Brace Research Institute (Canada)

Solar water distillation

General considerations

Distillation of sea water or brackish water can be obtained by solar stills or by conventional methods such as multiple effect, thermal compression, inverse osmosis, electrodialysis, humidification-dehumidification and freeze-desalination. In this article, only direct distillation in solar stills that do not require external power sources will be discussed.

The principle of solar water distillation is based on the greenhouse effect. A layer of brackish or salt water is put in an air- and water-tight container covered with sheet glass or other transparent material. The bottom of the still is black; it absorbs a large part of the solar radiation and heats the water, which begins to evaporate. The vapour reaches the cooler transparent cover, on which it begins to condense. A system for collecting the condensed water is provided.

Many distillation plants of various sizes have been constructed in several countries. In 1973, Dolyannis of the Greek Atomic Energy Commission published the list given in table 2 and illustrated in figure 22. Figure 23 gives the annual variation of the productivity of the Nisiros (Greece) plant over the period 1969-1973.

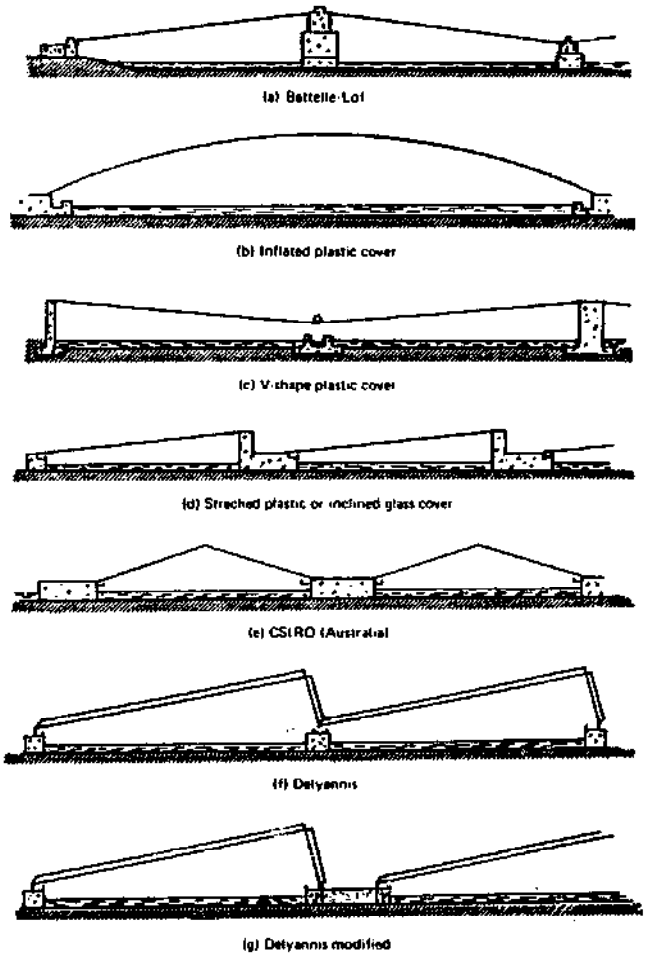


Figure 22. Solar still designs

The number of variables influencing the productivity of solar stills is very high and they are often interdependent. Among the most important are:

Solar radiation regime
Wind velocity
Rainfall
Design of still
Depth of the water layer
Filling and flushing regime
Maintenance

Materials of construction

The Office of Saline Water (United States) has this to say about the materials of construction of solar stills:

> "Since the building of the first large commercial solar still in Las Salinas, Chile, around 1872, the most significant gains in solar still technology have come by way of improved materials of construction. The productivity has not been increased much, but the maintenance and operating expenses have been reduced appreciably. For example, the 4 800 m^2 still at Las Salinas was constructed of wood, glass and putty, and its operation required a clerk, a glazier, two full-time labourers, and occasionally a carpenter. By contrast some recently built stills require only one full-time attendant and a few are designed to operate unattended for long

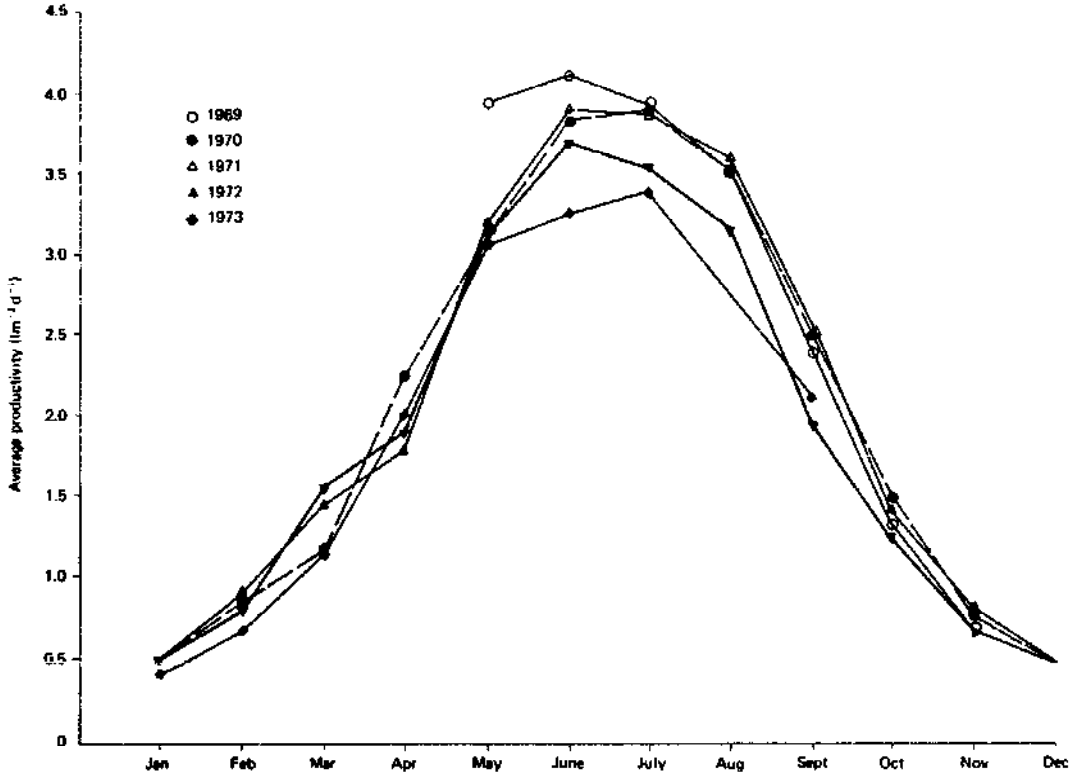


Figure 23. Annual variation of productivity (amount of fresh water produced per unit area of still per day) of solar distillation units at Nisiros, Greece, 1969-1973

TABLE 2. DATA ON THE MOST IMPORTANT SOLAR DISTILLATION PLANTS THAT HAVE BEEN BUILT, 1872-1973

Country or area	Location	Design[a]	Year built	Area (m^2)	Feedwater	Cover	Status in 1973
Australia	Muresk I	e	1963	372	Brackish	Glass	Rebuilt
	Muresk II	e	1966	372	Brackish	Glass	Operating
	Coober Pedy	e	1966	3 160	Brackish	Glass	Operating
	Caiguna	e	1966	372	Brachish	Glass	Operating
	Hamelin Pool	e	1966	557	Brackish	Glass	Operating
	Griffith	e	1967	413	Brackish	Glass	Operating
Cape Verde	Santa Maria	c	1965	743	Sea water	Plastic	
	Santa Maria	c	1968				Abandoned
Chile	Las Salinas	e	1872	4 460	Brackish	Glass	Abandoned
	Quillagua	e	1968	100	Sea water	Glass	Operating
Greece	Simi I	b	1964	2 686	Sea water	Plastic	Rebuilt
	Simi II	d	1968	2 600	Sea water	Stretched plastic	Dismantled
	Aegina I	c	1965	1 490	Sea water	Plastic	Rebuilt
	Aegina II	d	1968	1 486	Sea water	Stretched plastic	Abandoned
	Salamis	c	1965	388	Sea water	Plastic	Abandoned
	Patmos	f	1967	8 600	Sea water	Glass	Operating
	Kimolos	f	1968	2 508	Sea water	Glass	Operating
	Nisiros	f	1969	2 005	Sea water	Glass	Operating
	Fiskardho	f	1971	2 200	Sea water	Glass	Operating
	Kioni	f	1971	2 400	Sea water	Glass	Operating
	Megisti	f	1973	2 528	Sea water	Glass	Operating
Haiti		d	1969	223	Sea water	Glass	Operating
India	Bhavnagar	c	1965	377	Sea water	Glass	Operating
Mexico	Natividad	d	1969	95	Sea water	Glass	Operating
Pakistan	Gwadar I	f	1969	306	Sea water	Glass	Operating
	Gwadar II	g	1972	9 072	Sea water	Glass	Operating
Spain	Las Marinas	a	1966	868	Sea water	Glass	Operating
Tunisia	Shakmou	d	1967	440	Brackish	Glass	Operating
	Mahdia	d	1968	1 300	Brackish	Glass	Operating
USSR	Bakharden	e	1969	600	Brackish	Glass	Operating
United States	Daytona Beach	a	1959	228	Sea water	Glass	Rebuilt
	Daytona Beach	a	1961	246	Sea water	Glass	Dismantled
	Daytona Beach	b	1961	216	Sea water	Plastic	Dismantled
	Daytona Beach	b	1963	148	Sea water	Plastic	Dismantled
Windward Islands	Petit St. Vincent	b	1967	1 710	Sea water	Plastic	Operating

Source: AEC.
[a]See figure 22.

periods of time. Glass, concrete, and asphalt materials appear to require only a minimum of maintenance.

"Indigenous materials are usually preferred. However, in selecting materials, the overall economics must be carefully considered, including maintenance and rebuilding intervals as well as initial capital cost. The present trend is toward materials that will last 20 years with minimum upkeep. Such materials include concrete, glass, butyl rubber, and stainless steel.

"The following lists still-component materials that have proved to be reasonably satisfactory in actual use around the world. For each component, the materials are listed in order of preference from the standpoint of durability. When a solar still is to be built directly on the ground using a basin liner, it is advisable to first use an insecticide and a weed killer to reduce the possibility of punctures.

Component	*Materials*
Basin liner	Butyl rubber (0.015 to 0.030 inch thick)
	Asphalt mats (0.12 to 0.25 inch thick)
	Black polyethylene (0.008 inch thick)
	Roofing asphalt (over concrete, etc.)
Cover	Window glass (0.10 or 0.12 inch thick)
	Wettable [PVF film]* (0.004 inch thick)

Component	*Materials*
Support structure	Concrete. Concrete block. Aluminium. Galvanized metal. Redwood*
Distillate trough	Stainless steel. Butyl rubber (lining) Black polyethylene (lining)
Sealant	Silicone rubber. Asphalt caulking compound Butyl-rubber extrusions
Piping and valves	PVC (polyvinyl-chloride). Asbestos cement (for saline water). ABS (acrylonitrile-butadiene-styrene)
Water storage reservoirs	Concrete. Masonry

*Relatively short lifetime.[1]

UNIDO/UNICEF solar distillation plant in Somalia

UNIDO, with UNICEF financing, is implementing a solar distillation project in Somalia, the main component of which is a solar water distillation plant of about 2 000 m^2 net evaporating surface. The expected production of the still, including rainfall collected, is 5-6 m^3 of fresh water per day.

The design of the plant was adapted from a design that had been prepared by the Central Salt and Marine Chemicals Research Institute (India) for use in India. Modifications include improving the piping design, reducing the passages between the stills, changing the inclination of the cover glass to 15° instead of 20°, using aluminium instead of wood for the supports of the upper side of the sheet glass, and changing the location of the sea-water, distilled-water and blending-water tanks.

The plant is composed of 15 blocks, each consisting of 6 symmetrical and intercommunicating basins about 13 m long and 1.5 m wide. The main construction materials are bricks, cement, sheet glass, plastic, tar, mastic tank paint, electrical cotton insulating tape to cover the sheet-glass joints and support the putty, aluminium profiles and sheet, and galvanized pipe. The estimated cost of these materials and two hand pumps in India is about $23,000 and the estimated cost of labour is about $4,600. The cost per unit area of net evaporating surface is thus about 14 $/$m^2$.

It has been suggested that in another distillation plant of 200 m^2, 12 experimental units of 3 m^2 each will be constructed to compare behaviour of materials, effect of insulation etc. One of the units will serve as the reference unit; each of the other 11 will be identical with the reference unit except for a change in one of these variables: inclination, depth of water, wall construction, liner material, basin insulation.

[1] Office of Saline Water, Report No. 546.

Design considerations

A consensus does not yet exist on the optimal design of a solar distillation plant. However, the following considerations seem to meet with general agreement:

(a) Local materials and simple technology should be used as far as possible;

(b) Plastered brick or cement blocks able to withstand weather conditions and the effects of salt water and to ensure tightness should be used;

(c) An aluminium structure with sheet glass for the construction of the walls and the cover represents a good, but expensive, solution and would not often be available;

(d) For the absorbing black surface, two solutions could be envisaged at the moment: concrete with special bituminous paints, which has been successfully experimented with in India, or thin butyl rubber sheet about 1 mm thick, which has also been successfully experimented with in Australia, Greece and other countries. The latter material, while it requires rather more sophisticated technology (sealing by vulcanization or with adhesives), is not affected by solar radiation, high temperature or dry spots; however, it is often not available in developing countries;

(e) Insulating the still under the basin is not justified when the surface is large because the ground acts as a semi-infinite medium through which there can be very little heat loss, and insulating the sides of the still should not significantly increase the productivity owing to the relatively small heat-transfer surface involved. The cost of the insulation materials and its installation is therefore not economical in terms of increasing the productivity of large stills. Nevertheless, the use of available local insulation materials should always be studied. It is essential that any insulation used be kept dry. A layer of dry earthy material beneath the basin liner is usually sufficient for insulation purposes;

(f) Regarding the cover, sheet glass about 3 mm thick still seems to be the best solution. Use of a cover of two sheet-glass layers is not justified. The experience with plastics is not yet conclusive. Several kinds (PVC, PVF, PTFE, polythene, polyester, polytrifluoromonochloroethylene, and nylon) have been tried in conditions less severe than in full-sized stills. The only materials that will last as long as five years are 0.005-in. (0.13-mm) PTFE, 0.004-in. (0.10-mm) PVF and 0.005-in. (0.13-mm) weatherable polyester. In general, the lifetime of plastic material exposed to solar radiation is very short. In addition, very thin covers do not withstand the effect of wind;

(g) The tightness of the still is very important and at present no efficient, cheap sealant materials are on the market. Silicone rubber is very good, but it is also very expensive. A cold-application mastic bituminous compound intended for repairing leaky roofs has been successfully used on stills in India, but it is too soon to forecast what the lifetime of the seals may be;

(h) Regarding the depth of the layer of water in the still, it is generally agreed that shallow layers give better productivity, but if the ground is not level, dry spots on the absorbing bottom can appear if butyl rubber or equivalent material is not used; a depth of 5 cm seems to be a realistic solution;

(i) No general agreement exists as to the best inclination of the sheet-glass cover. It is important to ensure the formation of a film that permits both adequate condensation and adequate transmission of solar radiation; 10°-20° seems to be acceptable. For a given horizontal surface to be covered, increasing the inclination increases the surface of the cover and thus its cost, and may decrease the productivity of the still;

(j) Any effect of the geometry of the covering on the fraction of incident energy entering the still is negligible in large units, where the area of shadow caused by the sides is small compared with the area of the evaporating surface;

(k) A basin still is usually oriented with its long axis along the E-W or N-S direction. The orientation of the symmetical-cover or low-slope still does not affect productivity: asymmetrical and single-sloped covers should be oriented with the long axis in the E-W direction, with the low-slope or single-cover plate facing towards the equator (S in the northern hemisphere, N in the southern);

(l) The still should serve also as a rainfall catchment surface;

(m) The optimal regime of feeding the still with fresh water (continuously or by batch) has not yet been determined. It is certain, however, that periodic flushing of the still with fresh water can prevent the deposit of salt and the growth of algae, both of which decrease productivity. Salt deposition should be avoided, as it increases the reflectivity of the black surface and thereby decreases productivity;

(n) The addition of a few parts per million of a copper salt should help prevent the growth of algae.

Solar drying

Drying food, agricultural products or fish by solar energy is a very old practice. However, in recent years there has been intensive R and D in developed and developing countries to systematize the process and to protect products from rainfall, dust and insects. The Brace Research Institute[2] (Canada) has prepared a very useful study of the process; most of this section is based on it. Data on solar driers are presented in the form of case studies which deal with descriptions of the driers, experimental results and drawings. Economic information has also been included.

Case study 1. *Solar cabinet drier: general design*

The solar cabinet drier is essentially a solar hot box in which fruit, vegetables or other matter can be dehydrated on a small scale. It is insulated and is covered with a double-layered transparent roof. Holes drilled through the base permit fresh ventilating air to be drawn into the cabinet by convection.

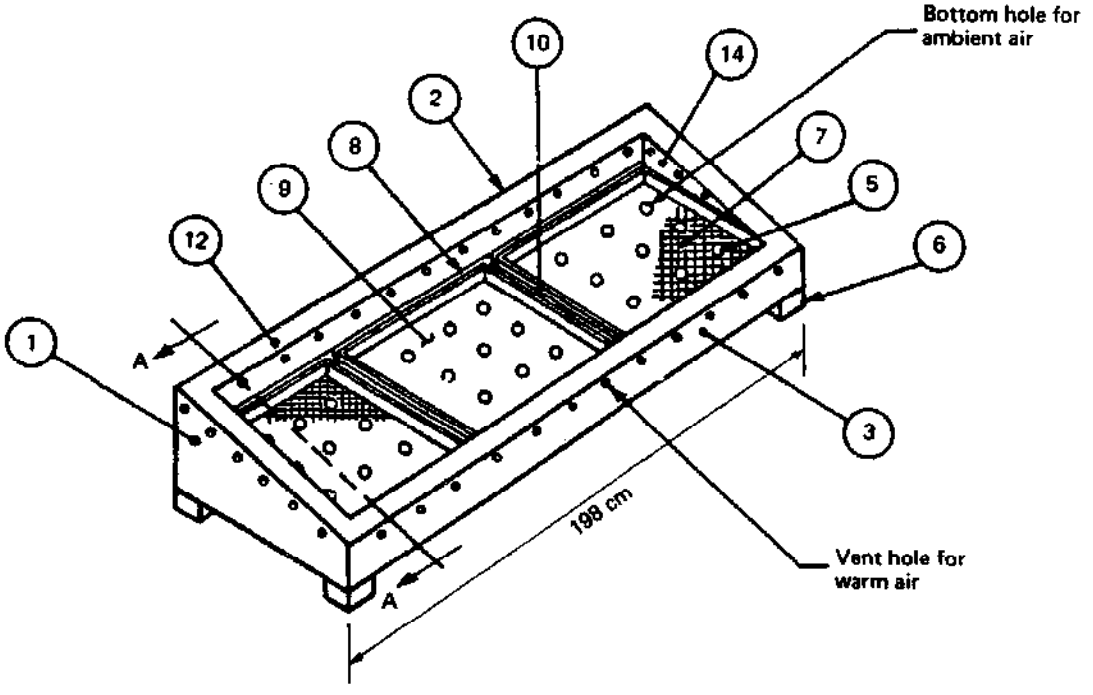
The construction of such a drier can take many forms. Nevertheless, certain specifications can be recommended for all driers of this type (figure 24).

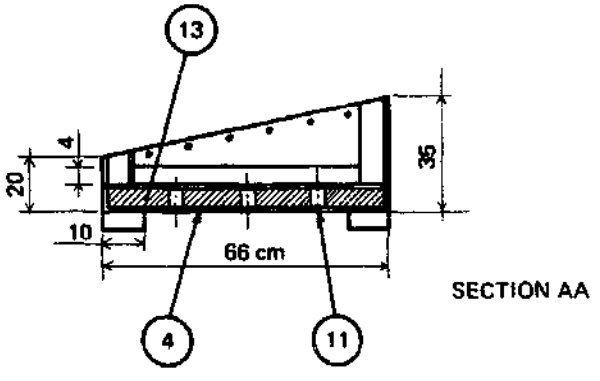
The length of the cabinet should be at least three times the width so as to minimize the shading effect of the side panels. The angle of the slope of the roof covering should be taken from figure 25, which gives the recommended angle for drying seasons as a function of latitude. The graph is equally applicable to areas north and south of the equator. Note that for latitudes less than 20°, the slope of the transparent roof is constant at 6°. This is to allow a minimum difference in elevation from one side of the collector to the other to permit adequate convective air circulation over the drying area and to allow rain to run off the cover. The transparent cover should be made from two layers of either glass panes (2 mm thick) or plastic film (about 0.13 mm thick).

In general, covers made with plastic film have a limited life and therefore films that have been treated to give protection against ultraviolet radiation must be used. They can be of polyester or PVC; films of polyethylene or cellulose acetate should not be used because they would have to be replaced at the end of each drying season and might not give favourable results in service. Although it may be advantageous to replace covers seasonally in certain cases, trouble may occur with films that are not able to withstand the high cabinet temperatures generated, which may reach 80°-100°C in some driers. It is advisable in this type of unit to use ordinary window glass supported by a suitable frame.

The frames of portable models may be of wood, metal or hardboard. Plywood may be used for the more sophisticated units, basketwork, wicker or bamboo for the more primitive units. Perforated cabinet bases and side panels may be fabricated by placing insulation between layers of blackened wicker

[2] *A Survey of Solar Dryers*, Technical Report T99, Brace Research Institute, McGill University, Ste. Anne de Bellevue, Quebec, Canada (1975).





	Description	*Material*	*Dimensions (cm)*	*Number required*
1	Side panel	Wood	2 thick	2
2	Rear panel	Wood	2 thick	1
3	Front panel	Wood	2 thick	1
4	Base	Plywood	198 X 66 X 2	2
5	Hole liner	Polythene pipe	12.7 diam. X 6 long	27
6	Leg	Wood		4
7	Tray	Wood and wire mesh	62 X 62	3
8	Door	Wood		3
9	Transparent cover	Glass	61 X 62	3
10	Tray runner	Wood		4
11	Aperture screen	Fibreglass		27
12	Cover frame	Wood		1
13	Insulation	Wood wool	5 thick	—
14	Internal side-wall covering	Aluminium foil		2

Figure 24. Drawings and specifications for a solar cabinet drier

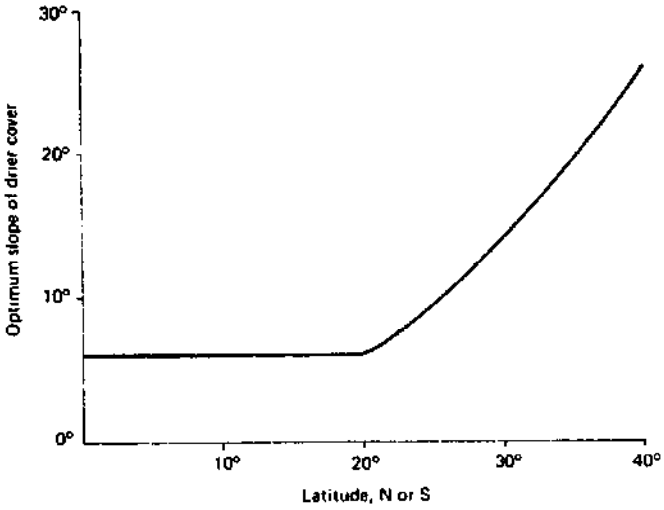


Figure 25. Optimum slope of solar drier cover as a function of the latitude of the location

or open basketwork. This would cut down costs and make use of local industry.

Permanent structures may be made of adobe, bricks, stone or concrete.

The insulation should consist of locally available materials, such as wood shavings, sawdust, bagasse, coconut fibre, reject wool and animal hair. In areas affected by wood ants, termites or other noxious insects, the susceptible materials should be properly protected before being placed in the base.

The hot box should be constructed along the lines outlined in figure 24. (The dimensions shown are those actually used in the drier of case study 2 below.) The insulating layers lining the base and sides should be at least 5 cm thick. Holes should be drilled in the insulated base and fitted with short lengths of pipe (plastic or rubber garden hose, bamboo etc.). Where insect infestation is prevalent, all cabinet apertures should be covered with fine mosquito netting (preferably fibreglass) or gauze. Generally the high temperature of the cabinet interior discourages insects and rodents from entering and feeding on the drying produce. Furthermore, in arid areas where there is a high concentration of airborne dust and debris, the transparent cover eliminates product contamination.

The transparent cover can be attached to a frame that can then be fixed to the chassis of the cabinet. If glass is used, a sealant may be used to hold it to the frame; otherwise, the glass should be held firmly in place by a suitable moulding. Care must be taken to ensure that the cover is completely watertight to prevent the interior from deteriorating and the insulation from getting wet. All components of the cover framework should be painted black or some other convenient dark colour to absorb the maximum amount of solar radiation. Hold-down strips should be secured to the upper exterior rim of the cover frame to protect the film against excessive lift caused by wind.

Once the cover and chassis are secured, several holes should be drilled in the rear and side panels. These provide the exit ventilation ports to remove the warm, moist air. The number of holes depends on climatic conditions and the nature of the drying material. A satisfactory method is to provide the drier initially with a minimum of side ventilation ports and to drill further holes as needed to prevent internal moisture condensation. This method ensures the right number of ventilation ports are drilled.

The rear panel should be fitted with access doors to give entry into the cabinet. All doors should be placed on the rear side to prevent excessive shadowing of the drier during handling operations.

Trays should be constructed, as indicated, of galvanized chicken-wire or some similar material. They should be placed on runners a few centimetres high so as to ensure a reasonable amount of air circulation under and around the material being dried.

The interior of the cabinet should be painted black. The exteriors of the side, rear and base panels should be painted with aluminium paint. If desired, the interiors of the side and rear panels can be covered with a layer of aluminium foil. If the foil is not available, these surfaces should be painted black.

Drier operation is not complicated. The produce to be dried is pretreated in the usual manner (i.e. blanched and fumigated) and placed on the perforated trays, at a loading rate of about 7.5 kg per square metre of drying area. A small thermometer inserted into one of the ventilation ports, its bulb shielded from the direct rays of the sun, is a convenient accessory; the upper temperature limits that agricultural produce can withstand vary greatly.

Where the produce being dried might suffer from the direct rays of the sun or where the light colour of the produce reflects much of the incident radiation, it is advisable to cover the loaded trays in the drier with a black plastic mesh or black gauze. This covering should not inhibit the flow of air through the trays, but absorb the radiation and transmit the heat to the produce by conduction and convection. The resultant temperature increase can be controlled by opening the rear access doors. This approximate temperature control system can be easily mastered with experience.

Case study 2: *Solar cabinet drier at Kanpur, India; experimental results*

Climatological data

The pertinent climatological data for the test site are:

Maximum temperature in summer	45°C
Minimum temperature in winter	10°C
Hours of sunshine per year	4 000
Days with no sunshine per year	30

It was found that the optimum tilt of the drier was 13° in summer and 40° in winter.

TABLE 3. EXPERIMENTAL RESULTS ON A DRIER AT KANPUR, INDIA

Produce	*Amount dried (g)*	*Pretreatment*	*Moisture content (%)*		*Maximum allowable temperature (°C)*	*Drying time (h)*
			Initial	*Preferred final*		
Prunes	750	Sulphuring	85	15-20	77	18
Peaches	275	None	80	5-6	[illegible]	11
Peas	420	Blanching	80	5-6	[illegible]	5
Cauliflower	200	None	85	5-6	[illegible]	2.5

Drying data

The drier was used on an experimental basis from July 1971 to July 1972. Table 3 gives results obtained.

For purposes of comparison, table 4 gives some indication of the temperature limits and possible throughputs of other produce with a drier of the same size and specifications in the dry, arid, cloudless Mediterranean climate.

TABLE 4. PROBABLE PERFORMANCE OF THE DRIER IN THE MEDITERRANEAN CLIMATE

Produce	*Amount (fresh) dried per unit (kg)*	*Processing time (d)*	*Maximum allowable temperature (°C)*
Apricots	4	2	66
Garlic	2.6	2	60
Grapes	5.7	4	88
Okra	3	2	66
Onions	3	2	71

Operating conditions

It was observed that an average temperature of 75°C was attainable inside the drier as compared with an average outside temperature of 35°.

The drier was built according to the specifications of figure 24 in two days and cost about $20 in 1973. Annual operating expenditures were as follows (rupees):

Depreciation	16
Interest on capital (at 10%)	16
Contingencies	8
Total	40 (about $5)

Conclusions

The estimated life of the drier is 10 years. Solar drying saves considerable time as compared with simple drying in the open. Also, the final product obtained from the drier was found to be superior in taste and odour and was not contaminated by dust or infested by insects.

Sometimes it may be preferable to have a plastic cover rather than a glass cover, which can be broken by flying stones [illegible] the glass would [illegible]mally have a longer life, say 10-20 years if th[illegible] r is installed on the roof of a building. In the [illegible] analysis, the farmer himself must decide which [illegible]s the more economical and acceptable cover for him. Discounting the breakage hazard,

Since the drier is simple to construct, the farmer can build it himself using simple hand tools, thus lowering labour costs.

The drier can also be used to warm foods and other materials. It is particularly advantageous as a self-contained source of heat at 70°-80°C in the field and in isolated farm areas.

Case study 3: *Solar wind-ventilated drier (Syrian Arab Republic)*

Several wind-ventilated driers of the kind described below were used in the Syrian Arab Republic on an experimental basis during 1964-1968.

Characteristics

The drier can be described as a drying chamber through which warm air, heated in a solar collector, is drawn by means of a rotary wind ventilator. (See figure 26.)

The solar air-heating collector used consists of a blackened hardboard sheet, insulated at the bottom and covered by a plastic (or glass) sheet. The collector is mounted facing due south and tilted at the optimum angle for the area and season.

Air enters through the open bottom end of the collector. It passes up between the hardboard blackened bottom (absorber) and the cover. The effectiveness of the collector is increased by placing a black mesh screen midway between the cover and the absorber; solar radiation that passes through the transparent cover is then absorbed by both the mesh and hardboard. The mesh provides an additional heat transfer surface area, and increased heat is supplied to the passing air. Collector efficiencies of over 75% have been achieved using this system.

The warm-air outlet of the collector is connected to the base of the drying chamber, which holds adjacent stacks of six trays each. Hot air circulates up through the drying produce. Additional heating is obtained from solar radiation transmitted through

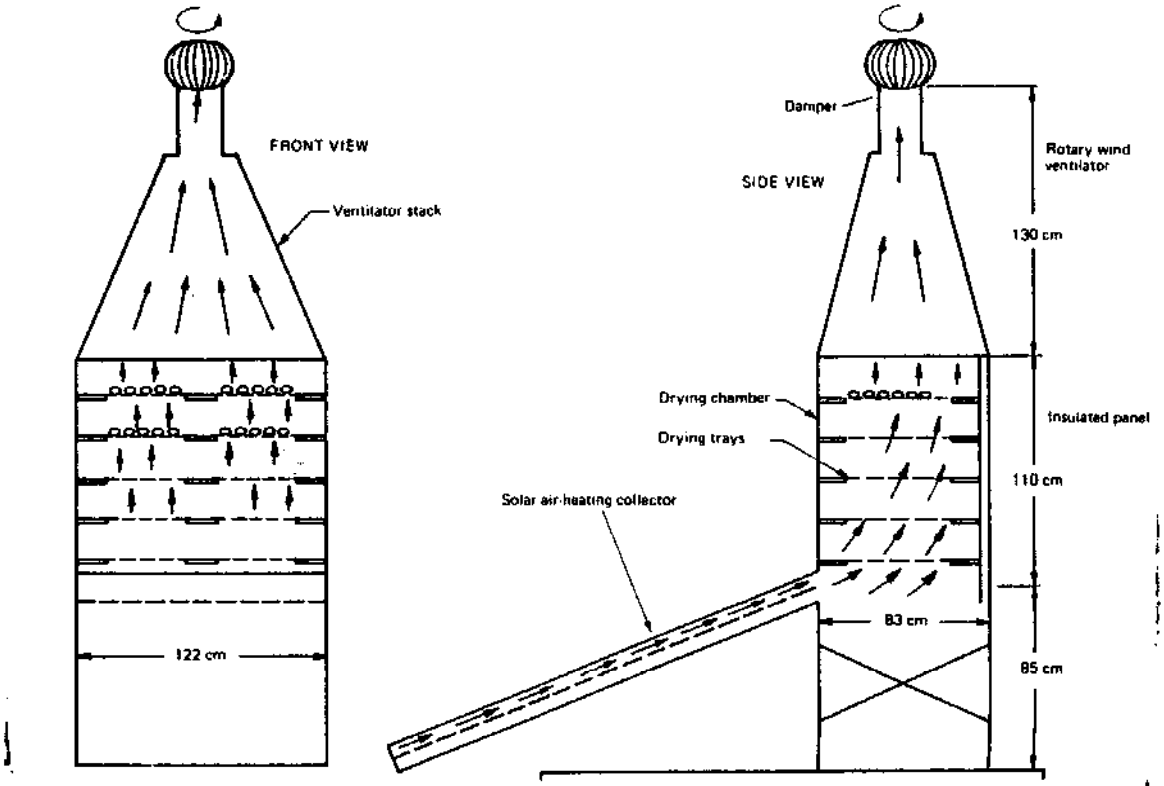


Figure 26. Solar wind-ventilated drier

transparent sheets covering the east, south and west sides of the drying cabinet. The rear vertical and bottom horizontal panels of the drier are of blackened hardboard insulated to reduce heat losses. A rotary wind ventilator is placed on top of a stack above the drying chamber. An adequate length of this stack is required both to achieve a chimney effect and to catch more wind.

The rotary wind ventilator is a corrugated vane rotor. As it spins in the wind, it expels air from the ventilator stack. The rotor is mounted on a ball-bearing suspension. The friction is low, and momentum keeps the head spinning even in sporadic winds. Quantitative tests carried out using the ventilators indicate that the rotary ventilator yields a constant exhaust of high volume in spite of intermittent winds. A stationary eductor placed on top of a chimney can also be used; however, it would rely solely on natural convection during periods of no wind.

The materials of construction are as follows:

Drying chamber	
Transparent cover	Polyester film
Frames	Blackened hardboard for the back wall and bottom panels
Insulation	Straw
Trays	Wire mesh
Solar air heater	
Transparent cover	Polyester film
Absorber	Blackened hardboard bottom sheet with a black plastic mesh 2 cm above it
Insulation	Straw
Frames	Blackened hardboard sheets on bottom and side walls

Climatological data

The drier is located at Dūma (near Damascus) at latitude N 33°33′ and longitude E 36°24′. The climate is characterized by dry, cloudless summers, and cool, partly rainy winters. There is a substantial annual variation in monthly mean temperature that divides the year into four distinct seasons. Nevertheless, the spring and autumn periods seem to blend partly into the traditional desert summer climate–high daytime temperatures; low relative humidities; clear, cloudless days; no precipitation for nearly six months. In most of the country the percentage of sunshine during the period May-October is over 85%. During the period June-September, the percentage is generally above 95%.

Drying data

The unit successfully dried okra, cousa (Baladi variety), squash, Jews' mallow, egg-plant, tomato paste and yams. As an example of the drying yields attained by the unit, drying times for okra and cousa were reported to be, respectively, 20% and 58% shorter than with sun drying. In addition, the final product quality obtained using this solar drier was reported to be superior.

The efficiency of the solar air heater was reported to vary between 64% and 88% (ratio of useful heat absorbed into air stream to the energy transmitted through glazing).

The operating conditions during the tests the results of which are reported above were as follows: The day was fairly sunny, and the ambient air temperature was 30°-34°C. The temperature of the heated air entering the drying chamber was 36.2°-58.4°C.

Comments

For solar drying purposes, the greater the air flow within the drying chamber, the greater the yield. If the average wind speed is high, the use of a stationary eductor instead of a rotary ventilator will be just as practicable. When higher temperatures are desired for drying particular crops, dampers installed in the ventilator stack will permit control over the air-flow rate and thus the temperature of the drier. If the ventilator diameter is small, it seems better to use a stack of a larger cross-section with a smooth transition to the ventilator section. That will reduce air friction and ensure adequate air flow.

Evaluation

These solar driers are simple to construct and economical to use. However, local materials and technology should be used to the maximum. Farmers may be encouraged to construct their own solar driers based on models designed by local institutions and available for demonstration purposes.

The only possible external source of energy in small applications is, in the present conditions, the wind. When using forced convection obtained by fans operated by thermal, electrical or solar engines, a feasibility study should be undertaken to find out what percentage of the consumed energy can be delivered as mechanical energy by the engines. Many research projects are being undertaken in various developing countries, and it seems that the following suggestions could be included in these research programmes when forced convection is used:

(a) Study of the influence of the temperature of solar-heated air. This temperature could be varied until it reaches the maximum compatible with the conservation of the quality of the dried products by varying the performance of the solar collectors or the velocity of the heated air;

(b) Study of the influence of the Reynold's number of the flow of air across the dried product by changing the discharge of the fan;

(c) Reduction of the useful fluid power by optimizing the pressure drop between the solar collectors and the outlet of the dryer. In the intermittent drying regime, calculation and measurement of the moisture should be made at the end of each period.

II. TECHNO-ECONOMIC EVALUATION OF SOLAR EQUIPMENT

Comparison of solar and internal combustion engines

The term "solar engine" designates in this study a complete installation of an engine powered by solar energy, and the term "internal combustion engine" will be limited to diesel and gasoline engines (gas turbines of very small power do not exist yet on the market).

Many factors could be considered when undertaking a techno-economic comparison of this nature, but to simplify the study, these will be limited as much as possible without significantly altering the validity of the comparison. The cost of the installed equipment, depreciation, maintenance, repairs and consumed energy and the impact of solar-energy technology on industrial development will be discussed.

A general equation to find the maximum cost per unit of installed power after which the solar engine begins to be more economical than a diesel or gasoline engine will be presented below. To keep the equation simple certain assumptions were made; these should be kept in mind in reaching conclusions based on the equation.

Assumptions

A solar engine in favourable solar radiation conditions may work about 6 h daily, but it does not give its maximum output all of that time. Hence, an operating time at nominal power of 1 500 h a year seems to be reasonable. This duration could be extended in the case of extensive heat storage.

Except for experimental purposes, the use of fractional-kilowatt solar engines does not seem to be justified in developing countries in the short and medium term. For instance, a ½-kW solar pump could be replaced by a ¼-kW animal-powered pump working 8 h daily. The energy saving in using small solar engines is small; for example, a ½-kW solar engine will save only about 250 kg of fuel per year. The transport of such a quantity of oil would not pose difficulties. Solar engines in the 2-15 kW range would be more economic and would sell better.

A diesel or gasoline engine can easily work 8 h daily (3 000 h in a year). A set of two engines each having half the power of the solar engine will be considered, so that a stand-by will be available and a reliable performance can be expected.

Most current small diesel engines in the speed range 1 000-15 000 rpm have a power of 2 kW or more. Therefore, in the low range only gasoline engines, and for the range 10-15 kW only diesel engines, will be considered.

It will be assumed that the annual cost of the loans made to finance the installation will be equal to

half the rate of interest multiplied by the amount of the loan. This simplification will not significantly affect the accuracy of comparison because it applies to both solar and conventional installations and is relatively unimportant as against the other terms.

This comparison omits the effect of inflation.

Cost comparison equation

Based on the above considerations, the following equation can be written:

$$\left(a_s + b_s + \frac{i}{2}\right) K_s = \left(a_t + b_t + \frac{i}{2}\right) K_t + q_f c_f + q_l c_l \quad (1)$$

where the symbols have the following meanings:

Variables

- a annual rate of depreciation (equal numerically to the inverse of the expected lifetime of the engine in years)
- b ratio of the annual cost of maintenance and repair to the cost of the installed engine
- i rate of interest on the loan used to finance the cost of the installed engine
- K Cost of engine per unit of installed power
- q Annual rate of consumption of diesel fuel, gasoline or lubricant (per unit of installed power)
- c Unit cost of diesel fuel, gasoline or lubricant

Subscripts

- s solar engine
- t thermal engine (specifically: d = diesel; g = gasoline)
- f diesel fuel or gasoline
- l lubricant

Numerical application

Values of the variables

The probable value of the variables in equation (1) will now be discussed.

Expected lifetime of the engine

Solar engine. Commercial companies speak of a lifetime of 20 y for the solar engine. In view of the present technological conditions, that figure seems optimistic. Here we shall assume a lifetime of 10 y; hence we have $a_s = 0.1$.

Diesel engine. The lifetime of a diesel engine can be as long as 20 000 working hours depending on the power, the design and especially on the speed of rotation, the piston speed, the type of cooling system, the material used, the accuracy and the process of manufacture, and the operating conditions (duty cycle, level of maintenance, climatic conditions). A lifetime of 6 000 working hours will be assumed here. This seems to be a reasonable lifetime in isolated places where changing the engine before major repairs are required makes economic sense. The rate of depreciation will then be $a_t = 0.25$.

Gasoline engine. A lifetime of 3 000 working hours will be assumed for the gasoline engine, giving $a_t = 0.5$.

Maintenance and repair

Solar engine. Commercial companies sometimes refer to free (or insignificant) maintenance and repair of solar engine installations. A machine to be operated by a solar engine as well as the solar engine itself will always need maintenance and repair (replacement of broken sheet glass of solar collectors, replacement of deteriorated insulation, repainting of containers of solar collectors, possible repainting of the black surface of the solar absorbers, replacement of working fluid, correction of leaks, plumbing). The cost of a full or partial salary of a person to take care of the day-to-day maintenance will not be included because it will also be required for the diesel and gasoline engines. Taking the expected lifetime into account, it will be assumed that $b_s = 0.02$-0.03 for solar thermal engines and $b_s = 0.01$ for solar photocells.

Thermal engine. The maintenance and repair ratio for both diesel and gasoline engines will be taken as $b_d = b_g = 0.20$.

Rate of interest

The rate of interest will be taken as 8% ($i = 0.08$), even though it is higher than that now.

Fuel and lubricant consumption

Diesel engine. The consumption of diesel fuel is about 0.25 kg/kWh and that of lubricant about 0.007 kg/kWh.

To combine the cost of fuel and lubricant, it will be assumed that the cost of the lubricant is 5 times that of the fuel. Hence the equivalent fuel consumption is $0.25 + 0.007 \times 5 = 0.285$ kg/kWh. If the engine runs 1 500 h annually, we obtain q_f (equiv) $= 0.285 \times 1\,500 = 427.5$ kg/kW as the annual rate of consumption per unit of installed power. As the conditions of exploitation of the engine will not always be optimal, it would not be unreasonable to increase this figure by about 17% to get a round 500 kg/kW, or 0.5 t/kW, as the value of q_f.

Gasoline engine. The annual equivalent fuel consumption for gasoline engines will be assumed to be 20% greater than that of diesel engines, giving $q_f = 0.6$ t/kW.

Comparisons

A 10-kW solar engine working 1 500 h a year will be compared with a set of two diesel engines each having 5 kW and 1 500 rpm and working 6 000 h over 4 y. A 2-kW solar engine will be compared with a set of two gasoline engines each having 1 kW and working 3 000 h over 2 y.

Taking into consideration the above assumptions, the following equations can be written:

For the diesel engines:

$$(0.10 + 0.03 + 0.04)\, K_s = (0.25 + 0.20 + 0.04)\, K_d + 0.5\, c_f$$

or

$$K_s \approx 3\, K_d + 3\, c_f \qquad (2)$$

and for the gasoline engines:

$$0.17\, K_s = (0.50 + 0.20 + 0.04)\, K_g + 0.6\, c_f$$

or

$$K_s = 4.35\, K_g + 3.53\, c_f \qquad (3)$$

where the K are expressed in currency units per kilowatt and c_f is in the same units per ton of fuel.

Since taxes vary from country to country, it will be assumed that no taxes will be placed on the equipment and its installation and on the consumed fuel.

The unit cost of diesel fuel is difficult to estimate; it depends on many factors, such as the price of crude oil, the distance between the refinery and the crude-oil supplier, and the cost of internal transport and distribution.

The unit cost of installing a diesel engine of the size being considered in the present (1976) conditions of the international market may be assumed to be 150 $/kW. In the same conditions, the unit cost of installing a gasoline engine in the 1-kW range is 50-70 $/kW.

Substituting K_d = 150 $/kW, K_g = 50 $/kW and c_f = 150 $/t in equations (2) and (3), we find that the cost of installing a solar engine should not exceed 900 $/kW if it is to compete with a diesel engine and 834 $/kW if it is to compete with a gasoline engine. It is important to note that these figures are the cost of the solar engine without heat storage.

The present cost of solar engines varies greatly; amounts as low as 3 000 $/kW and as high as 20 000 $/kW have been asked by manufacturers. The price depends strongly both on the size of engine and on the number of identical units produced, as can be seen from the example provided by one manufacturer presented in figure 27.

Comments and conclusions

(a) Calculations of the cost per unit of energy (kWh for example) is not useful because the variables vary too much from country to country. A general equation, such as equation (1) above, is more useful;

(b) A solar thermal engine within the range of 2-10 kW begins to be economically feasible when its unit cost does not exceed 1 000 $/kW. The present cost on the market is 3-20 times higher (1976);

(c) Solar photocells would be economically feasible at 2 000 $/kW because the cost of repair and maintenance and depreciation are lower. Also, the cost of an electric generator was not included in the costs of the diesel and gasoline engines.

(d) Economy of scale can not be fully applied in the case of solar thermal engines, since the required surface area of the solar collector is approximately proportional to the power of the engine. (The improvement of the efficiency of larger engines can be neglected in a first approximation.) The solar collectors represent an important part of the total cost of the installation. However, the cost per unit power of other components, transport and installation will be greatly reduced when the power increases;

(e) The investment is higher for solar engines;

(f) The solar engine installation will occupy a ground surface of 20-50 m^2 for each kilowatt of installed capacity; this extra land cost should be taken into consideration. However, if solar collectors are used as roofs for buildings, the cost per unit of installed capacity will decrease;

(g) If there were a feasible way of storing solar energy, the cost per unit of installed power capacity would increase, but the cost per unit of energy delivered would decrease;

(h) It is difficult to obtain a constant speed on the shaft of a solar engine unless a costly and possibly sophisticated system of control is provided. A constant speed may be necessary for some applications;

(i) The machine that will be coupled to a diesel or gasoline engine giving the same energy will have half the power of that coupled to the solar engine, so its cost, transport and installation will be cheaper and easier.

Solar refrigeration and air conditioning

Solar refrigeration and air-conditioning systems are still bulky, complicated, too expensive and require as much as 30% of their input energy to come from an external source. It was determined in the third case study of a solar air-conditioning system above that, with the cost of fuel at 480 $/t and increasing 20% annually and an interest rate of 9%, 20 years would be required for a 10-kW solar air-conditioning unit to pay for itself, and that calculation was rather optimistic. It is obvious that further R and D is necessary, particularly to decrease the proportion of external energy needed.

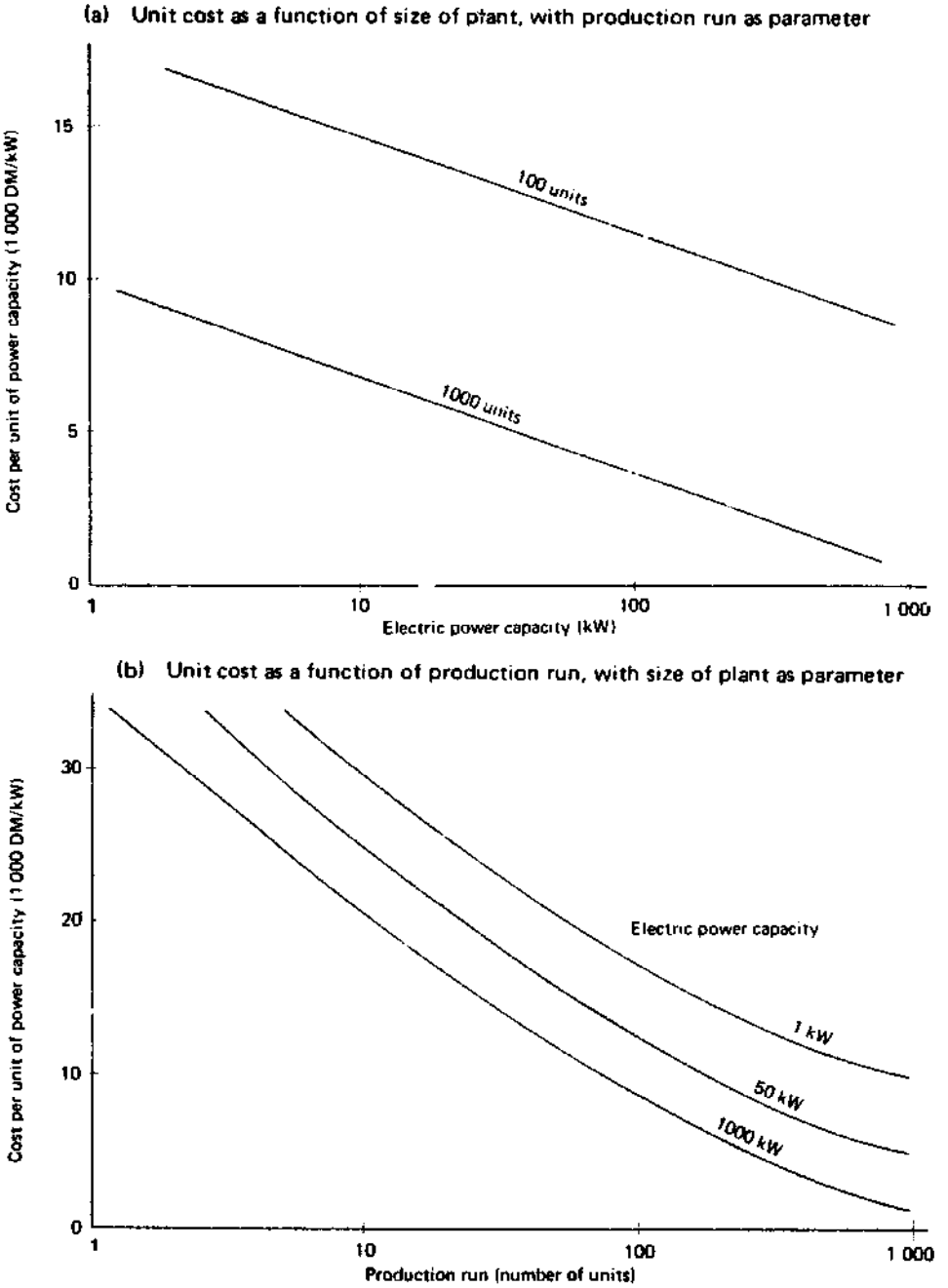


Figure 27. Unit cost of installation of solar power plants

III. SOLAR ENERGY UTILIZATION IN DEVELOPING COUNTRIES

Evaluation of experience in developing countries

Greece

In Greece, the major development in solar energy is water distillation. The most important installations in the world are here, at Nisiros and Fiskardho for example (see table 1).

The basic design of the stills is an aluminium structure with sheet glass for the walls and roof (figure 22 (f)). The black absorbing surface is made of thin sheets of butyl rubber sealed with silicone rubber. This technology seems to be reliable, but it requires materials that are not often available in most developing countries and its cost is relatively high. Such stills can be reproduced only if good technicians are available.

India

India has an ambitious programme in solar energy R and D:

Solar water desalination

One installation for solar water desalination is located at Bhavnagar with a capacity of 0.9 m^3/d, and another of 5 m^3/d is under construction. The principal materials are bricks, cement, glass, wood

and cotton electrical insulating tape. A small quantity of aluminium is also used. The black absorbing surface is concrete painted with mastic. The total estimated cost for this installation is about $28 000 or about $14 per square metre of effective evaporating surface. The expected average rate of production of this installation is about 2.5 $l\,m^{-2}d^{-1}$. The technology seems to be reliable and easily transferable to other developing countries.

Solar water heaters

An electrical equipment company is experimenting with solar collectors with a view to mass producing solar water heaters. It plans to use existing facilities for the aluminium roll-bond technique to construct the collectors.

Solar space heating

A system of heating by hot air has been developed, but the costs of such a system cannot be evaluated until the results of the R and D programme on solar collectors are known.

Solar pumps

The Birla Institute of Technology and Science at Pilani has already constructed two prototypes of a solar pump without moving parts. These two prototypes are now under experimentation. The first evaluation shows that the water pump is promising and that the cost per unit power of the installed prototype could be about 2 000 $/kW. Many technological problems are still to be resolved.

Other work

Work is just beginning on solar drying, solar air-conditioning, solar refrigeration and conversion of solar energy into mechanical energy. The National Aeronautical Laboratory is working on windmills using a technology similar to that used in developed countries. This work is conducted in three directions:

Irrigation: Improvement of the existing multiblade model

Electric power generation: model with two or three blades and flap control, with a nominal output of 1-5 kW at a wind speed of 5 m/s

Pumping: windmills to power pumps for salt works

An attempt is being made to combine the pumping of water with the generation of electricity. The hope is to achieve a cost per unit power of 1 000 $/kW.

Mexico

The most important solar energy programme in Mexico is solar pumping, which is based on the SOFRETES technology. A low-temperature solar turbine of 25 kW driving an electric generator, which in turn supplies energy to one or more pumps, is operating at San Luis de la Paz, about 350 km from Mexico City. The cost, however, is still prohibitive. Eleven 1-kW pumps are already installed, eight are under construction and one solar pump to be driven by a rotating solar engine is planned.

Interesting work has been done on the construction of solar collectors using a container made of asbestos cement, imported aluminium roll bond as water ducting and absorbing surface, double glazing, silicone rubber sealant and fibreglass insulation. A solar collector using a fibreglass container is in the R and D stage.

Mexico is planning to produce low-power solar pumps in large numbers for export to other developing countries. However, with the present reciprocating Freon engine and the high cost of the other components of the system (solar collectors, heat exchangers), it will be very difficult to withstand the competition of diesel and gasoline engines.

Discussion of problems and solutions

Applications of solar energy that are feasible for developing countries under present conditions are:

(a) Solar distillation of sea water and brackish water at low and medium fresh-water production rates; about 30 m^3/d seems to be reasonable;

(b) Solar domestic water heating on an individual or collective basis. Solar water heaters have been proved competitive and are already very popular in Australia, Cyprus, Japan and the United States. The technology of this application is easy and can be adapted to local conditions;

(c) Solar drying. Heretofore, this type of drying has always taken place in the open air. Now, with a simple apparatus, it should be possible to obtain clean, healthy, products of better quality. The equipment is simple and can be manufactured without great difficulty. Local institutions should prepare adequate designs for demonstration purposes. Farmers could use these models to manufacture their own driers. The use of solar driers with an additional source of energy could be envisaged where energy is cheap and maintenance and repair can be carried out easily. But it will not often be a good solution to transform the mechanical or electrical energy into heat to drive the necessary fans. Combining wind energy with solar drying may be a good solution.

Applications that are not yet feasible are:

(a) Solar engines. Many prototypes already exist on the market. Some of them have been tested over years, some for months, and others are only now ready for testing. It would be inadvisable for developing countries to use these solar engines for purposes other than experimental. Their cost is still prohibitive and the technology has not yet been thoroughly tested;

(b) Solar electricity generation by photocells. Although photocells are claimed to be reliable, their cost is still very high and it is not advisable to use them in developing countries for purposes other than experimental. The technology of photocells is still being developed, and it is hoped that in the not too distant future these cells will have the same success that transistors have had. In such a case, small developing countries could envisage the assembly of such units, and large ones could envisage partial or total manufacture;

(c) Solar refrigeration. Units independent of external sources of power are being developed, but even for small cooling capacity, they are very large and heavy. For intermittent or continuous absorption machines, the solar energy equipment will be a supplement to conventional machines. The existing technology seems to be feasible; however, an exact feasibility study should be prepared to determine to what extent external sources of power would be acceptable. The manufacture of ice is often a good solution because the ice can be transported and used to preserve food or other products.

BIBLIOGRAPHY

American Society of Heating, Refrigeration and Air-Conditioning Engineers. The 1972 handbook of fundamentals. New York.

_____ The 1972 handbook of systems. New York.

_____ The 1972 handbook of applications. New York.

_____ The 1972 handbook of equipment. New York.

Austrian Solar and Space Agency. Small solar power systems. August 1976. (FA-3) The Austrian Solar and Space Agency (ASSA) was charged by the Federal Ministry of Science and Research to carry out an inquiry amongst all member countries of IEA concerning national activities in the field of small solar power systems. This inquiry includes work being carried out in member states on R and D on solar power plants and their subsystems as well as information systems covering this area.

Backus, Charles E., ed. Solar cells. New York, IEEE Press, 1976.

Brace Research Institute, Macdonald College of McGill University. A survey of solar agricultural dryers. Ste. Anne de Bellevue, Quebec, Canada, December 1975. (Technical Report T99)

This report describes some of the solar agricultural driers actually built by experimenters and practitioners in the field.

Brinkworth, B. J. Solar energy for man. Salisbury, Compton Press, 1972.

Eggers-Lura, A. Flat plate solar collectors and their application to dwellings. Low temperature conversion of solar energy. Commission of the European Communities.

The documentation section of this report surveys the present state of the art, and thereafter a summary is given of solar R and D work undertaken so far in the individual EEC countries, in other European countries, and in countries outside Europe that have made important contributions to solar energy research.

International Solar Energy Society, U.K. Section. Solar energy–a United Kingdom assessment. London, May 1976.

An analysis of all aspects of solar energy systems, made to assess the potential for solar energy utilization and R and D needs in the United Kingdom of Great Britain and Northern Ireland and for export.

Kredder *and* Kreith. Solar heating and cooling. New York, McGraw Hill, 1975.

Messel, H. *and* T. S. Butler, eds. Solar energy–a course of lectures. Oxford, Pergamon, 1975.

Noyes Data Corporation. Solar energy for heating and cooling of buildings. Patton, 1975.

Photovoltaic power and its applications in space and on earth. Paper prepared for the International Congress: The Sun in the Service of Mankind, Paris, 2-6 July 1973.

Solar desalination–status and potential. *By* C. Mustacchi *and others.* Rome, ASIS, May 1976.

Prepared for the Commission of the European Communities. The aims of this study include: a summary of the state of the art in the field of solar desalination; a choice in priorities for future programmes of research and development; and indication of the potential benefits of technological advance and of the appropriate siting of the research efforts.

United States. Library of Congress, Science Policy Research Division. Survey of solar energy products and services, May 1975.

This survey was conducted to obtain descriptive information on solar energy hardware and related services.

Vaillant, J. R. Les problèmes du dessalement de l'eau de mer et des eaux saumâtres. Paris, Eyrolles Editeur, 1970.

Part two

SUMMARIES OF COUNTRY AND INSTITUTIONAL PROGRAMMES ON SOLAR ENERGY

Country programmes

Austria

Austrian Solar and Space Agency

The Austrian Solar and Space Agency (ASSA) co-ordinates solar energy research and applications in Austria. Its main tasks are:

(a) To serve as a contact with foreign and international solar organizations;

(b) To advise the Austrian Government on solar research, technology and applications of interest to Austria, taking into account international developments in this field;

(c) To process and distribute information and data on solar technology to Austrian industry and scientific institutes; to organize lectures and conferences; to train Austrian specialists in solar energy.

ASSA has carried out three studies so far. One deals with solar energy systems in member countries of IEA, particularly in the field of solar power plants and their subsystems.

The study *Kleine Sonnenkraftwerke für Entwicklungsländer* (FA-4) (Small Solar Power Systems for Developing Countries) considers existing small solar thermal power stations up to a capacity of 50 kW and suggests that a prototype with a capacity of 10 kW (flat collectors or concentrating collectors) be established.

The study *Meteorologische Messdaten für die Nutzung der Sonnenenergie* (FA-5) Meteorological Data for the Utilization of Solar Energy, discusses meteorological facts for direct use of solar energy in view of their importance for setting up solar technical plants.

ASSA wishes to promote R and D projects in scientific institutes, universities, research centres and industry in close co-operation with other countries. Austria is participating in the IEA programme and has initiated a co-operative programme with UNIDO.

Activities of other institutions

Several Austrian working groups at universities, research centres, and in industry are concerned with solar energy R and D activities, especially in the area of solar heating and cooling systems and in the production of electrical or mechanical energy.

Solar heating and cooling

To promote the economic use of solar energy in Austria, several projects, e.g. houses, swimming pools, collector test stations in various parts of the country, have been established with the support of the Federal Ministry for Science and Research. The essential factors for the economic use of solar energy plants in given geographical, meteorological and other environmental circumstances are being summarized and evaluated. The possibility of integrating solar techniques with conventional systems is investigated under this programme. From the experience gained, guidelines are to be established with regard to equipping solar technical plants for producing warm water and heating houses with the simplest possible control systems.

Design of solar houses

The designing of buildings to have the lowest primary energy demand is one of the most effective methods of saving energy. For over five years the Institute of Building Construction has advocated the adoption of a low-energy philosophy both in building construction and design method and has promoted a "heavy-weight" integrated design approach that has resulted in significantly improved thermal response, energy savings and economy of building systems.

Production of solar collectors

Austrian firms produce various kinds of flat-plate and concentrating collectors and special test stations have been established to make comparative tests of them.

Solar heating systems

In 1976, the manufacture of complete solar installations for heating homes and swimming pools was begun. Approximately 100 installations of this type are in operation. A special collector control system has been developed that enables the collector-fluid flow rate to be regulated depending upon the temperature level.

When considering application of solar heating in Austria, the following possibilities must be investigated:

Off-season heat storage

Combination of solar energy and heat pumps to increase the temperature of solar-heated water or the output of the solar collectors

Combination of solar heating with conventional stand-by heaters during cold spells and cloudy periods

For economic reasons, seasonal storage is unrealistic at present in Austria. Concerning the two other possibilities, the Institute of Applied Physics of the University of Vienna carried out a study to design a solar energy installation for the newly founded Institute of Molecular Biology, in Salzburg, of the Austrian Academy of Science. This installation is to serve as a demonstration plant for the use of solar energy under the specific climatic conditions in Salzburg. It is the first large-scale solar-heated building in Austria. The main purposes of this demonstration plant are:

(a) To test on a long-term basis the performance and ability to resist corrosion of the solar collectors;

(b) To gain experience on the joint operation of the solar collector and heat pump;

(c) To collect and evaluate extensive data to provide the technical and economical basis for further application of solar heating (and cooling) of buildings in Austria.

Solar cooling systems

Research on space cooling with an absorption machine and flat-plate collectors is being carried out. The first installation will be put into an apartment building in Spain. It is planned to have a heating-fluid temperature of 80°C and a cooling-fluid temperature of 30°C.

Conversion of solar energy into electrical or mechanical energy

Photovoltaic systems

Four university institutes are carrying out theoretical studies, and a government testing laboratory is implementing an extended field test programme to evaluate solar cell panels.

The Institute of Physics of the University of Vienna is actively interested in this field and is planning research on the preparation and properties of solar cells for earth applications. CdS and polycrystalline Si are regarded as the most promising candidate materials.

The Institute of Physico-Chemistry of the University of Vienna deals with material characterization of semi conductors.

At the Institute for Applied Physics of the Technical University of Vienna, investigations have been carried out since 1965 on the photoconductivity of single crystals of CdS and the enhancement of their sensitivity by doping with Te. In 1972, the investigations were expanded to the study of thin films of CdS. The work was finished in 1974 with a research paper about evaporation techniques and photoconductivity of the thin films. Investigations on photovoltaic cells are planned.

A research team at the Institute of Solid State Physics, University of Linz, has been engaged for several years in research and preparation of infrared detectors. The researchers are experienced in preparing thin-film devices using epitaxial growth and ion implantation techniques. The research could be shifted to solar cells.

The Federal Testing and Research Institute, at Vienna, has installed four solar cell panels at a test site in eastern Austria. The panels, consisting of Si solar cells, will be tested for two years. Each panel has a maximum power output of 1.6 W. The test programme includes recording of power output as a function of solar radiation, weather conditions etc.

Solar thermal-electric systems (including collectors)

Solar-thermal conversion systems. In recent years universities, research institutions and industries have co-operated closely in developing solar collectors. The possibility of obtaining higher concentration factors in flat collectors by change of surface structure or selective coatings is being investigated. Water temperatures of 300°-400°C seem possible. For small power plants such types of collectors may be versatile. The co-operating institutions include: in Vienna, the Institute of General Physics of the Technical University, Institute of Physico-Chemistry of the University of Vienna and Federal Testing and Research Institute, in Graz, Institute of Thermal Power and Nuclear Engineering of the Technical University and the Research Centre, Institute for Environmental Research.

Solar power plants. The International Institute for Applied Systems Analysis (IIASA) at Laxenburg near Vienna is evaluating large-scale solar-thermal power plants of the power-tower types.

The Institute of Thermal Power and Nuclear Engineering of the Technical University, Graz, has developed thermal storage systems (steam storage by means of pressurized hot water) for energy storage in power plants. The proposed scheme is particularly suitable for load balancing in solar-thermal power plants. Depending on size and operating pressure, either welded steel vessels or pre-stressed cast-iron pressure vessels will be employed.

Denmark

About 50% of all the energy consumed in Denmark is used for domestic water and space

heating. Hence, the solar R and D effort is directed towards those purposes.

In 1975, the Zero-Energy house, a one-family house with a floor area of 125 m^2, was completed. It is heated by solar energy, the waste heat from the electrical installations in the house (e.g., light bulbs, refrigerator and washing machines), and the body heat of the inhabitants. The Zero-Energy house has a vertical solar collector of area 42 m^2 and a water storage tank of capacity 30 m^3. The Zero-Energy house is uneconomic, but does conclusively prove that even at the high latitude of Denmark (56°) a house can be heated by solar energy alone, provided that it is well insulated.

In 1976, a new building code was introduced requiring increased insulation of new buildings. Through proper insulation alone, the annual energy requirements of a single storey, one-family house can be decreased from about 25 000 kWh to 10 000 kWh.

Further work has been directed especially towards space and water heating by solar energy in combination with heat pumps. A solar house at Skive, North Denmark, was constructed in 1977. The total heat requirements of the house are covered by a solar collector of area 28 m^2 combined with two heat pumps that recover heat from the exhaust air and waste water of the house.

Finally, significant R and D work is being done on solar refrigeration by a solid absorption plant. The preliminary study covers a plant producing ice at the rate of 500 kg/d.

There are many solar-heated houses in Denmark, and three or four firms are producing flat-plate solar collectors for space and water heating.

France

Since the energy crisis in the early 1970s, the French Government has shown a great interest in new energy sources. A special ministry "La delegation aux energies nouvelles" was created to co-ordinate research, development and industrial programmes. About 300 researchers in several national laboratories are engaged in fundamental research to find ways to use solar energy (biological, chemical and physical processes). The industrial application of these developments is very different for developed and developing countries, from the viewpoint of both the objectives and the needs of the countries.

French industry has developed solar heaters for domestic and industrial water and for heating houses. About 50 experimental houses have been built using flat-plate collectors (area 20 m^2). A total collector surface area of about 15 000 m^2 has been installed in industry.

The Government expects to reduce total energy consumption by 5% by 1980. French industry is developing possibilities of converting solar energy into electricity by a high-temperature thermal process through a programme carried out jointly by the national laboratories and international partners. At Odeillo, a converter using the concentration system is in operation. Day and night, it supplies electrical energy at the rate of 60 kW. The working temperature is around 350°C.

For developing countries, French industry is engaged in a programme concerned with:

Irrigation pumps using small collectors
Supply of electricity
Refrigeration (of foods)
Desalinization
Air-cooling

For greater feasibility of technology transfer, the flat-plate collector technology with low-temperature cycle conversion has been chosen. Around the world, about 50 prototypes of 1-kW solar pumps are being operated. The surface of the collector is about 50 m^2 and the overall efficiency is about 2%. It is hoped to increase performance further, having in mind the same principal objective: the possibility of transferring technology.

Federal Republic of Germany

The R and D programme of the Federal Republic of Germany for the utilization of solar energy was launched as a part of the non-nuclear R and D programme at the beginning of 1974, immediately after the oil crisis. Up to then, solar energy had been considered uninteresting because of the extreme northern latitude of the country, with a mean insolation of only 110 W/m^2 and a mean sunshine duration of 1 300-2 000 h a year, depending on the region under consideration. However, studies and experiments with test houses carried out in recent years have proved that utilization of solar energy is of interest even to countries situated in mid-Europe.

For the time being, activities are focused primarily on the possibilities for supplying hot water or heating buildings and not on generating electricity because of the structure of the country's energy consumption. About 40% of final energy in the Federal Republic of Germany is required for space and water heating, 36% for generating process heat and merely 24% for generating light and power. Thus, the heating sector is the major area of interest in terms of securing the energy supply in the long run. The expenditure on solar R and D was DM 6.2 million in 1974, DM 15.9 million in 1975, and DM 27.0 million in 1976.

Based upon the experience gained since 1974, a new solar energy research programme (1977-1980) has been launched, with a budget of about DM 150 million. The major objectives of the programme are discussed below.

Thermal uses

Systems for producing hot water using solar radiation are already commercially available in the Federal Republic of Germany. However, the main components, such as collector and hot-water storage, have to be improved in order to become competitive with oil, gas or coal heating systems. In addition, long-term behaviour and maintenance of solar heating systems have to be evaluated. Therefore, the following activities are of major importance in the R and D programme of the Ministry of Research and Technology:

Measurement of data to assess the efficiency of hot-water supply systems
Short- and long-term testing
Standardization of components and systems
Development of new absorbers and minimization of collector losses

Solar systems for heating buildings are being tested in several solar demonstration houses. The major objective is to improve the economy of already existing systems, so that the houses can be introduced on the market within 10 years. Activities are predominantly concentrated on:

Improving collectors and storage technically to facilitate mass production
Expanding knowledge of system behaviour
Strengthening the capacity of adequately trained architects, engineers and skilled workers

In addition to these activities, data will be collected on climatic conditions, types of building that can be equipped with solar systems, effects on the environment and construction practices.

Process heat is another sector of interest for the application of solar power. For the Federal Republic of Germany, the ranges below 200°C and around 2 000°C are important. At present, R and D activities are directed mainly towards temperatures below 200°C for processes of drying, distillation, cooling, petrochemistry or evaporation.

Electrical utilization

Developments in the sector of electrical utilization are focused at the moment on systems with a closed thermal cycle. The collectors that have already been developed for heat supply purposes can be used in these systems. Turbines and expansion machines are available, operating with Freon as a working medium. The prospects of success in generating power by means of photocells are poor, on account of the high cost of solar cells, the low efficiency and the very considerable area requirements in Central Europe. However, in the long run, it may be possible to introduce this method in the sunny regions of the world.

The generation of electricity with the aid of solar energy—whether by thermodynamic or photovoltaic means—is one of the most promising possibilities for supplying energy to rural areas in the developing countries. R and D activities are oriented particularly to this aim, namely, to develop well-functioning systems in the 10-kW range that are easy to maintain and to produce less expensive facilities.

There are plans to construct solar power stations of 500 kW capacity within the framework of the European Communities (tower concept) and IEA.

The wind-energy potential for the area covered by the Federal Republic of Germany is, in theory, extremely high—the average power of the winds is about 200×10^9 kW, but in practice wind energy can be utilized only to a very limited extent. On the one hand, new kinds of technical effort must be applied; on the other hand, the problem of storing energy arises, as it inevitably does when solar energy is used on a broad scale. Both these limiting factors prevent the wide use of wind energy in the Federal Republic of Germany, which would suggest that it could be used for special purposes only, or where local conditions are particularly favourable. R and D activities are now primarily focused on the design of a 1-3 MW windmill plant, to go under construction in 1979 and a 10-kW vertical-axis windmill.

The energy provided by wave motion has been utilized for years to supply electricity for buoys and lighthouses. Such facilities have a low capacity, however, usually under 100 W. They operate where the utilization of another form of electricity would be both difficult and costly, meaning that even the high costs of power generation by wave energy can still be accepted. The switch from small facilities to use in industry entails several problems. To date, no large-scale facility has been built. Analyses have invariably shown that such facilities would not be competitive with other power plants. It has been estimated that, for the Federal Republic of Germany, the power of the ocean waves along the entire North Sea coast is modest: 3 600 MW. Without doubt, it would be possible to utilize only a small proportion of this capacity for practical purposes. In this respect, the situation for countries with long coastlines, such as Ireland or the United Kingdom, certainly holds more promise. Because of the low energy potential in this sector, R and D activities in the Federal Republic of Germany are minimal.

Biological and chemical utilization

Another broad field is the biological and chemical utilization of solar energy. As a result of natural biological processes, a vast amount of solar energy is converted into chemically combined energy and stored. This energy can be released again with the aid of thermal fermentation processes. The efficiency of these systems is, however, very low. The

technically and economically usable potential is so small in the Federal Republic of Germany that corresponding R and D projects are being promoted to a modest extent only. The investigation of biological processes occurring in photosynthesis and photolysis constitutes the focal point of the R and D work currently in progress.

International co-operation in R and D

The new solar energy R and D programme is being carried out in part through international co-operation. Major partners in multilateral co-operation are the European Community, IEA and UNESCO. In addition, numerous bilateral agreements on solar energy utilization have been signed, including technology transfer agreements with developing countries, such as one for the construction and operation of a 10-kW electricity generation plant in Egypt and a similar plant in India.

India

Interest in solar energy utilization was revived in 1973 in the wake of the energy crisis. In that year, the National Committee on Science and Technology appointed a committee to compile a status report on solar energy and to recommend to the Government action to be taken. The Committee brought out, in 1974, a comprehensive report entitled "Solar energy—hope and challenge". The report critically evaluated the technology available in the country and also the state of the art in the world. It examined the energy consumption of various sections of society and identified urgently needed R and D programmes. Based on these recommendations, solar energy programmes are being pursued in the country. Collector development has been given highest priority.

The Indian energy scene is characterized by low *per capita* energy consumption, about 100 kWh per day, and hence low *per capita* gross domestic product. India is essentially an agricultural country with 70% of its population living in rural areas. There are as many as 350 000 villages with a population of less than 500. Because of their low load factor and their distance from the industrial belt, it is most uneconomic to electrify these villages. It is equally difficult to reach them with fossil fuels. Therefore locally available energy sources must be found. Thus, a solar energy programme in India is heavily biased towards meeting the energy needs of the rural sector.

India has a well co-ordinated and broad-based R and D programme in solar energy with targets to be achieved within certain periods. The Energy Research Committee, which monitors this programme, consists of Secretaries in the Government and presided over by the Union Minister for Energy.

The Government is deeply committed to developing solar energy utilization. It is liberally funding R and D. The Government has also permitted all expenses incurred on solar applications in industry to be treated as research expenditures and therefore eligible for tax reduction. Among the organizations actively engaged in solar energy utilization or in funding R and D are the Tata Energy Research Institute, Kirloskar's, Jyoti Ltd., Metal Box and Khatau.

R and D is being pursued in relation to the three approaches to the utilization of solar energy: *(a)* low-grade thermal devices, *(b)* direct energy conversion and *(c)* biological conversion. In each of the areas, a project co-ordinator has been appointed to monitor the projects and prepare to produce these devices. In addition, extensive work is in progress in the India Meteorological Department to establish a network of radiation stations and collect solar energy data at as many places in the country as possible. Some 36 stations have been set up, of which 13 are principal stations measuring total, diffuse and normal-beam radiation and hours of sunshine. Other stations measure total radiation and sunshine hours. The necessary instruments (pyranographs, pyrheliometers, sunshine recorders) are being manufactured in India.

Collector development

Various selective coatings are under investigation. Stagnation temperatures as high as 180°C have been achieved. Punjab Agricultural University is developing low-concentration, modified Winston collectors. Steam up to 5 atm has been obtained. Very high-concentration, high-temperature collectors are under development at Radio Telescope Laboratories, Ootacmund. Bharat Heavy Electricals Ltd (BHEL) is responsible for manufacturing these collectors and co-ordinating the programme.

Solar pumps

Solar pumps have received very high priority. The National Physical Laboratory (NPL) has developed an organic Rankine cycle engine using spiral expanders. Prototypes of the 1-kW ABHIMANYU pump have been in operation since mid-1976. Auroville Centre for Environmental Studies is developing organic Rankine cycle engines similar to SOFRETES pumps. The Birla Institute of Science and Technology has developed a low-temperature direct-contact vapour pump for lift irrigation. Feasibility and cost analysis studies for heads up to 30 m and a capacity of 10^5 l/d have been completed. Similar pumps have also been developed by the Central Mechanical Engineering Research Institute. Medium-temperature 200-W hot-air engines based on the Stirling cycle are under development at

the Central Salt and Marine Chemicals Research Institute (CSMCRI). One private enterprise, Metal Box Ltd., has entered into an agreement to manufacture Fluidyne pumps developed at Harwell. Jyoti Ltd. is developing 1-kW pumps using cylindro-parabolic stationary concentrators and steam Rankine cycles.

Solar drying

Cabinet driers have been developed by the Central Arid Zone Research Institute at Jodhpur, RRL at Jammu and the Indian Institute of Technology (IIT) at Kharagpur. In 1976 a major portion of the apricot crop in Kashmir was dried using cabinet driers developed at RRL. Annamalai University has built a prototype of a 1-t/d paddy drier that has been in operation for over a year. The National Industrial Development Corporation has also fabricated a 1-t/d paddy drier that is under test. The Forest Research Institute has undertaken a pilot project to establish four timber drying kilns in four parts of the country. Amul Ltd. has undertaken the project of making powdered milk using solar energy.

Desalination

CSMCRI (Bhavnagar) is active in desalination. It has provided drinking water facilities for several lighthouses and distilled water facilities for many R and D laboratories and educational institutions. It is providing two villages in Gujarat with drinking-water facilities. The laboratory has also built a 10^3-l/d solar still. Based on a humidification-dehumidification technique, the laboratory has set up a pilot plant producing at the rate of 2×10^3 l/d.

Solar power plant

A 10-kW solar power plant is being established at Madras as a joint venture between the Government of India and the Government of the Federal Republic of Germany. BHEL, NPL, and IIT (Madras) are the executing agencies on the one side and MBB the executing agency on the other. This solar power plant will have a flat-plate collector array and an organic Rankine cycle engine with a Linde screw expander. Feasibility studies on another 10-kW power plant using spiral expanders are in progress.

Solar water heater

Several laboratories have developed solar water heaters. These are now commercially available in the country. A few other commercial enterprises are entering the field. Industrial solar water heating is also being attempted in two or three industrial enterprises.

Space heating and cooling systems

In 1975, BHEL undertook a major project in technical collaboration with NPL to provide space heating in one wing of its factory at Harwar. The system has a collector area of 200 m^2 and stores 10^4 l of water at 60°C during the day. This hot water is passed through fan-coil units to provide heating to the workers in the factory.

IIT (Madras) has developed a space cooling system that has been on trial for several months. NPL has provided space heating in one room in the building and is setting up a combined space heating and cooling system. The cooling cycle based on the vapour absorption refrigeration principle will operate during the summer. IIT (Madras) and BHEL have developed 1-t air-conditioners based on the ammonia-water absorption cycle.

Direct energy conversion

A well co-ordinated R and D programme concerned with various aspects of direct energy conversion has evolved. Various options are being tried. The Solid State Physics Laboratory is making single-crystal Si solar cells of the quality used in space programmes. The efficiency of these cells is around 10%. The Central Electronic Engineering Research Institute, Pilani, is exploring the possibility of using high concentrations to reduce the cost of solar cells. The National Aeronautical Laboratory is studying the feasibility of growing single-crystal Si ribbons. IIT (Kanpur) and NPL are exploring the possibility of making Si solar cells from polycrystalline films. Cds-Cu_2S solar cells are being developed by IIT (Delhi) and NPL. Programmes in the area of direct conversion are being co-ordinated by Central Electronics Ltd., a Government of India enterprise.

Biological conversion

Relatively little attention is being paid to biological conversion. Biogas systems are becoming very popular in the country. Solar energy is being used to heat the slurry with a view to increasing the efficiency of biogas conversion. In addition, some attempts are being made to convert agricultural waste into methane, ethanol etc.

Italy

Flat-plate collectors

Over 20 manufacturers are already on the market with standard flat-plate collectors, mostly 2 m X 1 m, with single or double glass and galvanized-steel, fibreglass or painted steel case. Commercial prices range around 100 $/$m^2$ and installations to provide

hot water for one-family houses or apartments range between $600 and $800, made up with a collector area of 4 m^2, a 100-l tank, piping, pump, insulation and controls. The manufacturers have scarcely been able to penetrate the market.

Research on collectors, begun in 1958, is carried out in five universities and by six private manufacturers. It concerns, among other things, sealants, surface treatment and the use of plastic honeycombs to increase efficiency. Few funds have been budgeted for it.

Solar pumping units

Research was carried out at the University of Milan in the 1940s on a solar engine using sulphur dioxide as working fluid. This engine, coupled with a pump, has been produced on a small scale by a private company and installed in several tropical countries.

Solar power stations

The first solar boiler working at high temperature and pressure was built in 1961. With conical concentrators and manual tracking, this installation could produce steam at the rate of 7 kg/h at a pressure of 100 bar and a temperature of 500°C.

In 1963 a second solar boiler supplying 38 kg/h at 100 bar and 450°C with an efficiency of 0.6 was built. This installation was later assembled in Marseille in 1964. In 1965, with support of the Italian Research Council, a third solar boiler was built (150 bar, 500°C) with 121 cone-mirrors clock-operated by an appropriate mechanism and producing steam at an average rate of 40 kg/h from 11 a.m. to 3 p.m.

In the period 1966-1977 a new mechanism with 271 flat mirrors 80 cm in diameter (205 m^2 total surface) was developed. The steam was produced at the rate of 130 kg/h at 150 bar, 600°C with an efficiency 0.73 at an isolation of 800 W/m^2. Tests carried out at 800°C showed equally good efficiency.

Desalination

The Universities of Cagliari, Bari and Rome are carrying out a limited amount of work in desalination. During the past 20 years, solar stills have been studied. Several pilot-scale installations were built (mostly by Nebbia University of Bari, with the financial support of the Italian Research Council) and have operated successfully. Feasibility studies and engineering estimates are being carried out on the completed flat collector and multistage flash units at the University of Rome.

Silicon cells

Very limited work on radiation damage to such cells is being carried out at two universities.

Institutional programmes

Austria: Institute for Environmental Research

Since 1974, a team of experts has been exploring possibilities of using solar energy in Austria. The Institute for Environmental Research at Graz developed a solar collector that is now commercially manufactured in Austria.

In 1976, a 600-m^2 solar collector system was installed for heating a swimming pool in the village of Eggersdorf. The design criteria were based on achieving a water temperature of 24°C from May until September. Other projects involving the use of solar energy include the reduction of heating costs for greenhouses, crop drying (tobacco barns) and cooling (air-conditioning). The design for an Austrian solar house is under way.

A contract has been signed for co-operation in the field of solar energy with the University of Dhahran, Saudi Arabia.

Canada: Brace Research Institute

The activities of the Brace Institute in Quebec are devoted particularly to problems in rural areas in developing countries. The Institute is active in development and application of solar distillation, solar agricultural driers and solar cooking.

The Institute has a number of co-operative projects in development, fabrication, installation and testing of solar stills, driers and cookers in several developing countries. The Institute also has assisted institutions in developing countries in formulating solar energy programmes.

Egypt: The Industrial Development Centre for Arab States

The Industrial Development Centre for Arab States (IDCAS) located in Cairo, is affiliated with the Arab League. The 21 Arab States are members of the Board of Directors. One of the main activities of IDCAS is to further co-operation among Arab countries in the various branches of industry.

IDCAS has held two meetings on solar energy in the Arab countries as a start towards collecting the information required on steps that the Arab countries must take to make the utilization of solar energy economic. IDCAS is ready to co-operate with any organization interested in solar energy and is willing to prepare comprehensive studies on possibilities of using solar energy in the Arab countries.

India: the National Physical Laboratory, New Delhi

In the early 1950s the National Physical Laboratory began work in the field of solar energy and continued until 1958 or so. During this period, the Laboratory developed solar water heaters, solar cookers and solar stills. A few solar water heaters were made and installed, and they are still working. Many solar cookers were also fabricated. However, because of the plentiful supply of conventional forms of energy there was little demand for appliances run by solar energy. Consequently, the work in this field was largely abandoned.

NPL is responsible for developing high-efficiency, medium-temperature flat-plate collectors. In the process, it has investigated a variety of selective coatings such as oxides of copper, nickel and chromium, lead sulphide, cadmium telluride, and cermet films of MgO and gold. It has also developed structural selective coatings and selective windows on the glazing surfaces using SnO_2 or In_2O_3. Stagnation temperatures as high as 180°C have been obtained.

NPL is also responsible for establishing testing procedures and standards for these collectors. It has set up extensive facilities for testing them. Emissivity and absorptivity of selective coating and transmission characteristics of glazing surfaces can be measured over the spectral range 300 nm to 20 m. All the parameters of a flat-plate collector can now be measured. Testing of assembled collectors to determine their efficiency can also be done. Facilities are set up to study the influence of environmental conditions, humidity, salt spray etc. on the performance of solar collectors. The field testing is done by BHEL. NPL is in the process of establishing helio centres where artificial sun conditions in respect of solar insolation will be created to test solar collectors and solar cells.

NPL has developed 75-l and 150-l solar water heaters that are now being tested.

The Libyan Arab Jamahiriya: Arab Development Institute

The Arab Development Institute was established in the Libyan Arab Jamahiriya in 1975 to mobilize the efforts of Arab scientists for the benefit of Arab countries. Its objective is development through scientific and technological research.

The Conference on Physics of Solar Energy, held in 1976 at Gar Yumo University in Benghazi, made recommendations to the Institute on the establishment of a centre for solar energy studies. The Institute is now in the process of establishing this centre.

Research is concentrated at present on solar collectors. Work will begin soon on cycle optimization for solar engines and on radiant exchange through glass covers.

Parallel to the work of the Institute, research is being carried out on solar stills by a group at El-Fateh University (Tripoli).

Saudi Arabia: College of Engineering– University of Riyadh

From 1969 to 1973, several solar water heaters and solar stills were made and tested at the College of Engineering of the University of Riyadh. Since 1973 work has been carried out in the following areas: radiation estimations, single-slope concrete stills, night cooling, solar homes and their prospects, convection suppression and honeycomb structures, effect of ultraviolet light on skin, thermal pile storage and other types of storage, flat-plate collectors and their environments, and air heaters.

United States: Solar Energy and Energy Conversion Laboratory of the University of Florida

Over the years, the Solar Energy and Energy Conversion Laboratory of the University of Florida has been measuring the amount of solar energy available and its characteristics and has developed tables giving data for design purposes. Solar properties of material are measured in a solar calorimeter, developed by the Laboratory, which is the only instrument of its kind described in the guide of the American Society of Heating, Refrigerating and Air-conditioning, which is the main reference book in this field.

The laboratory has developed collectors for water heating, space heating and cooling, swimming-pool heating, fresh-water generation and liquid-waste recycling. The work also includes conversion of solar energy for cooking purposes, baking or in solar furnaces. The Laboratory has developed two solar electric cars, two solar electric buses and a solar house in which over 90% of the energy used is provided by solar energy.

Part three

SELECTION OF TECHNICAL PAPERS ON THE UTILIZATION OF SOLAR ENERGY

A 10-kw solar electric power plant

Hans Kleinrath

Institut für Elektrische Maschinen, Technische Universität, Vienna, Austria

There are many options open to the designer of a solar power plant with an output of some 10 kW of electricity. Some of these are set out below.

Component of plant	*Options*
Collector	Flat-plate Concentrating (low concentration factor) Concentrating (high concentration factor)
Working fluid	Water Organic liquid Mixture of systems
Storage	Thermal Electrical
Prime mover	Steam engine Turbine (low-speed) Turbine (high-speed)
Primary generator	High-frequency machine Machine with a frequency of roughly 50 Hz with or without gears
Electrical network	DC AC

The current projects of several manufacturers consequently employ a wide range of ideas and many different permutations of the above-mentioned possibilities. This paper describes an Austrian project to build a plant that had the lowest possible number of control devices and could operate automatically. Figure 1 is a schematic diagram of the plant.

Collector circuit

The concentrating collectors selected were of the parabolic-trough type with a concentration factor of 10. Compared with fixed-direction flat-plate collectors, parabolic-trough type collectors can have a higher working temperature without the efficiency of the collectors decreasing strongly, and hence a better Carnot efficiency: they are also better at collecting energy throughout the day, since they can be made to track the sun.

Due to the relatively low concentration factor the receiver pipes produce hot water at 135°C. This implies a relatively low pressure and consequently low stresses for the fittings, valves and insulation. The total area of the collectors is about 300 m^2.

Freon circuit and prime mover

The primary circuit is connected by a pre-heater and an evaporator to the secondary Freon circuit. A Freon turbine is used as prime mover. Unlike screw

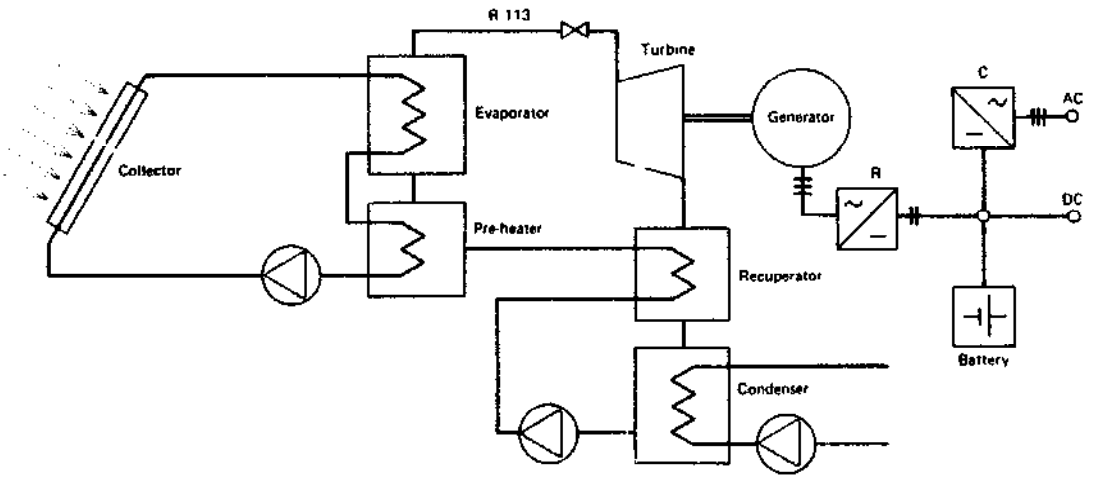


Figure 1. Schematic diagram of the Austrian 10-kW solar electric power plant

expansion engines, a turbine maintains an approximately constant speed even under partial load. It is thus easy to obtain a constant voltage from a directly coupled AC generator.

The turbine specifications are as follows:

Working fluid	R113
Inlet temperature	120°C
Outlet temperature	73°C
Inlet pressure	7.0 bar
Outlet pressure	0.7 bar
Rated output	16 kW

By placing a recuperator between the turbine outlet and condenser, about 11 per cent more primary energy can be utilized. This reduces the total collector area needed, as well as the amount of cooling water needed in the condenser.

Generator and electrical network

A synchronous generator is directly coupled to the turbine. When an AC machine of the homopolar type is used, the rotating part consists of solid steel without any windings, slip rings or brushes.

The voltage of the high-frequency generator is rectified and then connected to a battery. This battery operates both as an electrical store and as a buffer for the rotating unit, keeping its speed approximately constant. The third aim of the battery is to feed all auxiliary drives during the starting procedure.

Performance of the plant

As the collectors track the sun, the energy produced increases very quickly to its peak value. As soon as the energy produced can cover both the auxiliary drives and the losses of the whole equipment, the pumps for the three circuits start. After the turbine has started, equipment utilizing the electricity is switched on automatically according to the amount of electrical energy available.

Figure 2 shows the characteristic curves calculated for operating conditions in Austria in June. Curve 1 is a plot of the variation of direct insolation as measured by a meteorological station. The absorbed energy is plotted on curve 2; this is reduced by shadows cast by one collector on another when the inclination of the collectors is more than 45°.

Curve 3 is a plot of the efficiency of the collectors and curve 4 of the useful electrical output.

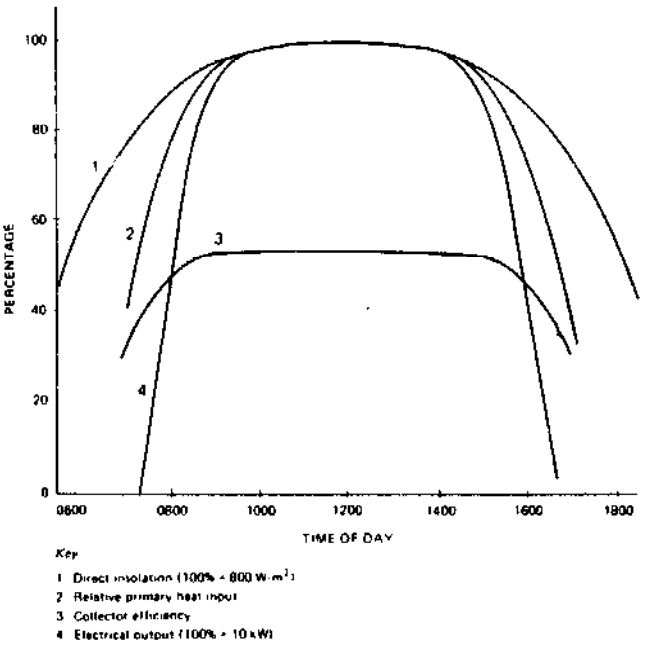


Figure 2. Calculated characteristic curves of the plant (June)

Supplementary equipment

The simplest network is the DC network described, with the battery acting as a store. The main advantages of this network are:

No need for a high-precision speed control

No gear between the prime mover and the generator (this would be indispensable if 50 or 60 Hz AC were to be produced, because prime movers of only 10 kW are of higher speed than 3 000 rpm)

No additional equipment is needed for the starting phase

The simple control system has a high degree of safety

A power plant with an output of only 10 kW will in most cases be enough to power lighting, broadcasting and television equipment. Electrical drives can also be fed if DC motors are used. Nevertheless, AC motors may sometimes be used. Then a supplementary converter of the single armature-converter type is needed. In the classic single-armature converter with its commutator and slip rings, the commutator needs cleaning and the brushes need changing from time to time. Nevertheless, it has some advantanges over the thyristor converter: it is much cheaper; it has very low losses; and it is very insensitive to overload, for example during the starting period of AC motors.

Conversion of solar into mechanical or electrical energy: Indian experience

V. G. Bhide

National Physical Laboratory, New Delhi, India

The total area of land under cultivation in India is about 143×10^6 ha, of which 30%, or 43×10^6 ha, is irrigated. Of this irrigated area, 23×10^6 ha are served by tube wells, ponds or other minor irrigation schemes. The Fifth Five-Year Plan (1974-1979) envisaged an increase in irrigated area of 11.2×10^6 ha, of which 6×10^6 ha were to be served by minor irrigation schemes.

It was originally envisaged that 1.5 million 1.5-kW (2-hp) pumps would be installed during this period. However, because of the oil crisis, not only have these additional pumps not been installed but even a fair fraction of the existing 2.5 million pumps do not have an energy supply (diesel or electricity). Consequently, the development and production of solar pumps in the range 1.5-4 kW (2-5 hp) have received highest priority. The pumps will preferably be in modular form so that when pumping is not required, the same system can be used to produce equivalent mechanical or electrical energy for minor industrial operations or for lighting.

Another approach that the planners in India have adopted is to initiate research, development and the installation of solar power stations in the range 10-100 kW, each of them meeting the total energy needs of a village or a cluster of villages.

Photovoltaic or thermoelectric conversion of solar energy does not appear practical, and hence efforts have concentrated on directly utilizing heat from the sun.

Abhimanyu solar water pump

Figure 1 shows the Abhimanyu solar water pump developed by the National Physical Laboratory (NPL). Its primary components are a flat-plate collector array and a closed-cycle organic Rankine-cycle engine. During operation, a heat-transfer fluid (water) flows through the collector array and is heated to a temperature of 80°-95°C, depending upon the collector efficiency and configuration and the solar flux. This hot water is used to vaporize an organic liquid with a low boiling-point in a reverse-flow heat-exchanger (boiler). The hot, high-pressure organic vapour is then used to drive the

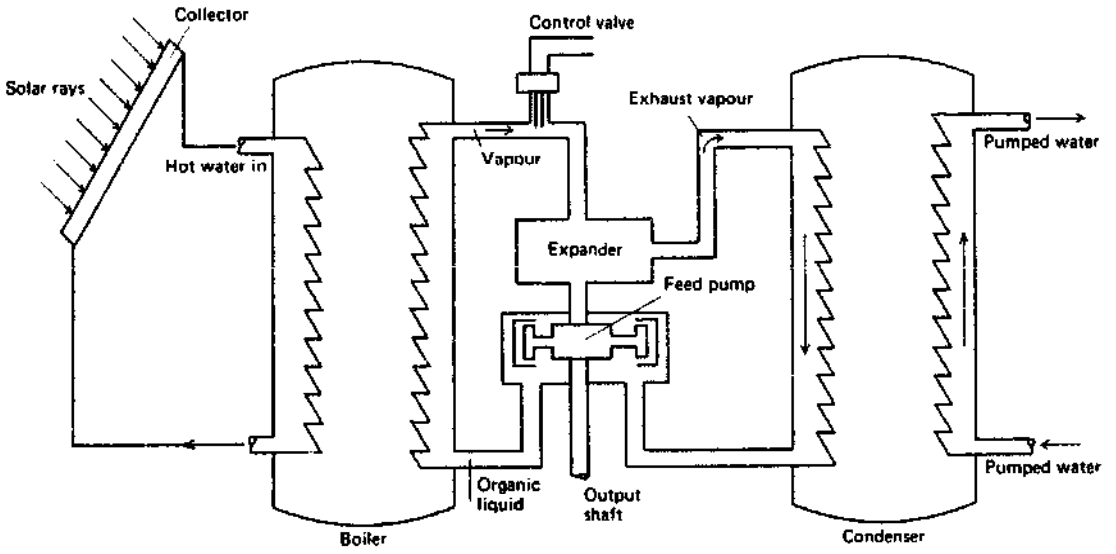


Figure 1. Diagram of Abhimanyu solar water pump

expander of the Rankine-cycle engine. After leaving the expander, the vapour is condensed in a condenser, where the water being pumped is used as the heat sink. The condensed organic liquid is pressurized and then pumped back into the boiler with the help of a reinjection feed pump mounted and driven by the shaft of the expander. For some organic fluids, there may also be a regenerator that utilizes exhaust vapour superheat to pre-heat the fluid coming into the boiler.

The organic Rankine-cycle engine is particularly suitable for solar pumping and power generation and for waste-heat utilization for several reasons:

(a) High thermal efficiency even when operating with the low to moderate temperatures (80°-95°C) achievable with flat-plate collectors;

(b) Low-cost components owing to the use of commonly available construction materials and simple mechanical components;

(c) High reliability because of its sealed construction, which protects it from harmful effects of environment such as sand, dust and moisture;

(d) No problem with freezing, since the working fluids have very low freezing-points.

The efficiency of the system, which to a great extent determines the collector area requirement and hence the cost, is defined here as $\eta_s = \eta_c \times \eta_e$, where η_e is the engine, and η_c the collector, efficiency.

Whereas the engine efficiency increases as the collector temperature increases, the collector efficiency decreases on increasing the collector temperature. It is therefore necessary to determine the temperature range for each collector-engine combination that produces the maximum system efficiency. As we shall see later, this optimum system efficiency depends upon several factors such as the insolation, the condenser temperature, and the characteristics of the collector array, expander, reinjection feed pump and working fluid. Nevertheless, it is obvious that the higher the efficiency of the collector array and the higher the temperature it can produce, the higher the system efficiency. It is all the more necessary to optimize the collector assembly in a large-scale power plant because a substantial fraction of the total cost is accounted for by the collectors.

Collector arrays

Flat-plate collectors were used in the Abhimanyu pump (see figure 2). The absorber plate is made of aluminium alloy with channels built into it by the pressure-bonding technique. The complete mechanical design of the collector was optimized.

Selective coatings of oxides of copper, nickel, chromium, as well as PbS, CdTe and other materials were tried. With the best collector, it was possible to obtain a stagnation temperature as high as 180°C for an insolation of 1 000 W/m² (figure 3). Figure 4 shows the annual variation in the daily useful gain in thermal energy from a typical collector assembly operating at 90°C. Although it was attempted to create selective windows by coating glass covers with SnO_2, In_2O_3 etc., the cost involved in the process did not justify the improved efficiency.

Since it is advisable to operate the expander at a constant input temperature, a reservoir is needed to store hot water; the reservoir is connected to the array by means of a thermostatically controlled bypass valve. Under operating conditions nearly one half of the heat is required to pre-heat the organic liquid and the other half is used during the process of boiling. Some saving on the collector area requirement can be effected by having one collector array for low temperatures and one for high temperatures. The former is used to provide pre-heating whereas the latter serves to boil and superheat the organic vapour.

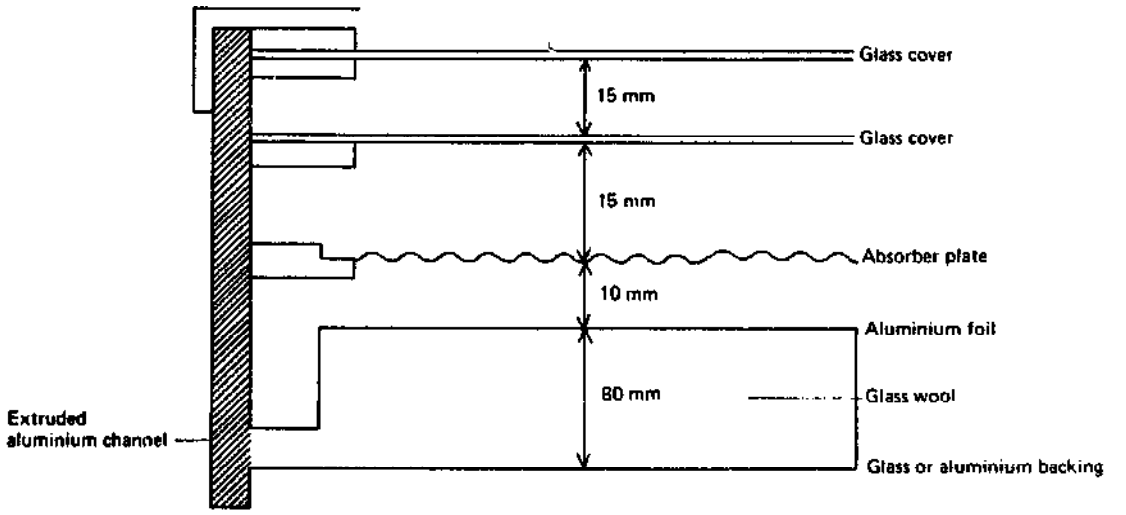


Figure 2. Cross-section of a collector assembly

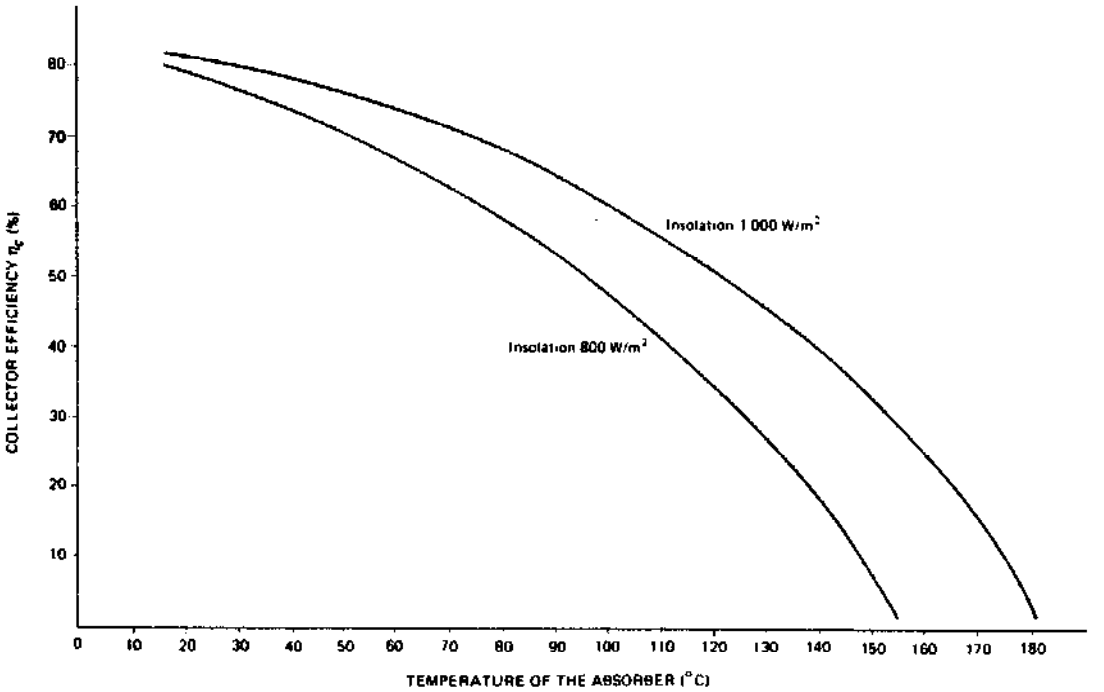


Figure 3. Efficiency of the collector chosen for the Abhimanyu pump

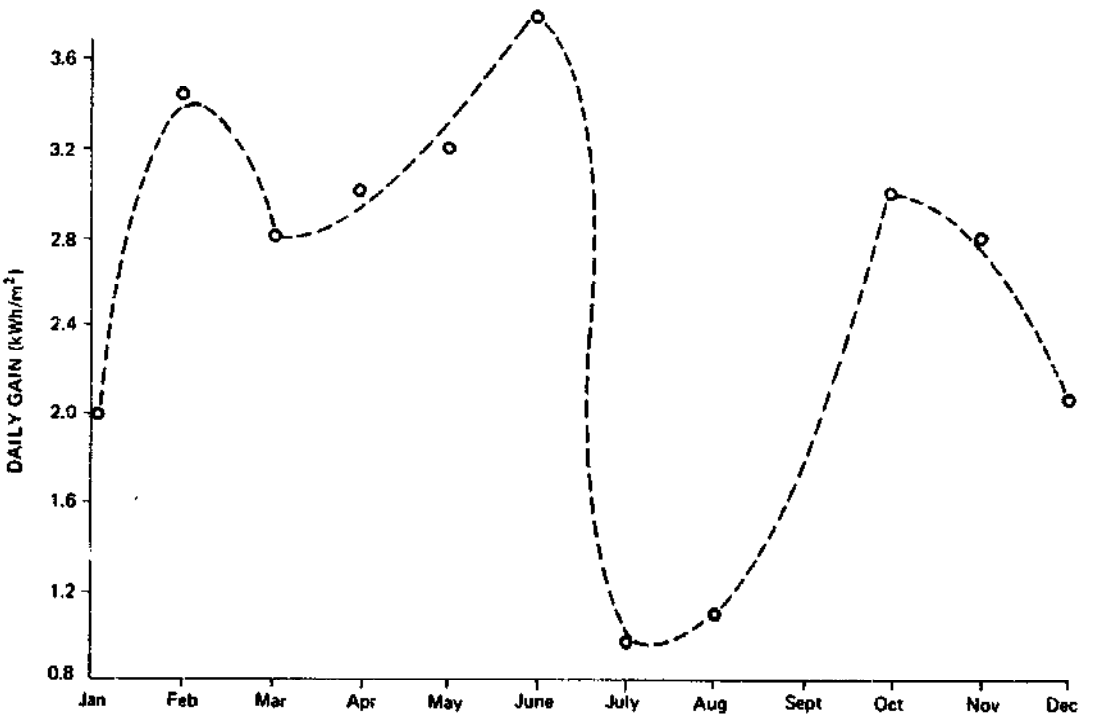


Figure 4. Annual variation of the daily useful gain in energy by a typical collector operating at 90°C

Expander

The heart of the pump is the expander, in which high-pressure vapour does mechanical work and generates shaft power during the process of expansion. To a large extent, the expander determines the reliability and the efficiency of the system. The expander could in principle be a reciprocating machine, a turbine or a positive-displacement rotary machine.

In a reciprocating machine, linear motion is converted into rotary motion by a crankshaft mechanism. The reciprocating machine needs inlet and outlet valves to control the flow of vapour under pressure through the engine. For low-power pumps, the use of reciprocating equipment makes the system complex and inefficient.

Turbines can be used when the power is high. For low powers the turbine size is smaller and its speed higher, which creates a variety of problems. A

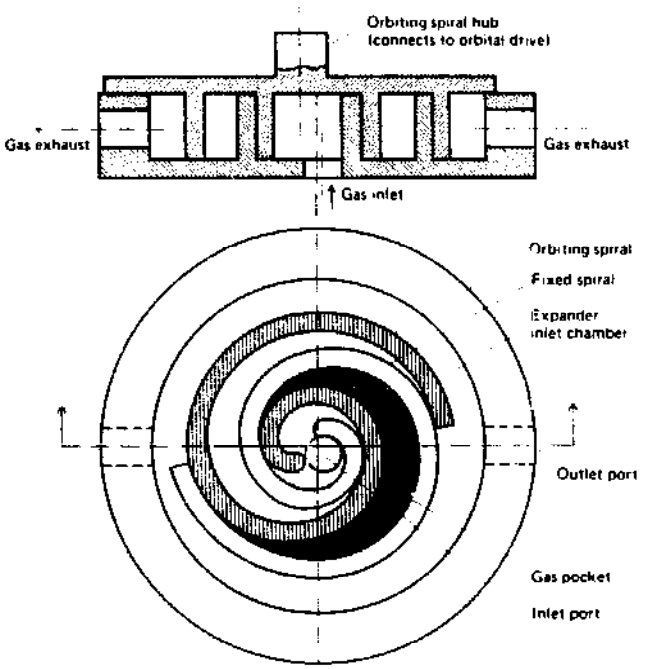


Figure 5. Typical spiral expander configuration

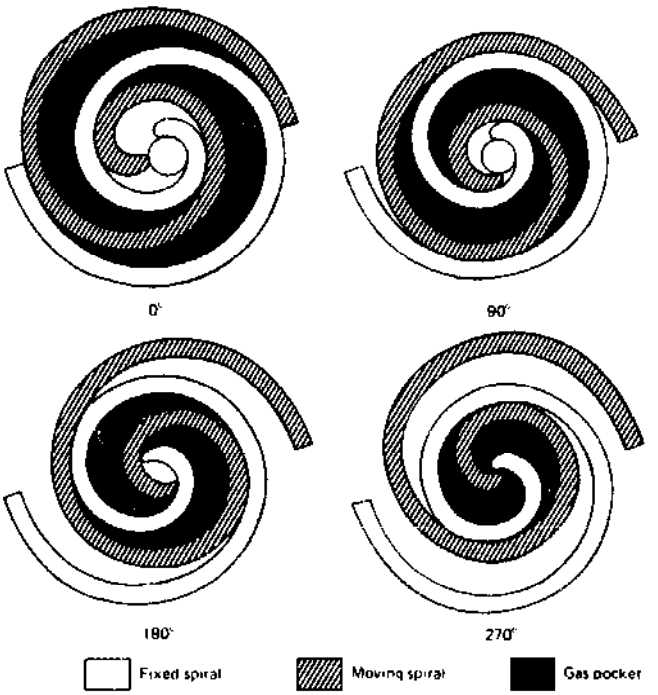


Figure 6. The positive-displacement rotary machine operating as a compressor, at different phases of the orbit of the moving spiral

gear mechanism has to be used to reduce the speed to match either the pump or the generator. Since turbines are not positive-displacement machines, the efficiency of the turbine drops as the vapour flow is reduced. Furthermore, the response of a turbine to variable load is rather poor. For low power it is therefore preferable to have positive-displacement machines running at a moderate speed of 1 000-8 000 rpm.

The expander used in the Abhimanyu pumps is a positive-displacement rotary machine. It consists of an assembly of two oppositely cut spirals, as shown in figure 5. One of the spirals is fixed to the cover plate, and the other orbits round the centre of the inlet port with a slight degree of eccentricity. When these two spirals fit together a number of pockets are formed. As the moving spiral orbits, the volume of the pockets changes (figure 6). Depending upon the direction of the orbital motion, the pocket size either increases or decreases during the orbital cycle. The machine can thus be used either as a compressor or as an expander. When it is worked as an expander, high-pressure vapour enters the spiral assembly at the centre and after expansion leaves the assembly from the periphery.

When it is used as a compressor, the inlet is from the periphery, and compressed gas leaves the assembly through the centre. This expander has no valves to regulate the flow and there are very few moving parts. The volume displacement of the expander per revolution is a function of the volume of the pockets formed between the two spirals, which in turn is determined by the pitch (distance between successive spiral loops) and depth of the spiral, and the thickness of the spiral walls. The cover plates seal these pockets, thus serving the same function as the cylinder walls in a reciprocating machine. Table 1 compares the characteristics of the Abhimanyu positive-displacement rotary machine, a reciprocating machine and a turbine.

TABLE 1. COMPARISON OF MACHINE TYPES

Characteristic	*Abhimanyu pump expander*	*Reciprocating machine*	*Turbine*
Efficiency (%)	70-80	70-80	60-80
Valves	None	Inlet and exhaust	None
Moving parts	Few	Many	Few
Operating speed (rpm)	900-1 800	900-3 600	3 000-80 000
Connection to feed pump	Direct drive	Direct drive	Large gear reduction
Variable speed capability	Good	Good	Poor
Partial load operation	Good	Good	Poor to fair
Noise level	Low	High	Fairly high
Reliability	Good	Fair	Fair

Since the spiral expander operates at low speeds, it can drive a pump or generator directly and use fairly effective shaft seals. Since the expander has few moving parts, there are low rubbing velocities and contact pressures: the spiral expander wears in instead of wearing out. These attributes result in highly reliable operation, with measured efficiencies in the vicinity of 80%.

The volume ratio that can be obtained is a function of the diameter and the pitch of the spiral. The dimensions of a typical spiral expander used in a 1-kW Abhimanyu pump are as follows:

	Inches	*Millimetres*
Pitch	0.625	15.88
Axial length	0.875	22.22
Wall thickness	0.125	3.18
Outside diameter	6.5	165
Orbital radius of the moving spiral	0.1875	4.76

The volume displacement per revolution of such an expander would be 5.7 in.^{3} (93.4 cm^3), and the volume ratio would be 3.0.

Working fluid and cycle description

The size of the expander is greatly influenced by the choice of working fluid. Various working fluids, including the well-known refrigerants R11, R113, R114, were considered. R11 was eliminated because of its low pressure (and consequently poor performance) at temperatures that can be achieved with flat-plate collectors. The drawback of R113 is that it needs a regenerator. Eventually, R114 was selected, since it was ideally suited to the expected temperatures and power generation.

The working cycle of the engine is shown in figure 7. Hot water from the storage tank at about 90°C exchanges heat with the working fluid R114 in a counter-flow heat-exchanger. The working fluid leaves the boiler at a temperature of 82°C and pressure of 9.3 bar (120 psig) (AB in figure 7). High-pressure vapour enters the expander at 82°C and 9.3 bar (120 psig) pressure. After expansion, the exhaust vapour has a temperature of 37.5°C. The vapour leaving the expander is slightly superheated and is at a pressure of 2.4 bar (20 psig); the condenser temperature is 30°C. This isentropic expansion is shown by BC on the figure. The work done by the vapour per unit mass of vapour expanded is 20.9 kJ/kg. The exhaust vapour from the expander is condensed in the condenser by cold water. This process is shown by CD on the figure. The condensed liquid is pressurized and reinjected into the boiler by the feed pump (DA on the figure), completing the cycle. The Carnot efficiency of the cycle is 14.7%, and its thermodynamic efficiency is 12.5%, giving an expander efficiency ratio of 85%. The detailed specifications of a 1-kW Abhimanyu pump are set out below.

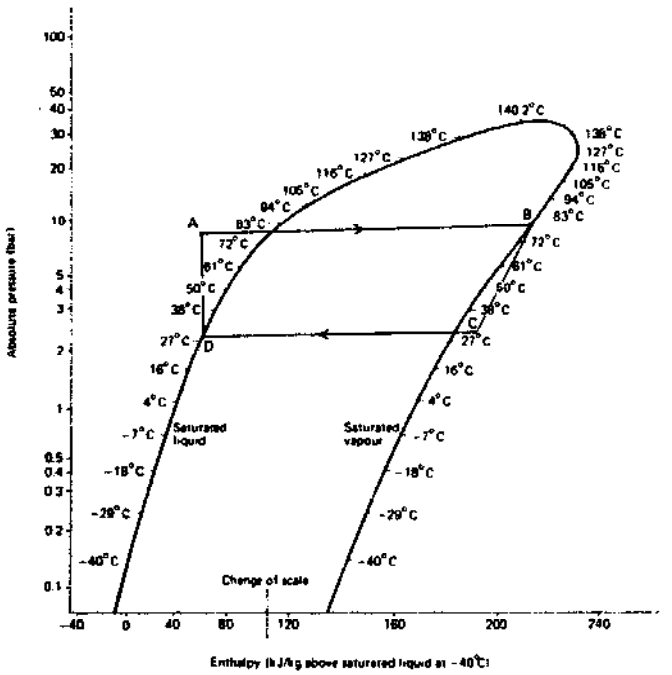


Figure 7. Engine working cycle

Item	*Specification*
Inlet pressure	9.3 bar (120 psig)
Inlet temperature	80°C
Condenser temperature	30°C
Working fluid	R114
Enthalpy at expander inlet	223.3 kJ/kg (96 Btu/lb)
Pressure at outlet	2.4 bar (20 psig)
Enthalpy after expansion	202.4 kJ/kg (87 Btu/lb)
Work done during isentropic expansion	20.9 kJ/kg (9 Btu/lb)
Specific volume of working fluid at inlet	0.015 m^3/kg (0.24 ft^3/lb)
Rate of circulation of working fluid needed to give shaft power of 1 kW (1.3 hp)	168 kg/h (370 lb/h)
Rate of flow of vapour into expander at inlet pressure	2.49 m^3/h (88.8 ft^3/h)
Volume of high-pressure vapour drawn by the expander per revolution	22.9 cm^3 (1.4 in.^{3})
Expander speed	1 827 rpm
Boiler-generator	Reverse-flow finned-tube heat exchanger
Temperature of water entering the boiler	90°C
Temperature of water leaving the boiler	81°C
Rate of flow of water through the boiler	3.5 l/min
Enthalpy of working fluid vapour at 37.5°C	202.4 kJ/kg (87 Btu/lb)
Enthalpy of working fluid liquid at 30°C	53.5 kJ/kg (23 Btu/lb)
Total heat that has to be removed in the condenser	24.9 MJ (23.6 × 10^3 Btu)
Collector area required to operate the pump for 4 h a day	10 m^2

System optimization

The engine efficiency, which is the product of the efficiency of the expander and the feed pump, was of the order of 70% of the Carnot efficiency.

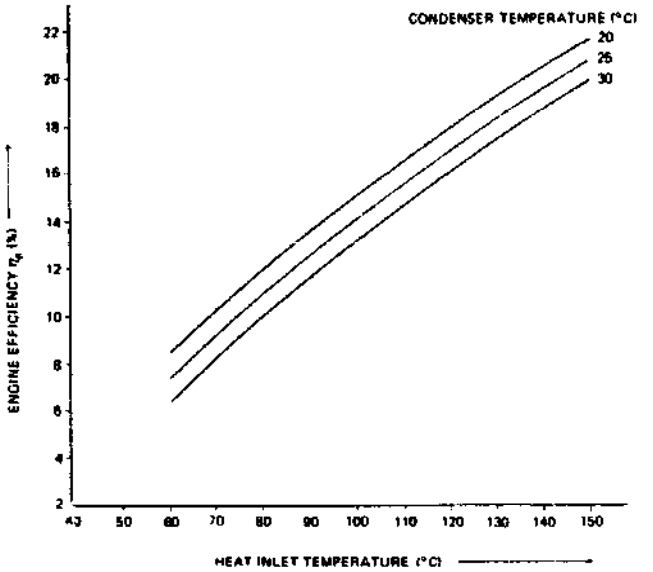


Figure 8. Engine efficiency against inlet temperature at different condenser temperatures

Figure 8 gives the engine efficiency as a function of the expander inlet temperature for various condenser temperatures. The lower the condenser temperature, the higher the engine efficiency. Combining the engine efficiency data of figure 8 with the collector efficiency data of figure 3, one obtains the system efficiency shown in figure 9. For a given insolation there is an optimum range of temperature of the collector for which the system efficiency is a maximum. These considerations have to be kept in mind in designing the system. The system is versatile in that, when pumping is not needed, it could be used to generate electrical power or to drive a mechanical system such as a thresher or a small lathe. The collector assembly has an area of 10 m^2; the dimensions of the other subsystems are given below.

	Height (cm)	*Diameter (cm)*
Condenser	50	25
Boiler	50	30
Expander	35	30
Storage tank	200	65
Pump	25	20

The 1-kW Abhimanyu pump has been in operation for the last six months. Pumps of up to 12 kW can be designed following the same principles.

10-100 kW power generation

Two 10-kW solar electric power plants are at different stages of development in India. One is a joint venture between the Government of India and the Government of the Federal Republic of Germany. Bharat Heavy Electricals Ltd., the National Physical Laboratory and the Indian Institute of Technology at Madras, are the executing agencies on the Indian side. Messerschmidt, Bölkow and Blohm (MBB) of Munich, are the executing agencies from the Federal Republic of Germany. The objective of the project is to set up a 10-kW demonstration plant that utilizes solar

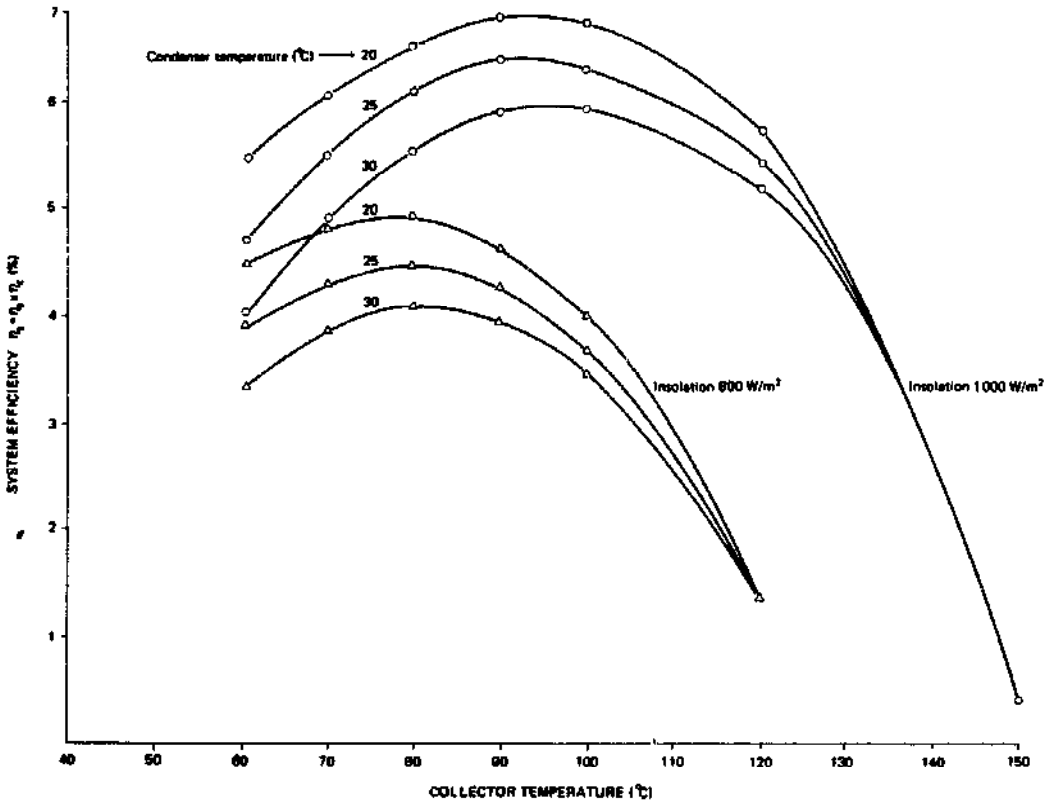


Figure 9. Variation of system efficiency with collector temperature at insolations of 800 W/m^2 and 1 000 W/m^2

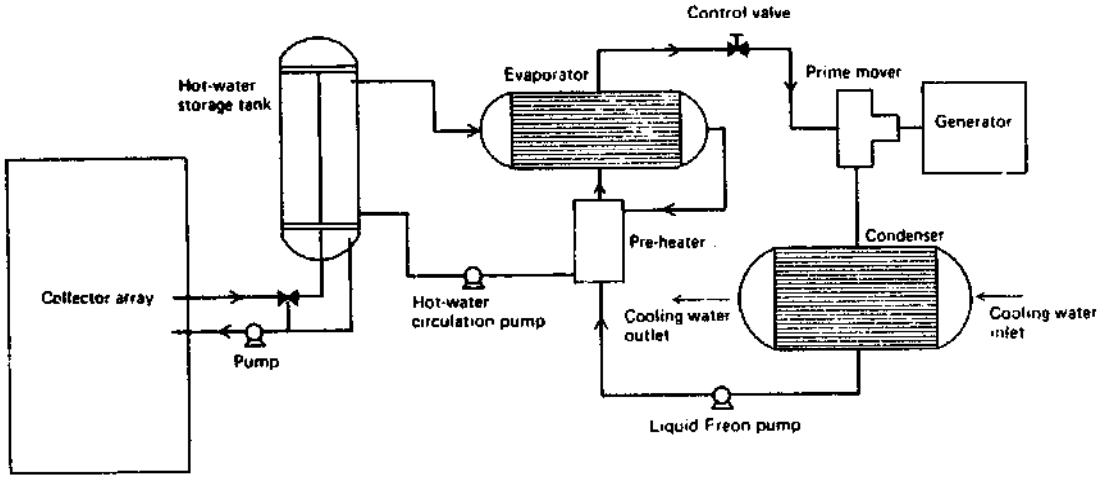


Figure 10. Diagram of a 10-kW power station

energy. Figure 10 is a diagram of the power station. The Linde screw expander, a flat-plate collector array and a conventional electric generating system are to be used. The working fluid will be R114.

The second project to install a 10-kW solar power plant is totally an Indian effort, which envisages the use of spiral expanders. Both projects use the organic Rankine-cycle engines in conjunction with a flat-plate collector array. Some of the design parameters of this system are given below.

Item	*Specification*
Shaft power	10 kW
Expander	Positive-displacement spiral expander
Working fluid	R114
Inlet temperature	80°C
Inlet pressure	9.3 bar (120 psig)
Exhaust temperature	37.5°C
Exhaust pressure	2.4 bar (20 psig)
Spiral pitch	5.7 cm (2.25 in.)
Spiral axial length	7.6 cm (3 in.)
Spiral wall thickness	6.4 mm (0.250 in.)
Orbital radius of the moving spiral	22.2 mm (0.875 in.)
Spiral outside diameter	50.8 cm (20 in.)
Volume displacement per revolution	524.5 cm^3 (32 $in.^3$)
Volume ratio	3.5
Expander speed	1 500 rpm
Rate of circulation of working fluid	49 kg/min (108 lb/min)
Boiler-generator	Reverse-flow finned-tube heat exchanger
Temperature of water entering the boiler	90°C
Temperature of water leaving the boiler	81°C
Rate of flow of water through the boiler	180 l/min
Collector area	400 m^2

Utilization of solar energy in the development of arid zones: Solar water pumps

Jean Paul Durand, Max G. Clemot, J. Pierre Girardier and Marc Y. Vergnet

SOFRETES et Mengin, Montargis, France

Basic design of a solar pump

The first goal of SOFRETES, working in co-operation with Dakar University in Senegal, was to develop water-pumping equipment with no external fuel requirements, initially for domestic use in small villages and in raising livestock, and then for irrigating crops in arid regions. Since the equipment would have to operate at isolated sites where there are usually no specialists able to provide maintenance for sophisticated equipment, it had to be simple, rugged and reliable. It was decided as a first step to use a low-temperature thermodynamic cycle between a hot source supplied by solar energy and a cold source maintained by the pumped water.

A solar pumping station includes the following components (see figure 1):

(a) A battery of flat-plate collectors in which water or another heat-carrying liquid circulates in a closed circuit;

(b) A heat exchanger inside which heat is transferred from fluid circulating in the collectors to the fluid circulating in the motor circuit, causing the latter fluid to evaporate;

(c) The motor circuit, which, in addition to the heat exchanger, includes the expansion motor, a condenser and a reinjection pump;

(d) The pumping circuit itself, which for low-power installations of about 1 kW includes a hydraulic motor driving a well pump or, for higher powers (25-50 kW), an alternator and an electric motor driving one or several pumps.

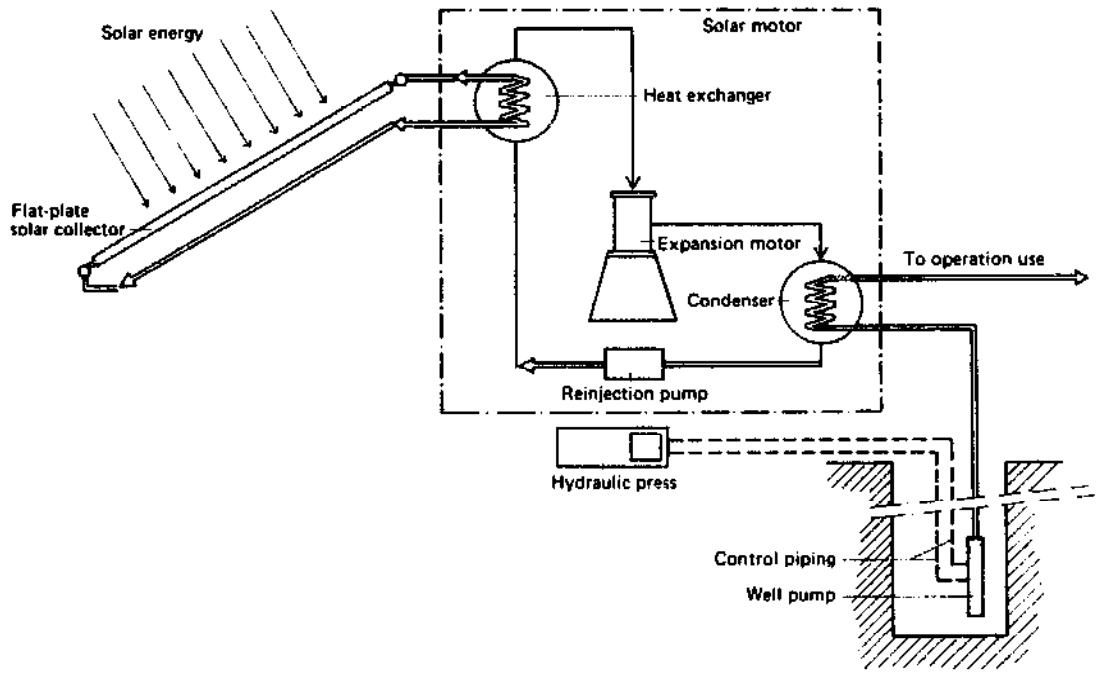


Figure 1. Schematic diagram of a solar pumping station

Practical applications of solar pumps

Domestic water for villages

To ensure a water supply for isolated villages in arid regions is essential. Hand pumping consumes the time and energy of the inhabitants Conventional pumping by internal combustion engines is subject to all the uncertainties of fuel supply, and the equipment requires maintenance, which is made difficult by severe climatic conditions and the lack of skilled manpower and a stock of spare parts.

The integration of a solar pumping station into a village is a practical means of providing a water supply. In addition, the installation of the collectors on the roof of a building makes the building cooler inside, since a large portion of the heat received by the collectors is conducted away by the fluid. This building can be used to house a school, a cattle market, a dispensary etc.

Water for livestock

In livestock grazing regions, the uncertainty of the wells often means that flocks and herds must depend on a single well, sometimes with disastrous results. The multiplication of small-volume watering places by means of reliable equipment powered by solar energy would make it possible to supply water rationally to nomad tribes and their herds and flocks.

About 40 1-kW stations are now being tested in 12 countries: Brazil, Cameroon, Cape Verde, Chad, India, Mali, Mauritania, Mexico, Niger, Senegal, United Arab Emirates, and Upper Volta.

In Mexico, with the support of the Government, solar hydraulic pumps have been set up in villages scattered around the country. A 30-kW station to supply drinking water and water for irrigation has also been set up. These pumps are being operated under varied climatic, economic and social conditions.

1-kW solar pump characteristics

The standard equipment now used in the 1-kW installations has the following characteristics:

Collector	
Active area	70 m²
Area available underneath collector	100-120 m²
Fluid circulation	Thermosiphon or circulator
Motor circuit	
Heat-exchanger/condenser	Tubular or plate elements
Fluid	Butane or Freon
Expansion motor	Two-cylinder; displacement 12
Rotational speed	200 rpm
Pumping circuit	
Well pump	Hydraulically driven
Operating conditions	
Mean insolation	800 W/m²
Air temperature	20°C
Pumped water temperature	20°-30°C
Daily operating time	5-7 h
Daily output for a total discharge height of 20 m	30 m³
Number of inhabitants that can be supplied with 20 l each	1 500
Number of head of cattle that can be supplied with 40 l each	750

Solar pump for irrigation in Mexico

The first large solar unit devoted to irrigation has been established at San Luis de la Paz, in the state of Guanajuato in Mexico. It is part of a long-range government programme, run by the agency responsible for environmental improvement in the Health Secretariat. The 30-kW installation, which delivers electricity for pumps, has been operating since September 1975. San Luis de la Paz belongs to the semi-arid zone of Mexico. It has an average mean temperature of about 17°C (62°F), a maximum of 41°C (106°F) and a minimum of about −5°C (23°F). In an average year, rain falls on 39 days and the town has sunny weather on 250 days.

The installation operates according to the same principle as the 1-kW stations, except that the expansion motor is replaced by a turbine that drives an alternator.

The general characteristics of the installation are as follows:

Surface area of collectors	1 500 m²
Working fluid	R11
Turbine rotation speed	7 400 rpm
Pump	Electric centrifugal
Pumping rate for a discharge height of 40 m	150 m³/h average

This solar power station delivers about 900 m³ of water per day. It is presumably the most powerful solar unit working in the world. The water, pumped from a depth of 40 m, is delivered to 15 000 village inhabitants and will eventually also be used to irrigate 20-30 ha of experimental crops. The room under the 1 500-m² solar collectors is to be used for the facilities of an experimental farm.

Future development

At the present stage of solar energy technology, it is quite feasible to use solar pumps in remote arid zones. However, these techniques and systems must be adapted individually to local conditions. The experience of SOFRETES is that solar pumps using the low-temperature thermodynamic cycle with flat-plate collectors can indeed be so adapted.

Future work anticipated in this area includes:

Improving existing equipment in the 1-kW range and in the 25-100 kW range; research on collectors, heat-exchangers, motors and turbines, fluids etc.

Applying the low-temperature thermodynamic cycle to the use of geothermal energy

Solar refrigeration for preserving food and medicines

Solar air-conditioning and space heating

Economic aspects

In choosing an energy source, the advantages and disadvantages of using it must be analysed and each component of the total cost calculated. In this way, a comparison can be made between a conventional energy source (e.g. a diesel engine) and solar energy on the basis of the volume of water that needs to be pumped. The comparison in the table below can be used to make such an analysis. It should be realized, however, that the efficiency of solar energy utilization and its competitiveness with that of conventional sources depend on local conditions and that therefore a special study of these conditions must be included in the analysis.

Energy source	*Advantages*	*Disadvantages or constraints*
Diesel engine	Low investment Great flexibility in installation and use	High operating cost Need to import, transport and store fuel, lubricants and spare parts Consumption of non-renewable resources Localized pollution (exhaust gases) Skilled manpower Uncertain prices for fuel and manpower (50% of cost)
Solar radiation	Low operating cost In situ availability of energy Long lifetime of equipment (10-20 years) Reliability Possibility of technology transfer No degradation of natural resources No pollution Refrigeration possible underneath the collectors No skilled manpower needed Maintenance reduced to care-taking Operating costs known	High investment Discontinuous supply (storage tank required) More extensive civil engineering

A comparison of the relative cost of pumping water using a diesel engine, electricity and solar energy is illustrated in figure 2. It can be seen that the distance to the conventional energy source is the determining factor. It is estimated that in the Sahel a 50-kW solar energy station used for irrigation will begin to be competitive with electricity when the distance from the electric power plant reaches 100 km.

It has been calculated that for solar pumps already installed in Africa the cost per unit of water pumped is about 0.60 $/m^3$ for 1-kW stations (assuming an operating time of 1 800 h a year and a water depth of 30 m) and approximately 0.05 $/m^3$ for 25-kW stations (same operating time, water depth 10 m). A similar calculation for a pump system using a diesel engine and doing the same job as a 1-kW solar station, gives a cost of about 0.47 $/m^3$.

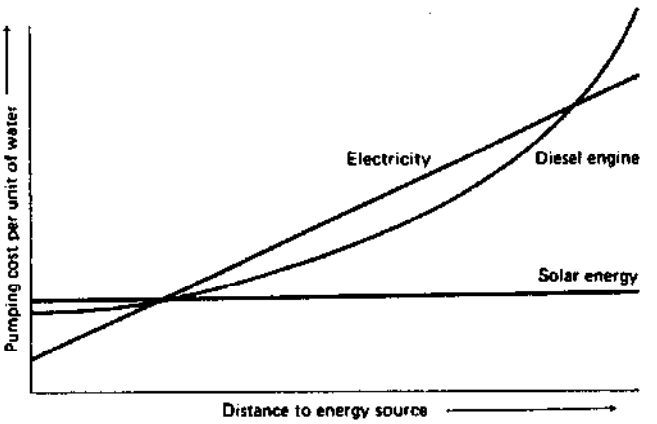


Figure 2. Cost of pumping water using various forms of energy as a function of the distance to the energy source

Theoretical conditions for maximum power from the sun

Kamal-Edin Hassan

Arab Development Institute, Tripoli, Libyan Arab Jamahiriya

A solar heat-engine, like any other heat engine, has limits imposed by the second law of thermodynamics. Its maximum efficiency is thus the Carnot efficiency (η_C):

$$\eta_C = 1 - (T_L/T_C)$$

where T_L and T_C are respectively the ambient and the collector thermodynamic temperatures.

The maximum power $\dot{W}''$ that can be generated per unit area of the solar collector is given by

$$\dot{W}'' = \eta_C \dot{Q}''$$

where the power $\dot{Q}''$ supplied per unit area of the collecting surface to the engine is the difference between the irradiance I of the collector and the power losses. For relatively low collector temperatures, the radiation and convection losses can both be collected into a single overall heat-transfer coefficient U; the losses per unit area are then $U(T_C - T_L)$. Therefore, we have

$$\dot{Q}'' = I - U(T_C - T_L) \quad (1)$$

and

$$\dot{W}'' = [1 - (T_L/T_C)]\ [I - U(T_C - T_L)] \quad (2)$$

For a given T_L, a high T_C would improve the Carnot efficiency, but would also increase the losses. The maximum work would, therefore, be obtained at some optimum collector temperature $T_{C,opt}$, at which the efficiency gain balances the heat loss. This optimum condition is attained when $d\dot{W}''/dT_C = 0$, which happens when

$$T_{C,opt} = \sqrt{T_L(I + U\,T_L)/U}$$

or

$$T_{C,opt}/T_L = \sqrt{(I/U\,T_L) + 1}$$

Defining the dimensionless variable M as

$$M = U\,T_L/I \quad (3)$$

we have

$$T_{C,opt}/T_L = \sqrt{(M+1)/M} \quad (4)$$

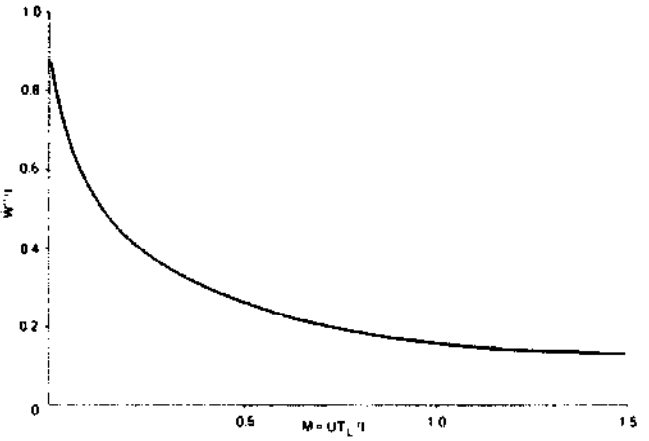
Equation 4 gives the source temperature for which a Carnot heat engine should be designed to give the maximum possible power under initial conditions given by I, T_L, and U.

The maximum fraction of the solar power that could be converted to mechanical power is obtained from equations 2 and 4:

$$\dot{W}''_{max}/I = 1 - (T_L/T_{C,opt})\ 1 - (U/I)(T_{C,opt} - T_C)$$
$$= (1 - \sqrt{M/(M+1)})(1 + M - \sqrt{M(M+1)}) \quad (5)$$

The figure shows a graph of equation 5. At $M = 0$, we see that $\dot{W}''_{max}/I = 1$, an unattainable condition, because $M = 0$ implies that $U = 0$, i.e., that there is no heat loss from the collector and its temperature would approach infinity, whereas it cannot be hotter than the sun itself (5 750 K). Indeed, the present analysis fails at very high collector temperatures where the losses would be mainly due to radiation and could not be expressed in the linear form used in equation 1. However, except in the vicinity of $M = 0$, the graph shows the trend properly: an increase in M, due either to an increase in U or a decrease in I, decreases the useful fraction of I; decreasing M, either by using a good insulating system to decrease U, or by concentrating the solar energy to increase I, results in an increase in the maximum usable fraction of the incident energy.

If one considers flat-plate collectors, it is difficult to imagine conditions in which M would take values less than unity. At $M = 1$, the maximum possible power that could be obtained is only about 17% of the incident solar power. This limit seems to rule out the use of flat-plate collectors for power generation.



Ratio of maximum usable to incident solar power as a function of the design parameter M (graph of equation 5)

Solar flat-plate collectors

A. A. M. Sayigh

College of Engineering, Riyadh, Saudi Arabia

Of all the applications of solar energy, the use of flat-plate collectors in heating is the most practical. The solar liquid heater was invented by H. B. Saussure during the second half of the 17th century; Herschel (1837) and Tellier (1885) also experimented with solar water heaters. Even in earlier times the indigenous peoples of Africa, the Arab countries, Australia, China, India and Pakistan used their ingenuity in heating water by placing a specially shaped copper pot filled with water in the sun during the winter. Air heaters, however, are of recent invention. K. W. Miller introduced the overlapped glass-plate air heater in 1943. Nowadays, it is cheaper to use solar water heaters for domestic applications, and as such they are used all over the world.

From 1960 onwards, flat-plate collectors have had the biggest share in research and development. This paper outlines the capabilities and limitations of such devices, with the intention of promoting the proper use of flat-plate collectors, especially in developing countries.

Characteristics of the components of flat-plate collectors

A flat-plate collector normally consists of an absorber, which is made of blackened metal–usually copper–and a grid of pipes soldered to the absorber. The assembly is placed in a box with insulation at the

TABLE 1. PROPERTIES OF SOME SURFACE COATINGS USED IN FLAT-PLATE COLLECTORS

Coating	*Solar energy absorptance* α	*Long-wave radiation admittance*[a] ϵ	*Reference*
Black enamel paint	0.83	0.83	Sabbagh, J. A. *et al.*
Tar	0.86	0.86	Sabbagh, J. A. *et al.*
Lamp-black	0.95	0.95	Sabbagh, J. A. *et al.*
Nickel black (oxides and sulphides of Ni and Zn) on polished Ni	0.91-0.94	0.11	Tabor, H. *et al.*
Nickel black on galvanized-iron (experimental)	0.89	0.12	Tabor, H. *et al.*
Nickel black on galvanized-iron (commercial)		0.16-0.18	Tabor, H. *et al.*
Nickel black, two layers on electroplated Ni on mild steel (after 6-h immersion in boiling water)	0.94	0.07	Tabor, H. *et al.* Schmidt, R. N. *et al.*
CuO on Ni (made by electrode deposition of Cu and subsequent oxidation)	0.81	0.17	Kokoropoulos, P. *et al.*
Co_3O_4 on Ag (deposition and oxidation)	0.90	0.27	Kokoropoulos, P. *et al.*
CuO on Al (by spraying dilute $Cu(NO_3)_2$ solution on hot Al plate and baking)	0.93	0.11	Hottel, H. C. and Unger, T. A.
Copper black on Cu (commercial treatment of Cu with solution of NaOH and $NaClO_2$)	0.89	0.17	Close, D. J.
Ebanol C on Cu (commercial Cu blackening treatment giving coatings mostly consisting of CuO)	0.90	0.16	Edwards, D. K. *et al.*
CuO on anodized Al is treated (Al with hot $Cu(NO_3)_2$ – $KMnO_4$ solution and baked)	0.85	0.11	Tabor, H.
Al_2O_3-Mo-Al_2O_3-Mo-Al_2O_3-Mo-Al_2O_3 interference layers on Mo	0.91	0.085[b]	Schmidt, R. W. *et al.*
PbS crystals on Al	0.89	0.20	Williams, D. A. *et al.*

[a] At temperatures typical of flat-plate solar collectors.
[b] Measured at 260°C (500°F).

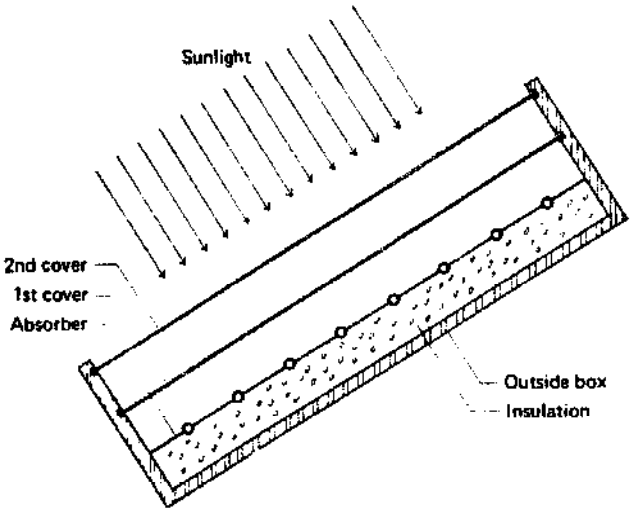


Figure 1. Cross-section of a flat-plate collector

back of the absorber and one or two transparent covers at the top to allow sunlight in (see figure 1).

Solar absorbers are commonly made of the following metals:

Metal	*Thermal conductivity at 100° C (W m^{-1}°C^{-1})*
Copper	393.56
Aluminium	217.71
Brass (60/40)	121.42
Steel	66.99

Notes about various coatings and where they can be purchased are contained in McDonald's work. Table 1 shows the properties of various surface coatings used in flat-plate collectors.

The properties of commonly used insulation materials are shown in Table 2. Figure 2 shows curves for three types of glass used for the transparent covers of collectors. It is clear that type A is the best. Figure 3 shows the properties of a typical clear, drawn sheet-glass at various wavelengths. Plastic materials such as PVF, and fibreglass sheets, have been used in solar heaters, but they are in general inferior to glass because they deteriorate with time

TABLE 2. PROPERTIES OF COMMONLY USED INSULATION MATERIALS IN FLAT-PLATE COLLECTORS

Material	*Approximate density (kg/m^3)*	*Thermal conductivity (W m^{-1}°C^{-1})*
Mineral wool (clay wool, fibreglass, rock wool)	12-14	0.0332-0.0404
Hair felt	80	0.0389
Granulated cork	120	0.0476
Re-granulated cork (0.474-cm particles)	30	0.04471
Compressed cork	136-176	0.0418-0.0462
Straw	10-13	0.0576
Sawdust	13-240	0.0649
Vermiculite (granulated)	128	0.0721
Polyurethane foam, rigid	24	0.0245
Polystyrene, expanded	16	0.0303

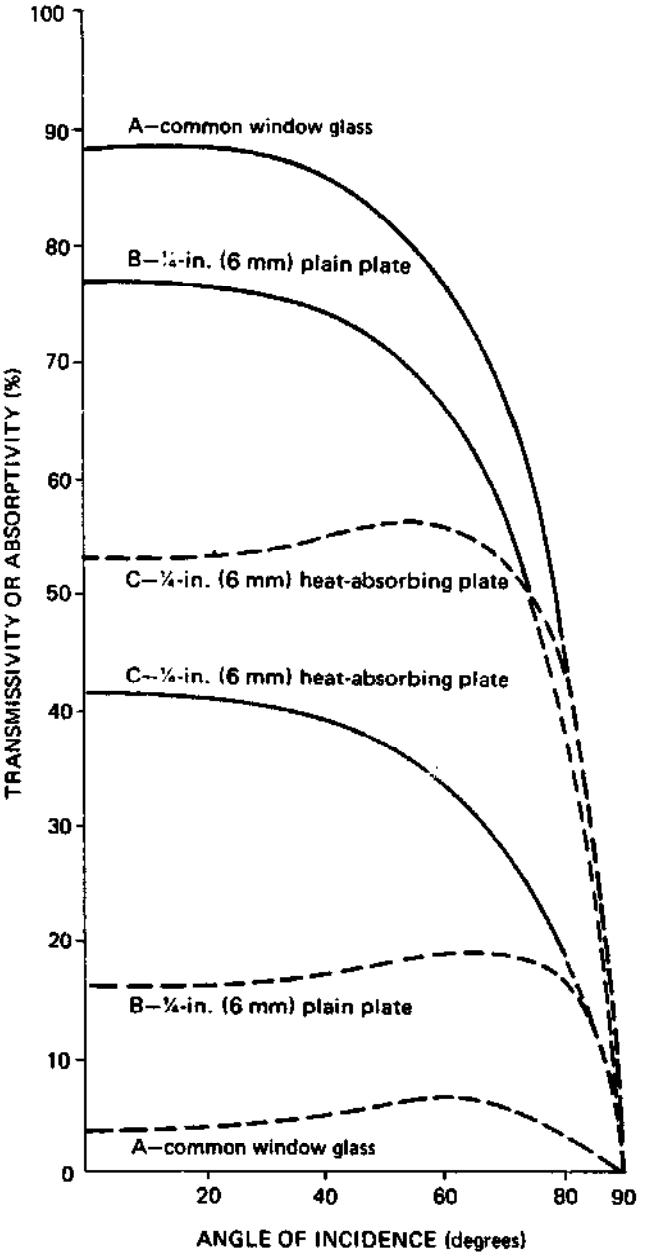


Figure 2. Transmissivity and absorptivity of common glass materials. Solid curves are transmissivity; broken curves, absorptivity

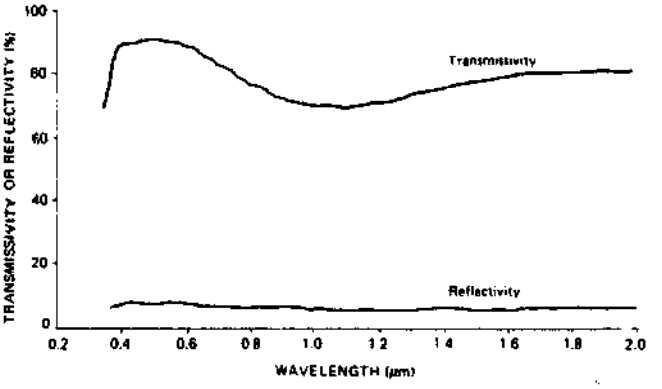


Figure 3. Transmissivity and reflectivity of a typical clear, drawn sheet-glass with respect to wavelength. Glass is type DME INT 528, 3.96 mm thick

and at high temperatures. Moreover, ultraviolet radiation discolours them. The plastic cover is, however, easier to handle than the glass cover.

The theoretical analysis for a flat-plate collector is well established and can be summarized in the equation $\dot{Q}_o = \dot{Q}_a - \dot{Q}_L$, where $\dot{Q}_o$ is the power output, $\dot{Q}_a$ is the power absorbed by the collector and $\dot{Q}_L$ is the power lost to the surroundings. The value of $\dot{Q}_a$ depends largely on the materials of which the collector is made, and its coating and the solar angle of incidence. Figure 4 shows the effect of angle of incidence on the surface absorptance.

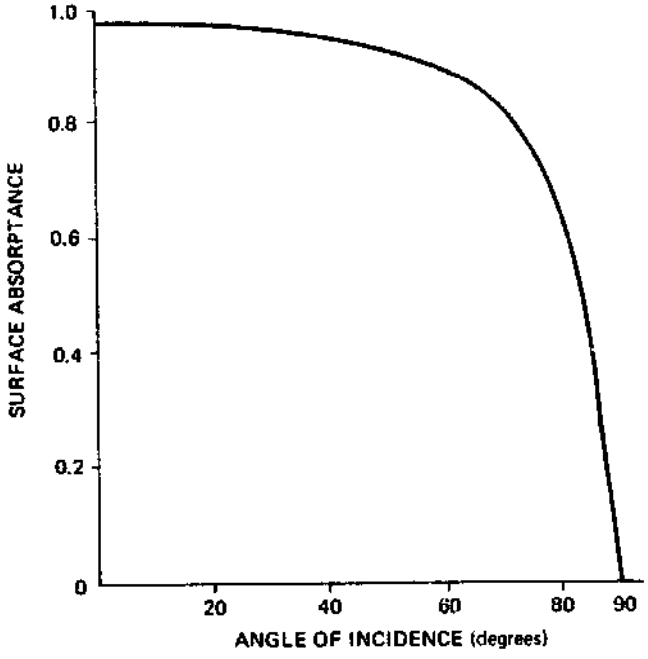


Figure 4. Effect of angle of incidence on the surface absorptance

A full theoretical treatment of the mathematics relating to heat losses from the top, bottom and edges of collectors is given in Hattel and Woerts (1942). Klein (1973) also discusses heat losses from the top of collectors, and covers corrections for the angle at which the collector is tilted from the horizontal.

By considering the distribution of temperature across the absorber and the efficiency of the fin-tube arrangement, $\dot{Q}_o$ can be determined, as can the collector efficiency. Figure 5 shows how collector efficiency varies with normalized temperature gain, i.e. the temperature gain of the collector per unit insolation, for different kinds of covers.

As the collector temperature rises, the efficiency falls, because the heat losses to the surroundings increase. The use of more than one glass cover improves the efficiency at high collector temperatures, but reduces the amount of heat collected. In theory the optimum performance curve is that which is shown dotted in figure 6; but it is obviously not feasible to realize such a curve in practice, since it requires different numbers of covers at different temperatures.

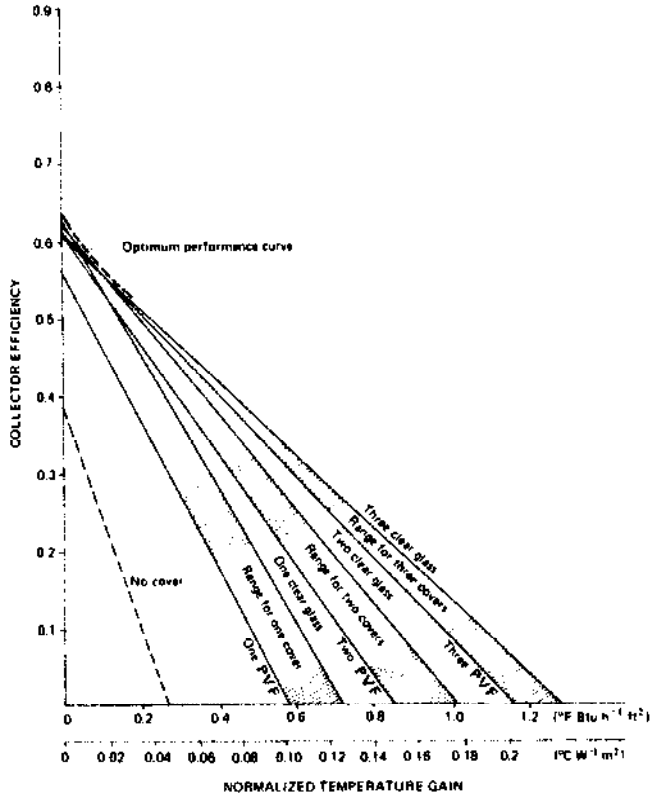


Figure 5. Collector efficiency as a function of type and number of covers

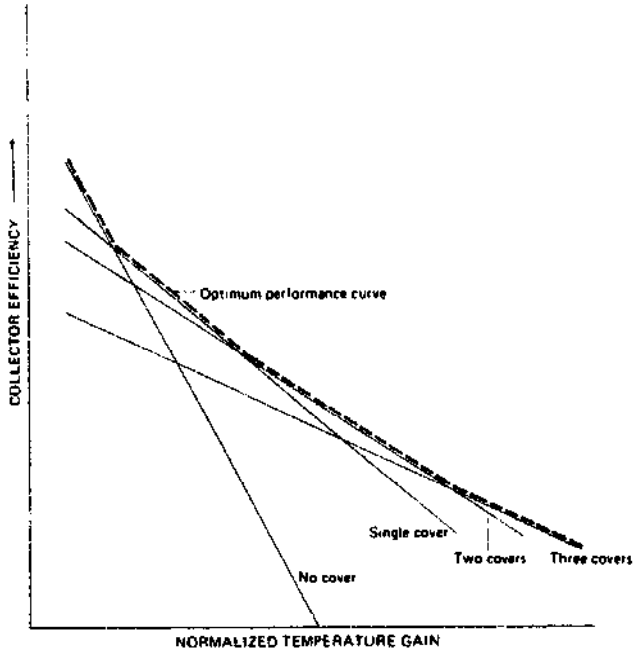


Figure 6. Collector efficiency with various numbers of covers

Optimization and comments

The best design will take into consideration the optimum air gap between the absorber and the glass covers. The problem was studied by the author, who found that the best gap was over 4 cm and, owing to the side-shading effect caused by the collector box, less than 8 cm. In figure 7 the gap conductive-

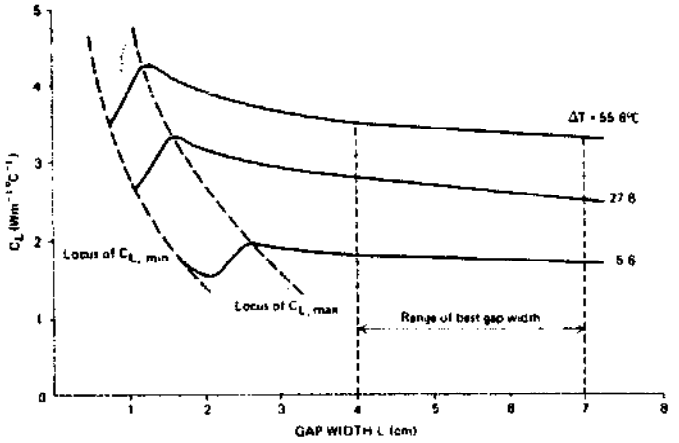


Figure 7. Gap conductive-convective coefficient C_L as a function of gap width for $T = 70°C$, tilt angle 40°

convective coefficient C_L is plotted against gap width L. This coefficient is related to the Nusselt number Nu, which has the value 1 for pure conduction and higher values when convection is important, by the equation $C_L = \mathrm{Nu}K/L$, where K is the thermal conductivity of the fluid in the gap. The performance of a collector absorber plate is shown in figure 8. The top half of this figure shows how the temperature varies across the plate; the bottom half shows how the water temperature lags behind the absorber-plate temperature at the centre of the fin by almost 10°C. This temperature lag is of the same order over the whole temperature distribution in the flow direction.

Most commercially made flat-plate collectors have an efficiency ranging from 50% to 67%. The breakdown of heat losses is as follows:

Type of loss	*Percentage points*
Edge	1-3
Back	5-10
Radiation	5-7
Convection	22-30

It can be seen that, in order to improve the collector efficiency, losses due to convection must be reduced to a mimimum. If there is to be no convection, Nu must equal 1 and the Rayleigh number Ra should be less than 1 708 (see figure 9). There are two ways of reducing convection. The first is to produce a vacuum (partial or total) in the collector spacing. A partial vacuum is only effective with selective surfaces; it is not effective in collectors with painted surfaces.

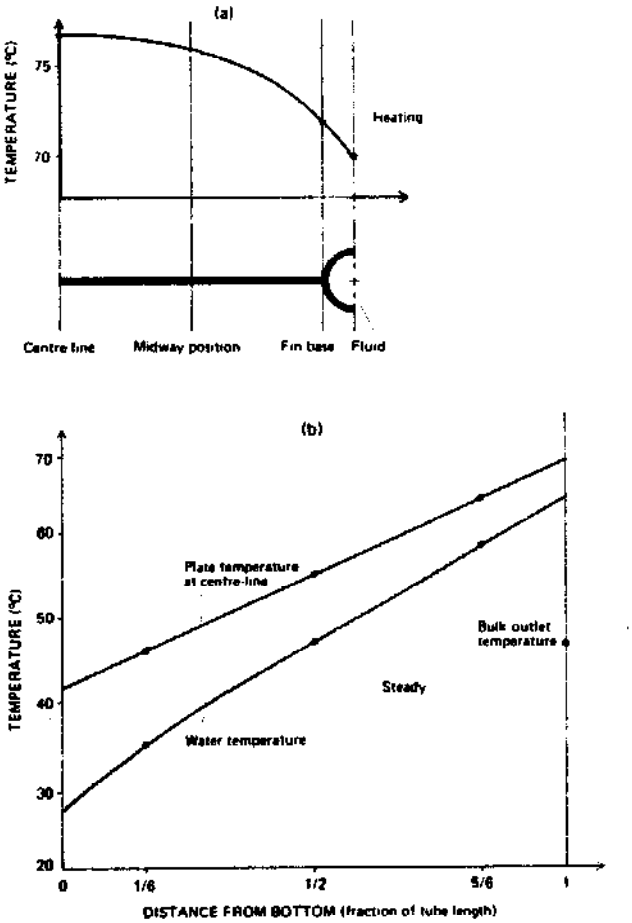


Figure 8. Temperature distribution over the absorber plate of a collector:
***(a)* transverse temperature variation of the plate; *(b)* plate and water temperature variation in the flow direction**

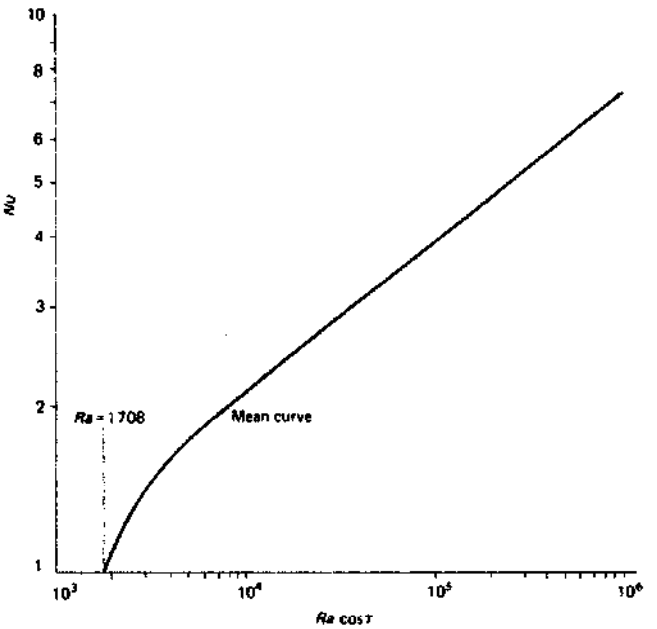


Figure 9. Nusselt number versus Rayleigh number multiplied by the cosine of the tilt angle

The second way to reduce losses due to convection is to place transparent honeycombs in the air gap. Figure 10 illustrates the effect of this type of structure on Ra. The parameter a mentioned in the figure is defined as $\pi\sqrt{5}(d/w)$ where d is the depth and w the width of a honeycomb cell. To suppress convection, a honeycomb should be chosen such that the collector operates in the stable region of figure 10.

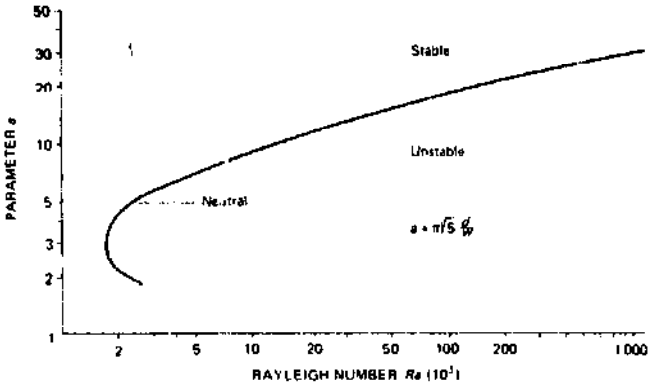


Figure 10. a-Ra stability chart for honeycombs in the air gap of a collector

An example of the effect of temperature gain on collector efficiency is shown in figure 11, while figure 12 shows how the glass temperature of an actual flat-plate collector varied during a short period on a particular day.

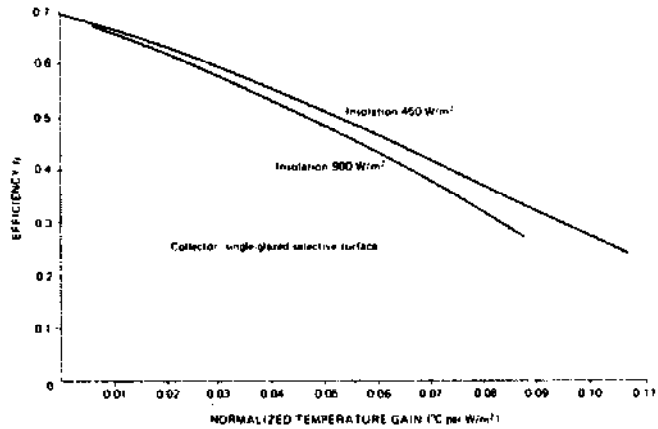


Figure 11. Collector efficiency as a function of temperature gain and insolation. Temperature gain is normalized by dividing the difference between the mean fluid temperature and the inlet temperature by the mean insolation

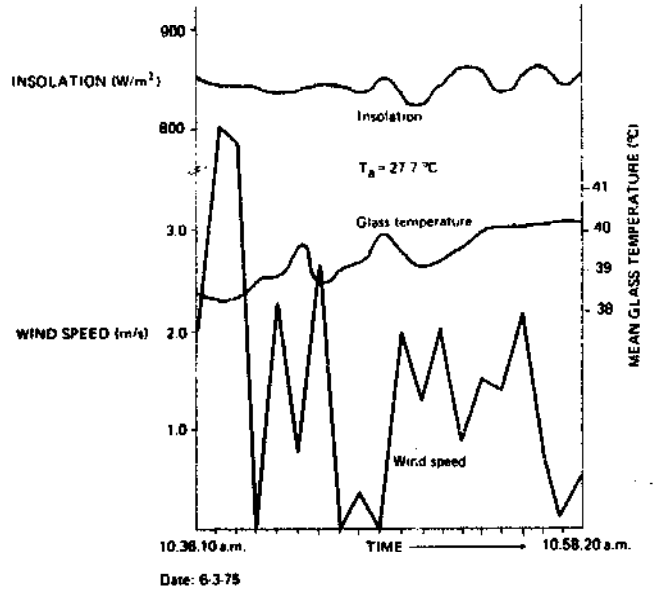


Figure 12. Variation of the glass temperature of an actual flat-plate collector during a short period on a particular day. Shown also are the variations of insolation and wind speed over the same period

Practical points

The following points should be noted with regard to the manufacture of flat-plate collectors:

(a) Poor adhesive is often used between the glass covers and the collector box. This is because it is preferable to let the pressure inside the collector gap be atmospheric so as to reduce convection and air-conduction losses. This can only be achieved by not making the covers airtight. However, as a result, dust and moisture penetrate the collector and erode the surface of the absorber plate;

(b) Insulation materials may contain moisture before they are used in the collector. As the collector gets hot, this moisture evaporates and condenses on the inside surface of the glass and affects the incident radiation. It also corrodes the absorber plate;

(c) Allowance must be made for glass expansion, and the edges of the collector must be bevelled so that no rain water collects on them;

(d) The collector should not be used without any liquid inside it. Otherwise, the high interior temperatures generated cause abnormal expansion of the covers, which become distorted or break;

(e) In order to alleviate problems due to the freezing of water in tubes, a water/ethylene-glycol solution can used;

(f) The maximum area of a collector should be 2 m^2;

(g) To reduce the amount of infra-red radiation escaping from the collector, specially coated glass covers can be used. This coating should be on the inside of the covers.

BIBLIOGRAPHY

Ackerman. The utilization of solar energy. Annual report. Washington, D.C., Smithsonian Institution, 1915. p. 141-146.

Basic studies on the use and control of solar energy. *By* D. K. Edwards *and others.* University of California, Department of Engineering, October 1960. (Report 60-93)

Chinnery, D. N. W. Solar water heating in South Africa. *NBRI information sheet* (Pretoria) 44.

Close, D. J. Flat plate solar absorbers: the production and testing of a selective surface for copper absorber plates. Melbourne, Commonwealth Scientific and Industrial Research Organization, 1962. (Report E.D.7)

Duffie, J. A. *and* W. A. Beckmann. Solar energy thermal processes. New York, Wiley Interscience, 1974.

Further studies on selective black coatings. *By* H. Tabor *and others.* Proceedings of the United Nations Conference on New Sources of Energy, Rome, 21-31 August 1961. (Solar energy: I, v.4, p. 618 (S/46))
Sales no.: 63.I.38.

Hottel, H. C. *and* B. B. Woertz. The performance of flat plate solar heat collectors. *American Society of Mechanical Engineers. Quarterly transactions* (New York) 64:91-104, 1942.

Hottel, H. C. *and* T. A. Unger. The properties of a copper oxide-aluminium selective black surface absorber of solar energy. *Solar energy* (Elmsford, N.Y.) 3:10:3, 1959.

Klein, S. A. The effects of thermal capacitance upon the performance of flat-plate solar collectors. M.S. thesis. University of Wisconsin, 1973.

Kokoropoulos, P., E. Salam *and* F. Daniels. Selective radiation coatings--preparation and high temperature stability. *Solar energy* (Elmsford, N.Y.) 3:19:4, 1959.

Kondratyev, K. Ya. *and* M. P. Fedorova. Radiation regime of inclined surfaces. Paper prepared for the Solar Energy Symposium, Geneva, 30 August-3 September 1976.

McDonald, Glen. Research highlights choice of coatings. *Solar engineering* (Dallas) 23, October 1976.

Meinel, A. B. *and* M. P. Meinel. Applied solar energy: introduction. London, Addison-Wesley, 1976.

Sabbagh, J. A., A. A. M. Sayigh *and* E. M. El-Salam. Solar water heaters in Saudi Arabia. Paper prepared for the Seventh Arab Scientific Conference, Cairo, 1973.

Sayigh, A. A. M. Investigation into solar heating with some methods for convection suppression. Paper prepared for Solar Cooling and Heating, A National Forum, Miami Beach, Florida, 13-15 December 1976.

_____ The uses of solar energy. Paper presented to the Cultural Activity Programme, College of Engineering, University of Riyadh, Saudi Arabia, 4 April 1974.

Sayigh, A. A. M., ed. Solar energy engineering. London, Academic Press, 1977. Academic Press, 1977.

Schmidt, R. N., K. C. Park *and* E. Janssen. High temperature solar absorber coatings. Honeywell Research Centre, September 1964. (Part two, technical report ML-TDR-64-250)

Tabor, H. Selective surfaces for solar collectors. Low temperature engineering applications of solar energy. New York, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, 1967.

_____ Solar energy collector design with special reference to selective radiation. Research Council of Israel, 1955. (Bulletin 5C)

_____ Stationary mirror systems for solar collectors. *Solar energy* (Elmsford, N.Y.) 2:3-4:27-33, 1958.

Williams, D. A., T. A. Lappin *and* J. A. Duffie. Selective radiation properties of particulate coatings. *American Society of Mechanical Engineers. Quarterly transactions* (New York) 85A:213, 1963.

Zarem, A. M. *and* D. D. Erway. Introduction to the utilization of solar energy. New York, McGraw-Hill, 1963.

Aspects of solar-heated swimming-pools

Gangolf Bräunlich

Institut für Umweltschutz, Graz, Austria

Basic concepts

A project intended to popularize solar energy should meet some of the following requirements:

(a) It should be economically advantageous;

(b) As many people as possible should share the profit;

(c) It should be seen by many people.

Projects involving the heating of swimming-pools by means of solar energy are thus an excellent way to introduce the public to solar energy technology. Compared with the many other possible uses of solar energy, such projects have several important advantages, including:

(a) Working temperatures are relatively low;

(b) Auxiliary heating is not needed;

(c) There are no problems with thermal storage.

Collectors

Glazing

The problem of glazing can be reduced to two questions: should the cover used be glass or synthetic? Should it comprise one or more layers?

Synthetic glazings are easier to handle than glass; they are light, elastic, and resistant to thermal shocks. However, they are sensitive to overheating and to the optic properties of the surface; they are inflammable and their chemical stability over long periods is not proven. The type of glazing chosen will depend on the requirements of the customer and the particular situation.

As the working temperature of swimming-pool solar collectors has to be low, only collectors with one glazing should be used. In regions where the air temperature tends to be the same as the water temperature in the pool, glazing can be omitted. Two glazings should never be used, since the reflection losses due to the second glazing will be greater than the reduction in thermal losses it produces, provided the working temperature is below 50°C.

Specific heat capacity

The collector mass impedes energy gain through losses of rest energy from the collector system after operation. It also influences the speed of temperature increase.

There are three different methods to avoid losses of rest energy:

(a) The thermal mass of the collector system can be made approximately zero;

(b) All the energy in the collector system can be transferred to the consumer;

(c) The collector system can be designed to incur nearly no thermal losses during times of non-operation.

Most designers of solar-energy equipment consider only the first method. However, in every case where solar collectors transfer their energy to a very low-temperature system (temperatures near ambient) the thermal energy of the collector system is completely delivered to the user system. This condition is met by collectors heating a pool. In this case, there are no losses of rest energy after operation. The third method to avoid these losses is to prevent the collector system from cooling down after operation. This requires good thermal insulation during times of non-operation, which although it may be feasible, is too expensive.

For some applications, rapid increases in the temperature of the collector system may be necessary; but a "quick" collector loses more energy than a "slow" one if the heat-transport and heat-transfer system cannot handle the thermal peak-power without undergoing an unnecessary temperature rise. A typical flat collector loses 1%-2% of its efficiency for every degree Celsius of temperature rise. A "slow" collector avoids these losses in systems with a low-heat removal factor (i.e., the thermal power transported per unit of temperature difference). For swimming-pool heating, "quick" collectors provide unnecessary temperature peaks and need high-quality pumps to withstand the continual on-off switching.

Hydraulic features

The most important design goal is certainly to ensure low power consumption by the circulation pumps. A good collector system needs only about 5 W/m² to drive the water circulation at sufficient speed to avoid a temperature increase in the collectors of more than 8°C. The consumption of such a system during the summer is about 1% of the net energy gain. However, there are collector systems that use more than 10% of the energy gain to power the circulation pumps; this reduces the amount of electricity that can be produced by the collector surface.

Pump control

The circulation pump of the collector system should be controlled by an electronic device that switches the pump on when the temperature of the pool water exceeds the temperature of the collector. More important than the temperature difference at which the system starts to work is the temperature difference at which the system stops the pump. The collector temperature increases with the increasing rate of heat transfer through the heat exchangers. Thus there is a minimum temperature difference between collector water and pool water at which the collector pump should still work, in order that the heat transferred to the pool corresponds to the energy gain at low insolation. For a well-designed pool, this temperature difference will be in the range 0.5°-1.5°C. Depending upon the thermal mass of a collector, the operational starting-point of the system should be selected at a temperature difference of 2°-6°C. Otherwise a continuous switching on and off occurs.

The heat exchanger

For collectors operating at high temperatures, small heat-exchangers may be sufficient. However, a high collector-temperature reduces its efficiency and so more collectors need to be installed. Depending upon the relative values of collector cost and heat-exchanger cost, one can find any optimal heat-exchanger size. Given the current price conditions in Austria, an economically viable heat exchanger should transfer heat at the rate of 50 W per degree Celsius for every square metre of collector surface.

Control of pool temperature

The best way to prevent overheating of the pool is certainly to cool the pool water by adding fresh water. If this is not possible, there is another way: if one reduces the heat transport either in the collector loop or in the pool water circulation, a higher collector temperature ensues, and the efficiency of the collector system decreases. As the piping of the collector system for an open-air swimming-pool does not need thermal insulation, the energy gain by the collectors can be reduced to zero via the piping without the risk of overboiling.

Conclusions

If solar energy is to be used for space-heating in Austria with reasonable efficiency in the near future, then collectors must be combined with heat-pumps. The same operating conditions are necessary to feed a heat-pump from solar collectors as prevail in the case of pool heating.

Only when the system design is non-optimal is the return worse than that obtained in the heating of swimming-pools. The relationship between costs and available insolation is very unfavourable in the case of space heating, and therefore the development of this technology is an important step in the development of the use of solar energy.

Practical experience

The Institut für Umweltschutz has planned and built several solar-heated swimming-pools and has provided consultants for several other projects. Its main efforts were devoted to the planning and construction of Austria's largest collector system, the solar-heated outdoor swimming pool at Eggersdorf.

Approximately one year was required to plan this pool. It was necessary to compute the energy conversion and several other factors. Much value was derived from practical experience. Construction began during the first week of May 1976, and consisted of building a new hall and redesigning the roof. The original saddle roof was rebuilt to make it slant in one direction and corrugated asbestos cement was laid down. During the construction, the normal functions of the swimming-pool were not disturbed. The official opening of the solar-heating system was 10 July 1976. The use of only local craftsmen contributed to the short construction time.

The main data for the Eggersdorf pool are:

Surface area of pool	300 m²
Water capacity of pool	1 300 m³
Total open space	15 000 m³
Attendance capacity	1 500 persons

The pool is heated by three separate systems, with a total of 360 collectors, each with an absorber surface of 1.55 m², or a total net surface of 558 m².

This allows a maximal thermal power gain of some 450 kW.

These items were used in each system: circulation pump (1.1 kW), one-way valve, expansion tank, pressure valve, heat-exchanger, differential thermostat.

Clear weather predominated for several days after the pool opened. The water temperature reached a record high of 27°C. During the period of bad weather that followed, the temperature fluctuated between 22°C and 24°C. The swimming-pool operated with the same frequency as other pools. Attendance decreased only when the air temperature was cold. The water temperature could always be maintained above air temperature after the solar-heating system was installed.

A solar energy system for greenhouses

M. Posnansky

Polisolar Ltd., Bern, Switzerland

The functions of greenhouses are to supply plants with the light and warmth required for optimum growth the year round. Although greenhouses consume a large amount of thermal energy, they draw a substantial portion of the necessary heat directly from the sun. The effect by which the thermal balance in greenhouses is maintained is well known as the greenhouse, or glasshouse, effect (see figure 1).

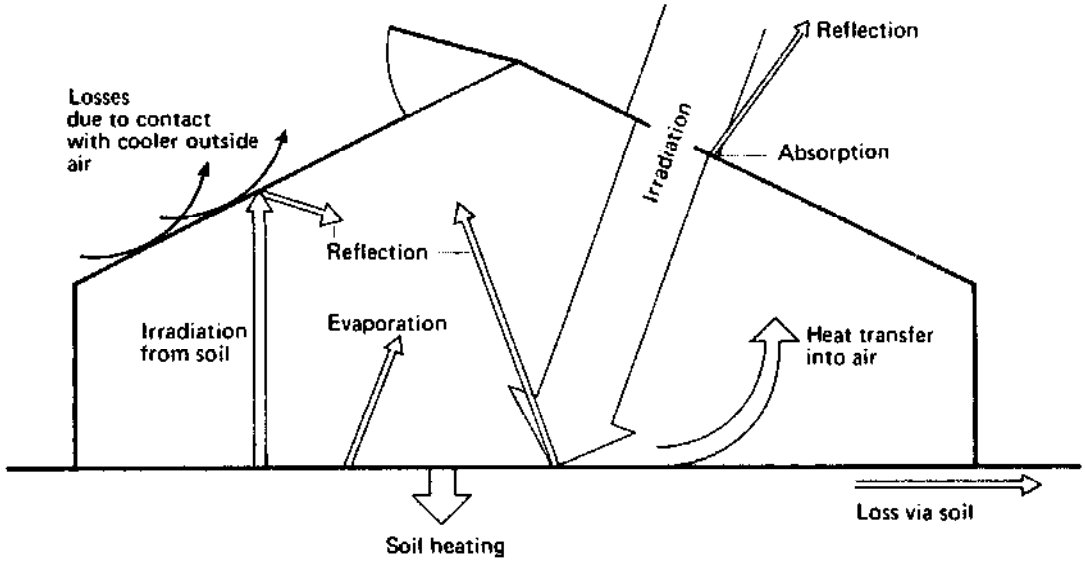


Figure 1. The greenhouse effect

For most types of plants, shading is necessary during the summer months. Formerly, almost all greenhouses were permanently shaded during the summer. To some extent this is still true today, although the idea of movable or variable shading has met with growing acceptance. Shading has become a practical means for the gardener to control the greenhouse atmosphere, particularly its temperature.

The system described here collects and removes heat, keeping the growth area cool. It shades the plants, heats the room during cold weather and insulates it at night.

The heart of the system consists of concentrating solar-collectors in a parallel-series configuration 2.20-2.80 m above the floor and at the height of the greenhouse bracing structure. The solar collectors are parabolic cylindrical models designed, unlike conventional concentrating collectors, to reflect light on both sides. A special control system automatically positions the collectors towards the sun using an electric drive system (see figure 2).

The thermal energy withdrawn by the absorber pipes helps keep temperatures at a lower level than that in greenhouses with conventional shading. Since both collector surfaces reflect, most of the indirect light can be routed into the greenhouse for almost the entire day.

Figure 3 shows the collector lamellae in the position for collecting diffuse radiation during times of poor weather. Also, when a certain irradiation angle is reached, the collector lamellae are put into this vertical position by the electric drive system. In this position, light entry into the greenhouse is practically uninhibited.

Figure 4 illustrates the installation at night. At dusk, the lamellae automatically assume a horizontal position over the absorber pipes. This is achieved using a sensor that, when darkness falls, causes the electronic control system to activate the drive motor

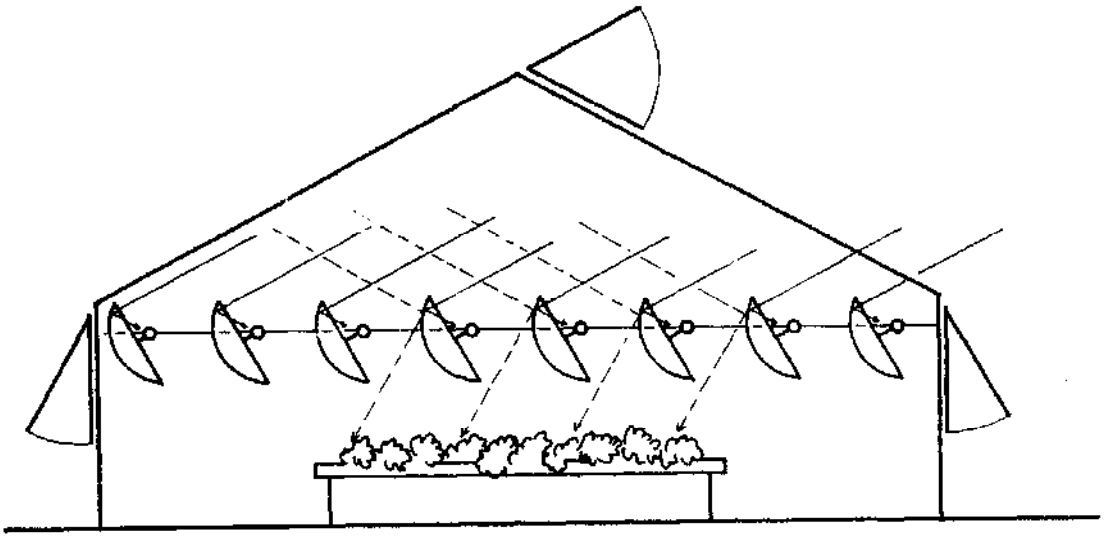


Figure 2. Greenhouse with concentrating solar collectors

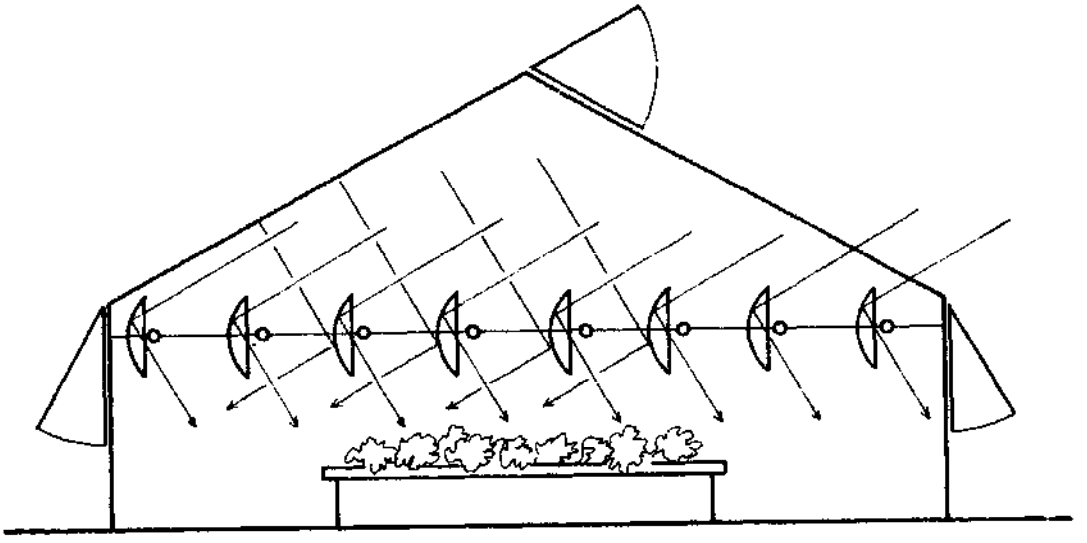


Figure 3. Collector position for collecting diffuse radiation

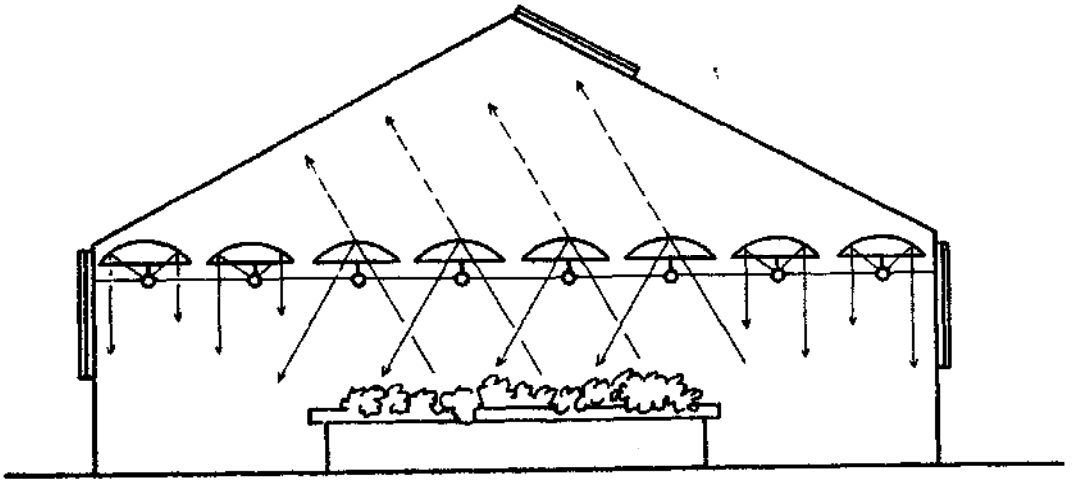


Figure 4. Collector position at night

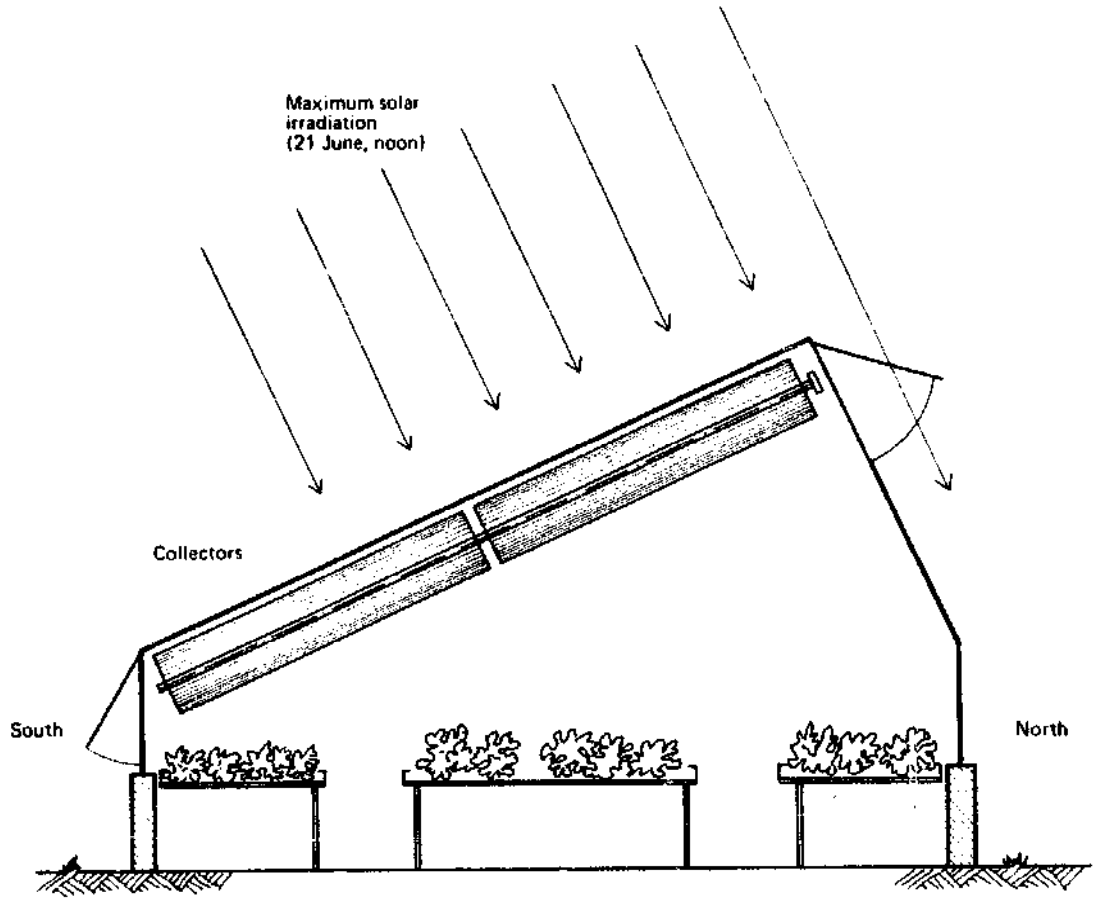


Figure 5. Greenhouse for solar energy exploitation

that positions the lamellae horizontally. In the nocturnal position, the collectors inhibit outgoing radiation. The heat from the plants is reflected on to the collectors and stays inside the greenhouse.

A conventional accumulator (a tank or pond) can be used to store surplus thermal energy. When the room requires additional heat, the recirculation pump routes the warm water from the accumulator back to the absorber pipes, which then supply the additional energy to the plants via the lamellae.

Some comments should be made on the selection of the collector system. When a collector system with radiation-absorbing elements is installed movably or even permanently on the surface of the roof, the loss of light would be so large in the diffuse position (vertical arrangement) that there would be insufficient light for optimum plant growth. For this reason, the reverse sides of the collector lamellae were designed to reflect light also.

Many homes and schools, hospitals and other public institutions operate their own gardens either for internal supply or for educational purposes. These facilities also require relatively large amounts of thermal energy for heating water, even in the summer months. The optimum solution would be a greenhouse with heating that exploited solar energy.

A special type of greenhouse has been developed for this purpose (see figure 5). In comparison with conventional greenhouses, the southern roof area is larger, making the northern side of the roof steeper. The inclination on the latter side is 65°, so that no direct sunlight can enter the greenhouse even at midday. The collectors are aligned parallel with the southern roof surface. Energy recovery is approximately 30% over the year. In those cases where the recovered energy can be used to the full extent in the summer, this represents a very interesting advantage. This kind of greenhouse fulfils its objective as a plant-growing room just as well as a conventional greenhouse. The cooling area is not larger, and ideal shading is guaranteed. Ventilation possibilities are not restricted, and the collectors can also be used for heating purposes.

Solar timber kilns: Their suitability for developing countries

R. A. Plumptre

Commonwealth Forestry Institute, Oxford, United Kingdom of Great Britain and Northern Ireland

Unless solar kilns are competitive with or complementary to conventional methods of drying timber, solar seasoning will never be used commercially and it will remain what it has been up to now, an interesting research exercise. Any discussion of solar seasoning should therefore begin with a description of the main conventional methods.

Conventional methods

The conventional methods described below are all likely to compete with solar kilns except the last, which is very expensive.

Air drying in stacks

Timber is stacked on supporting bearers in an open yard either with or without waterproof or sunproof covers. Drying is by circulation of air through the stacks; the air picks up moisture from the surface of the timber. There is no control of temperature, humidity or rate of air flow other than through correct orientation and spacing of the stacks and good methods of stacking. Air drying, a widely used method, is apparently cheap and simple to carry out, but the costs of holding stocks of timber for long periods and maintaining yards can be considerable.

Air drying in sheds

The timber is covered by an open-sided shed. Protection against rain and sun is normally better than with open stacks, but it is more difficult to design sheds with as good a circulation of air as can be obtained with a good layout of stacks. The cost is greater than with open stacks, since the capital costs of sheds are greater.

Forced-air drying

Air is forced through a stack of timber, normally under a shed, by placing one or more fans at one side of the stack. No extra heat is applied. There is an added cost of fans and the power to drive them. The fans normally have to be large to give an even flow of air through the stack.

Pre-driers

Pre-driers are similar to conventional kilns but with less complicated heating, ventilating and control systems. They are larger than normal kilns and have been used extensively in cold climates to dry large quantities of timber down to about 20% moisture content, after which drying is completed in conventional kilns.

Conventional kilns

There are many designs and degrees of sophistication of conventional kilns, but in all of them the temperature, humidity and ventilation are controlled to give optimum drying conditions for any given species of timber. For the kilns to be used efficiently, timbers must be sorted into individual species before being dried, and each species must be dried according to a specific schedule.

Dehumidifiers

Dehumifiers are kilns where no external heat is applied, but instead humid air from the kiln is refrigerated, which causes the water to condense. The dried air is then allowed to reheat and is returned into the kiln or exhausted. This method of drying timber has proved successful in drying small quantities of timber in warm climates, but it has the disadvantage that, since no heat is normally applied to the timber, the rate of drying within the timber is slow.

Radio-frequency heating

Timber can be dried by heating it internally, using radio waves. It is, however, expensive and impracticable for large quantities of timber.

Review of research on solar kilns

The table gives information on experimental solar kilns. Research on solar drying appears to have started more or less simultaneously in India and the United States.

Dehra Dun, India

Rahman and Chawla[1] worked on a laboratory scale and tried out nine designs of miniature kiln. The first used a small pump to cause air to flow through the timber placed inside one chamber. Another chamber was used to heat the air and connected by a pipe to the chamber containing the timber. The other kilns used convection as a means of circulating air through the timber, some by having the heating chamber underneath the chamber containing the timber and some by using a chimney. Small gains in speed were found over normal air drying, but all models suffered because there was no method of recirculating heated air, which consequently was lost after a single pass through the timber. Regrettably the research appears to have stopped there; as far as is known, no further results have been published.

INFORMATION ON EXPERIMENTAL SOLAR KILNS

Location	*Kiln capacity or dimensions*	*Design*
Dehra Dun, India	Nine small laboratory-scale kilns	Various designs using separate chambers for air heating and timber and convection movement of air
Colorado, United States	. . .	South-facing roof, double layer of plastic, wind-powered fans
Wisconsin, United States	425 bd ft (1 m^3)	South-facing roof, double layer of plastic, single fan
Rio Piedras Puerto Rico	2 000 bd ft (4.7 m^3)	South-facing roof, double layer of plastic, four 16-in. (40-cm) fans
Rio Piedras, Puerto Rico	3 000 bd ft (7.1 m^3)	South-facing roof, double layer of plastic, four 16-in. (40-cm) fans, roof covered with glass
Philippines	480 bd ft (1.1 m^3)	North-south oriented, single layer of plastic, one 24-in. (61-cm) fan
Uganda	1 400 bd ft (3.3 m^3)	North-south oriented, double layer of plastic, two 18-in. (46-cm) fans, reflectors
Fort Collins, Colorado, United States	1 200 bd ft (2.8 m^3)	South-facing roof, fibreglass-reinforced polyester covering, two 24-in. (61-cm) fans
Philippines	480 bd ft (1.1 m^3)	South-facing roof, fibreglass-reinforced polyester covering, 24-in. (61-cm) fans
Kumasi, Ghana	1 700 bd ft (4 m^3)	Converted green-house, single fan
Tananarive Madagascar	1 200 bd ft (4 m^3)	North-south oriented, translucent fibreglass covering, two fans
Moshi, United Republic of Tanzania	4 000 bd ft (6 m^3)	North-south oriented, flat glass roof, polythene walls, three fans
Uganda	4 000 bd ft (9.4 m^3)	North-south oriented, pitched roof, weatherable polyester covering (two layers), four 20-in. (51-cm) fans, reflectors
Uganda	8 000 bd ft (18.9 m^3)	North-south oriented, pitched roof, six 20-in. (51-cm) fans, weatherable PVF covering (two layers)

[1] M. A. Rahman and O. P. Chawla, "Seasoning of timber using solar energy", *Indian Forest Bulletin*, No. 229 (1961).

Wisconsin, United States

Peck,[2] working at the Forest Products Research Laboratory at Madison, Wisconsin, designed a small kiln similar to a conventional dry kiln but with a roof sloping towards the south and a double layer of weatherable polyester to trap solar radiation and keep it inside the kiln. A black-painted corrugated-aluminium sheet was stretched across the top of the kiln 15 cm below the inner layer of polyester to absorb heat, and air was passed by means of one fan over both surfaces of the aluminium sheet. Inlet and outlet vents were used for letting in and evacuating limited quantities of air. Speeds of drying were appreciably faster than those of air drying, being about 60% of air-drying times for timber dried from green to air-dry. Drying defects were found to be less than for air drying. Although costs were roughly the same as those of air drying, they were half those of kiln drying. However, the kiln was a small one, capable of taking only 1 m^3 of timber.

[2] E. C. Peck, "Drying 4/4 red oak by solar heat", *Forest Products Research Journal*, vol. 12, No. 3 (1962), pp. 103-107.

Colorado, United States

Johnson[3] built a small kiln in Colorado to dry timber for his private use. The kiln consisted of a chamber in which boards were stacked in racks and solar heat was absorbed by window-type absorbers on the south-facing side. Air was circulated by wind-powered fans. The kiln dried 1-in. (25-mm) timber in two to six weeks, depending on weather conditions.

Rio Piedras, Puerto Rico

In 1962, Peck and Maldonado published a paper[4] describing a kiln built in Rio Piedras, Puerto Rico, capable of taking 4-5 m^3 of timber. It was similar to, but larger than, the one built by Peck in Wisconsin. Air was circulated by four 16-in. (40-cm) fans powered by a 1½-hp (1.1-kW) electric motor. Otherwise it was almost identical in design to the Wisconsin kiln.

In 1966, Chudnoff, Maldonado and Goytia published a detailed account of the operation of an enlarged version of Peck's and Maldonado's kiln at Rio Piedras,[5] an account that is one of the main contributions to the literature on solar kilns. The kiln had been enlarged to a capacity of 7.1 m^3 by lengthening it, and the original 1-mil PVF sheet on the inside of the kiln had to be replaced with 2-mil sheets after one year's use. The roof panels of 2 mil PVF sheet had to be replaced by glass after two years' use. The deterioration of the sheet was attributed mainly to flexing, but some brittleness owing to degradation from ultraviolet radiation was observed on the roof panels. Trials were subsequently started using 4-mil PVF sheet and 5-mil weatherable polyester sheet.

The speeds of air and solar drying under various weather conditions, including solar radiation, were compared. Temperatures inside the kiln were 28°F (15.5°C) above the outside temperatures, and the humidity was 21% lower. The equilibrium moisture content for air-dried timber varied from 13%-15% according to the time of year, while the equilibrium moisture content within the kiln varied 8%-10%. Trials of different timbers were carried out, and they were grouped into mahogany *(Swietenia macrophylla)* and mixed hardwoods varying in specific gravity at 12% moisture content from 0.48 to 0.82. One-inch (25-mm) mahogany dried from 50% to 12% moisture content in 18 d, while 1¼-in. (28-mm) took 25 d and 2-in. (50-mm) took 41 d. Mixed hardwoods 1¼in. (28-mm) thick took 43 d to dry from 60% to 12% moisture content. The quality of timber produced was as good as or better than timber dried by air drying. Some trouble was experienced with case hardening, and mist sprayers were installed to humidify the atmosphere inside the kiln during the early stages of drying and for conditioning case-hardened timber. The water for the sprayers was heated by a solar water heater before being sprayed into the kiln. Drying was two to four times as fast as air drying.

Philippines

Casin in 1967,[6] and Casin, Ordinario and Tamayo in 1968[7] described a small portable kiln built in the Philippines with a capacity of 1 m^3. It was oriented north-south, unlike most of the previous kilns. It had plywood end-walls and a door in the north wall. Circulation of air was produced by a single 24-in. (61-mm) fan powered by a 3/4-hp (560-W) motor. Three 4-in. X 4-in. (10 cm X 10 cm) vents were placed on one side of the kiln. Trials were carried out on four species, *Shorea polysperma, Pterocarpus indicus, Shorea negrosensis* and *Dipterocarpus grandiflorus.* The rates of drying were considerably faster in the solar kiln, indicating that the kiln not only dried timber in about half the time, but also dried it to a lower moisture content than was possible with air drying. Temperatures in the kiln were 7.2°-11.7°C higher than comparable outside temperatures. Case hardening was severe in some of the timber dried in the solar kiln, and humidification was considered necessary in future trials.

Uganda

Solar kiln No. 1

Trials with a small 3.3 m^3 solar kiln were begun in 1954, and the results of these trials were published in 1967.[8] The main features of the kiln are a double layer of 5-mil weatherable polyester film, which at the time of writing, had deteriorated only in the

[3] C. L. Johnson, "Wind powered solar heated lumber dryer", *Southern Lumberman*, vol. 203, No. 2532 (1961).

[4] E. C. Peck and E. C. Maldonado, "Drying by solar radiation", *Forest Products Research Journal*, vol. 12, No. 10 (1962), pp. 467-488.

[5] M. Chudnoff, E. C. Maldonado and E. Goytia, United States Forest Service Research and Paper No. ITF-2 (Rio Piedras, Puerto Rico, Institute of Tropical Forestry, 1966).

[6] R. F. Casin, *Solar Drying for Lumber*, Technical Note No. 76 (Los Baños, Philippines, Forest Products Research Institute, 1967).

[7] R. F. Casin, L. B. Ordinario and G. Y. Tamayo, "Solar drying of Apitong, Narra, Red Luan and Tanguile", *Philippine Lumberman*, vol. 15, No. 4 (1969), pp. 23-30.

[8] R. A. Plumptre, "The design and operation of a small solar seasoning kiln on the equator in Uganda", *Commonwealth Forestry Review*, vol. 46, No. 130 (1967).

outer-roof layer. The inner roof and walls were still sound. The kiln is oriented north-south and has two small vents on the north and south walls. Two 18-in. (46-cm) cross-shaft fans are powered by an externally mounted 3/4-hp (560-W) motor. Curved aluminium reflectors are used on each side of the kiln to reflect solar energy into the kiln from the sides. The false ceiling, central partition in line with the fans and other internal parts, including the floor, are painted with a matt-black blackboard paint. Nine species in differing thicknesses of timber were tried, and air drying in a shed and in a small open stack under a cover, solar kiln drying and steam kiln drying were compared. The quality of timber produced by drying in the solar kiln was as good as or better than that produced by air or steam drying. Timber could be dried to 12% moisture content in the solar kiln in a reasonable time, whereas air-dried timber never dried below 15%-20% (normally about 17%), which is not low enough for furniture or high-grade joinery use. Drying speeds in the early stages of drying were not much faster than those of air drying, but the gain was decisive below 30% moisture content. Normal medium-weight furniture timbers such as *Chlorophora excelsa* 1-in. (25-cm) thick could be dried from green to 12% moisture content in a month or less. Since 1967, the kiln has been in almost continuous use drying timber for the Forest Department or for government and private furniture workshops. Possibly because of the small vents, little or no trouble has been experienced with case hardening.

Solar kiln No. 2

Solar kiln No. 1 was so useful and remunerative that it was decided to design a larger kiln, one large enough to interest joinery and furniture workshops throughout the timber trade in the use of solar kilns. The result was kiln No. 2, of which the major design details are shown in figures 1 and 2. The main principles are the same as for the kiln No. 1, except that the air is circulated down the side of the kiln and then turned by a curved sheet of aluminium through 180° to go up and through the stack. Four 20-in. (51-cm) fans, powered by two 2-hp (1.5-kW) motors mounted on the roof of the kiln are used to circulate air. The fans are reversible. The kiln is capable of taking a stack of timber 7.2 m X 2.3 m X 1.6 m, approximately. Improved reflectors the same length as the kiln are polished with silicone car polish to reduce, as far as possible, dulling of the surface through oxidation. The kiln covering material is 5-mil weatherable polyester sheet in two layers 4.4 cm apart. The sheet is stretched vertically, rather than along the length of the kiln, and held along the joints by timber battens. Wall frames and roof trusses are thus spaced to coincide with the width of the sheet (107 cm).

Four vents (see figure 2) are placed opposite the fans, just under the eaves of the roof on each side of the kiln, and are controlled as shown in figures 1 and 2. The reflectors are placed beside the kiln. The holes in the adjusting quadrants are marked with the time

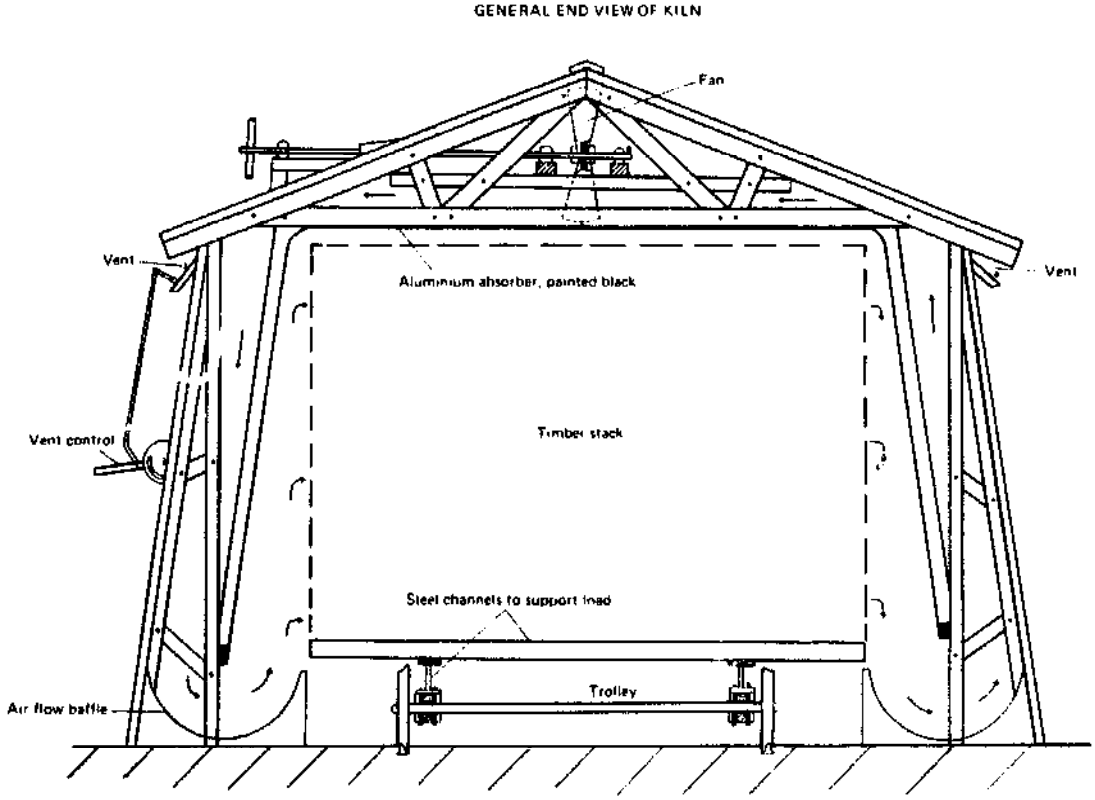


Figure 1. Cross-section of Uganda kiln No. 2

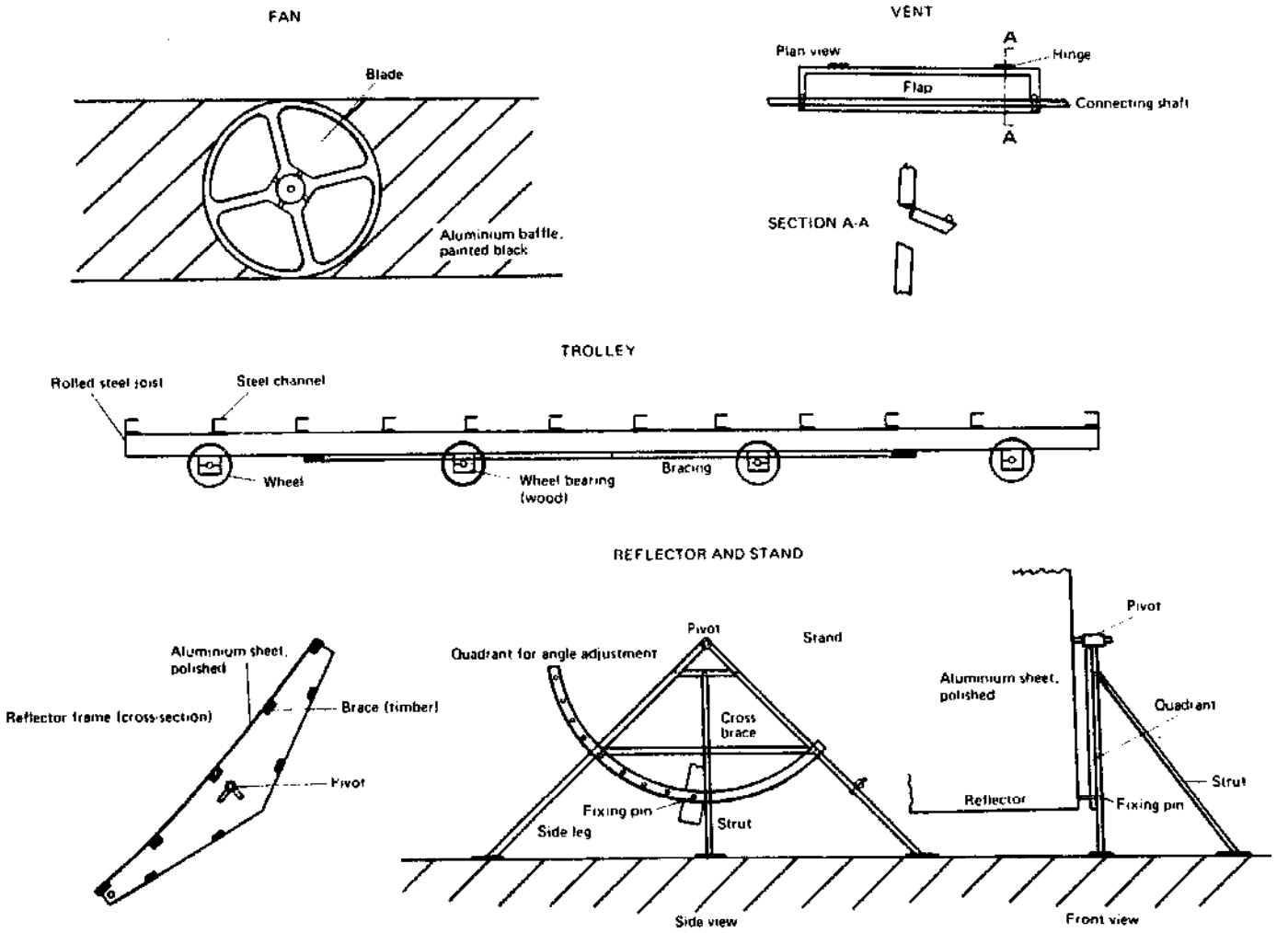


Figure 2. Uganda kiln No. 2: details of fans, vents, trolley and reflectors

of day. When the adjusting pin holding the reflector is in the proper hole, a band of light is reflected at right angles, in through the side of the kiln and on the black-painted aluminium absorber. Reflectors are 2.4 m wide and 3.6 m long, and there are two on each side of the kiln. The floor of the kiln is concrete that was laid free of charge by a building firm wanting timber dried for use in a hotel. The trolley and rails were fabricated from old sugar trolleys and rail, steel channel, rolled-steel joints and 1½-in. (38-mm) shafting in the Forest Department's Utilization Section workshop. An extra source of heating has been added in the form of a home-made solar water heater connected to a single coil of 3-in. pipe painted black and fitted to the wall of the kiln between the inner layer of plastic and the aluminium absorber. This forms a continuously circulating hot-water system. It is doubtful, however, whether it contributes much to raising the temperature in the kiln, owing to its small heat capacity compared with that of a full load of green timber.

This second kiln was compared with the first kiln and found to be about 10% slower. The quality of timber seasoned was better than in kiln No. 1. The vents are too large for optimum seasoning and need to be kept almost closed throughout the whole seasoning period.

The cost of building the kiln is estimated at about USh 12,000 ($1,700).

Since 1968 the kiln has been used almost continuously for commercial seasoning of furniture timber. Normally, charges have been made up of a single species at a time, but often, where small quantities of any one species were required, this species was mixed with others in the kiln. When species were mixed, or timber thicknesses were mixed, the slowest drying species or size was placed at the bottom of the kiln so that the quicker drying material could be removed without breaking down the whole stack. It was found inadvisable to mix small quantities of green timber with a charge of semi-dry timber unless it was a timber that dried fast with little degrade, since sudden drying in an atmosphere of low humidity is liable to cause case-hardening and other degrade. There is no doubt however, that, because of its slow drying rate, the

kiln is much more versatile than a conventional kiln with respect to its capacity to dry a mixed lot of green timber.

Only two kilns of this design, other than the one built by the Forest Department, were built in Uganda, one by Prison Industries to supply dry timber for their furniture workshop and one by a private company manufacturing furniture. Neither became fully functional because the first was covered with light-gauge polythene that disintegrated rapidly and the second was never completed because the manager interested in the kiln left the firm concerned without taking steps to obtain the correct covering material.

Solar kiln No. 3

The second kiln was complicated and time-consuming to build. Although it has been successful in that it has operated well and is in continuous use, it wastes space and material in relation to its timber-holding capacity and, therefore, in terms of its potential for earning money. It is also not geared to being mass-produced. A third kiln was designed in 1970 and built in the first half of 1971 with the aim of doubling the kiln capacity while at the same time keeping the cost and the complications of building it to a minimum. (See figures 3 and 4.)

One difference in design is that the air is not taken down the side of the kiln and then up and through the stack as is the case with the second kiln. It passes, mainly on the inside, but also partly on the outside, of the absorber, which stretches along the side of the kiln. Vents are positioned so that they are partially covered by the upper edge of this absorber, and only a small proportion of the air passing through the fans can come in at one vent and out at the opposite vent. They are smaller and better sealed, if lined with felt or similar material, than the vents in kiln No. 2. The main structure of the kiln remains the same, but the plastic sheet (in this case 4-mil PVF sheet for the roof and 2-mil PVF sheet for the walls, since the weatherable polyester became unobtainable) is stretched over standard-sized panels, which are

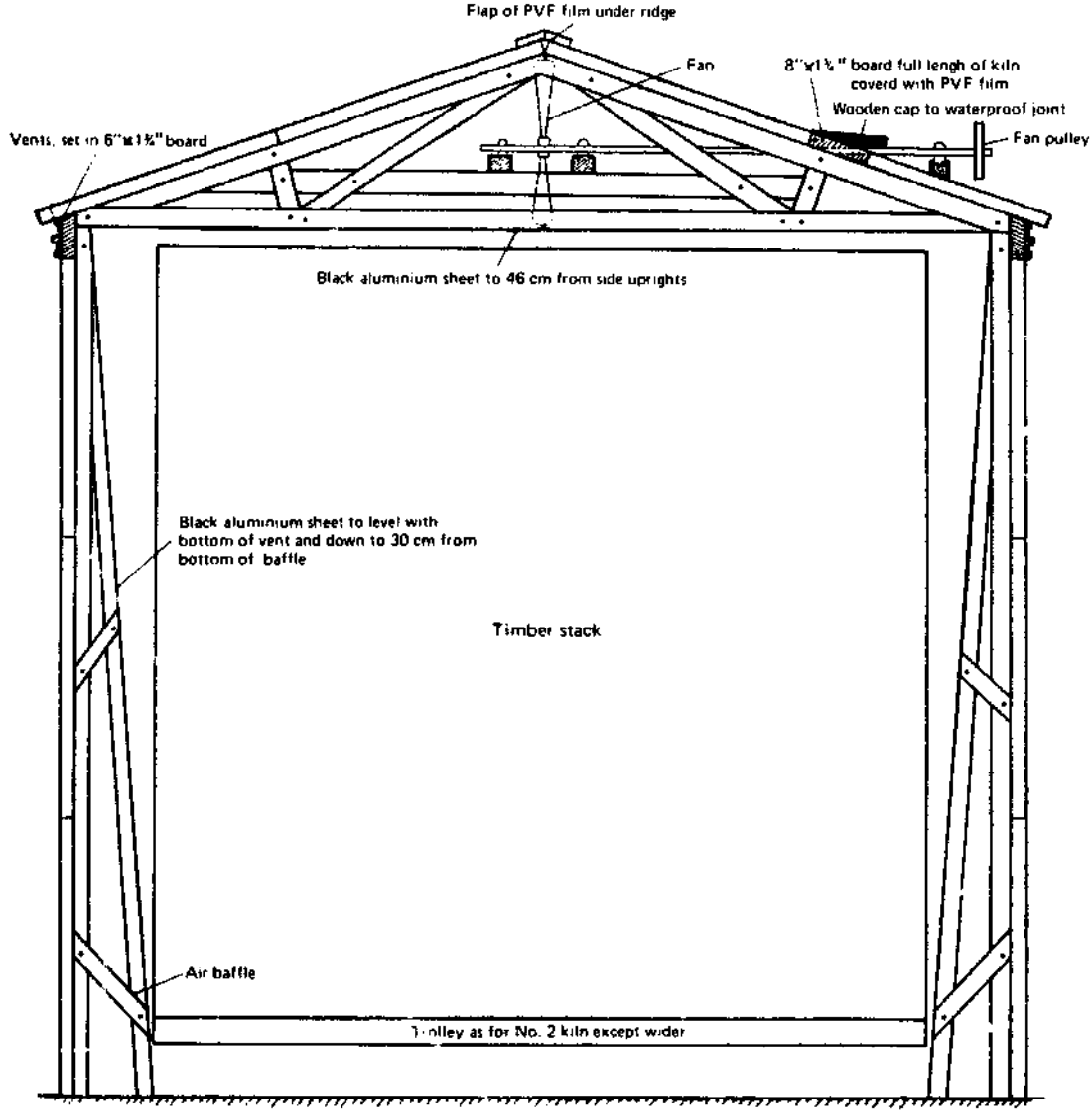


Figure 3. Cross-section of kiln No. 3 with details of component parts

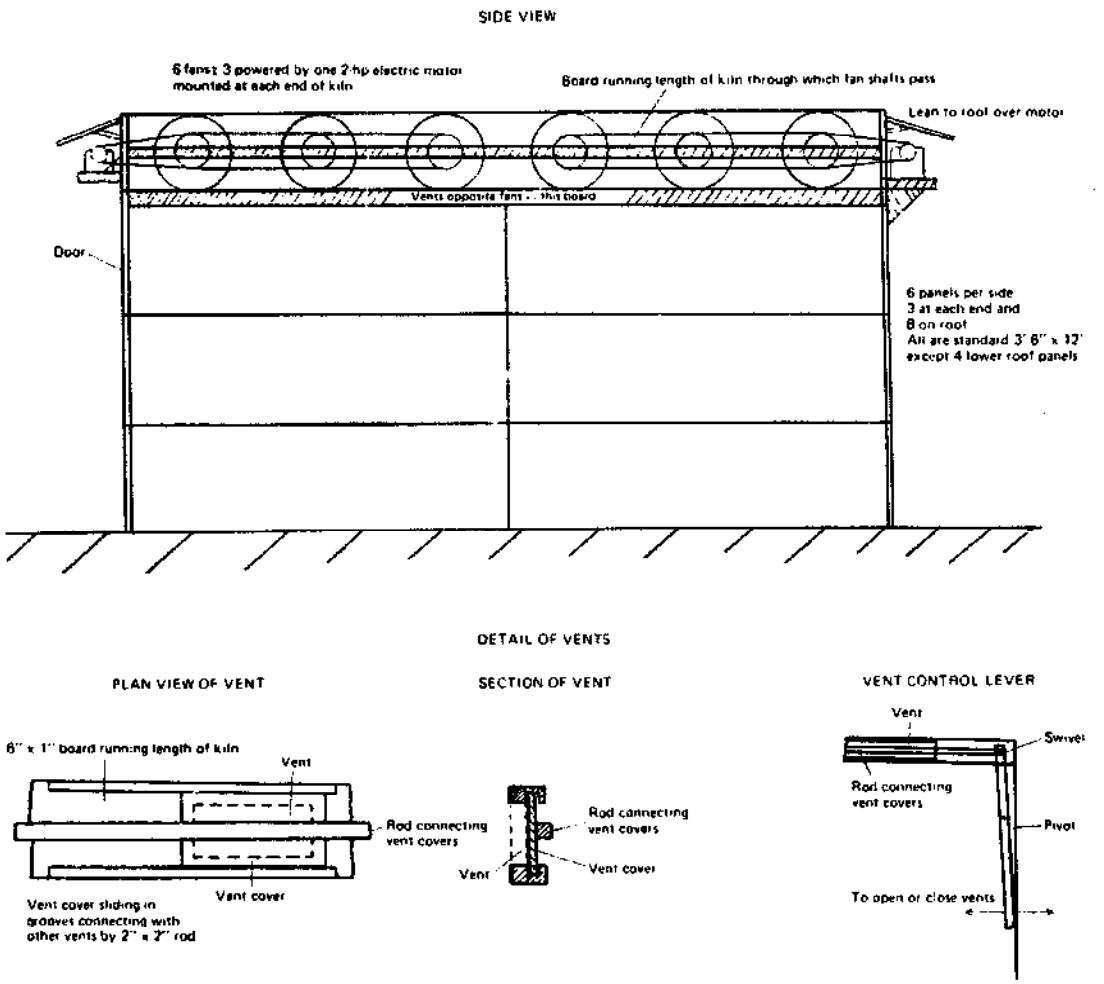


Figure 4. Details of fans and vents for kiln No. 3

bolted together before the sheet is finally fixed on the outside of the panels. In all, 22 such panels are used in the construction of the walls, the door and upper sections of the roof. Only four non-standard panels are required for the lower panels on the roof; the panels on the fan-shaft side are smaller than those on the opposite side. There are six 20-in. (51-cm) fans, instead of the four in the previous kiln, to cope with the greater stack width and height, but they are still powered by the same two 2-hp (1.5-kW) motors, which have ample power to drive three fans. The motors in this kiln are mounted at the end of the kiln to avoid shading the roof and reducing the amount of radiation entering the kiln. The door design has been altered to enable the door to be made from standard-size panels, and it can also be removed completely to one side. To lower the cost, the floor is made of rammed gravel covered by tarmac. The trolley rails are laid on pressure-treated timber sleepers with a concrete beam under each rail to give added bearing strength to prevent the rails from sinking.

The fans and motors have worked virtually trouble-free apart from the occasional need to tighten and grease bearings. The roof of the small kiln has required a new outer layer, but only after six years of operation. Occasional cleaning or repainting of the black surfaces inside the kilns is required but, normally, only once every two years. No permanent operator is necessary, since the kilns are switched on in the morning and off in the evening and the reflectors are moved hourly by a timber inspector doing other work during working hours and a watchmar at other times. The Ministry of Works has its own electrically heated, automatically controlled dry kiln capable of taking about 2 m^3 per charge.

Fort Collins, Colorado, United States

Troxwell and Mueller reported in 1968 on a 2.8 m^3 capacity solar kiln at Fort Collins.[9] A single layer of fibreglass reinforced corrugated polyester sheet was used to cover the kiln. This translucent material was tested against glass, to compare the properties of the two materials in transmitting solar radiation, using an Eppley pyrheliometer. It was

[9] H. E. Troxwell and L. A. Mueller, "Solar lumber drying in central Rocky Mountain region", *Forest Products Research Journal*, vol. 18, No. 1 (1968), pp. 19-24.

found only slightly inferior to glass in this respect. Previously, PVF film had failed in the high winds common in the area. The kiln was equipped with two 24-in. (61-cm) fans giving an air velocity of 100-300 ft/min (30-100 m/min). It was east-west oriented with a north-south slope on the roof. Differences in temperature were found in the middle of the day in summer. It was reported that vent control was important in obtaining optimum conditions. Using the pyrheliometer it was calculated, from the radiation reaching the inside of the kiln and the timber moisture content, that 25%-45% of the solar energy reaching the inside of the kiln was used in drying the timber. The rest was dissipated. Trials with Engelman spruce and lodgepole pine gave satisfactory rates of drying.

Wengert, in an interesting paper,[10] identified sources of energy loss from the Fort Collins solar kiln and indicated that only some 16% of the solar energy reaching the outer surface of the kiln was effective in evaporating water from the timber; the rest was lost approximately as follows (%):

Through walls and roof	30
Reflected solar energy	17
Through the floor	11
Heating fabric of drier or stored therein	7
As long-wave energy	13
Through air vents	14
Total	92

The sum of the above losses plus the 16% used exceeds 100% owing to an unmeasured input of energy from the fans and to experimental error. The kiln used had only a single-layered fibreglass-reinforced polyester covering, and Wengert suggested that a double layer be used; he also suggested better insulation of the floor, baffles in the roof of the kiln painted black to absorb more of the energy falling on the roof, and improvements in the system of venting. He proposed coating the walls with infrared-reflecting chemicals, such as titanium dioxide, to reduce long-wave radiation loss from the kiln.

Ghana

Martinka[11] used an old glass-covered greenhouse in Kumasi, with space for about 4 m^3 of timber as an improvised solar kiln to compare solar drying, with pre-drying in a converted oven and with air drying. The pre-drier was capable of taking 96 bd ft (0.23 m^3). A single fan was used in the kiln to circulate the air, and black-painted aluminium sheet was used to absorb heat inside the kiln. Using *Nauclea* and *Entandrophragma angolense* he found that the speed of drying in the solar kiln lay between that of air drying and the pre-drier, possibly because the insulation of the greenhouse was poor and less good air circulated than in the pre-drier. The pre-drier was also much smaller.

Madagascar

In 1970, Gueneau[12] described a solar kiln at Tananarive similar in design to the Fort Collins (see above) kiln but oriented north-south and with the slope on the roof facing west. It was covered with a single layer of corrugated fibreglass-reinforced polyester sheet. Two fans were used for circulation and a hygrometer was used to monitor the humidity inside the kiln. The cement on the floor was painted black. Polystyrene was used to seal the joints between the fibreglass sheets. The cost of building the kiln was FMG 417,000 (approximately $1,500). Two vents were placed on the high side of the kiln near the roof and two more near the floor on the opposite side. Trials were carried out using *Pinus kesiya* and *Dalbergia baroni*, and these showed reductions in drying time using the solar kiln compared with air drying of 34%-68% for pine and 48% for the *Dalbergia*. Savings in time were particularly apparent below 20% moisture content. It was recommended that the solar kiln be used after a preliminary period of air drying to bring timber down to the required equilibrium moisture content of 10%.

United Republic of Tanzania

In 1968 a solar kiln was built at the Forest Department Utilization Section at Moshi in the United Republic of Tanzania. It was flat-roofed with a single layer of glass on the roof and had polythene-covered side walls. A galvanized-iron absorber placed 6 in. (15 cm) inside the walls was painted black, and air was circulated by means of three fans placed above the absorber; the latter was carried across the kiln as a false ceiling. The kiln capacity was 6 m^3. Unfortunately, no information is available on its performance.

Important factors in solar drying

Insulation

Wengert[13] demonstrated that a large proportion of the heat loss in solar kilns was due to poor insulation of the roof, walls and floor. He was dealing

[10] E. M. Wengert, *Improvements in Solar Dry Kiln Design*, United States Forest Service Research Note FPL-0212 (United States Forest Service, 1971).

[11] E. Martinka, *Predrying of Some Ghanaian Timber*, Technical Note No. 11 (Ghanaian Forest Research Institute, 1969).

[12] P. Gueneau, "An experiment in solar drying wood", *Bois et Forêts des Tropiques*, No. 131 (1970), pp. 69-70.

[13] *Op. cit.*

with a kiln that had only a single layer of fibreglass-reinforced polyester sheet. Kilns with double layers of covering material are almost certain to be more efficient. Where flexible plastic sheet is used, the double layer is likely to be less effective than a rigid sheet, which retains a constant air space and reduces the movement of the air within the space during the vibration of the kiln caused by the fans. Doors could, almost certainly, be made to fit better with little extra cost, and vents need to be efficient and easily adjustable to be able to control, more exactly, the quantity of air entering and leaving the kiln.

The type of covering material used is controlled by the limited number of transparent or translucent weatherable materials available. Since the covering material forms a large part of the cost of building a kiln, a compromise has to be made between the ideal material and economy. It is unfortunate that the weatherable polyester sheet used on the first two Uganda kilns is now out of production, and in Uganda any suitable covering material, other than glass, which is expensive to use, has to be imported specially from abroad, usually with an attendant delay of six months. Undoubtedly, this, more than anything else, has prevented the wider use of solar kilns in Uganda.

Air circulation

The rate and evenness of flow of air through the timber stack is important in controlling the rate of drying. If kilns are only partially filled, a great deal of the air flow will go over the top of the stack. A piece of plastic sheet attached at one side to the roof of the kiln (or false ceiling) and rolled round a piece of timber that is lowered on to the top of the stack, provides an easy method of preventing this. Correct design of absorbers to give an even flow of air through the timber and good heat absorption is important.

The control of vents is also important. Over-ventilation has been a fault of many solar kilns and a correct balance has to be found between humidity and temperature. In the early stages of drying and particularly in the region of the fibre saturation point, the limiting factor is the rate at which water will pass from the centre to the outside of the timber. Too large a moisture gradient case-hardens the timber and, in the early stages of drying, high temperatures and high humidities are required. Only in the latter stages of drying is it possible in a solar kiln to obtain high temperatures and low humidities. Thus, further study to improve vent design and control is needed.

Size of kilns

To be of interest for commercial use a solar kiln needs to have a capacity of 10-20 m^3 even in a developing country, where furniture and joinery workshops are run on a smaller scale than in the more developed countries. Most of the experimental kilns have so far been small ones, and more work is required with sizes of kiln where the ratio of surface area of kiln to volume of timber is smaller. The third Uganda kiln was set up to study this problem. If the kiln operates successfully, it could provide a basis for a commercial kiln design suitable for conditions in Uganda.

Reflectors

With kilns of 10-20 m^3 or larger, as much heat is required as possible, and it should be collected from as wide an area as possible. In Uganda, which lies across the equator, it is easy to design and operate simple reflectors that reflect a considerable quantity of solar energy through the sides of the kiln. Away from the equator this would be more difficult. Simple air heaters might be designed to preheat air before it is drawn in through the vents.

Costs

While it is possible, no doubt, to increase the efficiency of solar kilns greatly, the cost of doing so must be considered. The main justification for solar kilns is their low cost and ease of building as compared with conventional kilns. There is no point in losing this major advantage in order to employ some sophisticated method of increasing kiln efficiency.

Quality of solar-kiln-dried timber

Almost all research workers in solar drying have reported on the high quality of timber produced. The reason is almost certainly that the lack of solar heating at night and the consequent lower temperatures, higher humidity and lack of air flow allow a nightly "conditioning" period, where internal and surface moisture contents have time to even out. This is particularly important with the harder, heavier, slower drying species. Good conventional kiln schedules properly applied can give the same results, but skilled operation is required.

Competitiveness of solar kilns

The competitiveness of solar kilns in relation to each of the main conventional methods described earlier will now be discussed.

Air drying

Costs of drying by solar kiln are generally accepted as being as high as, or higher than, air

drying, even when the extra length of time during which capital is tied up in air-drying timber is taken into account. Solar drying has three major advantages over air drying. First, it is quicker, normally about twice as fast to equilibrium moisture content of air-dried timber in the climate concerned. Secondly, it is possible to dry timber to a moisture content lower than the equilibrium moisture content of timber within closed buildings, which means that it can be dried sufficiently to be suitable for furniture and high-grade joinery manufacture, which is undoubtedly the greatest advantage of solar drying over air drying. Thirdly, solar-dried timber is almost always superior in quality to air-dried timber, since humidity is more uniform in all stages of drying. The timber is also not subjected in the same way to more air flow and more sunlight or heat at the ends of the timber than in the centre of the stack, which is common even in the best air seasoning. Thus, less chance of degrade in the form of end split exists than with air-dried timber.

The major disadvantage of solar seasoning is the small capacity of the kilns.

Forced-air driers

With research, forced-air driers may be made competitive with solar kilns. Large fans are required unless complicated baffle systems are designed; to be effective, they must be covered by a roof and mounted in a wall or partition. The capital costs for these driers are, therefore, considerable; and they do not give the advantages of the higher temperatures and humidity control of the solar kiln. At present, therefore, they do not threaten to compete with solar kilns in tropical areas.

Pre-driers

If pre-driers are used only for the purpose for which they were designed, it is unlikely that they will compete with solar kilns, since the latter are most efficient and can best be used for the final stages of drying. If, however, pre-driers are modified to form low-cost conventional kilns with a simple form of heating suitable for developing countries, the chances of their competing with solar kilns are much greater; it may well be possible, for instance, to augment solar heat with a simple hot-water system based on an open fire fed on wood waste and a 44-gal (Imp) (200-l) drum.

Conventional kilns

Solar kilns have proved in all cases, where costings have been carried out, to be cheaper than conventional kilns. Within the limitations of their size they are, therefore, competitive, but, since they are slower and must be placed so that they are exposed to direct sunshine for most of the day, they require a much larger area of ground per unit of timber seasoned than conventional kilns. In their present form, therefore, they are more suitable for seasoning small quantities of timber than for mass production of seasoned timber. This indicates an initial use for small joinery and furniture concerns. Later they may be used in batteries for seasoning larger quantities of timber, but development on a comparatively small scale is required first. One advantage of solar kilns is that they do not require highly skilled operators and need only periodic attention.

Dehumidifiers

Because of their low efficiency, especially in the drying of large-size timber, it seems unlikely that dehumidifiers can compete with solar kilns.

Remarks on cost comparisons

The only costings that have been carried out comparing solar seasoning with other methods are those of Peck.[14] In Uganda, neither the steam kiln operated by the Forest Department nor the electrical kiln operated by the Ministry of Works is representative of potentially competitive commercial kilns, since they are too small and expensive to run. No costings are available for the only commercially operated kilns in the country, which are located 50 miles (80 km) away from the solar kilns.

It is not considered valid to compare the costs of air drying with those of solar drying, since the best way to use a solar kiln is almost certainly for bringing air-dried timber down to a moisture content that cannot be reached by air drying alone.

Suitability of solar kilns for developing countries

In developing countries, the individual units in the timber industry are normally small and often separated from each other by considerable distances; communications are often poor. Requirements for seasoned timber are correspondingly low in any unit, which favours the solar kiln with its low capital and running costs and small output of seasoned timber. At the same time, most developing countries have climates that favour solar seasoning. A certain degree of sophistication of the industry is necessary, since the "bush" carpenter will not be able to pay for a solar kiln, nor does it matter to him or his customer if the timber used is not absolutely dry. Once the industry has developed to the stage where individual units use 10-40 m^3 of timber per month or where

[14] *Loc. cit.*

there are co-operatives of smaller units, there is likely to be a demand for solar kilns. At this stage of development it is often not the cost per unit of timber dried that determines which method of drying should be used, but the initial capital cost of the method. Thus, initial investment must be kept as low as possible. Kilns should be designed so that they can be easily made from readily available materials. In this respect modular building systems and standardized components are an advantage if they come with good drawings and instructions.

Recommendations

Co-ordination and centralization of basic research

Research along the lines suggested by Wengert[15] is required to discover the nature of energy losses and to test alterations in design intended to reduce them. Research directed towards finding the best covering materials is essential. This research can be done wherever there are staff, funds and facilities to do it; the results will be applicable to all areas of the world. The design of the best size and shape of kiln, which will vary from country to country, should be left to individual research workers in interested countries so that they can suit kiln designs to the particular conditions in their countries.

[15] *Op. cit.*

Funds for research and development

In many developing countries, funds for research are short, especially for the kind of research required for solar kilns, where immediate financial returns will probably not be great. Since "seeing is believing", commercially operated kilns are not likely to become a reality in any country until a solar kiln of commercial size can be demonstrated in that country or a nearby one, in operation. Thus, funds are needed not only for research but also for prototype commercial models.

Dissemination of information

Much of the research on solar kilns has been carried out without knowledge of research done elsewhere. A corresponding committee composed of persons working with solar kilns in different parts of the world would solve that problem. A convener or secretary would be required to keep the information circulating.

Solar refrigeration and cooling

Erich A. Farber

Solar Energy and Energy Conversion Laboratory, University of Florida, United States

Refrigeration is available in the more industrialized countries through the availability of electricity produced by fossil fuel but is not readily available in the major part of the world and to the great majority of people. Solar energy, however, is available in most areas where people live, and the conversion of solar energy into other forms which can provide the refrigeration or cooling needed could be a tremendous benefit to mankind. This paper discusses in detail some of the methods that can be used to this end and makes recommendations for their implementation.

Basic methods

The most widely used methods of refrigeration are the compression system, consisting of a compressor requiring high-grade energy such as mechanical or in most cases electrical, and the absorption system, in which the compressor is replaced by an absorber, a generator and a small pump. (See figures 1 and 2.) Both methods require a condenser, expansion valve or system, and an evaporator. In an absorption system with three fluid components, even the pump can be eliminated. Detailed descriptions of the methods are given below.

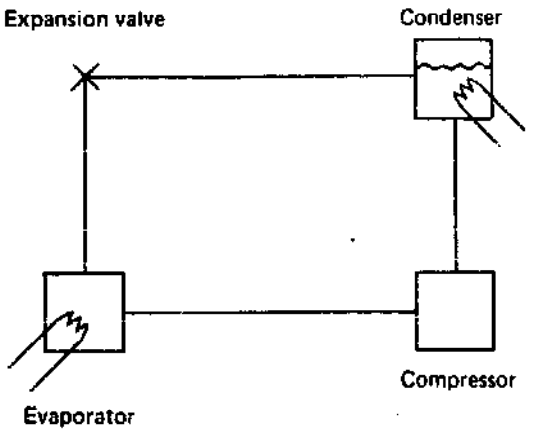


Figure 1. Conventional compression refrigeration system

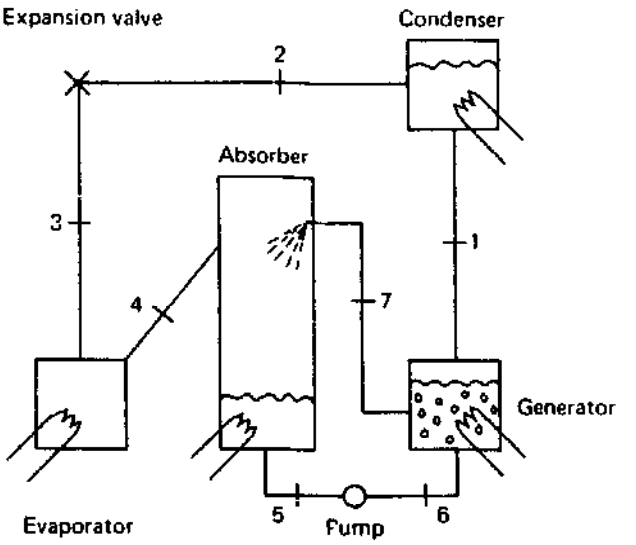


Figure 2. Continuous absorption refrigeration system

Solar refrigeration systems

When solar radiation is used as the energy source for refrigeration, many methods can be employed. Solar energy can be converted into mechanical energy and the compressor of a standard compression system be driven in this manner, or electricity can be produced either by a solar engine driving a generator or through a solid-state device, which then operates standard electrical refrigerators. However, since we can convert solar energy more efficiently to heat than to mechanical or electrical energy, the use of an absorption system with solar energy seems to be the best solution at this time.

In higher-temperature applications the solar energy must be concentrated, which requires in most cases systems that can track the sun, which makes them more cumbersome and more costly. Wind loading, life expectancy of the reflecting surfaces, the tracking mechanism etc. are sometimes problems. It must also be realized that concentrating solar collectors can only utilize the direct rays of the sun and not the diffuse portion, meaning that even on

clear days some of the energy is lost, and of course in cloudy weather these systems cannot collect any solar energy.

In lower-temperature applications, which can utilize flat-plate collectors, both the direct and diffuse radiation of the sun is utilized. Refrigeration systems in this range are not commercially available at the present time and must be specially designed and manufactured. Examples of both of the above approaches will be described.

Operating characteristics

Most people are quite familiar with the operation of compression refrigeration systems because they are so common. There is less information about and familiarity with absorption systems, and so they will be briefly described.

The intermittent absorption system indicated schematically in figure 3 is simpler in construction and consists of two tanks, each of which does double duty. During the charging mode, one of them acts as the generator, driving refrigerant (ammonia) out of solution (in water) when heated, and the other as condenser, changing the state of the refrigerant from gas to liquid.

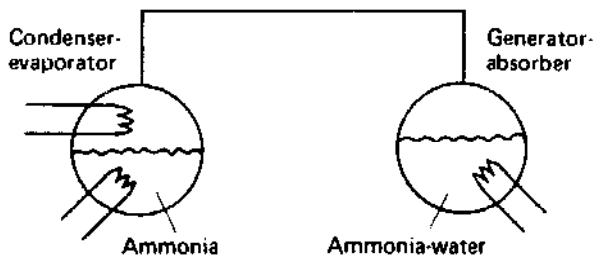


Figure 3. Intermittent absorption refrigeration system

The charging mode usually takes a short time compared to the cooling mode, during which the tank which was the generator becomes the absorber and the tank which was the condenser now becomes the evaporator, producing the refrigeration temperature needed.

The continuous absorption refrigeration system is similar to the compression system, with the compressor replaced by an absorber, a generator and a pump. The refrigerant-absorber solution is heated in the generator, driving the refrigerant from solution, which flows to the condenser where it is cooled and becomes liquid. From there it passes through the expansion valve and into the evaporator where the cold temperatures are produced. After the refrigerant has done its job it passes to the absorber, where it is reabsorbed into solution. The solution is pumped back to the generator to repeat the cycle. In other words the absorbent acts only as a carrier. In figure 2, the carrier circulates from 5 to 6 to 7 and back to 5, loading up with refrigerant between 7 and 5 and unloading it between 6 and 7. The refrigerant circulates through the system from 1 to 2 to 3 to 4 to 5 to 6 and back to 1.

Thermodynamic analysis

Many substances can be used for the absorber and the refrigerant; ammonia and water is the most widely used and best known combination and for this reason will be the only one discussed here.

Since the continuous system is more complicated than the intermittent, the analysis will be carried out for the continuous system. What are needed for the analysis are pressure-temperature charts for ammonia and enthalpy-concentration charts for ammonia-water solutions. These charts are readily available in refrigeration handbooks. The table gives data taken from such charts for the seven numbered points in figure 2, assuming the generator operates at a temperature of 160°F (71°C), easily obtainable with solar energy, the evaporator at 20°F (−7°C), and the condenser and absorber at 80°F (27°C).

OPERATING CONDITIONS IN THE CONTINUOUS AMMONIA-WATER ABSORPTION REFRIGERATION SYSTEM

Point in figure 2	*Temperature*		*Gauge pressure*		*Ammonia concentration (weight fraction)*	*Enthalpy*		*Flow rate*	
	°F	*°C*	*psi*	*bar*		*Btu/lb*	*kJ/kg*	*lb/h*	*kg/h*
1	160	11	140	9.6	1	696	1 620	1	0.5
2	80	27	140	9.6	1	132	307	1	0.5
3	20	−7	35	2.4	1	132	307	1	0.5
4	20	−7	35	2.4	1	618	1 438	1	0.5
5	80	27	35	2.4	0.50	−18	−42	20	9.1
6	80	27	140	9.6	0.50	−17.6	−40.9	20	9.1
7	160	71	140	9.6	0.47	67	156	19	8.6

For a typical 12-ft^3 (340-l) refrigerator and continuous operation, the quantities of heat which must be exchanged are as follows:

	Btu/h	*kJ/kg*	
Generator	2 321	5 399	added
Condenser	564	1 312	rejected
Evaporator	486	1 130	added
Absorber	2 251	5 236	rejected

The above values are within the accuracy which reading charts the size of a book page allows. For more exact values tables or larger charts must be used.

The coefficient of performance for this system under the above operating conditions is about 0.21 and the pump power needed for circulating the fluid is about 0.003 hp (2 mW).

A complete description of a system based on the above principles is in the article by Assad Takla, on page 7.

Solar space heating and cooling and solar water heaters

V. G. Bhide

National Physical Laboratory, New Delhi, India

Introduction

It has been fairly well established that human performance, in terms of productivity, is optimal under certain environmental conditions of temperature and humidity. The optimum temperature range is believed to be between 20° and 25°C.

India has a very broad spectrum of climatic conditions. In certain parts of the country, winter temperatures may drop below freezing, whereas in certain other parts, summer temperatures may rise to 45°C. To make these conditions more comfortable, space heating and cooling is normally resorted to.

Because of the energy crisis, there is an attempt all over the world to explore the possibility of providing space heating or cooling utilizing solar energy. Indeed, results over the last few years have shown that of all the applications of solar energy, space heating and cooling is not only technically feasible but is becoming economically competitive. In India also, some attempts have been made to study the feasibility of solar space heating and cooling. This paper presents the results of Indian experimental projects in this field.

Space heating

The first major experimental project on space heating was conducted by the National Physical Laboratory (NPL). The project sponsor, Bharat Heavy Electricals Ltd., (BHEL), was finding that the productivity of its factory at Haridwar was very low during the winter months. In order to see whether space heating could improve productivity at the factory, BHEL proposed that NPL collaborate with them to design, install and evaluate the space heating facility.

The chief objectives of the project were:

(a) To establish the feasibility of providing space heating to workers;

(b) To design an effective and economical system for factory heating with solar energy;

(c) To determine which of the several operating modes minimized auxiliary energy requirements;

(d) To estimate the performance of the complete heating system and each of its principal components;

(e) To appraise the utility by comparing its actual performance with results predicted by a mathematical model;

(f) To modify the design if necessary.

The factory consisted of a large building with big doors, windows and ventilators. Huge machines were installed in various places and there was a provision for a crane to move across the building. In view of these conditions, the idea of heating the entire space was abandoned and it was decided instead to provide localized heating to those working at the machines. The space heating system is shown schematically in figure 1. It essentially consists of an energy-collection cycle and an energy-radiating cycle. During the energy-collection cycle, water is circulated through an array of solar collectors mounted on top of the building. Water thus heated is stored in an insulated storage tank. During the radiation cycle, hot water is circulated through the fan-coil units. The design criteria for the two cycles are discussed below.

Energy radiation cycle

Assume an energy radiation system consisting only of the storage tank, pump and radiator in figure 1. To analyse and mathematically model the system performance, the following reasonable simplifying assumptions are made:

(a) The heat lost from the storage tank is negligibly small compared with the heat radiated by the fan-coil units;

(b) The heat-transfer coefficients of the different radiators are the same;

(c) The specific heats of water and air are constant over the temperature range involved;

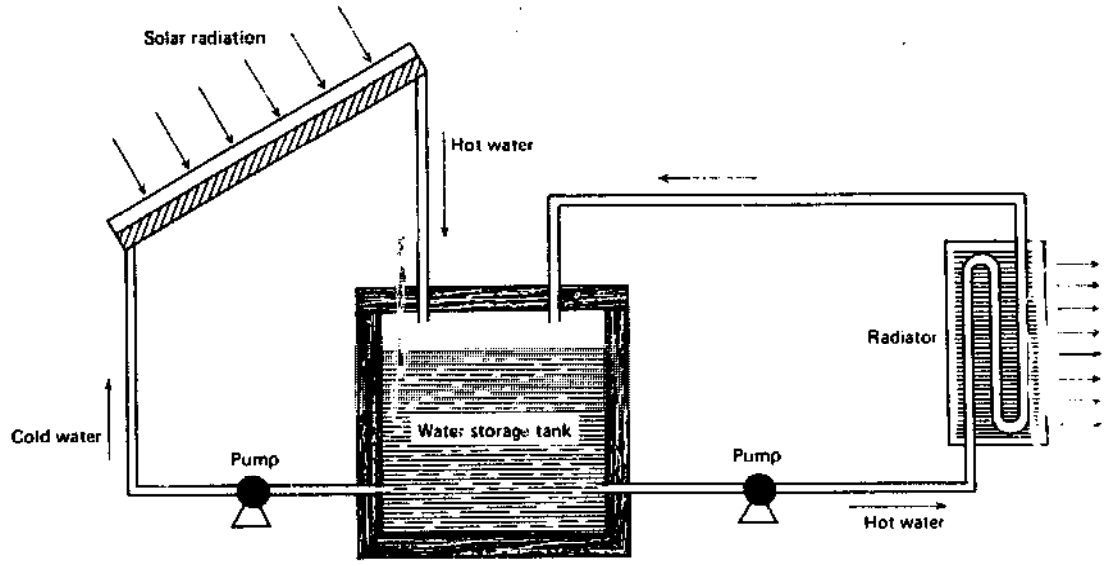


Figure 1. Solar space heating system

(d) During the cycle, no water is either added to or subtracted from the storage tank;

(e) The circulating pump does not alter the temperature of the water pump.

Let the mass of hot water in the full storage tank be M and the temperature of the water within it at the start of the radiation cycle ($t = 0$) be T_0. Let the mass rate of flow of water through the fan-coil unit be $\dot{m}_w$ and that of the air blown over the fan-coil unit be $\dot{m}_a$. As the water circulates through the fan-coil units and exchanges heat with the blown air, the temperature of the water in the tank decreases. Let the temperature at any instant of time t be T. If the specific heat of water is C_w and the temperature of the water after it has passed through the fan-coil units is T_{w2}, we can write

$$M C_w \frac{dT}{dt} = N \dot{m}_w C_w (T_{w2} - T) \qquad (1)$$

where N is the number of fan-coil units.

To find how T_{w2} varies with T, we must consider the heat balance during the heat exchange process. As the hot water exchanges heat with the air that is blown over the fan-coil unit, the temperature of the air increases from the ambient temperature T_a to T_{a2}. Under these conditions we have

$$\dot{m}_w C_w (T - T_{w2}) = \dot{m}_a C_a (T_{a2} - T_a) \qquad (2)$$

where C_a is the specific heat of air. We now define two parameters R and ϵ:

$$R \equiv \frac{\dot{m}_a C_a}{\dot{m}_w C_w} \qquad (3)$$

$$\varepsilon \equiv \frac{T_{a2} - T_a}{T - T_a} \qquad (4)$$

The product ϵR is the ratio of the actual heat exchanged to the maximum heat that could be exchanged, which we regard as a constant characteristic of the fan-coil unit, even though ϵ is a ratio involving the two variables in our problem.

Combining equations (1), (2), (3) and (4), we have

$$M C_w \left(\frac{dT}{dt}\right) + N \dot{m}_w C_w \varepsilon R (T - T_a) = 0 \qquad (5)$$

which has the solution

$$(T - T_a) = (T_0 - T_a) \exp(-N \dot{m}_w \varepsilon R t / M) \qquad (6)$$

The above equation states that the temperature of the tank falls exponentially with time. Using the above equations, it is possible also to determine how the temperature of the hot air will change with time. Using equation (4), we see hot-air temperature T_{a2} will be given by

$$(T_{a2} - T_a) = \varepsilon (T_0 - T_a) \exp(-N \dot{m}_w \varepsilon R t / M) \qquad (7)$$

This equation shows that the hot-air temperature will also fall exponentially with time. Defining a parameter $a \equiv N \dot{m}_w \epsilon R / M$, and plotting the variation of the temperature of the tank and the hot-air temperature as a function of time, the graphs shown in figures 2 and 3 are obtained. Figure 2 provides the design data. Depending upon the temperature one would like to have after a certain length of time (at the end of an eight-hour shift, in this case), the value of a is fixed. Knowing $\dot{m}_w$, ϵ and R, one can then proceed to fix the capacity of the reservoir.

Table 1 sets out the observed performance of the fan-coil unit.

Assuming that the temperature required at the end of the second shift—after six hours of operation of the plant—is 65°F (18.3°C), one obtains a value of a of 0.150. With this value one can determine the

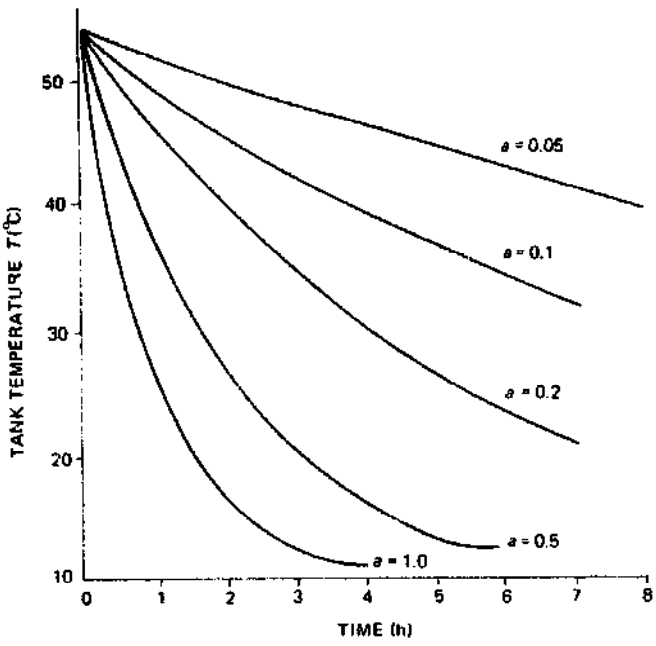


Figure 2. Variation of tank temperature over one radiation cycle with time for various values of a

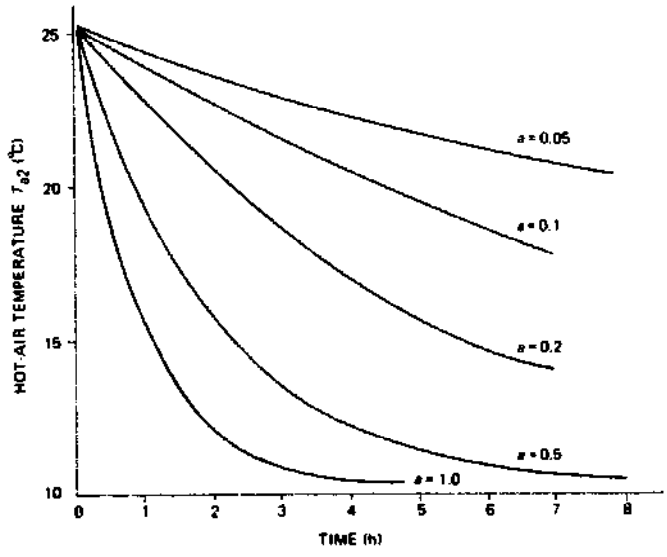


Figure 3. Variation of hot-air temperature over one radiation cycle with time for various values of a

storage tank capacity M. For $\dot{m}_w = 450$ kg/h (990 lb/h) and $\dot{m}_a = 408$ kg/h (900 lb/h), the value of M is 700 l per fan-coil unit. In this case the tank temperature and hot-air temperature will vary as follows:

$$(T - T_a) = (T_0 - T_a)\exp(-0.15\,t) \qquad (8)$$

and

$$(T_{a2} - T_a) = \varepsilon(T - T_a) \qquad (9)$$

These curves are shown in figure 4.

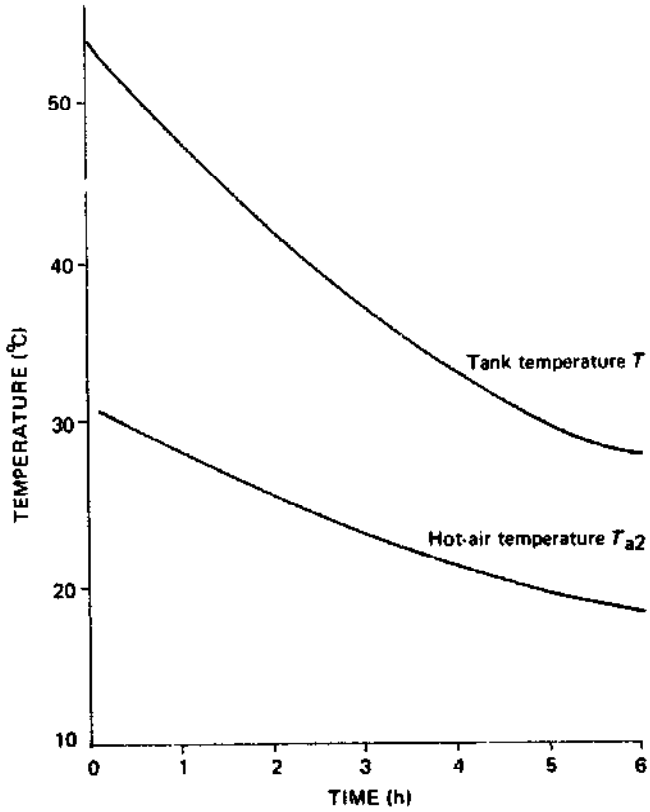


Figure 4. Variation of hot-water and hot-air temperature with time of utilization for $a = 0.15$

Thus, to obtain the required temperature at the end of the shift, the storage tank temperature at $t = 0$ of the radiation cycle has to be 130°F (54.4°C). Given these parameters, the collector area requirement can now be determined.

TABLE 1. PERFORMANCE OF THE FAN-COIL UNIT

Measurement number	Mass flow (kg/h)		Hot-water temperature (°C)	Fall in water temperature (°C)	Rise in air temperature (°C)	ϵ	R	ϵR
	Water	Air						
1	450	408	54.4	5.8	19.0	0.49	0.218	0.106
2	450	272	54.4	4.4	19.4	0.50	0.145	0.072
3	180	408	54.4	10.0	17.8	0.46	0.545	0.250
4	180	272	54.4	7.2	18.3	0.47	0.343	0.161
5[a]	450	408	60	4.7	20.3	0.45	0.218	0.098
6[a]	450	272	60	3.3	21.1	0.47	0.145	0.068

[a] Measurements taken in closed room.

Energy-collection cycle

During the energy-collection cycle, water from the storage tank is circulated through the collector array and hot water is stored in the tank. For given insulation H_f and heat-loss coefficient (U_L), it is possible to determine for a given flow rate the temperature of the tank as a function of time. It can be shown that under these conditions the tank temperature will vary as follows

$$(T - T_a) = \frac{H_f}{U_L}(1 - e^{-\gamma t}) + Pe^{-\beta t}$$

where

$$\gamma = \frac{N\dot{m}_w}{M}(1 - e^{-\beta_L})$$

and

$$P = (T - T_a) \text{ at } t = 0$$

In the above equation, β_L is a factor determined by H_f, U_L, specific heat etc. Since the insolation H_f is not constant throughout the day, this model is not physically realistic. However, there is another method to assess the area of the collectors.

The flat-plate collectors used by NPL in its experiments on space heating are the same as in the solar pump experiment (page 55). Figure 5 shows the efficiency of the collectors as a function of the collector temperature for various values of insolation. From these curves, it is possible to determine the efficiency of heat extraction at the required temperature (54.4°C) for various values of insolation. With that information and a knowledge of the diurnal variation of insolation, it is possible to determine the useful gain in thermal energy. Figure 6 shows the annual variation of daily useful gain in energy when heat is extracted at 60°C. From this curve, it is easy to determine the area of collectors required to provide 700 l of hot water per fan-coil unit.

System design parameters

Design parameters for providing comfort heating at 15 stations in the factory were as follows:

Ambient temperature	50°F (10°C)
Initial hot-water temperature	130°F (54.4°C)
Initial hot-air temperature	80°F (26.7°C)
Temperature of hot-air after 6 h	65°F (18.3°C)
Radiator specification	Fan-coil unit
Number of radiators N	15
Flow rate of water per radiator $\dot{m}_w$	990 lb/h (450 kg/h)
Flow rate of air $\dot{m}_a$	900 lb/h (408 kg/h)
Value of ϵ	0.49
Value of R	0.218
Value of α	0.15
Collector area	105 m²

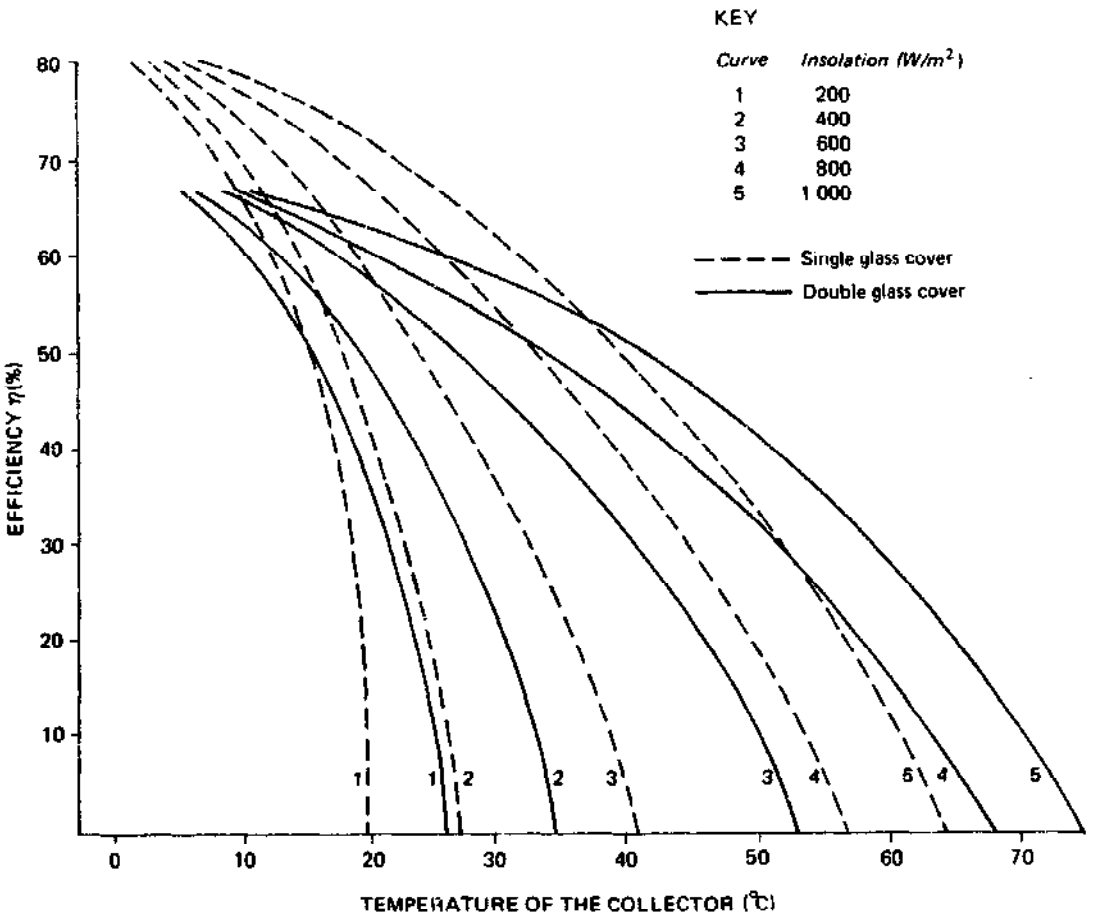


Figure 5. Variation of efficiency with collector temperature

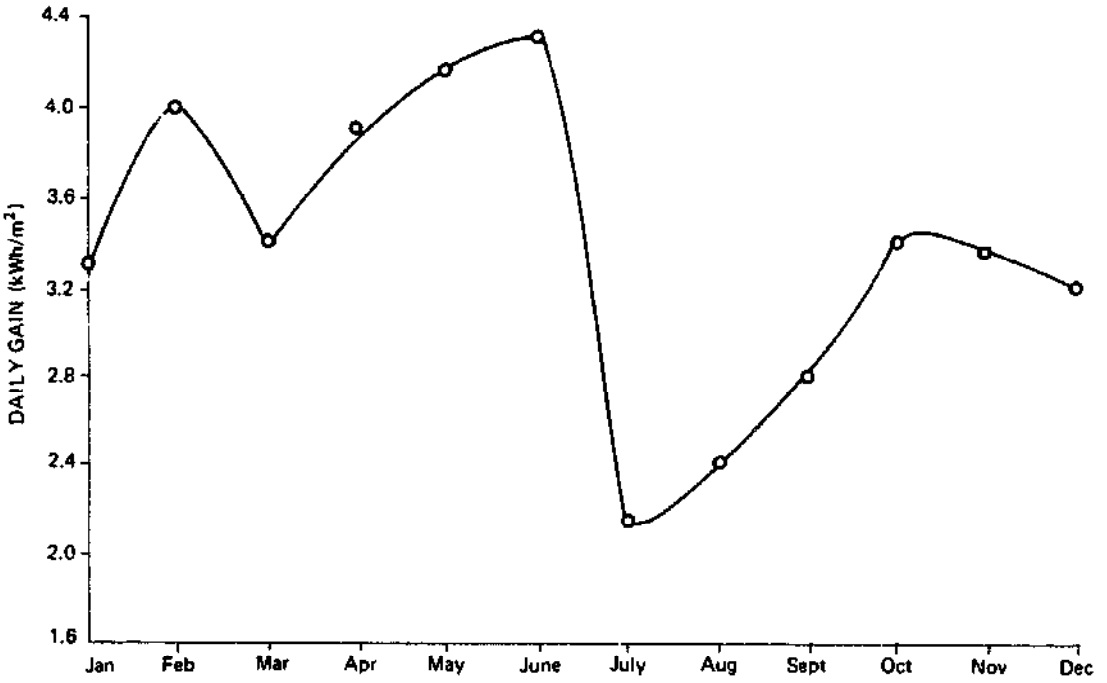


Figure 6. Annual variation of the daily useful gain in energy by a collector operating at 60°C

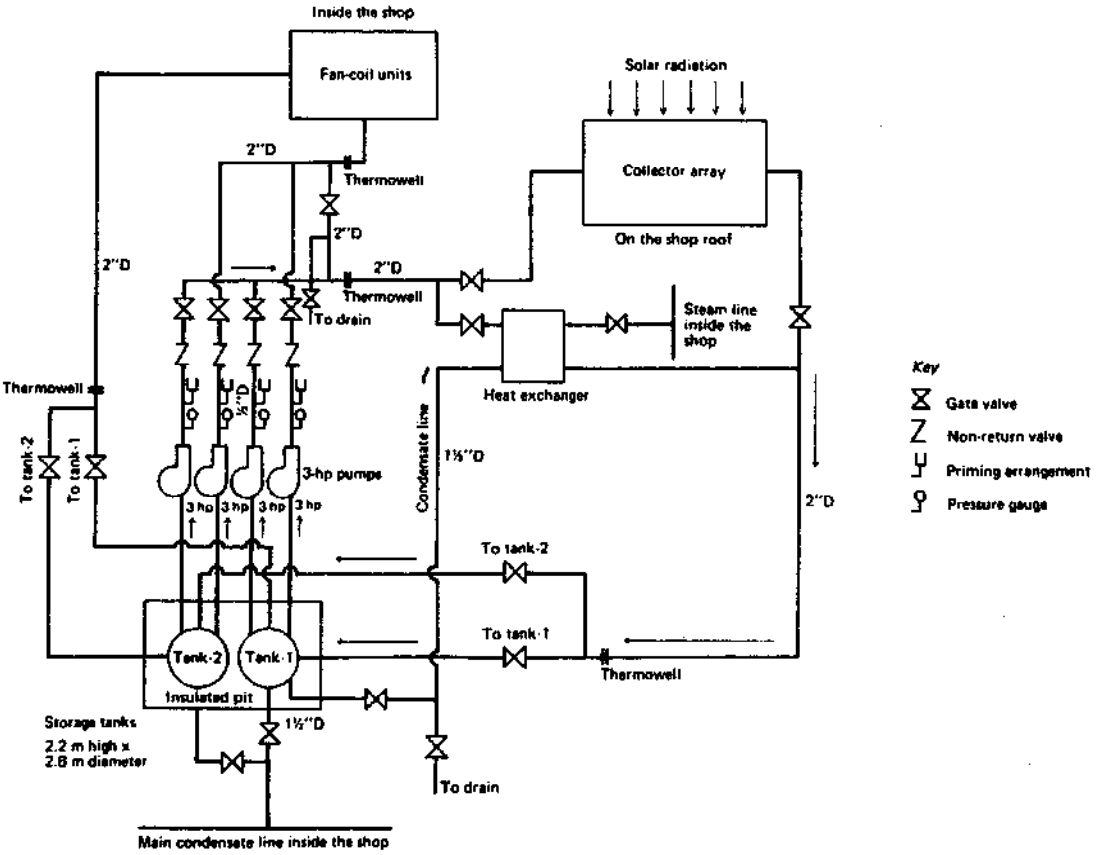


Figure 7. Solar space heating system at Haridwar; plumbing diagram

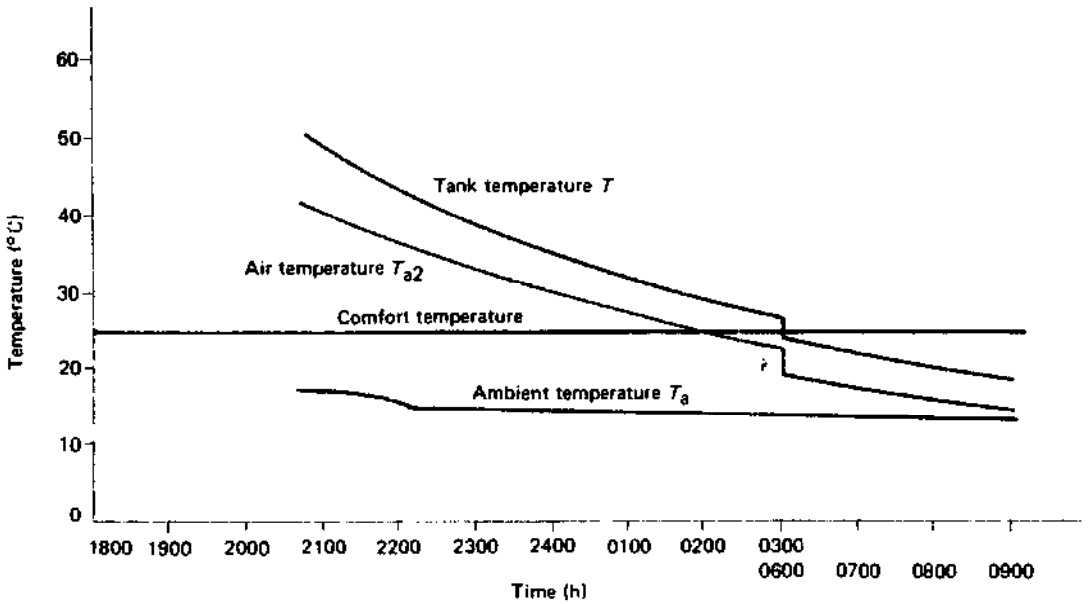


Figure 8. Radiation cycle at Haridwar, 6 February 1976

The plumbing of the whole system is shown in figure 7.

During the first 18 months of operation, the system has given very satisfactory performance. Actual performance characteristics on a typical day are shown in figure 8.

Combined space cooling and heating

Space heating cycle

Encouraged by the success in providing heating to workers in a factory, we started to design and install a combined heating and cooling facility in one room at NPL. The room was of the dimensions 6.1 m X 3.7 m X 3.0 m, with two doors (each 2.1 m X 1.2 m) and three windows (each 1 m^2). In designing the space heating system, it was assumed that the ambient temperature was 10°C, and that a temperature of 25°C was comfortable. In designing the space cooling system, it was thus assumed that the ambient temperature of 35°C was to be reduced to 25°C. It was calculated that approximately 9 430 MJ/h (2 250 kcal/h) needed to be supplied to the room during the heating cycle. The corresponding refrigeration required during summer months was nearly 12 600 MJ/h (3 000 kcal/h). The difference between the heat load and the refrigeration is due to the necessity to adjust for humidity during summer months.

The space heating system is based on figure 1 and consists of a collector array on top of the building, a small insulated storage tank, and a fan-coil unit. The fan-coil unit described earlier was used in the present experiment. The ϵ and R values calculated for this fan-coil unit were 0.49 and 0.218 respectively

In a typical experiment, hot water was passed through the fan-coil unit at 60°C at a rate of flow of 400 kg/h. The air flow rate was nearly 280 kg/h. This gave a rise in air temperature of about 21°C. The temperature of the water decreased to 54°C. Thus the loss of heat by water, equal to the heat supplied to the room, was 10 055 MJ/h (2 400 kcal/h). Thus, the area requirement of the collector array should be such as to provide 10 055 MJ/h (2 400 kcal/h) at 60°C. A thermostatically controlled bypass valve allows water to enter the storage tank only at 60°C. High-efficiency flat-plate collectors were used. The daily energy gain over a seven-hour period during the Delhi winter is as follows:

Month	*Energy gain (kWh/m²)*
November	3.5
December	3.1
January	3.3
February	4.0
Average	3.5

The average hourly energy gain was thus 0.5 kWh, or roughly 1 800 MJ $h^{-1} m^{-2}$. Thus, to obtain the required useful energy gain of nearly 9 430 MJ/h, 5 m^2 of collector area would be needed. The design parameters of the space heating system can be summarized as follows:

Collector area	5 m^2
Radiator specification	Fan-coil unit
Value of ϵ	0.49
Value of R	0.218
Rate of flow of water through collector	400 kg/h
Inlet temperature of water to the fan-coil unit	60°C
Rate of flow of air through the fan-coil unit	280 kg/h
Outlet temperature of water	54°C
Rise in temperature of air	21°C

The satisfactory performance of the heating system on a typical day is shown in figure 9.

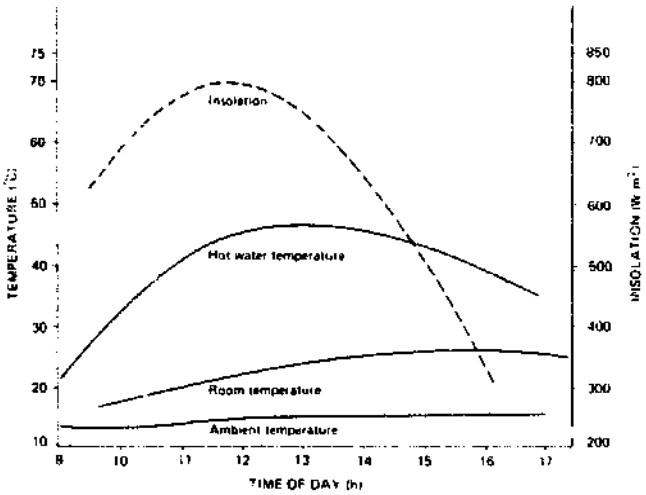


Figure 9. Performance of solar space heating system at NPL, 1 February 1977

Space cooling cycle

The space cooling cycle is more complicated and involved than the space heating cycle. There are essentially three approaches that can be taken to achieve cooling:

Dehumidification and evaporative cooling
Vapour compression
Vapour absorption

In the dehumidification and evaporative-cooling system, the room air is dehumidified by an absorbent; adiabatic evaporative cooling follows, with the solar desorption of the absorbent in a flat-plate collector open to the ambient air. This system is efficient at places where the humidity is very high, but rather inefficient where humidity is low. This system has the further drawback that it cannot be integrated with the heating system.

A vapour compression system is ruled out because it requires the use of a compressor.

In a solar cooling system, energy is available in the form of heat at temperatures of up to 100°C. This makes the vapour-absorption cycle the most appropriate.

The main components of a vapour-absorption cooling system are shown in figure 10. A refrigerant-solvent mixture is used in the vapour absorption cycle. This refrigerant-solvent mixture is heated in the generator by water, itself heated in solar collectors. The heating of the mixture in the generator releases refrigerant vapour, possibly mixed with small amounts of solvent vapour. This vapour mixture, together with a small amount of solution, enters the separator where the solvent vapour is condensed and separated out. The refrigerant vapour then enters the condenser where it is condensed into liquid. The condensed liquid passes through the throttle valve and is evaporated in the evaporator. Here it takes latent heat from the surrounding bath and delivers the required refrigeration. The vapour is carried from the evaporator by the carrier gas (usually hydrogen) to the absorber where the refrigerant vapour is again absorbed by the solution. The resultant solution goes from the absorber to the generator and the cycle repeats itself.

Particular care needs to be taken with the choice of the refrigerant-solvent combination and with the following operations: the flow of the solution from the absorber to the generator, the separation of the refrigerant vapour from the weak solution in the separator, the condensation of the refrigerant vapour into liquid, and the transmission of vapour from the

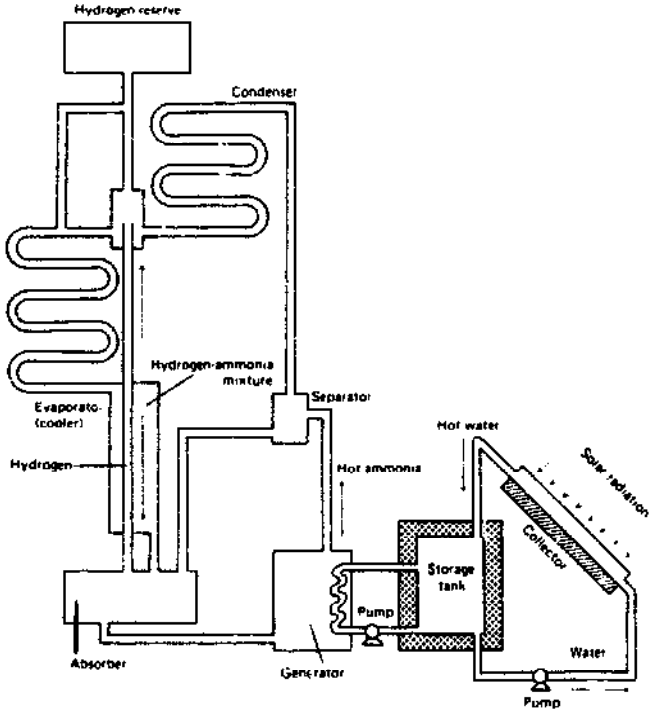


Figure 10. Solar space cooling system

evaporator to the absorber. The product of the separate efficiencies of these operations determines the system efficiency.

The refrigerant-solvent combinations that are commonly used are ammonia-water, water and lithium bromide, or fluoralkane-refrigerant/tetra-ethylene-glycol. The most important requirement of the refrigerant-solvent mixture is that the solvent should be able to absorb a large proportion of the refrigerant. For a given refrigeration to be delivered, the larger the concentration of the refrigerant in the solvent, the smaller the flow required from absorber to generator. It is well known that the higher the absorption of the refrigerant in the solvent, the higher the negative deviation from Raoult's Law; this also implies that there is increased binding between the refrigerant and solvent molecules. This increased binding would mean that the generator would need to produce more heat to vaporize the refrigerant. The most extensively used refrigerant-solvent combination is ammonia-water, which offers several advantages over the other combinations. The refrigeration capacity of ammonia is fairly high. The sort of temperatures obtainable using ammonia-water with flat-plate collectors are enough to operate the system. These and several other advantages prompted the selection of ammonia-water for the cooling system constructed at NPL.

Design constraints

As mentioned earlier, the heat load of the room was 12 600 MJ/h (3 000 kcal/h). The system was designed to deliver this refrigeration. The same fan-coil unit as was used in the heating cycle was used to provide cooling. Cold water was passed through the coil and air blown over it. The rate of flow of water through the coil was maintained at 400 kg/h, the same level as in the heating cycle. Cold water enters at 10°C and leaves at 18°C. The air-mass flow rate is 280 kg/h, with an air temperature of 35°C initially and 25°C after cooling. The change in relative humidity consequent on cooling of the air is accounted for.

In the vapour-absorption cycle, heat is absorbed at the generator and evaporator, and evolved at the absorber and condenser. The temperatures of these subsystems lead to other design constraints. In northern parts of India in summer months, cooling water is available at 30°C even during extreme conditions. Therefore, absorber and condenser temperatures of 30°C were chosen. Since the ammonia-water mixture is heated in the generator by hot water available from the solar collectors, the maximum temperature of water heated by solar means is another constraint. The maximum temperature was taken to be 90°C. Once the generator, condenser and absorber temperatures are fixed, the evaporator temperature is automatically fixed by the system. In this system the evaporator temperature will be 10°C.

Design parameters

The system provided is shown in figure 11. Water heated by solar energy is stored in an insulated tank at a temperature of 92°C. This is achieved by putting a thermostatically controlled bypass valve in the

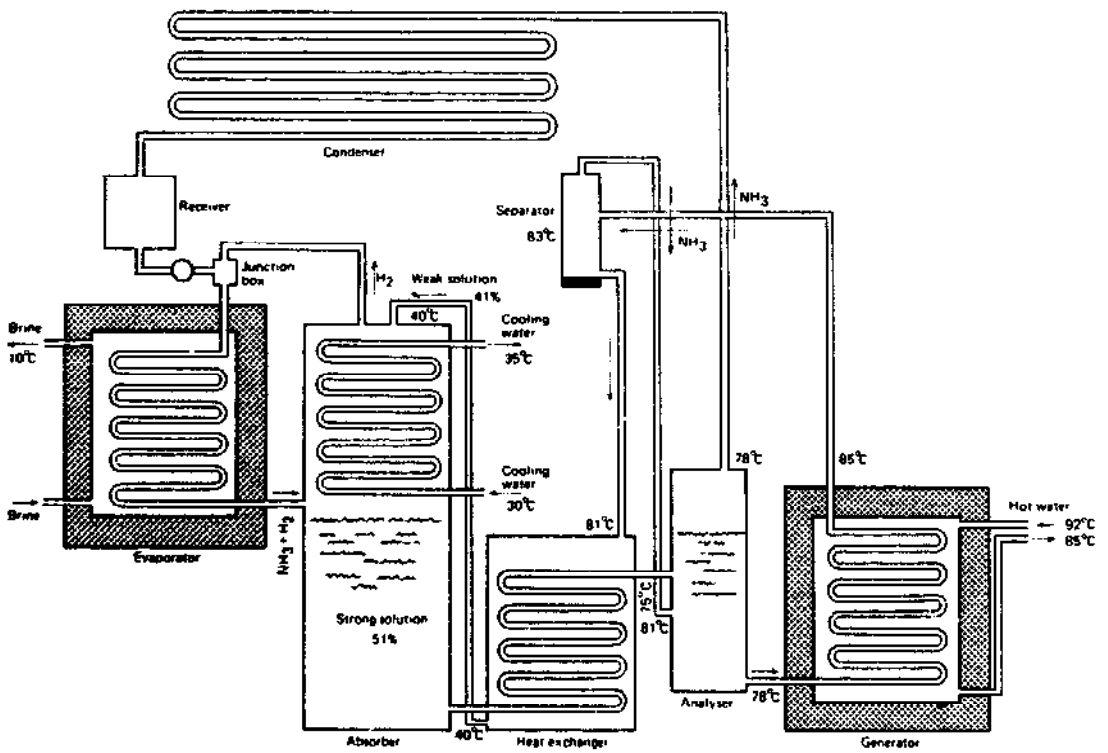


Figure 11. Solar energy cooling system

collector circuit. This hot water is then supplied to the generator. Hot water enters at the top and leaves at the lower exit at 85°C. The rate of flow is maintained at 5 l/min. The coil in the generator contains a strong ammonia-water mixture. The rate of flow of the ammonia-water mixture (51% ammonia) is 2 kg/min. In the generator, 0.2 kg/min of ammonia gas is liberated, and this gas, together with 1.8 kg of the solution (41%, or 0.82 kg of ammonia), enters the separator at 85°C. The weak ammonia solution drains from the bottom of the separator to the heat exchanger. Ammonia gas (0.2 kg/min) from the separator enters at the middle level of the analyser, which contains a strong solution of ammonia liquor. In the analyser, any trace of water vapour in the ammonia gas is filtered out. The dehydrated ammonia vapour leaves the analyser at a temperature of 78°C (and a rate of roughly 0.2 kg/min) and enters the condenser. The condenser is cooled by cold water at 30°C, and the ammonia gas condenses roughly at 35°C. During the process of condensation 242 000 MJ/min (57 700 kcal/min) of heat is removed by the cold water in the condenser. The liquid ammonia flows from the condenser to the receiver. The liquid ammonia is then throttled through a valve and the throttled liquid mixed with hydrogen in the junction box. The hydrogen-ammonia mixture enters the evaporator where the ammonia evaporates. The ammonia-gas/hydrogen mixture is heavier and therefore flows down into the absorber at the central inlet. The absorber is cooled by water at 30°C. The incoming ammonia mixes with the solution, and the concentrated solution (51% ammonia) collects at the bottom of the absorber. This strong solution enters the heat exchanger, where it exchanges heat with the weaker solution that came from the separator at 81°C. As a result of this heat exchange, the temperature of the strong solution rises to 75°C; the strong solution enters the analyser, and an equal amount of solution is transferred from the analyser to the generator to repeat the cycle. The entire system is kept at a pressure of 12.1 bar (175 psia). Hydrogen acts as a carrier gas and helps to move ammonia vapour from the evaporator to the absorber and also to reduce the partial pressure of ammonia to 5.2 bar (75 psia). It is because of this reduction in partial pressure that the boiling point of ammonia in the evaporator coil is about 5°C.

Five litres of water at 90°C needs to be passed through the generator per minute. This determines the collector area requirement. In the space cooling system, the demand for refrigeration is in phase with the insolation.

The daily energy gain over a seven-hour period during the summer is as follows:

Month	*Energy gain (kWh/m^2)*
April	3.0
May	3.4
June	3.8
Average	3.4

The average hourly gain in useful energy is thus roughly 0.5 kWh/m^2. On this basis one would need 7 m^2 of the collector array to produce the required cooling. Thus, the collector array needed is approximately the same for both the space heating and cooling cycles. The fan-coil unit is also a common feature of both the cycles. Such a combined space heating and cooling system is under trial. The heating cycle has been tested successfully and it is hoped that the cooling cycle can soon be tested successfully.

Preliminary design data for a solar house in Riyadh

A. A. M. Sayigh and E. M. A. El-Salam

College of Engineering, Riyadh, Saudi Arabia

One of the major applications of solar energy is in the home. The heating and cooling of houses and the use of household appliances accounts for over 20% of all the energy consumed in Europe, Japan and the United States[1] and for about 50% of the total energy consumption in the developing countries. The need for solar houses is the greatest in the developing countries, mainly to save energy for other more vital purposes.

Since Saudi Arabia is the richest country in the world with regard to solar energy availability,[2] designing and building solar houses in this country would not only save energy on the national scale but mean that houses could be built in remote areas of the country where the conventional forms of energy do not exist or are not economic. Therefore a study was carried out to find the best means of building solar houses in the Riyadh area. It dealt with building materials, air-conditioning systems, electricity generation and costs. The findings are discussed below.

Riyadh is almost in the middle of the country at latitude 24° 42′ N and longitude 46° 43′ E. It is about 600 m above sea level and has a population of roughly three quarters of a million. It has little rainfall per year (about 50 mm), and the annual mean relative humidity is 30%. Figure 1 shows the mean maximum and mean minimum temperatures and the total insolation at Riyadh[3] and the months in which heating or cooling is required. In summer electricity consumption increases owing to the cooling load while in winter gas consumption increases owing to the heating laod.

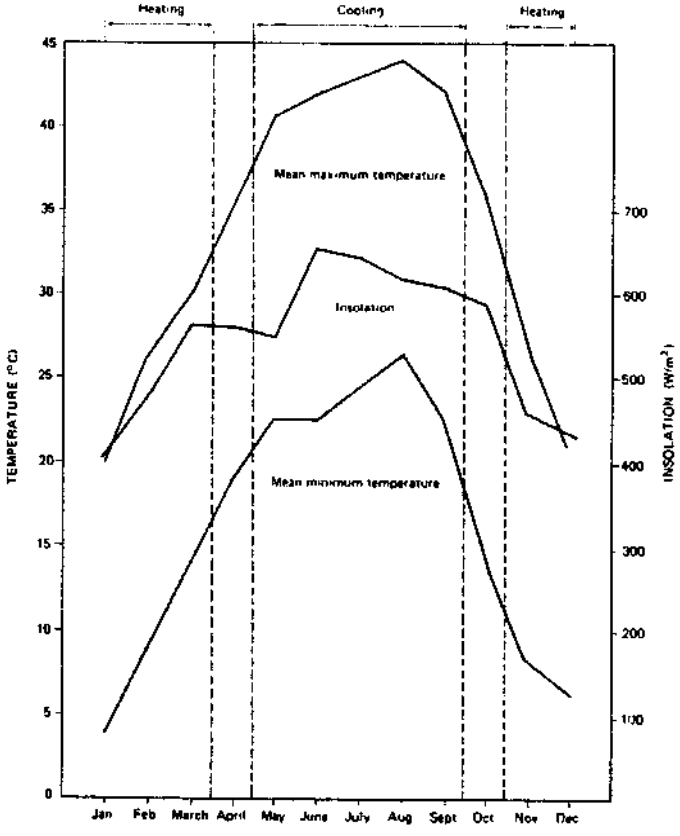


Figure 1. Heating and cooling seasons at Riyadh

Building materials

Several local building materials were tested for their strength and suitability for the solar house – clay bricks with and without straw, clay bricks baked at 1 000°C and partially hollow cement blocks. Tables 1-3 show the properties of such materials.

[1] C. A. Berg, "A tec nical basis for energy conservation", *American Society of Mechanical Engineers. Quarterly Transactions*, vol. 98, No. 5 (May 1974), pp. 30-42.

[2] A. A. M. Sayigh, "Saudi Arabia and its energy resources", Paper prepared for the International Solar Energy Conference, COMPLES, University of Petroleum and Minerals, Dhahran, 1-5 November 1975; "The energy prospects in the Arab World", Paper prepared for the International Conference in Mechanical Engineering, University of Engineering and Technology, Lahore, Pakistan, 6-11 October 1975.

[3] J. A. Sabbagh, A. A. M. Sayigh and E. M. A. El-Salam, "Estimation of the total solar radiation from meteorological data", Paper prepared for the ISES Conference, Los Angeles, 28 July-1 August 1975.

TABLE 1. PROPERTIES OF BRICKS MADE OF NASIRIA CLAY (SAMPLE A)

Number	Type of sample[a]	Weight (kg)	Dimensions (cm)	Cross-sectional area (cm^2)	Ultimate crushing load (kg)	Compressive strength (kg/cm^2)	Water content (wt%)
1	Cube without straw	5.119	14.5 X 14.3	207.35	3 700	17.84	2.85
2	Cube with straw	4.503	14.8 X 14.0	207.2	920	4.44	2.61
3	Cylinder with straw	6.672	15.0 diam.	176.63	570	3.22	3.34
4	Cylinder with straw	6.519	15.0 diam.	176.63	1 480	8.37	3.4
5	Cylinder without straw	7.895	14.5 diam.	165.05	700	4.24	5.47

[a]The mixing proportions, taken from an old formula used in building Riyadh houses in the past, were (wt%): *(a)* with straw: clay, 73.4; water, 25.5; straw, 1.1; *(b)* without straw: clay, 77.5; water, 22.5.

TABLE 2. PROPERTIES OF BRICKS MADE OF OLD MANFOHA CLAY (SAMPLE B)

Number	Type of sample	Weight (kg)	Dimensions (cm)	Cross-sectional area (cm^2)	Ultimate crushing load (kg)	Compressive strength (kg/cm^2)	Water content (wt%)
1	Cube without straw	4.465	13.8 X 13.6	187.68	4 920	27.03	2.82
2	Cube with straw	4.261	14.2 X 14.00	198.8	1 820	9.154	2.77
3	Cylinder without straw	6.976	13.9 diam.	151.67	2 570	16.94	2.81
4	Cylinder with straw	6.315	14.5 diam.	165.05	770	4.66	2.9
5	Cylinder with straw	6.155	14.5 diam.	165.05	630	3.82	2.9

TABLE 3. PROPERTIES OF SAMPLE C (CLAY BAKED AT 1 000°C) AND SAMPLE D (HOLLOW CEMENT BLOCK)

Sample	Type of sample	Weight (kg)	Dimensions (cm)	Cross-sectional area (cm^2)	Ultimate crushing load (kg)	Compressive strength (kg/cm^2)	Water content (wt%)
C	Cube	0.372	6 X 5.8 X 5.9	34.8	4 200	120	0.0
D	Block	23.25	40 X 20 X 20	800	18 160	22.7	0.0

Several building materials surfaces were exposed to solar radiation all day, and their temperatures were recorded as shown in figure 2. The emissivity and absorptivity for such materials were obtained experimentally as shown in table 4.

TABLE 4. EMISSIVITY AND ABSORPTIVITY OF VARIOUS BUILDING MATERIALS

Building material	Emissivity	Absorptivity
Fire-bricks at 1 000°C	0.75	0.75
Clay bricks	0.67	0.65
Cement blocks	0.90	0.90
Roof tiles	0.9	0.9

To test for the effects of rain and erosion on building materials, water was dripped continuously for a day on all samples. Also, the samples were blasted for a day with dry sand from a sand-blasting machine at moderate speed (30 km/h). The effects are shown in table 5.

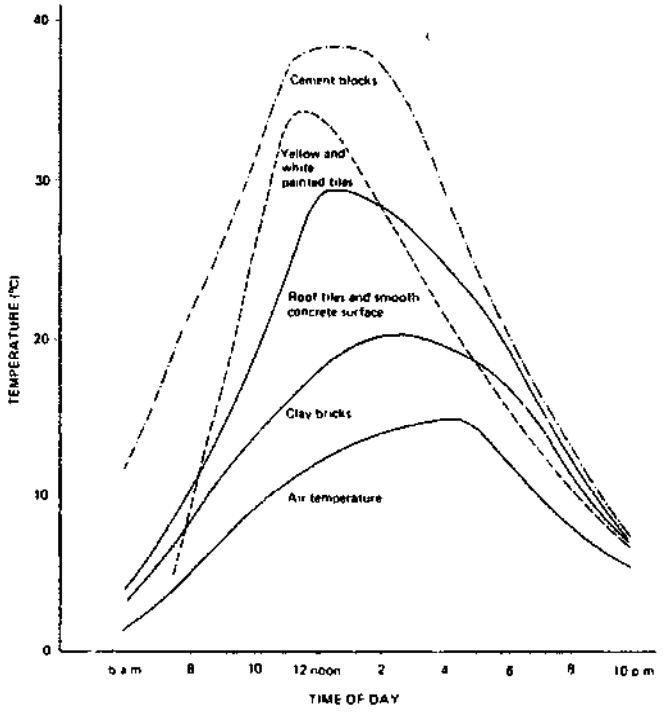


Figure 2. Surface temperatures for various building materials

TABLE 5. EFFECTS OF RAIN AND EROSION ON BUILDING MATERIALS

Sample	*Amount of rain absorbed*	*Erosion*
A		
With straw	Fair	Little
Without straw	Sizeable (disintegrated)	Little
B		
With straw	Fair	Little
Without straw	Sizeable	Little
C	None	None
D	Very little	None

Air-conditioning systems

Of all the uses to which solar energy might be put in tropical countries that of heating and cooling is the most feasible. During the summer, solar radiation is intense and it can be utilized for cooling; in winter, a system of flat-plate collectors can provide more heat than is actually needed.

Cooling

Several kinds of cooling system have been tried. A 3-ton lithium bromide absorption cooling unit was used by Ward and Löf[4] in their residential system. The unit was modified to utilize hot water instead of natural gas as the source of heat supplied to the generator. The ammonia-water absorption system was used for cooling in a California (United States) project.[5] Numerous papers describing other projects can be found in the literature.[6]

Night cooling was studied by measuring the temperature of different surfaces at night as shown in figures 3 and 4. Jones[7] suggests that for comfort the

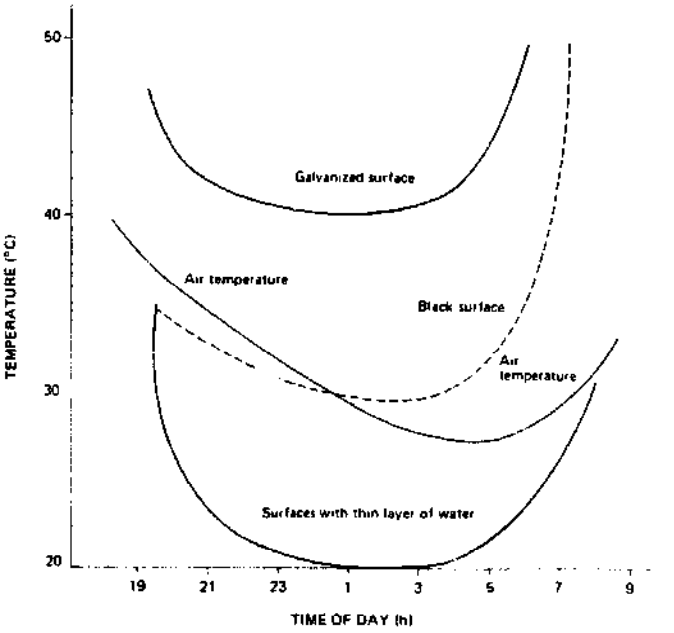


Figure 3. Temperatures of various surfaces during the night of 18 June 1975

[4] D. S. Ward and G. O. G. Löf, "Design and construction of a residential solar heating and cooling system", *Solar Energy*, vol. 17, No. 1 (1975), pp. 13-20.

[5] University of California, Lawrence Berkely Laboratory, *Control System for Combined Solar Heating and Cooling Systems*, Progress Report No. 1, January 1975.

[6] For example, R. L. Oonk, W. A. Beckman and J. A. Duffie, "Modeling of the CSU heating/cooling system", *Solar Energy*, vol. 17, No. 1 (1975), pp. 21-28; G. O. G. Löf and R. A. Tybout, "The design and cost of optimized systems of residential heating and cooling by solar energy", *Solar Energy*, vol. 16, No. 1 (1974), pp. 9-18.

[7] W. P. Jones, *Air Conditioning Engineering*, 2nd ed., Arnold, 1973.

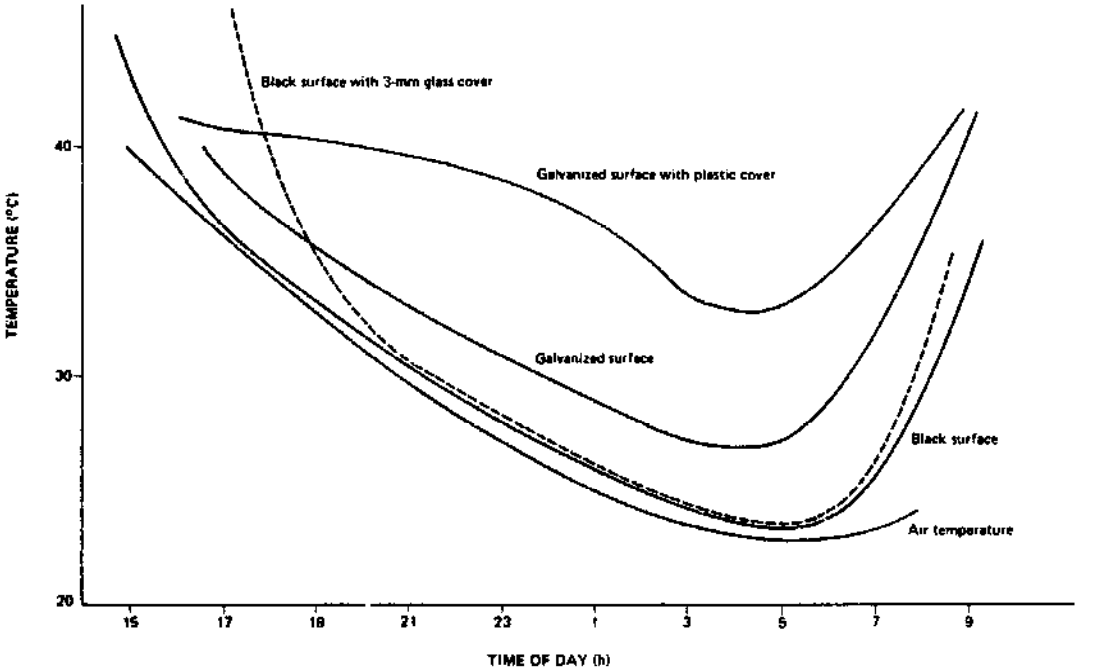


Figure 4. Temperatures of various surfaces during the night of 2 September 1975

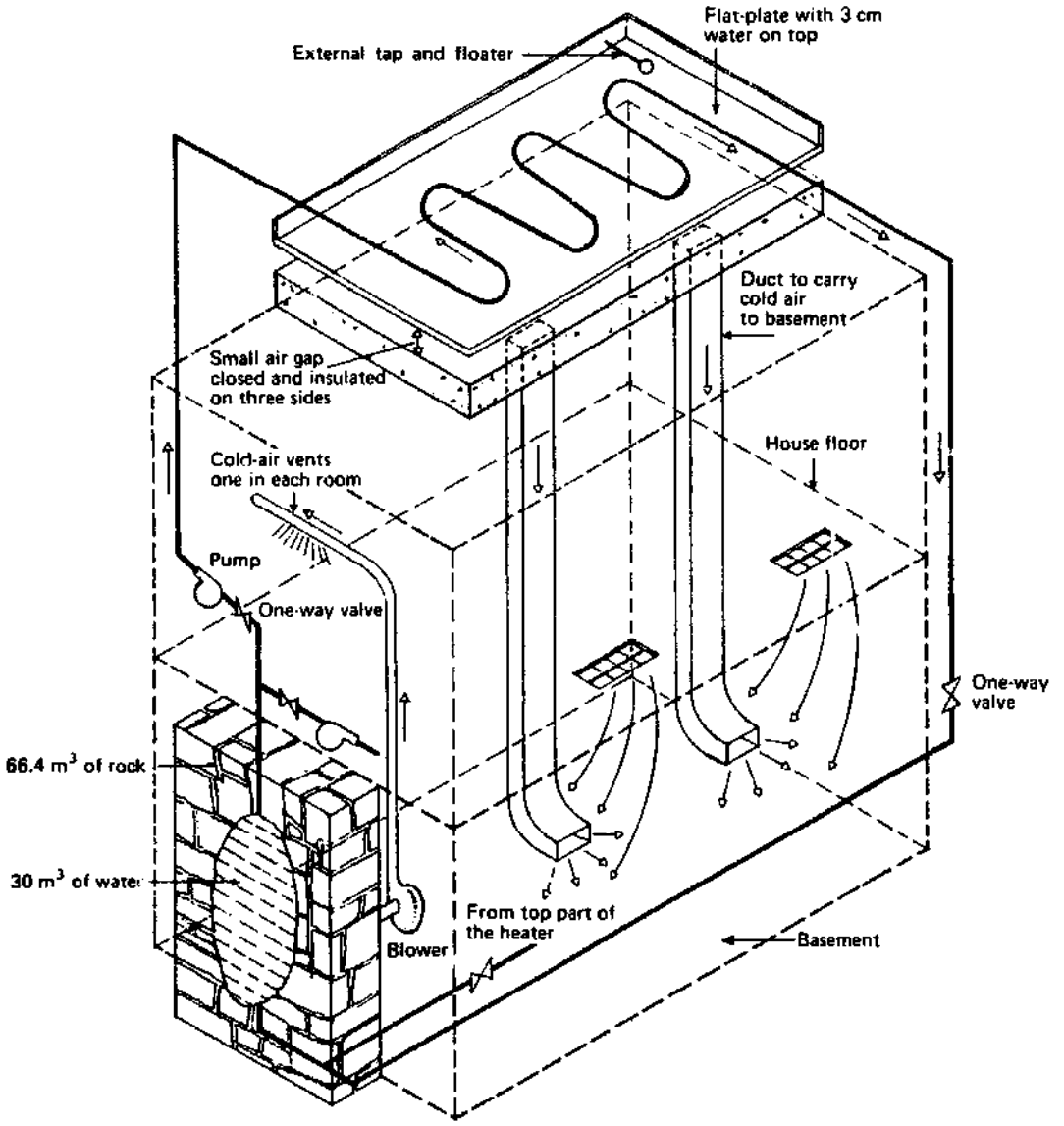


Figure 5. Night cooling system

indoor temperatures should be lower than the outdoor temperature by 4°-11°C, with a relative humidity of about 50%. The best combination for night cooling is that of using surfaces with a thin layer (2-5 cm) of water as shown in figure 3. In this method an average temperature of 10°C below ambient temperature was recorded for seven hours during the night. Bahadori[8] reported that by circulating the outside air in Shiraz for two hours at night (2 a.m.-4 a.m.) at an average velocity of 9.1 m/min through a bed of rock having a volume of 39.4 m^3 the rock could attain the average minimum air temperature, which was about 17.8°C. Using the minimum temperature in the collector with a layer of water in Riyadh, which is 20°C during the summer, and if the rate of flow is 10 m/min, a rock pile of 160 m^3 can be cooled to this temperature during the night. If the heat is stored partly in water and partly in rock, and if the water tank has a capacity of 30 m^3, then 66.4 m^3 of rock will be required as extra storage.

The proposed house has a 100-m^2 ground area and a height of 3 m. It consists of two rooms besides a bathroom, a kitchen, an attic and a basement 3 m deep under the entire house.

If the outside and inside design conditions, the kind of structure, the doors and windows, the lighting and other equipment inside the house, the number of occupants and the ventilation requirements are taken into consideration, the cooling load needed for such a house will be 3 refrigeration tons (10.56 kW). In the Riyadh area this represents an extraction rate of about 40 W/m^3 at peak load. After 10 hours of operation, the total energy dissipated is 3.3×10^8 J for an average rate of 9 kW. From these data, it can be calculated that the temperature in the house will be 21.56°C, i.e., a rise of 1.56°C, which is tolerable.

Figure 5 illustrates the night cooling system.

[8] M. N. Bahadori, "A feasibility study of solar heating in Iran", *Solar Energy*, vol. 15, No. 1 (May 1973).

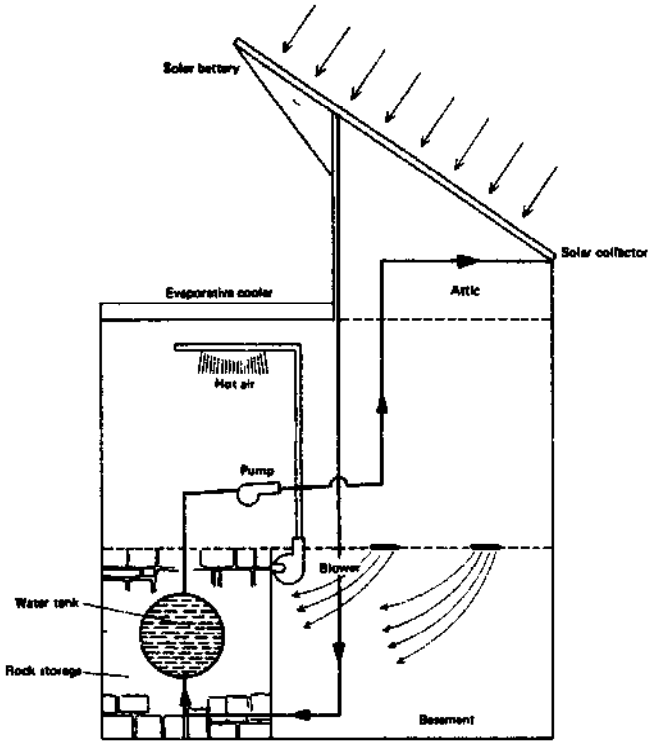


Figure 6. Solar heating system

Heating

A good storage material *(a)* has a high heat capacity; *(b)* is highly kinetic, i.e., heat can be rapidly extracted from it: *(c)* does not freeze; and *(d)* does not corrode or rust the containers in which it is stored.

Heat can be stored in the form of:

(a) Sensible heat in a liquid or solid. Examples are: water, providing that the temperature remains between 0° and 100°C; rock, which is inexpensive but has only one fourth the specific heat of water and hence requires a mass of rock four times the mass of water for the same storage capacity; C_{15} wax, which with a melting point of 5°-10°C and a heat capacity 28 times that of an equal volume of water, can be used as storage in a cooling system;

(b) The latent heat of melting, such as that of an inexpensive solution of salt in water. A major disadvantage is the occurrence of stratification effects in melting and freezing;

(c) The heat of a solid phase transition, such as in vanadium oxide or ferric sulphide. In the latter, the transition takes place at 138°C; storage capacity is 230 kJ/l;

(d) The heat of a reversible reaction, such as in the two-chamber system with sulphuric acid at a weak concentration in one chamber and strong in the other. Use is made of reversible reactions between the acid and water to store and regain heat.

Figure 6 illustrates the solar heating system, which uses water and rock for sensible heat storage and a solar battery to generate electricity.

Electricity generation

The electrical power load for the house, taking into consideration all needs of electrical appliances, lighting, water pumps and blowers was estimated at 1 kW. The solar power supply equipment (solar battery, storage battery, control box and inverter) was designed to meet this need. The following design factors were used:

Average number of hours of sunshine per day	10
Sunshine ratio = (fraction of time sun shines) × (incident angle factor)	0.2
Storage-battery efficiency	0.834
Inverter efficiency	0.65
General loss factor	0.9

Four 24-V silicon solar-battery arrays, each with a power output of 89 W, were used in parallel. The area of each array was about 3 m^2; they were

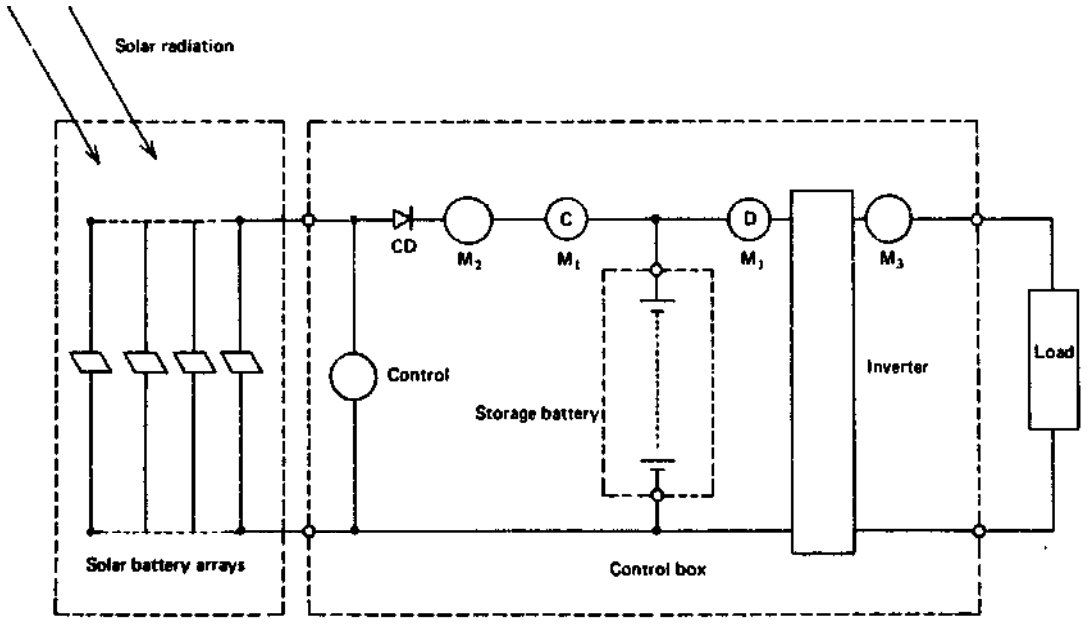


Figure 7. Diagram of the solar-battery power supply; CD is a diode for blocking reverse current, and M_1, M_2 and M_3 are volt-ammeters for measuring charging and discharging currents, terminal voltages etc.

mounted on the top of the house facing south, with a tilt of 35° from the horizontal. The storage battery used was a 24-V sealed lead-acid storage battery with a capacity of 12 kWh. The inverter produced single-phase, 50-Hz alternating current at 110-120 V and was rated at 500 VA.

A diagram of the solar-battery power supply is shown in figure 7. When the sun shines, the output current passes through the diode to charge the storage battery and drive the inverter. The blocking diode prevents the storage battery current from being returned and consumed by the solar batteries when they are not receiving solar energy at night or in bad weather.

Cost analysis

A solar house still costs more than a conventional house, mainly because of the high cost of the electrical energy required in a solar house. Costs for a solar house are given below (thousand Saudi riyals):[9]

Building materials and construction	50
Heating and cooling system (night cooling)	20
Storage and light fittings	10
Electric power generation	140
Total cost, excluding the land	220

A conventional house would cost about SRIs 100,000. The cost of solar and conventional heating and cooling equipment is almost the same. This finding is corroborated by other investigators.[10]

[9] $1 = SRIs 3.5.

[10] R. K. Swartman, V. Ha and C. Swaminathan, "Comparison of ammonia-water and ammonia-sodium thiocynate in a solar refrigeration system", Coopération mediterranéenne pour l'énergie Solaire (COMPLES), first semester 1974.

Conclusions

A study of all the parameters for designing a solar house in Saudi Arabia indicates that construction of such a house is not only feasible but practical. Of the various building materials shown in tables 1-5, the best combination is sample C. The wall should be 40 cm thick, with bricks 10 cm thick on the outside and inside and a 20-cm foam-filled cavity between them. The cooling system may be either the night-cooling system of figure 5 or a solar-operated lithium-bromide/water absorption air-conditioning system.[11] To use night cooling or evaporative cooling, the amount of water evaporated per day must be estimated because of the water shortage in Riyadh. The average pan evaporation during June, one of the hottest months in Riyadh, is 300 mm,[12] an average rate of 1 cm per day. The area of the pan is 50 m^2. Therefore, the amount of water lost through evaporation per day will be 0.5 m^3. As for heating, several flat-plate collectors covering an area of 80 m^2 with selective surfaces are suggested. The amount of solar energy that can be used for heating during January was calculated to be 59×10^8 J per day. This can raise the house temperature by 5°C during the day. As for the solar battery, it can be utilized for heating, which will result in an additional energy gain of about 8×10^8 J per day. As for the cost analysis, the major cost is due to the solar battery. Apart from this, the costs of a solar house and a conventional house are about equal. Using solar heating and cooling will result in a saving of about SRIs 14 per day.

[11] J. A. Duffie and W. A. Beckman, *Solar Energy Thermal Processes* 1st ed. (New York, Wiley Interscience, 1974).

[12] Raikes and Partners, "Hydrological service for the period 1 August 1968 to 31 August 1970", Report prepared for the Ministry of Agriculture and Water, Saudi Arabia.

Solar refrigeration in developing countries

A. Eggers-Lura

International Solar Power Co. Ltd., Gentofte, Denmark

Solar refrigeration technologies that may be applied economically in developing countries must meet the following requirements:

(a) The refrigeration equipment must be simple and cheap, so that it can be manufactured in developing countries using materials and working skills available in those countries;

(b) The equipment must be socially acceptable to the population and conform with their living and working habits;

(c) No auxiliary power or equipment should be required.

Most of the basic research on solar refrigeration took place in the 1950s and was reported on at the United Nations Conference on New Sources of Energy in Rome in 1961. Then research virtually came to a standstill, and only since the "energy crisis" has it been actively resumed. However, from the work that has already been undertaken, it is fairly easy to conclude which of the technologies available at present would be suitable or economical for application in the developing countries.

Only two refrigeration technologies can be chosen at present for application in the developing countries: evaporative cooling and the intermittent absorption refrigeration process. All other refrigeration processes are either too complicated or too costly to be considered. The continuous absorption refrigeration process requires too high working temperatures and therefore the use of concentrating collectors, which are too expensive to build and too complicated to operate.

Evaporative cooling

The evaporative food cooler, in principle, consists of a container surrounded by a suitably shaped piece of cloth, the lower part of which is submerged in a tray containing water. The water is absorbed by the cloth, and through capillary action it acts like a wick, the water moistening most or all of the cloth. If the climate is dry and the cooler is kept in a breezy spot in the shade, the food will be cooled, as the water evaporates, to a temperature that lies considerably below ambient.

Three simple types of evaporative food coolers that could be constructed cheaply—perhaps even mass-produced—from materials available in almost any developing country are described below. To introduce such food coolers on a large scale in rural villages in developing countries would, more than anything else, entail education of the population on how to build and utilize them.

Basket coolers

A basket with a loose fitting cover is woven from bamboo or other slender elastic wooden branches. The size depends on the needs of the family. A square or round pan, of earthenware or metal, is made in which the basket can be placed. The bottom part of a clean oil drum may be used. The pan should be 25-30 cm high and wider than the basket. The pan is placed in a cool, shady place in the kitchen, away from the stove, and with a regular breeze. A number of bricks or flat stones are placed in the pan so that the basket can balance evenly on them.

Burlap, of the soft type, or other suitable fabric, is sewn around the rim of the basket. It must hang loosely around the bottom and extend into the pan. Likewise, burlap is sewn loosely over the cover of the basket. Then, the basket is placed on the bricks, food put into it, and the cover placed on top of it. The bottom of the pan is filled with water, and the burlap cover of the basket is wetted with water the first time the basket is used, and occasionally thereafter.

The basket itself should not be in the water, but the burlap should hang down in the water. The burlap acts like a wick, and through capillary action the water wets the burlap. As the water evaporates, the food is cooled. An added advantage of this cooler construction is that it keeps flying insects away from the food, and cockroaches and other crawling insects cannot enter the food through the water.

Cupboard coolers

Utilizing the same cooling technology as the basket cooler, a large cupboard type of evaporative food cooler may be constructed. A wooden frame is nailed or screwed together and placed in a pan of water. A pan of water may also be placed on top of the frame. A hinged, framed door may be arranged to allow easy access to the food, which is placed inside on wire-mesh shelves. The frame is covered with burlap or other suitable fabric, and part of the burlap is immersed in the top and bottom pans, which are filled with water.

Jar coolers

Evaporative coolers may be manufactured entirely from earthenware, in the form of jars or jugs, a system that has been used for hundreds of years in Asia for cooling drinking and bathing water. Such coolers are ubiquitous in the villages of Burma, China, Democratic Kampuchea, Indonesia, Malaysia, Philippines, Thailand and Viet Nam. Until the Second World War, small earthenware evaporative coolers were used extensively in Europe to cool butter and cheese.

Intermittent absorption refrigeration

While evaporative cooling is suitable only for small domestic coolers, the intermittent absorption refrigeration process may be applied both in individual domestic households and on a community basis. This process has the advantage that the generating and absorption cycles follow the solar cycle.

Intermittent absorption refrigeration equipment is somewhat more complicated and expensive than evaporative coolers. Therefore it is necessary to determine whether the refrigeration equipment in the rural villages should be used on an individual or on a communal basis.

For a start, it may be preferable to concentrate on plant and equipment that can be used communally, because it would be easier to educate a few technically minded persons to operate a collectively owned plant than a large number of individual household members. If the plant produced block ice, and if each household had an insulated ice box for food storage, some member of the household could fetch a portion of ice every day from the community plant and place it in the box. It would probably be possible to find local entrepreneurs, for example storekeepers, who could organize the production, sale and distribution of the ice, possibly with some sort of government support.

It is, however, also possible to construct small, simple, and cheap intermittent absorption refrigerators for individual households, but for most areas they would likely prove to be too costly at present.

Both small and large intermittent absorption refrigerators can be powered by a flat-plate collector, perhaps with slight concentration added in the form of flat metal mirrors.

Individual refrigerators

For the individual household absorption refrigerator, the type to be considered would be the "icy-ball", a 1920 invention that uses water as an absorbent and ammonia as a refrigerant and may be heated by kerosene, paraffin, gas, or even firewood. Icy-balls were used extensively in Canada and the United States and in Europe between the First and Second World Wars. With the advent of the electric compressor refrigerator use gradually dwindled. Very few of these refrigerators are still in existence today. There are six in the United States but only two of them are still in working order. A United States firm is resuming production of an icy-ball type of refrigerator.

The icy-ball was cheap and simple. It consisted of a generator-absorber connected with a pipe to a condenser-evaporator. In the generator-absorber there was a mixture of water and ammonia. It was heated by some means, and at the same time the condenser-evaporator was immersed in cold water. When all the ammonia had been boiled out of the water, which took 1-2 hours, the cycle was reversed. The condenser-evaporator was placed in an insulated refrigerator box, the generator-absorber was cooled by the air, and during the next 24-36 hours the ammonia would flow back from the condenser-evaporator into the generator-absorber, at the same time producing cold in the refrigerator. There was only one drawback. During the boiling out of the ammonia, some water vapours were carried over simultaneously to the condenser-evaporator, reducing the efficiency of the process.

Chung and Duffie suggest that by redesigning the icy-ball slightly it may be driven by solar energy and preliminary experiments have shown that it is feasible to do so.

In 1957, the Wisconsin group (Duffie, Löf, Williams and Chung) reported on experiments they had undertaken with an icy-ball type of domestic refrigerator. The generator was heated for about 2 hours in the focus of a small parabolic reflector, whereafter the unit was transferred to a "refrigeration box", which remained cool for about 24 hours. Apparently, no further work has been done on this project.

It should be fairly easy, by obtaining one of the icy-ball units that remain and studying the available literature, to begin manufacture of a simple and cheap icy-ball type of domestic refrigerator, powered by the sun, which can be used for individual

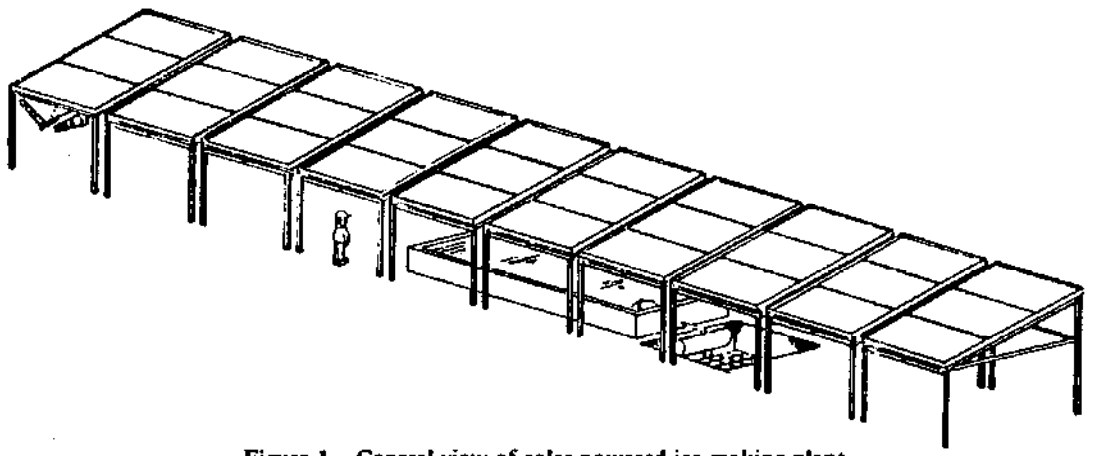


Figure 1. General view of solar-powered ice-making plant

households in the developing countries. There would be an immense market for them. The generator should probably be constructed in such a way that it can also be heated by a fossil fuel when there is no sunshine. In the case of solar generation, a flat-plate collector with slight mirror concentration or, alternatively, a cylindrical concentrating collector with a pipe-shaped generator placed in the focal line should be used.

Communal refrigeration plants

A communal solar refrigeration plant could be either a cold-storage building in which the inhabitants of a village store their food on shelves, each family being allocated a small volume of storage space, or a plant producing block ice for ice boxes in individual households. A suitable plant for a village should be able to produce, on the average, 500 kg of ice per day. A plant of that size has been designed by the author. It uses calcium chloride/ammonia as the absorber/refrigerant combination, but in principle many other combinations could be used.

A prototype in reduced scale is at present being made in Denmark and will be sent to the Sudan later for testing under tropical climatic conditions. To allow for periods of cloudiness, the system has been designed for a production of 720 kg ice on a clear day. The length of the generating period was set at 5 hours around noon, that of the absorption period, which is also the freezing period, at 12 hours during the night.

Figure 1 gives a view of the proposed plant. A stagnant-water condenser and ice generator are underneath the solar collector. Figure 2 shows an exploded view of the combined solar collector, absorber and generator, which is constructed from steel tubes and separated by steel-plate fins. Except for the glazing, the collector is painted with a black selective coating.

The insulation on the back of the collector is mounted so that it can be removed during the absorption period. This is necessary because the

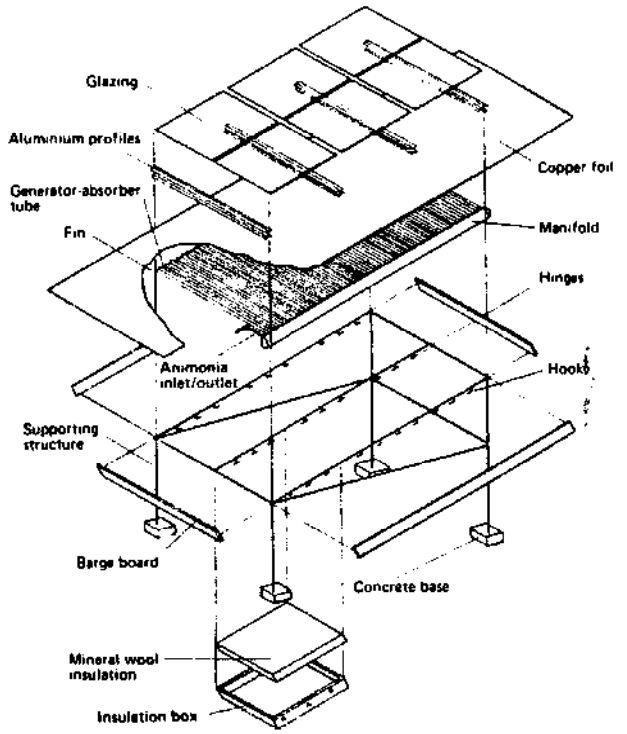


Figure 2. Exploded view of one section of the combined solar collector, generator and absorber

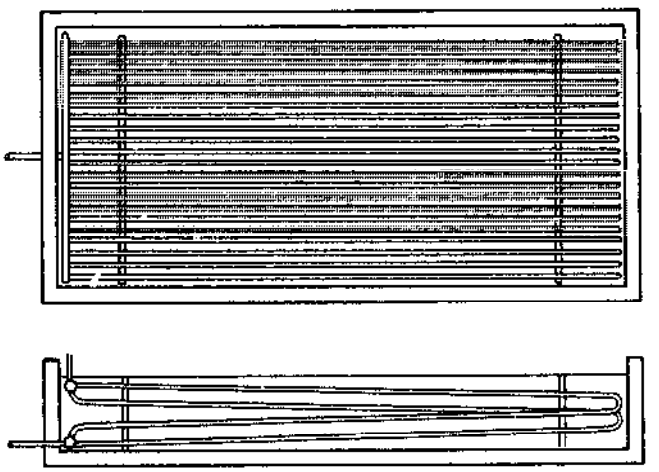


Figure 3. Stagnant-water condenser

selective collector surface and glazing do not allow for adequate cooling by radiation during the night.

If there is no means for providing water circulation (apart from natural convection), a stagnant-water condenser (figure 3) is the best solution. Simulation studies show that an average condensing temperature of 40°C can be achieved even with a small basin.

The principal dimensions of the ice-making plant are as follows:

Solar collector

Total projected area: 156 m² (10 sections, 3 m × 5.19 m each)
Tube size: 33.7 mm OD, 28.5 mm ID
Number of tubes per section: 60

Condenser

Water basin: 6 m × 2.8 m × 0.8 m
Total heat-transfer area: 18 m²
Tube size: 21.4 mm OD, 16.1 mm ID
Total tube length: 270 m

Ice generator

Brine basin: 1.7 m × 1.5 m × 0.85 m
Total heat-transfer area: 16.5 m²
Number of ice cans: 60
Dimensions of ice block: 120 mm × 180 mm × 600 mm
Weight of ice block: 12 kg

The ice generator (figure 4) operates without forced circulation of the brine, which means that the evaporator area must be fairly large. The best solution appears to be a plate-type evaporator with the plates between the rows of ice cans. The rather small block-size chosen means that freezing can be completed in 12 hours with an evaporation temperature of approximately −11°C.

The typical operating conditions for the plant are as follows:

Direct	890 W/m²
Diffuse	150 W/m²
Ambient temperature during generation	31°C
Efficiency of solar collector	0.55-0.45
Condensing temperature	40°C
Evaporation temperature	−10°C
Final absorption temperature (liquid absorbent)	40°C
Duration of generating period	5 h
Duration of absorption period	12 h
Estimated specific mass of generator vessel (mass of vessel divided by mass of refrigerant generated)	10

Based on the preliminary design, the following cost estimate for the plant was made (cost in Denmark in dollars):

Solar collector, generator and absorber	21 000
Condenser	500
Ice generator	2 500
Piping and installation	2 000
Total	26 000

In a developing country the plant could probably be built for approximately $16,000.

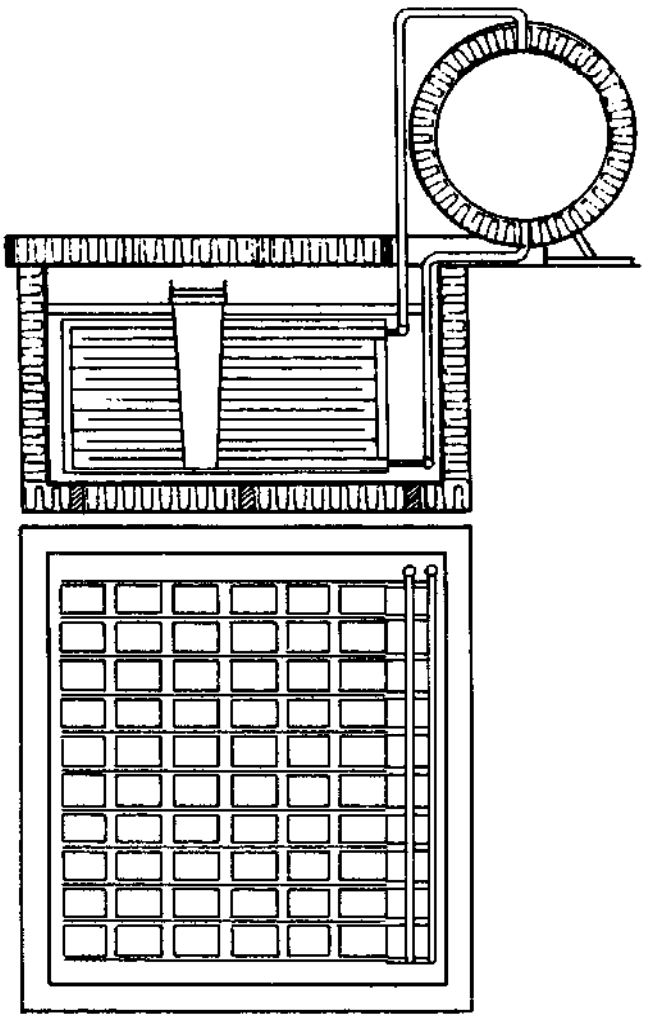


Figure 4. Ice generator

Based on an annual production of approximately 180 000 kg of ice, an interest rate of 6% per annum, and a working life of the plant of 12 years, ice could be produced at a price of 0.02 $/kg. This price does not appear unreasonable, judging from figures given in the literature.

As the working susbtances for the absorption system of the plant, several absorbent/refrigerant combinations could be considered, both liquid and solid, but those most likely to prove successful are the following:

Lithium bromide/water ($LiBr/H_2O$)
Water/ammonia (H_2O/NH_3)
Sodium thiocyanate/ammonia ($NaSCN/NH_3$)
Lithium nitrate/ammonia ($LiNO_3/NH_3$)
Calcium chloride/ammonia ($CaCl_2/NH_3$)
Strontium chloride/ammonia ($SrCl_2/NH_3$)

In all but one of the above cases ammonia is the refrigerant, and the first four absorbents are liquid, while the last two are solid. There are possibilities of using other refrigerants, alcohol or methylamine, for example, Niebergall has provided extensive data for most of the absorbent/refrigerant combinations that might be considered.

Research results

The following remarks are based on the research of the author and others in Denmark.

The use of liquid absorbents is advantageous, since the concentration of refrigerant in the absorbent can be adjusted at will to suit the lower temperatures met with in solar refrigeration. On the other hand, with solar liquid systems it is difficult to obtain adequate circulation, especially during the regeneration cycle, without utilizing pumps; also, the risk exists that part of the liquid absorbent will vaporize together with the refrigerant during the generation cycle. This can be remedied either by a better choice of absorbent/refrigerant combination or by installing a fractionation column, which, however, is costly. (Fractionation is imperative when using the water/ammonia combination.)

The solid absorbent systems have the advantage that the absorbents cannot evaporate at all; however, owing to their density, some difficulties are encountered during the regeneration cycle, and also it has proved difficult to keep the layers of solid absorbent in the generator-absorber porous and to prevent them from clogging the piping.

The generation temperatures required in connection with solid absorption refrigeration are at the upper limit of what flat-plate collectors can yield namely, 100°-120°C, depending on the absorbent/refrigerant combination used. However, the technical problems encountered in this respect could probably be solved by means of available technology, for example, selective surface coatings and slight concentration by means of metal mirrors. The real problems are economic rather than technical.

For the condensation process, temperatures of about 40°C are required. Such a low temperature may be difficult to achieve in certain tropical regions. Using a stagnant-water condenser, where the temperature of the condensing water is kept down by evaporative cooling, has been suggested.

Experiments have shown that with a mixture of 85% calcium chloride and 15% Portland cement an absorbent granulate can be made having reasonable mechanical strength and sufficient porosity so that when filling the absorber-generator an even distribution can be obtained without difficulty. After 200 generation-absorption cycles with this granulate no decrease in the absorption capacity was noticed. The addition of cement does not reduce the yield in comparison with pure calcium chloride. A similar strontium chloride granulate was produced, but it showed no advantages over calcium chloride.

Simulation experiments have been conducted in Copenhagen on a plant to be placed in Khartoum, the Sudan. The greatest efficiency was achieved when the degree of generation was kept at about 70% of the maximum that could be obtained on clear days. Under these conditions maximum collector temperature was 110°-115°C. The simulation experiments indicate an optimum generator pipe diameter of about 40 mm and a distance between the pipes of about 100 mm.

The heat radiated away to the surroundings during the night is insufficient to secure full reabsorption of the ammonia. Extra cooling, for example, by means of arranging for a slight distance between the collector and the rear insulation is likely to prove insufficient, and will increase the heat loss during the generation cycle. The best solution appears to be a hinged rear insulation, which can be swung open at nightfall.

A pilot plant for the production of refrigerated drinking water is being constructed at the Technical University at Copenhagen. It has a collector area of 4 m^2, and the calculated yield is about 7 500 kJ every 24 hours. The plant may later be tested at the Institute of Solar Energy and Related Environmental Research, University of Khartoum. Both the experimental work and the revised calculations in connection with the design of this demonstration plant confirm that an intermittent calcium-chloride/ammonia solar absorption refrigeration plant can be used to produce ice. Daily production per unit of collector area is likely to be 4 kg/m^2.

The design of an intermittent absorption refrigeration plant can be very simple; no advanced technology is required for building one.

Calcium chloride/ammonia appears to be the best all-round absorbent/refrigerant combination.

Refrigeration chains

In many developing countries "refrigeration chains" are needed for the cold storage of perishable products while they are being transported and distributed. In Mexico, for example, such chains are needed for fruit because the present facilities are barely sufficient to cover the cold-storage requirement of 10% of production.

Since 1971, the Material Research Center of the University of Mexico has been working to establish a refrigeration chain for the distribution of perishable foods. From the studies undertaken so far it has concluded that an effort should be made to develop in rural areas in Mexico:

(a) Large, regional cold stores (capacity 5 000-10 000 t) where products can be processed and stored before distribution to urban centres or exported;

(b) Small, multipurpose cold stores (capacity 20-200 m^3) for rural communities.

The National Council for Science and Technology has approved the development of small cold stores.

Solar refrigeration plants with solid adsorbents may prove useful for refrigeration chains in Mexico and other developing countries.

BIBLIOGRAPHY

A case for a solar ice maker. *Solar energy* (Elmsford, N.Y.) 7:1:1-2, 1963.

Chinappa, J. C. V. Experimental study of the intermittent vapour absorption refrigeration cycle employing the refrigerant-absorbent systems of water ammonia lithium nitrate. *Solar energy* (Elmsford, N.Y.) 5:1:1-18, 1961.

_____ Performance of an intermittent refrigerator operated by a flat-plate collector. *Solar energy* (Elmsford, N.Y.) 6:4:143-150, 1962.

Chung, R. *and* J. A. Duffie. Cooling with solar energy. Proceedings of the United Nations Conference on New Sources of Energy, Rome, 21-31 August 1961. (Solar energy: III, v. 6, p. 20 (S/82))
Sales no.: 63.I.40.

Factors affecting the use of solar energy for cooling. *By* K. H. Khalil *and others.* Proceedings of the International Conference on Heliotechnique and Development, Dhahran, 1975. (V. 2, p. 125-132)

Niebergall, W. Arbeitsstoffpaare für Absorptionskälteanlagen und Absorptionkühlschränke. Mühlhausen, Federal Republic of Germany, Verlag für Fachliteratur, 1954.
In German.

Possibilities for solar ice-makers. *By* F. Ba Hli *and others.* Proceedings of the International Solar Energy Society Conference, Melbourne, 1970. (6/59)

Potential use of solar-powered refrigeration by an intermittent solid absorption system. *By* A. Eggers-Lura *and others.* Proceedings of the International Conference on Heliotechnique and Development, Dhahran, 1975. (V.2, p. 83-104)

Stubkier, H. B. *and* B. Bechtoft Nielson. Solar refrigeration plants. M. Sc. thesis. Technical University of Denmark, Refrigeration Laboratory, Copenhagen, 1974.
In Danish.

Survey of solar-powered refrigeration. *By* R. K. Swartman *and others. American Society of Mechanical Engineers. Quarterly transactions.* (New York) 73-WA/Sol-6, 1973.

Swartman, R. K. Survey of absorption refrigeration systems. Proceedings of the International Conference on Heliotechnique and Development, Dhahran, 1975. (V.2, p. 71-82)

Trombe, F. *and* M. Foëx. Economic balance sheet of ice manufacture with an absorption machine, utilizing the sun as the heat source. Proceedings of the United Nations Conference on New Sources of Energy, Rome, 21-31 August 1961. (Solar energy: III, v. 6, p. 56 (S/109))
Sales no.: 63.I.40.

Solar distillation: The state of the art

B. W. Tleimat

Sea Water Conversion Laboratory, Richmond, California, United States of America

Background

The modern use of solar energy for the distillation of saline waters began in 1872 with the installation in northern Chile of a large basin-type solar still which served the needs of a mining community for many years. The original still[1] consisted of parallel bays 1.14 m wide by 61 m long, with a total area of 4 700 m^2. The still basin was constructed of wood blackened with logwood dye and alum to absorb the sunlight. Other means of obtaining potable water having come into use, the only remains of this still in 1965 were reported to be some of the foundation and numerous pieces of glass.

Figure 1 is a simplified diagram of a solar still. It consists of a basin containing saline water with a black bottom to absorb the sunlight, covered with transparent glass sheets that form an airtight enclosure. The transparent covers slope toward a collection trough. In operation, solar energy passes through the transparent cover and is absorbed by the water and basin liner. The absorbed energy warms the saline water in the basin, causing the evaporation of some of the saline water and increasing the humidity close to the water surface, thus producing convection currents within the still enclosure. The warmer humid air rises to the cooler glass, where part of the water vapour condenses on the surface, slides down and drips into the collection trough, and is withdrawn from the ends as fresh water. In order to prevent precipitation of salts in the basin, salt water could be added either continuously or on a batch basis. The rate of adding feed water should be at least twice the rate of production of fresh water.

Interest in solar distillation began again during the Second World War with the development of plastic stills for use in emergency life rafts. These stills consisted of an inflatable transparent plastic container with a felt pad on the bottom and a distillate collector bottle attached to the plastic container. During use, the container was inflated, the felt pad was saturated with sea water, and the assembly floated alongside the raft. In operation, solar energy, passing through the transparent plastic and being absorbed by the felt pad, produces water vapour which then condenses on the inside of the plastic and is collected in the bottle at the bottom of the assembly.

During the decades following the Second World War, sustained drought conditions in many parts of the world brought water supply problems into sharp focus. The use of desalination to produce potable water seemed to give a promise of relief from the drought. All over the world, programmes for the development of methods for desalting saline water were begun. Solar distillation was one of the many methods investigated. However, research on desalting

[1] Josiah Harding, "Apparatus for solar distillation", *Proceedings of Institution of Civil Engineers*, No. 73 (1883), pp. 284-288.

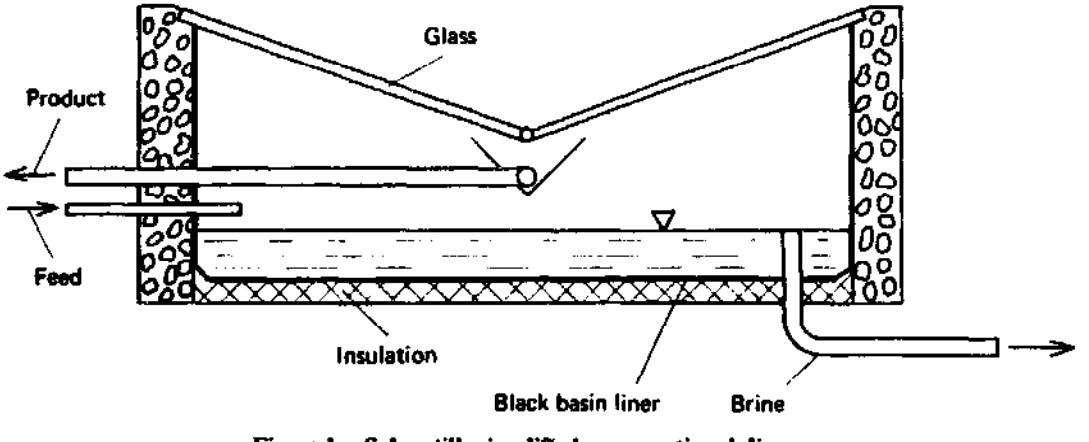


Figure 1. Solar still: simplified cross-sectional diagram

methods using electrical and fossil-fuel energy seemed likely to reach commercial application sooner than solar distillation, which received a relatively small part of available financial support.

The Sea Water Conversion Laboratory at the University of California started its investigation of desalination methods in 1951. During the initial phases of its investigation, it concluded that processes using non-fuel sources of energy should be given close consideration. This conclusion was based on the calculation of the energy required to desalt sea water by the then available desalination methods. For example, if sea water were to be distilled to supply all the needs of a city the size of Los Angeles, the energy required by the then-in-use multiple-effect type distiller would be more than all the oil fuel produced in Southern California. Based on this conclusion, the University built a solar distillation station at the Engineering Field Station in Richmond, California, and continued these investigations for the next 10 years at a vigorous pace. Various configurations for simple solar stills were built and tested to reduce construction costs and improve efficiency. The United States Government, through its Office of Saline Water, also instituted a solar distillation programme at about the same time and financed the building and testing of varieties of solar stills at its testing station at Daytona Beach, Florida.

The investigators at the University of California and other research centres eventually concluded that the basin-type solar still in any of the forms considered could not compete economically with large plants using other desalting processes to produce large quantities of water. Since about 1961, the work on solar distillation at the University of California has been shifted toward the development and improvement of small plants to supply drinking water to small communities. A summary of the work at the University of California has been summarized by Howe and Tleimat.[2]

Although work on the development and construction of large-scale stills was discontinued in most parts of the world, medium-scale solar-still development has continued in Australia under the auspices of the Commonwealth Scientific and Industrial Research Organization (CSIRO). The most up-to-date review of work on solar distillation has been summarized for the Office of Saline Water by Talbert *et al.*[3]

The cost of water produced from desalination plants is the sum of the cost of energy, capital and labour. Because the solar energy is free, the cost of water produced by simple basin-type solar stills is a function of the initial cost of the still. Efforts to reduce the water cost have focused on the lowering of the initial capital cost without unduly affecting performance. The bulk of these efforts has involved different geometric configurations. Some of those tried out at the University of California are shown in figure 2. The most promising design in terms of initial

[2] E. D. Howe and B. W. Tleimat, "Twenty years of work on solar distillation at the University of California", *Solar Energy*, No. 16 (1974), pp. 97-105.

[3] S. G. Talbert, J. A. Eibling and G. O. G. Löf, *Manual on Solar Distillation of Saline Water*, Research and Development Report No. 546 (Washington, United States Department of the Interior, Office of Saline Water, 1970).

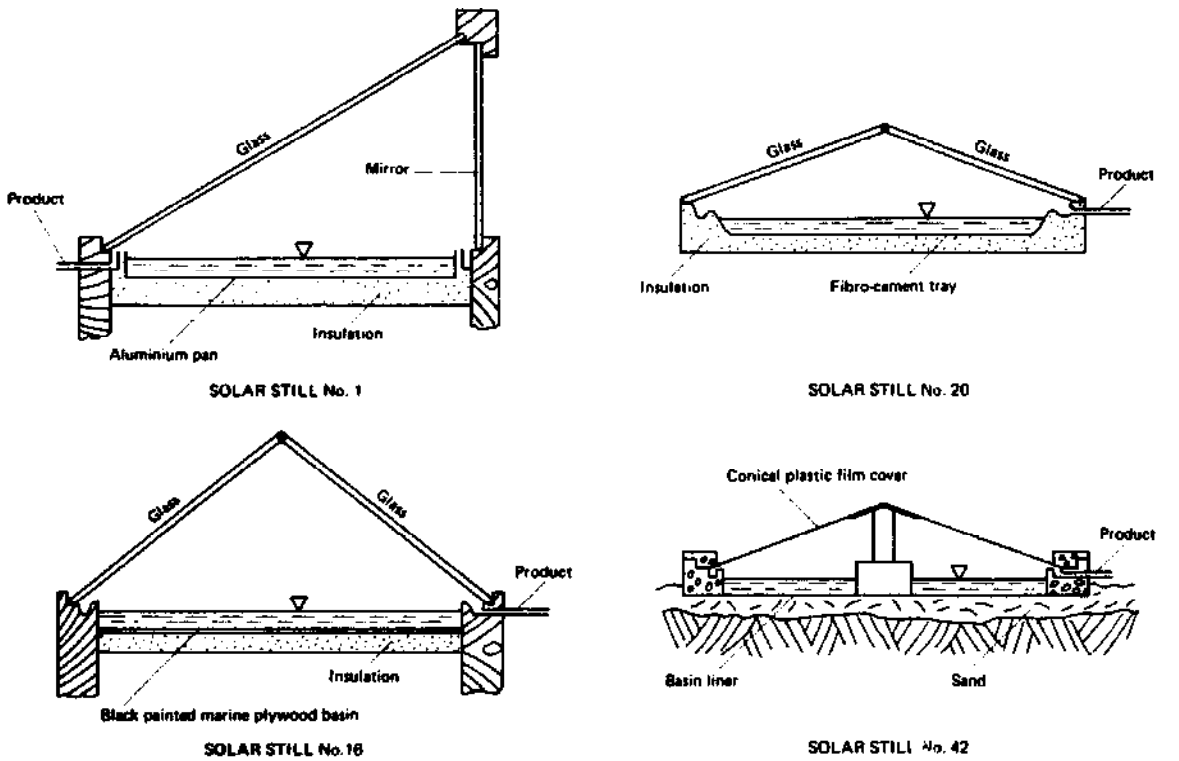


Figure 2. Cross-section of some solar stills at the University of California, Richmond

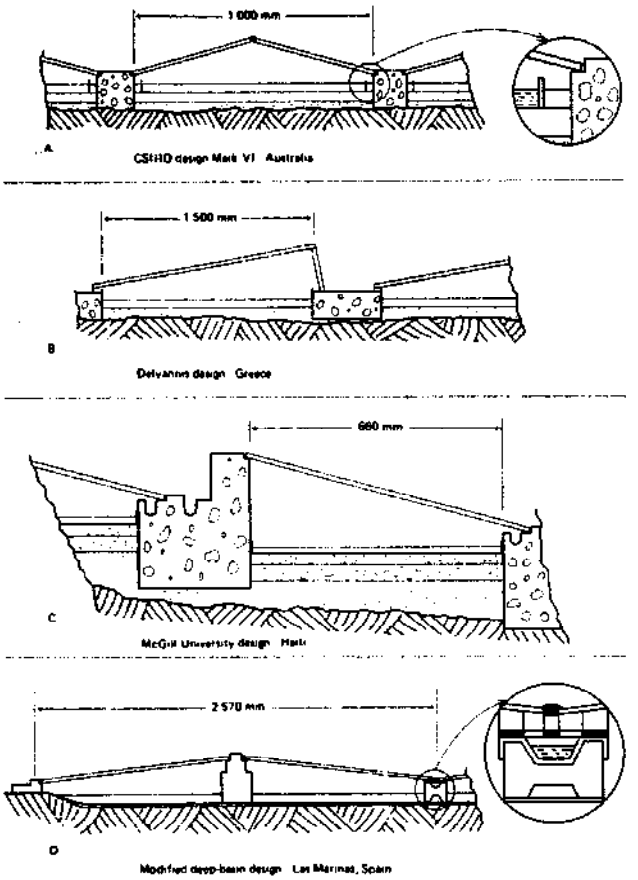


Figure 3. Simplified cross-sectional diagrams of some large stills in various places

cost and relative efficiency was, however, that of figure 1. It has been installed at several locations[4] in the South Pacific. The glass-covered basin has an area of 5 m^2. This design was also used in modular form with additional modules of 2.4 m^2 each, giving flexibility of size and production.

Cross-sections of some of the large solar stills constructed throughout the world are shown in figure 3. Cross-section A consists of concrete side members which contain grooves to support the glass cover and form the product trough. A black basin liner is laid over the insulated bottom, formed into the product trough and sealed against the glass edges. The top ridge, between the two sheets of glass, is formed by using silicone rubber sealant which, after drying, acts as a hinge for the two glass panes. This design has been successful and has been used in several Australian installations.

Cross-section B in figure 3 is similar to a large installation on the Greek island of Patmos. It is glass-covered with aluminium distillate troughs and glass supports. Cross-section C is similar to the one used by the Brace Research Institute of McGill University at the installation in La Gonave, Haiti.

Cross-section D is similar to the still used at Las Marinas, Spain. It was modelled on the deep-basin concept tried at Daytona Beach, Florida. The deep-basin concept is based on the argument that this construction does not involve accurate levelling of the ground and would prevent the occurrence of dry spots when evaporation took place. Also, because of the large mass of water in the basin, evaporation continued into the night because of the heat stored in the saline water. However, after considerable experimentation and comparison with shallow-basin stills, it was concluded that for better performance the depth of water should be as small as practicable.

Other designs of solar stills that have been tested at different stations include the tilted-tray still and the wick-type stills, shown schematically in figure 4. The tilted-tray solar still is a unit in which the basin is broken up into narrow parallel strips, with each strip at a different height. Because of this arrangement, the water surface is brought closer to the glass surface. This type of construction resulted in higher efficiency than the simple basin-type; however, the additional cost of construction could not compensate for the increase in performance. The wick-type still is a glass-covered type and consists of a cloth wicking material laid on an inclined surface. Saline water is distributed along the upper edge of the inclined surface and flows down through the absorbent material, maintaining it in a wet condition. Because of the small thermal capacity of this type of still, it can operate at high efficiency; however, difficulties in keeping the wick wet and clean and the cost of construction prevent its use on a large scale.

The most recent entry in the field of solar distillation is taking place in Mexico under the auspices of the Comisión para el aprovechamiento de

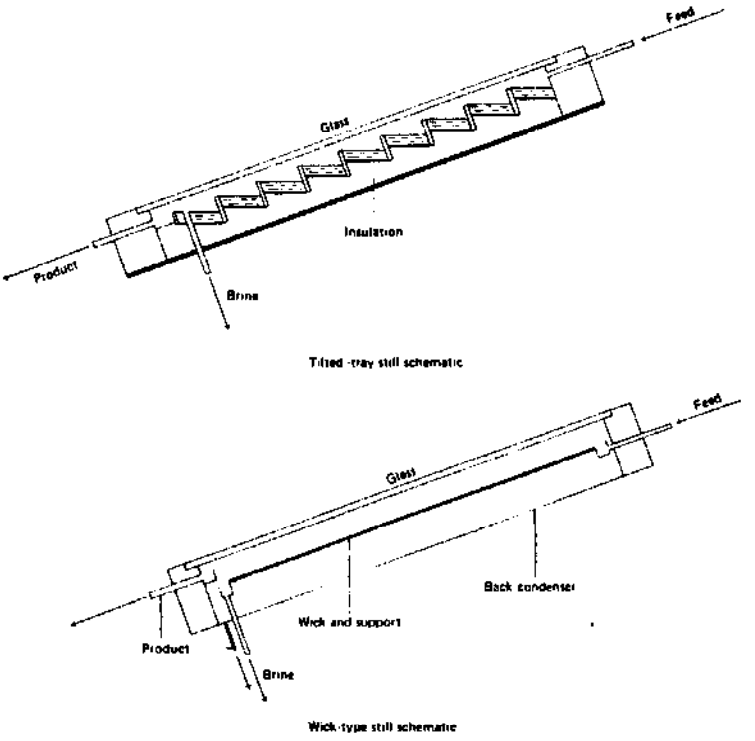


Figure 4. Tilted-tray and wick-type solar stills

[4] E. D. Howe and B. W. Tleimat, "Solar distillers for use on coral islands", *Desalination*, No. 2 (1967), pp. 109-115.

aguas salinas in Tecamachalco, Mexico. It involves three operating installations with rated outputs of 1-1.5 m^3/d. These installations consist of individual stills laid on the ground and connected together with PVC piping. These individual stills are similar to the fibro-cement tray stills constructed by Gomella and consist of a fibreglass tray, 0.93 m X 1.063 m, with a black-painted bottom and covered with glass sloping at 30° to the horizontal. The reported average cost per still in Mexico is about $25 and the cost per unit of product water is 3-4 $/$m^3$, including capital cost, labour and maintenance.

Performance of solar stills

The performance of a solar still is usually expressed as the quantity of water produced per unit of area per day. This quantity varies with the geometry of the still, the insolation and the surrounding conditions. Once a solar still is built and installed, its geometry is fixed, and thus the performance of the still would be a function of the insolation and ambient conditions only. Figure 5 shows the productivity of the stills shown in figures 1 and 2 as a function of the insolation on a horizontal surface. They were built and tested at the University of California. Solar still No. 1 was the first built at the University. It was kept in good working condition and used as a model for comparison with other stills. Except for still No. 41, which was of the tilted-tray type, all the other stills were of the basin-type. Although figure 5 shows the productivity only of solar stills built and tested at the University of California, a similar trend was observed in other stills constructed elsewhere, with productivities somewhat lower than that of the tilted tray.

The presence of these features in a still seems to lead to high efficiency:

Low heat capacity
Low water content
Low air content
Vapourtight cover
Watertight basin
Good insulation around basin

The work done to date at various laboratories has also yielded useful information on construction materials. The transparent cover can be either glass or plastic. Except for vulnerability to mechanical damage, glass possesses all the desirable properties, such as high transmissivity for solar radiation, low transmissivity for low-temperature radiation, wettability with water, availability and high stability of properties over extended periods of exposure. Transparent plastic film-condensing covers used for solar stills have shown relatively high transmissivity for solar radiation and low-temperature radiation, but also degradation due to ultraviolet radiation. They must be mechanically treated to be wettable with water, and are usually manufactured only in highly developed countries. Moreover, although plastic films are less vulnerable to mechanical damage, they have shown failures because of wind conditions and have not yet been developed to be sufficiently long-lasting under conditions encountered in solar distillation.

Figure 6 shows the productivity of solar stills, No. 38-1 and No. 38-2. These two stills were of the

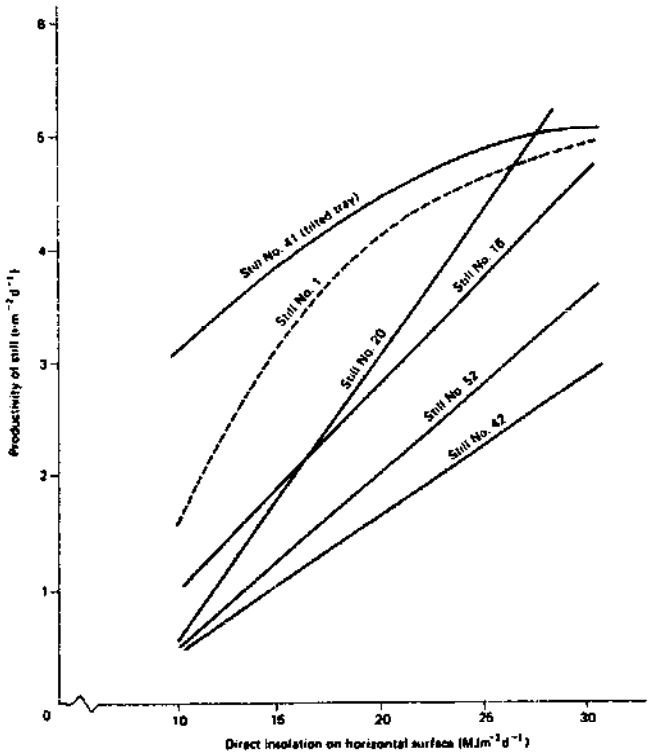


Figure 5. Productivity of some solar stills tested at the University of California, Richmond

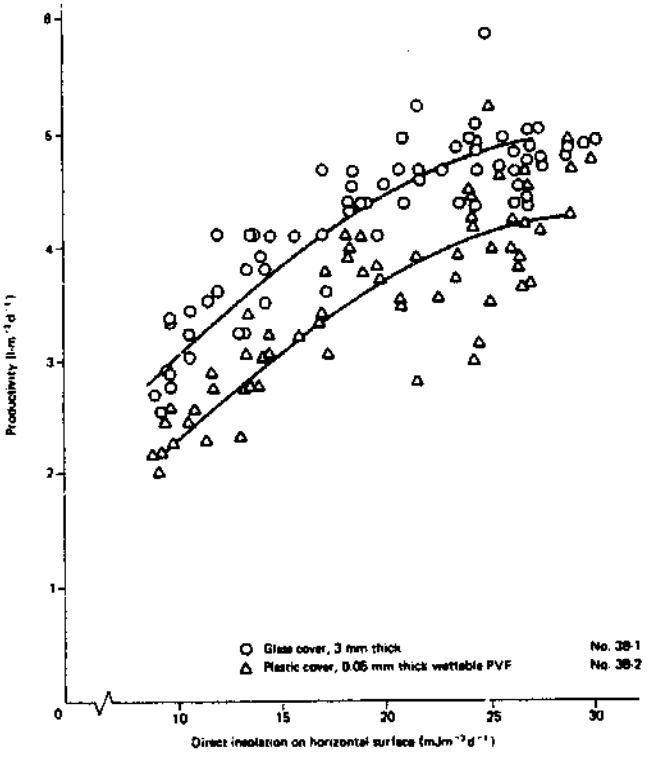


Figure 6. Comparison of productivities of University of California solar stills Nos. 38-1 and 38-2

tilted-tray type and, except for the transparent covers, of identical construction. Still No. 38-1 had a double-strength glass cover, 3 mm thick, while still No. 38-2 had a cover of mechanically-treated PVF film 0.05 mm thick. The two stills were installed next to each other and tested under identical conditions for two years. It is evident from figure 6 that the average producitivity of the plastic-covered still was about 20% lower than that of the glass-covered still.

Since vapourtightness strongly affects the performance of solar stills, the sealing of the transparent cover to prevent vapour leakage from the still is very important. The most effective and longest-lasting sealant used at the University of California was silicone rubber. Other sealants, such as ordinary putty, tar and plastic adhesive tape, deteriorated with time and formed cracks that permitted leakage of condensate and water vapour.

Basin-liner materials must be watertight and capable of absorbing solar radiation. Also, because the still may run dry, the basin liner must be capable of withstanding relatively high temperatures without being damaged. The most satisfactory material found so far is butyl rubber. Other materials have been tried, such as asphalt mats, used for lining stock tanks and roofing buildings, and polyethylene. While the asphalt mats were found satisfactory for the deep-basin stills, they are too stiff for shallow-basin stills with long narrow bays, and the polyethylene degrades rather rapidly when exposed to ultraviolet radiation.

The product trough to collect the condensate and the piping must be made of materials that can withstand distilled water. Plastic can be used for this application. Steel was found to corrode very quickly, and galvanized-steel sheets were found satisfactory but showed corrosion at the points where joints and bends were made. Aluminium, if protected galvanically, can be used successfully. Stainless-steel product troughs were found to be most satisfactory and showed little, if any, corrosion.

The use of simple solar stills has been limited to the production of relatively small quantities of water. This is because of the large area requirement, which means capital investment and maintenance costs so high that these stills cannot compete with other methods of desalination.

In solar stills, the solar energy is applied only once in the process, as contrasted with multiple-effect distillation where the energy is applied several times. Efforts to use solar energy more effectively have been expanded by several investigators.[5] Figure 7 is a schematic representation of a multiple-effect still investigated by one of them (Dunkle). It consists of a series of vertical plates within a box, with the first plate heated by solar-heated water and the last plate cooled by saline water, inside tubes bonded to the first and last plates. The saline-water feed, heated by the condensing vapour on the left side of the last plate, is introduced into an open trough and is allowed to fall as a thin film on the right-hand side of the first three plates. Vapour produced from the right-hand side of the first plate condenses on the left side of the second plate, and so on, until the last plate. In this arrangement, the solar heat delivered to the first plate by the solar-heated water passes to the second plate and, in turn, then passes to the third plate and then to the fourth plate to pre-heat the saline water feed. Condensates forming on the left sides of the second, third and fourth plates are collected and used as fresh water. The number of plates (effects) depends on the temperature difference between the solar-heated water and the cold saline-water feed. It will be recognized that such a still uses solar energy indirectly. If the left side of the box were made of transparent material and the first plate painted black with the tubes eliminated, the still would then utilize the solar energy directly. This arrangement has the advantage of producing when the sun is not shining, if only the solar-heated water is available. Unfortunately, the additional productivity of such stills does not compensate for the increase in construction costs. The cost of water from a simple basin-type still is lower than that from the multiple-effect still, and this seems to account for the lack of interest in such construction.

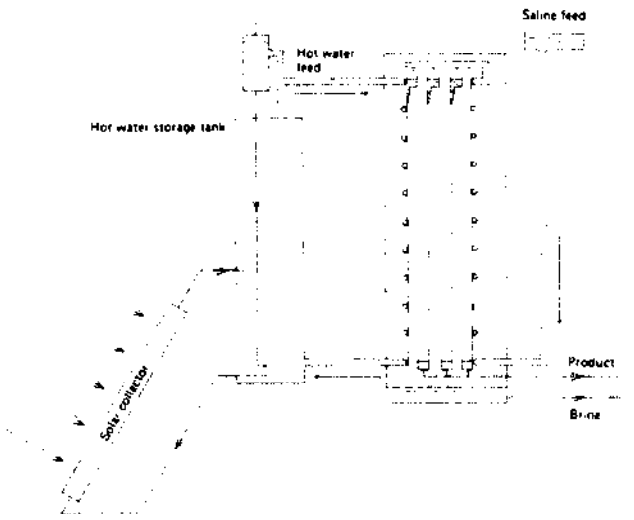


Figure 7. Multiple-effect solar still

Numerous methods to utilize solar energy for the production of steam to drive conventional multiple-effect and multiple-stage distillation systems have

[5] R. V. Dunkle, "Solar water distillation: the roof type still and a multiple effect diffusion still", *American Society of Mechanical Engineers. Quarterly Transactions*, 1961, pp. 895-902; M. K. Selcuk, "Design and performance evaluation of a multiple-effect tilted solar distillation unit", *Solar Energy*, No. 8 (1964), pp. 23-30; Maria Telkes, *Research on Methods for Solar Distillation*, Research and Development Report No. 13 (Washington, United States Department of the Interior, Office of Saline Water, 1956).

been proposed and tried.[6] In these schemes, solar collectors were used to capture solar energy for the production of steam. This steam is then used as the heating steam in the first effect of a multi-effect still or in the brine water of a multi-stage flash still. Of all these schemes, only that of Baum was built and tested. He used a concentrating paraboloid collector to generate steam at high temperature to drive a three-effect still. Unfortunately, because of the low heat-transfer coefficient in the still, only three effects could be used, and the cost of steam from the solar boiler was too high for economical operation.

The performance of a multiple-effect still is defined as the amount of water produced per unit of heat released by the condensing steam in the first effect and is called the gained output ratio (GOR). The GOR increases with the number of effects and with increasing steam temperature. For a constant steam temperature and constant cooling-water temperature, the GOR is a function only of the number of effects; consequently, increasing the number of effects decreases the amount of steam required to produce a unit amount of water and results in a smaller collector. However, increasing the number of effects increases the cost of the evaporators in the multi-effect still. This increase must be balanced against the benefits resulting from decreasing the size of the solar collector.

As an illustration, figure 8 shows a schematic flow diagram adapted from a scheme proposed by Tleimat and Howe.[7] In this scheme, flat-plate solar collectors are used in the steam-production (solar boiler) section and rotating-disc evaporators in the multi-effect section. In operation, solar-heated water is taken from one of the storage tanks and introduced into the degasser to eliminate non-condensable gases. After the degasser, the water is introduced into the flash chamber, where a small part flashes into steam. The other part is reheated in the solar collector during sunny hours and stored in the second tank or

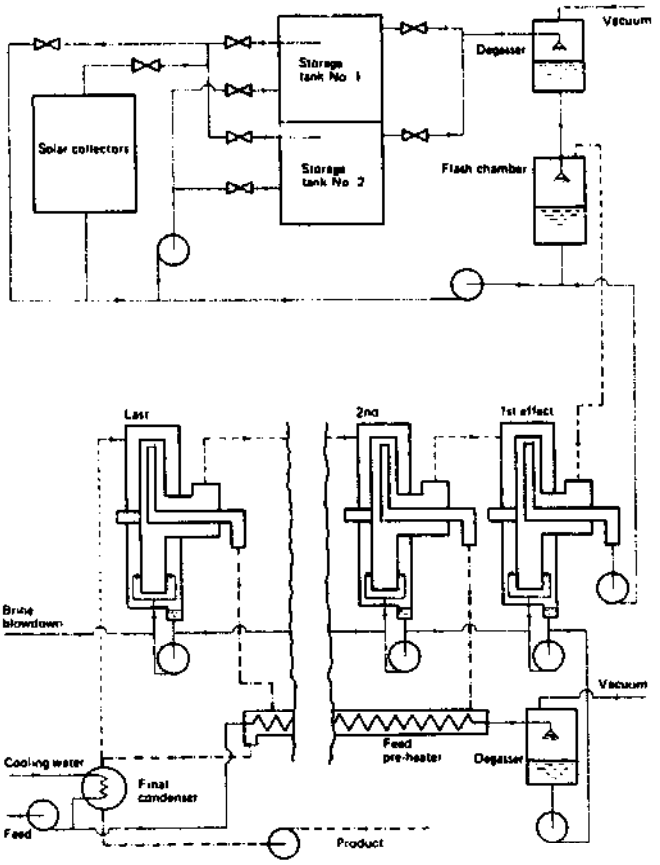


Figure 8. Solar-assisted multi-effect still

is sent directly to the second storage tank during the night and the condensate from the first effect returned to the solar boiler.

The unique feature of this scheme is the use of the Tleimat wiped-film, rotating-disc evaporator, an extremely high-performance evaporator developed at the Sea Water Conversion Laboratory, University of California, Berkeley. Overall heat-transfer coefficients of 2-5 W $cm^{-2}°C^{-1}$ have been obtained experimentally. These values are almost 10 times higher than values obtained in multi-stage flash stills now used in sea-water desalination. Because of these high heat-transfer coefficients, a large number of effects can be used, which means small-size collector systems. From data on the Tleimat evaporator, Tleimat and Howe were able to show that, for 60°C steam from the solar boiler and 20°C cooling sea water, it is possible to have a 15-effect still, resulting in a GOR of 12.8. Also, because the steam from the solar boiler is needed at 60°C, the collectors operate at relatively low temperature and consequently higher collection efficiency. Such a scheme could be used to increase the productivity of solar stills far above that of simple basin-type solar stills.

[6] V. A. Baum, "Solar distillers", Paper prepared for the United Nations Conference on New Sources of Energy, Rome, 1961 (35/S/119); D. B. Brice, "Saline water conversion by flash evaporation utilizing solar energy", *Advance in Chemistry Series*, No. 38 (1963), pp. 99-116; J. A. Eibling, R. E. Thomas and B. A. Landry, *An Investigation of Multiple-Effect Evaporation of Saline Waters by Steam from Solar Radiation*, Research and Development Report No. 2 (Washington, United States Department of the Interior, Office of Saline Water, 1953); H. Weihe, "Fresh water from sea water, distilling by solar energy", *Solar Energy*, No. 13 (1972), pp. 439-444; B. W. Tleimat and E. D. Howe, "Solar-assisted distillation of sea water", Proceedings of the International Conference on Heliotechnique and Development, Dhahran, 2-6 November 1975.

[7] *Op. cit., p. 439.*

Solar water distillation

Carlo Mustacchi and Vincenzo Cena

Rome, Italy

Solar water distillation is the solar technology with the longest history. Installations were being built for this purpose as early as 20 centuries ago. However, except for particular environments, such as islands, and for special requirements, such as emergency equipment for seafaring, only in the last 20 years has there been a revival of interest in this field as a result of population growth in arid regions and rising standards of living.

Two widely different approaches are possible: a low-technology integrated approach, whereby trapping solar energy and using it to evaporate water are done in the same piece of equipment, with low yields and low investment costs; and a high-cost, high-technology approach, whereby the two processes are carried out separately by means of specialized subsystems optimized for high yields.

Solar stills

The most elementary solar-still construction requires a flexible plastic sheet (polyethylene) of about one metre square, a small pan, a stone and a hoe. The last item is used for digging a round conical hole in the ground. This hole is covered with the plastic sheet, which is kept in place by piling up soil on its outer edges. The pan is placed at the centre of the hole to catch the water dripping from the plastic sheet, which is loaded at its centre with the stone. No feed water is required at all; capillarity and the temperature and humidity gradients in the soil are sufficient to feed the system. With suitable precautions, such as covering the bottom of the hole with well-trampled dark silt to increase absorptivity and capillary action, yields of over 1 l $m^{-2}d^{-1}$ have been observed in desert locations as far as 500 km from the sea, where daily humidity is of the order of 10%-15%. The unit installation cost is around 1 \$/m^2, including materials and manpower. This low cost does not justify the building of large installations, which would require an excessive amount of manpower for supervision and operation (emptying the pans at dawn).

The next step consists in covering the cavity with a black impermeable layer (tar, butyl rubber, black polyethylene) and sealing the joints between the transparent roofing and the sides. The increase in absorptivity entails a requirement of feeding the still with any available source of water (desert plants, brackish water, sea water etc.). The geometry of the basin seems to have only a minor effect on yield (typically 1-5 l $m^{-2}d^{-1}$). The advantage of also catching rainfall leads to symmetrical or asymmetrical shed-like constructions. The basin material can be compacted earth, concrete, masonry, asbestos-concrete, wood or plastic. The roofing is generally of glass or of PVF, polyester or other plastic film. The support for the roofing can be a frame made of the same material as the basin or of metallic frames (aluminium, or galvanized or painted steel). The sealant in most experimental stills is of silicone rubber, but recent reports concerning the good durability of asphalts or mixtures of asphalt and polyesters suggest that these can be selected as sealants, especially if suitable pigments are added to the mixture to inhibit further polymerization and embrittlement. Insulating the bottom or sides of the still appears to be less important than conditioning the soil by providing drainage and preventing the growth of vegetation that can damage the stills.

Current cost estimates for different designs have to be based on local materials, especially manpower. They range from 8 to 20 \$/m^2, and very often a higher investment is more than offset by lower intervention, maintenance and operation costs. In fact, large installations (20-50 m^3/d) should be provided with automatic filling and emptying systems, even though these operations are mostly carried out at weekly intervals. Plant maintenance, with renewal of the sealant every few years, is just about the only chore to be performed by the operation crews.

Observations show that convection and ground losses and vapour leakage are all of the same order of magnitude, namely, 4%-6%. No great advantage is foreseen in trying to improve geometry or thermal behaviour. Improved quality can rather be expected from combined systems, such as those which feed the basins with the cooling water discharge from a power plant condenser, with the glass roofing being cooled by pre-heating the feedwater or using condensation

surfaces (other than the transparent roofing) capable of providing increased radiation and convection.

With regard to construction materials other than sealants, there is no great room for technological improvements. However, more data could be found on the reliability and failure of materials over extended periods at different maintenance levels. Altogether, an approximate cost of $2 for each cubic metre of fresh water production seems to be a basic value for full-scale installations (2-50 m^3/d).

It must be stressed that basin stills are a poor solution for communities of 10 000 or more inhabitants with no other source of fresh water. The lack of an effective economy of scale leads to excessive investment levels and the collection area is so large that piping and pumping systems become major problems.

Indirect collection

Indirect collection and transformation of solar radiation for the separation of water and dissolved salts involves the use of flat-plate collectors in a conventional desalination plant of the multi-stage, multi-effect or vapour-compression type.

The flat-plate collectors are the same as those currently available on the commercial market for providing hot water to dwellings. No special provisions have to be made to increase the operating temperature, since 90°C is at present the upper limit for the operating temperature of distillation plants. Beyond this limit, sea water is highly corrosive for most common construction materials, and precipitation of calcium salts occurs unless costly additions of chemicals (sulphuric acid, polyphosphates) are made. Even below the limit of 90°C, the collector material must be a nickel-copper or an aluminium alloy. It is, however, often convenient to circulate fresh water in a closed loop to a standard carbon-steel collector and construct a separate heat exchanger to transfer the collected energy to the brine of the distillation plant.

The leading types of collectors for this use are made by encasing a double corrugated-steel plate inside a flat rectangular case of fibreglass, galvanized-steel and concrete. The metal collecting surface is either painted with flat black paint or receives a selective finish (copper oxide). The box cover consists of one or two layers of common window glass with a few centimetres separating the glass and the collecting surface. Below the metal collector, the box is lined with a layer of thermal insulating material (rock-wool, or polyurethane or polystyrene foam). A typical collector in one of our experimental loops is 1 m X 2 m X 15 cm, with a 1-mm glass-resin box, a 5-cm urethane foam insulation, double glass and silicone sealant. It costs 30-40 $\$/m^2$ for very small-scale production and provides a heat output of over 2.9×10^6 kJ/m^2 per year in Rome. In a desert location with a drier climate between the latitudes of 10° and 20°, it can provide about 7×10^6 kJ/m^2 per year.

All the construction materials (but not the assembled collector) are already proven for a lifetime of 20-25 years. Mass production of such collectors is expected to bring down the costs to 25-30 $\$/m^2$, even though the retail price of most collectors in Europe and the United States are, at present, in the 70-100 $\$/m^2$ range.

No skilled manpower at all is required for assembling the collectors, building the case and glazing the top.

The operating principles of the main distillation units which can be coupled to the solar collectors are reviewed below.

Multi-stage flash process

In this process (figure 1) the sea water is pre-heated by heat exchange with the condensing fresh-water vapours, then the warm brine receives the solar input energy and is brought to a temperature of 70°-90°C. Its pressure is decreased gradually in a series of enclosures which contain the tube bundle of the pre-heater. Condensed fresh water drips from the bundle and is collected and circulated along the chain of vessels to recover its sensible heat. The highest and lowest pressure stages are kept respectively at about 0.8 bar and 0.05-0.07 bar, and the number of stages is such that the overall temperature difference (between the hot collector and the cold sea water) is fractionated into temperature drops or "flashdowns" of about 2°C per stage. Current commercial installations are designed with 10-30 stages. Although theoretically in each stage the latent heat of evaporation is reused to evaporate as much water at a lower pressure, and therefore with 30 stages the theoretical maximum yield per unit of collector surface should be over $120\ l\ m^{-2}d^{-1}$, in actual practice some losses are incurred, due to pressure drops, the small size of the heat-transfer surfaces and ebullioscopic increase, so that the actual yields are in the range of 60-100 $l\ m^{-2}d^{-1}$.

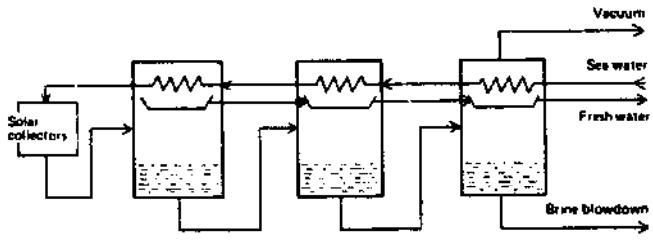


Figure 1. Multi-stage flash

A number of parametric estimates of multi-flash plants were carried out and the results were correlated by the following equation:

$$C = 256\,000 + 853\sqrt{PN} + 4.5(10\,764)\,NA + 0.45P + \\ + 20.0P^{0.8} + 562P^{0.6} + 12\,900P^{0.3}$$

The above equation has the following variables:

P = fresh-water production (lb/h)
N = number of stages
A = heat-transfer surface per stage (m^2)
C = cost ($)

The depreciation of this cost plus an estimated $200 per day for manpower and chemicals and the depreciation of the flat-plate collectors in the range of 50-70 $/m^2$ lead to a decrease in cost per unit volume of fresh water from 2 to 1 $/m^3$ in the range of 50-500 m^3/h. These estimates are considered conservative and are based on present-day technology. No attempt is made to store solar energy for use at night; a conventional fossil-fuel boiler is provided for operating the plant when the sun is not shining.

Typical optimized design data for two multi-stage flash plants are as follows:

Nominal production	(lb/h)	10^5	10^6
	(kg/h)	45 X 10^3	45 X 10^5
Sea temperature	(°F)	77	77
	(°C)	25	25
Concentrated brine discharge temperature	(°F)	82	82
	(°C)	27.8	27.8
Flashdown	(°F per stage)	4	4
	(°C per stage)	2.2	2.2
Maximum collector temperature	(°F)	180	200
	(°C)	82	93
Number of stages		24	29
Brine discharge (10^3 lb/h)		780	6 300
Brine recycle (10^3 lb/h)		75	590
Flow rate in collectors (10^3 lb/h)		950	7 900
Overall heat transfer surface	(10^3 ft²)	60	560
	(10^3 m²)	5.5	52
Investment cost (10^6 dollars)		3.48	16.3
Solar collector surface (10^3 m²)		6.1	66
Fresh-water cost ($/m²)		1.98	0.94
Daily fresh-water production per unit of collector surface (l/m²)		74	68.5

Multi-effect process

This process (figure 2) also involves a series of enclosures with decreasing pressure and temperatures. The warmest stage is fed directly by the solar collectors, and the coldest is kept close to the prevailing sea temperature. The steam output from one stage is circulated in the tubes of a bundle which heats the liquid of the next stage. Thus latent heat is recovered and transferred stage by stage. The temperature differential between two stages is of the order of 10°-15°F (5.6°-8.3°C), and therefore seldom are more than 5-10 stages used.

A parametric cost estimate based upon a number of detailed designs led to the following equation for the plant investment:

$$C = (2 - 1.37\,N^{-1})\,P + 556\sqrt{PN} + 4.3\,P^{0.8} + \\ + 139\,P^{0.6} + 7\,120\,P^{0.3} + 422\,000$$

In this equation P and N have the same meaning as in the preceding equation. The multi-effect process, from the point of view of convenience, appears to have a slight advantage over the multi-stage flash in the range of 10 to 80 m^3/h, but loses this advantage at higher design capacities. In the range of interest (about 50 m^3/h), a typical design would represent a fresh-water cost of 1.7-1.8 $/m^3$, including depreciation, manpower, collectors and chemicals.

Other processes

The vapour-compression process (figure 3) recovers heat by extracting steam from one stage, raising its thermal level by means of a compressor (steam ejector or centrifugal), and feeding it as heating steam to the stage it came from or to another stage. A study of parametric cost estimates and process designs show that this type of plant is not especially convenient unless it is combined with a multi-stage flash section. Further, it appears that the mechanical energy requirements have to be provided with a primary drive such as a diesel engine, and cooling the radiator of such an engine provides more than enough heat for the thermal requirements of the process, so that solar collectors are redundant and cannot be conveniently connected to the system.

The humidification and dehumidification system warms the sea water in solar collectors, saturates the ambient air in a packed, counter-current tower, then recovers fresh water by cooling the wet air in a condenser where heat is partly recovered by pre-heating the sea-water feed to the solar collectors.

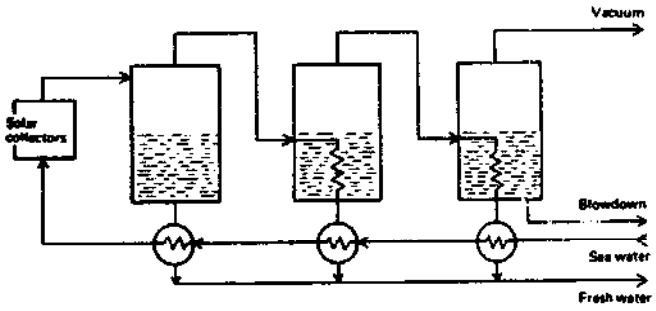


Figure 2. Multi-effect

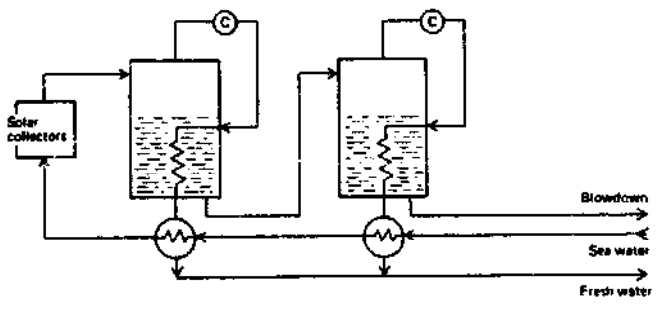


Figure 3. Vapour compression

As such, this process yields no promise for the purpose of providing fresh water alone, but can have an application if the humid air by-product is needed for other applications (greenhouse crops, air-conditioning etc.).

Limitations and outlook

At first sight, it may appear that the basin-still approach is the only one that can make full use of local manpower and materials in developing countries. On the other hand, the so-called high technology involved in the construction of, for example, a multi-stage flash is actually transferable with ease and in some cases already available in most arid countries, being the same technology required for constructing or repairing a conventional chemical processing unit. Except for purchasing a number of special materials for the warmest stages (nickel-copper alloys) and possibly the vacuum equipment, in addition, any crew of welders and pipe-fitters currently ensuring the maintenance of an oil refinery has all the skills necessary to manufacture the few pressure vessels and heat exchangers which make up the unit.

It must also be stressed that a number of arid countries (for example Bahrain, Kuwait, Qatar and Saudi Arabia) have built or are building large desalination plants using conventional fossil fuels. A constructive proposal is that a battery of flat-plate collectors could be added to these plants to save fuel without interfering with operations or requiring design changes. With a limited investment, one half of the fuel could be saved, or rather "frozen" and turned into collectors which, after a period of about 10 years, would go on to supply virtualiy free energy for the process.

This proposal circumvents one of the main difficulties of solar-fuelled desalination plants: the fluctuating energy input. Large desalination plants are mechanically designed so that the pressure drops between stages or effects are determined by liquid levels in the different enclosures. Raising or lowering the heat input will vary the flow rates and unbalance the operation. Thus, unless specific new designs are drawn up for solar desalination, some provision must be made for keeping temperature fluctuations within the range 2°-5°C at the heat source. This may be done by one of the following means:

(a) Installing a compensating fossil-fuel boiler;

(b) Shutting down the plant at night;

(c) Providing a reservoir to store the solar heat.

Solution *(a)* is the method upon which the above estimates were based and coincides with the proposal to add solar collectors to existing desalination plants. Solution *(b)* is just beginning to be possible, since the latest designs of desalination plants involve start-up transients as short as 15 minutes, thus entailing limited heat waste. Solution *(c)* requires more development work to make it economically convenient but holds the greatest potential.

A recent survey of the main procedures for storing the huge thermal energy requirements of a sizeable desalination plant at night led to the following conclusions. The idea of storing warm water should be discarded since it would add about 2 $/m^3 (depreciation cost of the reservoirs) to the cost of the fresh water, thus doubling costs. Chemical storage, frequently advocated in many proposals, is not yet convenient. For instance, releasing ammonia from an absorbent such as calcium chloride during the day and allowing reabsorption at night to yield the heat of reaction, requires compression and liquefaction of the ammonia and would waste almost as much heat as that to be stored. Another possibility involves the storage of heat by melting a compound and recovering the latent heat of melting when the compound refreezes at night. The four studies that have been conducted suggest that this solution is feasible with paraffin (melting-point 70°-80°C) kept in polyethylene bags in the warm-water tanks. This would save 50%-80% of the tank volume for an equal thermal energy storage. Further work is being carried out along these lines.

Future trends

Several projections of world market trends in the field of fossil and nuclear fuels indicate that energy costs will increase by 50% every 10 years. At present-day costs, of the 1-2 $/m^3 of the cost of fresh water produced by a sizeable distillation plant (50-500 m^3/h), 0.75 $/m^3 is accounted for by fuel costs. Looking 20 years ahead, the 0.75 $/m^3 will rise to about 1.7 $/m^3, whereas with solar collectors that will be fully depreciated by then, the cost will be nil. The overall saving would therefore be of this order of magnitude. On the other hand, the usual difficulty for most developing countries is that of securing sufficient capital to invest in collectors. It must be pointed out that in the mentioned range, the solar collectors represent 5%-25% of the overall investment cost. The decision can be simplified by reducing it to the acceptance of this additional lump-sum investment today in order to reduce by approximately one half the costs of fresh water 15 to 20 years in the future. However, if venture capital is unavailable, the increased use of solar stills represents an alternative. The modular character of such a construction allows the establishment of a small number of units each year, or whenever the few materials required (mainly glass) can be afforded.

This solution is expected to be the best one, at least when the population to be served by the installation is less than 5 000-6 000 people, as is the case for most villages in arid parts of the world.

BIBLIOGRAPHY

Bahadori, M. N. *and* F. E. Eldin. Improvement of solar stills by the surface treatment of the glass. *Solar energy* (Elmsford, N.Y.) 14:339, 1973.

Baum, V. A. Solar distillers. Paper prepared for the United Nations Conference on New Sources of Energy, Rome, 21-31 August 1961. (Solar energy: III, v. 6, p. 178 (S/119))
Sales no.: 63.I.40.

Bloemer, J. W. Experimental investigation of the effect of several factors on solar still performance. Ohio State University, 1963.
M.Sc. thesis.

_____ Factors affecting solar-still performance. *Journal of heat transfer* (New York) 65, November 1965.

Brice, D. B. Saline water conversion by flash evaporation utilizing solar energy. American Chemical Society, Washington, D.C., 1960. (Advances in Chemistry Series 38)

_____ Sunshine fuel combine for desalination. *Chemical and engineering news* (Washington, D.C.) 40:72, 1962.

Cooper, P. I. Digital simulation of transient solar still processes. *Solar energy* (Elmsford, N.Y.) 12:3:313-331, May 1969.

_____ Some factors affecting the absorption of solar radiation in solar stills. *Solar energy* (Elmsford, N.Y.) 13:373, 1972.

_____ The absorption of radiation in solar stills. *Solar energy* (Elmsford, N.Y.) 12:333, 1969.

_____ The maximum efficiency of single-effect stills. *Solar energy* (Elmsford, N.Y.) 15:205, 1973.

Delyannis, A. Water from the sun. *New Scientist* (London) 34:388, May 1967.

Delyannis, A. *and* E. Delyannis. Sea water distillation through solar radiation. *Chemie-Ingenieur-Technik* (Weinheim, Federal Republic of Germany) 41:90, February 1969.
Text in German, summaries in English and German.

_____ The Gwadar, Pakistan, solar distillation plant. Paper prepared for the Solar Energy Society Meeting, Palo Alto, California, October 1968.

_____ Operation of solar stills. Paper prepared for the United Nations Solar Distillation Panel Meeting, October 1968.

Delyannis, A. *and* E. Piperoglou. Solar distillation development in Greece. *Sun at work.* 12:1:14, 1967.

Dunkle, R. V. A simple solar water heater and still. Paper presented at joint AIRAH-SES Meeting, Perth, May 1971.

_____ Solar water distillation: the roof-type still and a multiple effect diffusion still. University of Colorado, 1961. (International Heat Transfer Conference, part 5: International Dev. a Heat Transfer, p. 895)

Dzhubalieva, P. A. Determination of the aerodynamic coefficients of solar stills in relation to the leakage of steam-air mixture. *Applied solar energy* (New York) 1:4:31-36, July/August 1965.

_____ Effect of leakage from a solar still on its performance under thermal head. *Applied solar energy* (New York) 1:4:37-42, July/August 1965.

Edlin, F. E. Air supported solar still. E. I. du Pont de Nemours, US patent No. 3,174,915, March 1965.

Eibling, J. A., S. G. Talbert *and* G. O. G. Löf. Solar stills for community use—digest of technology. *Solar energy* (Elmsford, N.Y.) 13:263, 1971.

Gomkale, S. D. *and* R. L. Datta. Solar energy applications in India. *Solar energy* (Elmsford, N.Y.) 14:321, 1973.

_____ Some aspects of solar distillation for water purification. *Solar energy* (Elmsford, N.Y.) 14:387, 1973.

Hay, H. R. Plastic solar stills: past, present and future. *Solar energy* (Elmsford, N.Y.) 14:393, 1973.

Khanna, M. L. Solar water distillation in North India. *Journal of scientific and industrial research* (New Delhi) 21A:9:429-433, September 1962.

_____ Solar water distillation in North India. New York, Plenum Press, 1964.
Proceedings of the International Seminar on Solar and Aeolian Energy, Sounion, Greece, September 1961.

Lawand, T. A. *and* R. Alward. Plans for a glass and concrete solar still. *Brace Research Institute Technical Reports* (Macdonald College of McGill University, Ste. Anne de Bellevue, Quebec) 58, December 1968.

Löf, G. O. G. Application of theoretical principles in improving the performance of basin-type solar distillers. Paper prepared for the United Nations Conference on New Sources of Energy, Rome 21-31 August 1961. (Solar energy: III, v. 6, p. 266 (S/77))
Sales no.: 63.I.40.

Löf, G. O. G., J. A. Eibling *and* J. W. Bloemer. Energy balances in solar distillers. *AICHE journal* (New York) 7:4:641-649, December 1961.

Martens, C. P. Theoretical determination of flux entering solar stills. *Solar energy* (Elmsford, N.Y.) 10:2:77-80, April/June 1966.

Morse, R. N. Solar distillation in Australia. *Civil engineering* (New York) 38:39-41, August 1968.

_____ The theory of solar still operation. Paper prepared for the United Nations Solar Distillation Panel Meeting, October 1968.

Morse, R. N. *and* W. R. W. Read. A rational basis for the engineering development of a solar still. *Solar energy* (Elmsford, N.Y.) 12:5, 1968.

Morse, R. N., W. R. W. Read *and* R. S. Trayford. Operating experiences with solar stills for water supply in Australia. Paper presented at the Solar Energy Society Annual Meeting, Palo Alto, California, October 1968.

Proctor, D. The use of waste heat in a solar heater. *Solar energy* (Elmsford, N.Y.) 14:433, 1973.

Satcunanathan, S. *and* H. P. Hansen. An investigation of some of the parameters involved in solar distillation. *Solar energy* (Elmsford, N.Y.) 14:353, 1973.

Scope and development of solar stills for water desalination in India. *By* S. Y. Ahmed *and others. Desalination* (Amsterdam) 5:1:64-74, 1968.

Soliman, S. H. Effect of wind on solar distillation. *Solar energy* (Elmsford, N.Y.) 13:403, 1972.

Szulmayer, W. Solar stills low thermal inertia. *Solar energy* (Elmsford, N.Y.) 14:415, 1973.

Telkes, Maria. Fresh water from sea water by solar distillation. *Industrial and engineering chemistry* (Washington, D.C.) 45:5:1108, May 1953.

Tleimat, B. W. *and* E. D. Howe. Comparison of plastic and glass condensing covers for solar distillers. Proceedings of the Solar Energy Society Conference, Phoenix, Arizona, March 1967.

Weihe, H. Fresh water from sea water: distilling by solar energy. *Solar energy* (Elmsford, N.Y.) 13:439, 1972.

Reports published by the United States Department of the Interior, Office of Saline Water, Washington, D.C.

No. 13 Research on methods for solar distillation (by M. Telkes). December 1965.

No. 50 Study and evaluation of solar sea-water stills. September 1961.

No. 60 Development of an improved solar still (*by* W. N. Grune *and others*). March 1965.

No. 147 Second two years' progress on study and field evaluation of solar-water stills (by the Battelle Memorial Institute). July 1965.

No. 190 Final three years' progress on study and field evaluation of solar sea-water stills (by the Battelle Memorial Institute). May 1966.

No. 233 Conceptual design study of a 50 million gallon per day msf desalination plant and test module. November 1966.

No. 251 Parametric cost studies of the multistage flash progress. March 1967.

No. 276 Preliminary design of a diesel-powered vapour-compression plant for evaporation of sea-water. August 1967.

No. 355 Analysis and optimization of a multi-effect multi-stage flash distillation system. May 1968.

No. 438 Sea water corrosion control by environment modification. April 1969.

No. 479 Test facility and vertical-tube-evaporator test-bed plant, Freeport, Texas. Annual report. September 1969. (FY 1968)

No. 490 Multistage flash distillation. Desalting state-of-the-art, 1968. October 1969.

No. 492 Pilot plant tests and design study of a 2.5 MGD horizontal-tube multiple-effect plant. October 1969.

No. 546 Manual on solar distillation of saline water. April 1970.

No. 635 Seawater desalting with chemical recovery. January 1971.

No. 638 Economic analysis of the membrane water desalting processes. December 1970.

No. 641 Study of unconventional methods for brine concentration. April 1971.

The potential of solar agricultural driers in developing areas

T. A. Lawand

Brace Research Institute, Macdonald College of McGill University, Quebec, Canada

Introduction

Since the dawn of civilization solar energy has been used to dry and preserve agricultural surpluses. The methods used are simple and often crude, but reasonably effective. Basically, crops are spread on the ground or on platforms, often with no pre-treatment, and are turned regularly until sufficiently dried so that they can be stored for later consumption. The process is labour intensive, and little capital is required for equipment.

Diverse products such as fruit, vegetables, cereals, grains, skins, hides, meat, fish and tobacco are dried using these simple techniques. There is probably no accurate estimate of the vast amounts of material dried in this way. Sun drying is a wide-spread technology practised in almost every country of the globe and at nearly every latitude.

Since sun drying originated in many of the developing countries there is no major social problem in persuading local populations to eat dehydrated foods. The process presents several technical problems, however:

(a) It is intermittent, being affected by cloudiness and rain;

(b) It is affected by dust and atmospheric pollution;

(c) It is not safe from intrusion by people and animals;

(d) The products being dried are subject to infestation by insects.

In the more advanced segment of the society, whether in developing areas or in industrialized regions, artificial drying has often supplanted traditional sun drying in order to achieve better quality control, reduce spoilage and cut down on the losses and inefficiencies engendered by the above-mentioned difficulties.

The high cost of labour in most industrialized areas and, until recently, the low cost of fossil fuel permitted artificial, large-scale drying processes to be developed. The cost of dehydration was added to the cost of selling the process materials. The advent of higher charges for fossil fuels and the prospect of depletion and scarcity of these fuels have stimulated renewed interest in solar agricultural driers.

The amount of agricultural produce dehydrated in 1968 using solar energy has been estimated at 255×10^6 t. In that year alone Australia exported over 72×10^3 t of sun-dried foods worth over $27 million. Over the past three decades, interest in developing solar agricultural driers that make use of known principles of heliotechnology to combat some of the principal disadvantages of traditional sun drying has been increasing.

In evaluating technologies that might be suitable for developing areas, one should distinguish between small- and large-scale operations. Small-scale systems would be used where land holdings are not large, and individual farmers, fishermen and herdsmen produce only modest surpluses. The objective is to dehydrate these surpluses for use only by the family of the producer or for sale in the local market in the immediate vicinity. At times, small-scale surpluses of certain products such as peanuts or rice are delivered to central facilities for processing, dehydration and eventual marketing. These systems are generally well established and require a certain degree of organization in the industry. Such handling facilities, however, often do not exist. Therefore, in choosing technologies, one must differentiate between the existence of commercial and physical infrastructures within a given locality.

Large-scale systems invariably require an external power source. Where conventional electric power is available, reliable and not excessive in cost, it is logical to use it for operating fans and blowers, vents and duct baffles to increase the efficiency and operating performance of a solar agricultural system. Some driers are of the portable, powered type wherein solar air-heater collectors are fitted with electrically powered fans (gasoline or diesel engines could as well be used) and are taken directly to the areas of production for *in situ* drying. Traditionally this process was used with fossil fuel, often butane or

propane gas, as the energy source. As the price of these systems increases, the tendency is to develop systems of this nature that rely on solar energy to provide the bulk of the energy required for dehydration. In fact, fossil fuels are sometimes used to supplement these solar collectors in order to maintain optimum operating conditions in a system partially operated by solar energy.

The other major system applicable for dehydration in the industrialized sectors of developed and developing countries is to use the roof area of buildings as the solar collector, fitting the buildings with suitable blowers, ducts, collectors and often storage mechanisms. In the United States, California Polytechnic University and Thompson Ramo Wooldridge Systems have undertaken a project, funded by the Government, in which solar energy is to be used as a substitute for natural gas in dehydration. The State of California alone produces annually fruit and vegetables valued at over $450 million. The system will no doubt become increasingly economic as the cost of fossil fuel continues to escalate.

Another system receiving increasing interest in this field, both in developed and developing regions, is the use of greenhouses to dehydrate surplus produce. The combination of drying and greenhouse operations has many advantages and should be examined for each set of circumstances. Finally, an older, but certainly no less valid, system has been the use of heat extracted from the underside of roofs. This system, one of the oldest applications in solar agriculture drying, has proved quite satisfactory in a number of applications.

Basic principles of solar drying

The two principal phases of the process used in solar agricultural driers are the solar heating of the working fluid (generally air) and the drying itself, wherein the heated working fluid extracts moisture from the material to be dried.

The first of these phases can be accomplished in two ways: (1) Indirectly, by separate solar air-heater collectors using natural or forced convection to pre-heat the ambient air and reduce its relative humidity; or (2) Directly, by *in situ* heating of the air, which in turn directly dehydrates the produce.

A discussion of drying theory is beyond the scope of this paper, but a few principles applicable to direct radiation drying may be outlined here, since the principles involved in the drying of materials in opaque enclosures by means of hot air, whether from a solar heater or some other type of heating unit, have been examined elsewhere.

The first requirement is a transfer of heat to the surface of the moist material by conduction from heated surfaces in contact with the material, by conduction and convection from adjacent air at temperatures substantially above that of the material being dried, or by radiation from surrounding hot surfaces or the sun. Absorption of heat by the material supplies the energy necessary for vaporization of water from it, some 2.5 kJ (590 cal) per gram of water evaporated. Water starts to vaporize from the surface of the moist material when the absorbed energy has increased the temperature enough for the water vapour pressure to exceed the partial pressure in the surrounding air. Steady state is achieved when the heat required for vaporization becomes equal to the rate of heat absorption from the surroundings.

To replenish the moisture removed from the surface, diffusion of water from the centre to the surface of the drying material must take place. This process may be rapid or slow depending upon the nature of the material being dried and upon its moisture content at any time. It may thus be the limiting rate in the drying operation; or, if moisture diffusion is rapid, the rate of heat absorption on the surface or the rate of vaporization may be the controlling factor. In some very porous materials, vaporization may take place even below the apparent surface of the material, vapour then diffusing through pores in the solid.

In direct radiation drying, part of the radiation may penetrate the material and be absorbed within the solid itself. Under such conditions heat is generated inside the material and at the surface, and thermal transfer in the solid is facilitated.

For economic reasons, maximum drying rates are usually desired. Product quality must be considered, however, and excessive temperatures must be avoided in many materials. In addition, because drying occurs at the surface, materials that have a tendency to form hard, dry surfaces relatively impervious to liquid and vapour transfer must be dried at a rate sufficiently low to avoid this crust formation. The heat transfer and vaporization rates must be closely controlled, either by limiting the heat supply or by regulating the humidity of the surrounding air.

The drying of a product simply by permitting dry air to circulate around it, without the use of any direct or indirect heat source, is known as adiabatic drying. The heat required for vaporizing the moisture is supplied by the air to the solid material, thereby reducing the air temperature while increasing its absolute and relative humidity. Because the heat capacity of air is low in comparison with the high latent heat of vaporization of water, large volumes of air at reasonably low relative humidity must be used in this type of drying. Air leaving the drier is nearly saturated with water at the wet-bulb temperature. The moist solids in contact with this air approach the same temperature.

The foregoing generalization must be somewhat modified if the materials being dried are soluble, even to a small extent, in the water present. Fruits and other agricultural products contain salts and sugars that cause a lowering of the vapour pressure. The surface temperatures of these materials must

therefore be higher than the wet-bulb temperature of the air to permit vaporization to take place. This means that the adiabatic drying of these solids requires air at lower relative humidities than do the materials having no solutes in the aqueous phase.

An important property of materials processed by direct radiation drying is their absorptivity of radiation. Fortunately, most solids have relatively high absorptivities, but they may change as drying proceeds, the surfaces of the materials becoming less, sometimes more, "black" during the process. Also, there may be changes in opacity of the surface of materials that are partially transparent at certain wave lengths represented in the spectrum of the radiant source.

The thermal conductivity of the material is also an important property, particularly if it is dried in a layer of sufficient depth to require conduction of heat from particle to particle. If the thermal conductivity is poor, circulation of heated air through and between the particles of moist solid would permit better heat transfer than direct radiation on the surface of a deep bed of particles.

In large-scale dehydration systems, forced convection, generally powered with an external, non-renewable power source, increases the diffusion transfer of moisture and, if properly applied, increases the rate of dehydration and improves the quality of the produce.

Solar agricultural driers mainly used in developing countries for small-scale applications are described briefly below.

Classification of driers

Solar driers are classified according to their heating modes, or the manner in which the heat derived from the solar radiation is used. In this regard, several general categories have been set up, which are defined below. In general, a drier has been classified according to its principal operating mode. Some of the direct and mixed-mode driers also use circulating fans and are not, strictly speaking, totally passive systems. Driers using only solar or wind energy for their operations are classified as passive systems.

Sun or natural driers. These driers make use of the natural action of ambient solar radiation, and of the ambient temperature, humidity and motion of the air to achieve drying.

Solar driers–direct. In these units, the material to be dried is placed in an enclosure with a transparent cover or side panels. Heat is generated by absorption of solar radiation on the product itself as well as on the internal surfaces of the drying chamber. This heat evaporates the moisture from the drying product. In addition, it serves to expand the air in the enclosure, causing the removal of this moisture by the circulation of air.

Solar driers–mixed-mode (direct and indirect). In these driers, the combined action of the solar radiation incident directly on the material to be dried and pre-heated in a solar air heater furnishes the heat required to complete the drying.

Solar driers–indirect. In these driers, the solar radiation is not directly incident on the material to be dried. Air is heated in a solar collector and then ducted to the drying chamber to dehydrate the product.

Solar timber driers. These driers have been put in a special category, since they constitute an important application of this technology. In most cases forced ventilation is used, since proper circulation of air helps control the drying rate so as to avoid case-hardening.

Other definitions

A chamber drier is a drier in which the material to be dried is dried in an enclosure.

A rack, or tray, drier is one in which the material to be dried is placed on wire-mesh or similar holding racks.

A hybrid drier is a drier in which another source of energy, such as a fuel or electricity, is used to provide supplementary heat or ventilation.

The characteristics of one or two solar driers belong to each category defined above are described in the next section.

Characteristics of specific driers

Drying grapes on racks (Australia)[1]

In Australia, grapes have been sun-dried on racks for quite some time. In 1972, about 100 000 t of fresh grapes were rack-dried in 8-14 days.

The drying rack consists of 8-12 tiers of galvanized-wire netting. The wire netting is reinforced lengthwise along both edges with fencing wire. At each end of the rack, the load is taken by two heavy posts embedded in the ground and sloped and stayed against the strain. One 50-m drying unit is considered to provide enough rack space to dry the fruits from three acres (1.2 ha) of vines. At 3-m intervals along the racks, intermediate posts carry cross-supports for the tiers.

The rack can be covered by a roof to protect the drying grapes against rain or excessive sun, thus

[1] Principal investigator: J. V. Possingham, CSIRO Division of Horticulture Research, Adelaide, Australia.

leading to a product of a better quality. The roof is constructed of corrugated-iron sheets fixed crosswise. Equal overhangs on both sides of the rack keep dripping rain water away from the racks. There is no pitch to the roof, so that when wind from any direction accompanies rain, it will blow the water on the roof away from the fruit. Certain raisin species obtain a superior quality when shade-dried. To provide the shade, burlap side curtains are often placed on the rack. (The use of such curtains should be avoided in wet climates, since excessive humidity favours mould development.)

Natural vertical drier (Colombia)[2]

In Colombia, a vertical drying system designed for drying cassava particles has been tested. It consists of two wire-mesh panels pinned on two wooden uprights, which are set in the ground and act simultaneously as supports and end walls. Top and bottom openings make the drier easy to load and unload. The distance between the wire-screen walls was variable in the experimental prototype so as to allow the drying space to be charged with different loading densities of cassava on the exposed surface. The unit is covered with a wooden roof to protect the product from rain and to allow the drying to continue overnight. The drying method gives a high-quality cassava that is easy to handle and store.

Solar cabinet drier (Syrian Arab Republic)[3]

A cabinet drier designed for direct solar drying has been used in the Syrian Arab Republic to dry a wide variety of agricultural products on a small scale. It is easy to build from almost any kind of available building materials and simple to operate, maintain and control. Tested and used in many countries with different climates, this drier has proved to be very effective for its purpose.

The drier is essentially a solar hot box in which fruit, vegetables or other matter can be dehydrated on a small scale. It consists of a rectangular container insulated at its base and sides and covered with a double-layered transparent roof. Solar radiation is transmitted through the roof and absorbed on the blackened interior surfaces. Owing to the insulation, the internal temperature rises. Holes drilled through the base and outlet ports located on the upper parts of the cabinet side and rear panels provide ventilation. As the temperature increases, warm air passes out of the upper apertures by natural convection, fresh air being drawn up through the base. As a result, there is a constant perceptible flow of air over the drying matter, which is placed inside on perforated trays.

See-saw drier (Ivory Coast)[4]

The see-saw drier was originally developed in the Ivory Coast for drying coffee and cocoa beans. Its design was further refined under work sponsored by the Government of Ghana and FAO. This simple drier is suitable for small-scale drying and can be easily operated. Its use is envisaged for tropical regions. The see-saw operation permits the drying material to receive more direct sunshine during the day, increasing output and leading to a more evenly dried product.

The drier consists of a rectangular tray framed in wood and divided lengthwise into parallel channels of equal width. Retaining bars are placed crosswise. The bottom of the tray, on which the material to be dried is placed directly, is made of bamboo matting. The cover is made of a film of transparent PVC, which provides a substantial screening effect against ultraviolet light, thus reducing photodegradation of the product being dried. All the internal parts of the drier are coated with flat-black paint.

The drying frame is mounted on a north-south trestle whose height is equal to one fourth of the frame length. The see-saw motion is thus in the east-west vertical plane, so that the drying frame can then be tilted to face east during the morning and west during the afternoon.

The effective area of the drier is limited by two transverse retaining bars fixed at 200 mm from each end of the drying frame and two others set 300 mm apart in the centre of the drying frame. The three small black bands thus delimited by the retaining bars are left free from the product being dried; their purpose is to convert the radiant energy from the sun into heat. The heated air is circulated by natural convection from the lower to the upper end of the frame by means of gaps provided at each end. Additional air is also drawn through the matting base by the natural convective effect. The produce to be dried is loaded, with the frame horizontal, up to the level of the crosswise retaining bars, allowing clearance under the cover to allow free flow of air.

Glass-roof solar drier (Brazil)[5]

A glass-roof solar drier is similar to a greenhouse, except that it has a special ridge cap made of folded zinc sheet that allows the heated air charged with the

[2] Principal investigator: Gonzola Roa, Department de Ingeniera Agricola, Universidad del Valle, Cali, Colombia.

[3] Principal investigator: T. A. Lawand, Brace Research Institute, Macdonald College of McGill University, Ste. Anne de Bellevue, Quebec, Canada.

[4] Principal investigator: M. Richard and M. Vincent, Institut Français du Café et du Cacao, Paris, France.

[5] Principal investigator: Biswa Nath Ghosh, Centro de Pesquises do Cacav (CEPEC), Itabuna, B. A., Brazil.

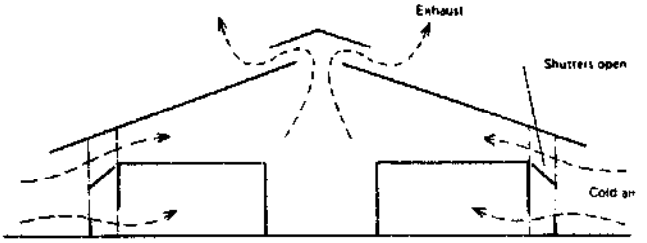


Figure 1. Air circulation in the glass-roof solar drier

moisture removed from the product to escape and fresh air to enter through side shutters. Inside the drier are rows of drying platforms along the long sides and a central passage for an operator. The long sides are oriented north-south and all inside surfaces are painted black to facilitate the absorption of solar radiation (see figure 1).

The drying surface is made of galvanized-iron wire mesh laid over wooden beams fixed across the platform. Strong metal wires stretched perpendicularly over the wood beams and under the wire mesh provide additional support to the loaded wire mesh during the drying operation. This permits heated air to pass easily through the wire mesh on which the product is being dried.

In the prototype drier, gas heaters are situated underneath one of the two rows of drying platforms and are used only during rainy periods or at night to shorten the drying time.

A free vertical space between the lower edge of the glass roof and the outer edge of the platform permits the proper ventilation of the drier. Six wooden shutters on hinges are located in this space along the length of the drier on each side, and they can be opened or closed independently to regulate the air flow inside during the solar drying hours.

Solar fruit and vegetable drier (United States)[6]

This simple chamber drier, operating in both the direct and indirect modes, was designed to dry food for domestic needs and for small restaurants. It has been successfully used for drying a wide variety of food products, ranging from fruits and vegetables to herbs and meat. Figure 2 gives a section view of this drier.

Air, pre-heated in a solar air heater located at the base of the drier, is admitted at the bottom of the drying enclosure. From there it rises through the drying racks, dehydrating the product laid on them, and is then exhausted, with its moisture content, through openings located at the top rear wall of the chamber by natural convection. Drying is also carried out with the help of direct sunlight reaching the product through the transparent sides, front and top panels. The drier faces south.

[6] Principal investigator: Peter Van Dresser, El Rito, New Mexico, United States.

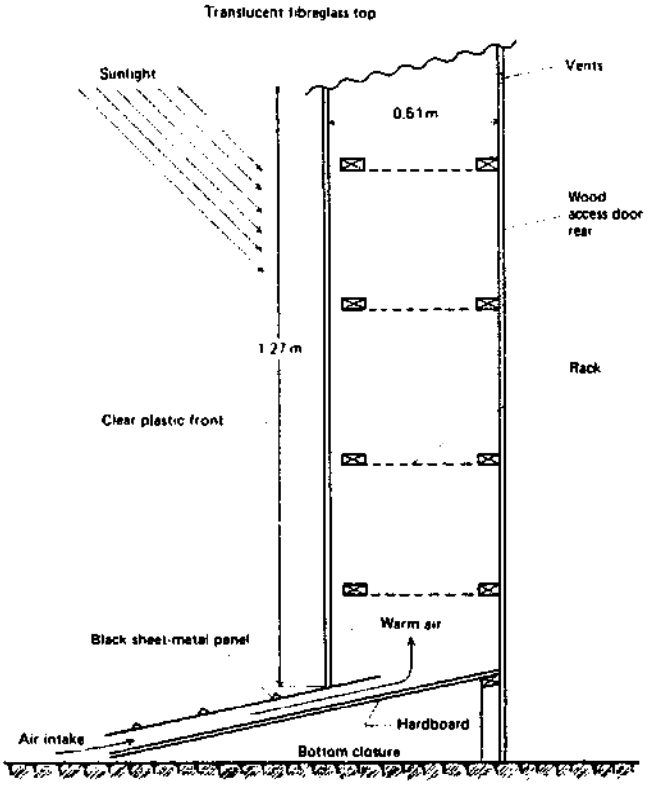


Figure 2. Section view of the fruit and vegetable drier

Solar wind-ventilated drier (Syrian Arab Republic)[7]

A solar drier in use in the Syrian Arab Republic has a unique air-circulation system. Air is drawn through the drier by a wind-powered rotary vane located on the top of a chimney. The temperature and air-flow rate are controlled by a damper. The drier is described in detail in the article by Assad Takla, on page 7.

Solar supplementary heat drying bin (United States)[8]

A conventional bin drier can be transformed into an indirect solar bin drier using the original structure of the drying bin. Considerable savings in fuel consumption will result.

The drying bin is oriented east-west, the side of the roof facing south being used as the solar heat collector (figure 3). This roof collector is sloped about 30° from the horizontal and is designed to produce an optimal temperature rise of 5°-12°C over the outside air. The bin structure provides about 1 m^2 of collector area for each 2 m^3 of grain. This ratio provides an acceptable drying rate for shelled maize The roof surface is painted black to absorb the

[7] Principal investigator: T. A. Lawand, Brace Research Institute, Macdonald College of McGill University, Ste. Anne de Bellevue, Quebec, Canada.

[8] Principal investigator: W. H. Peterson, South Dakota State University, Department of Agricultural Engineering, Brookings, South Dakota, United States.

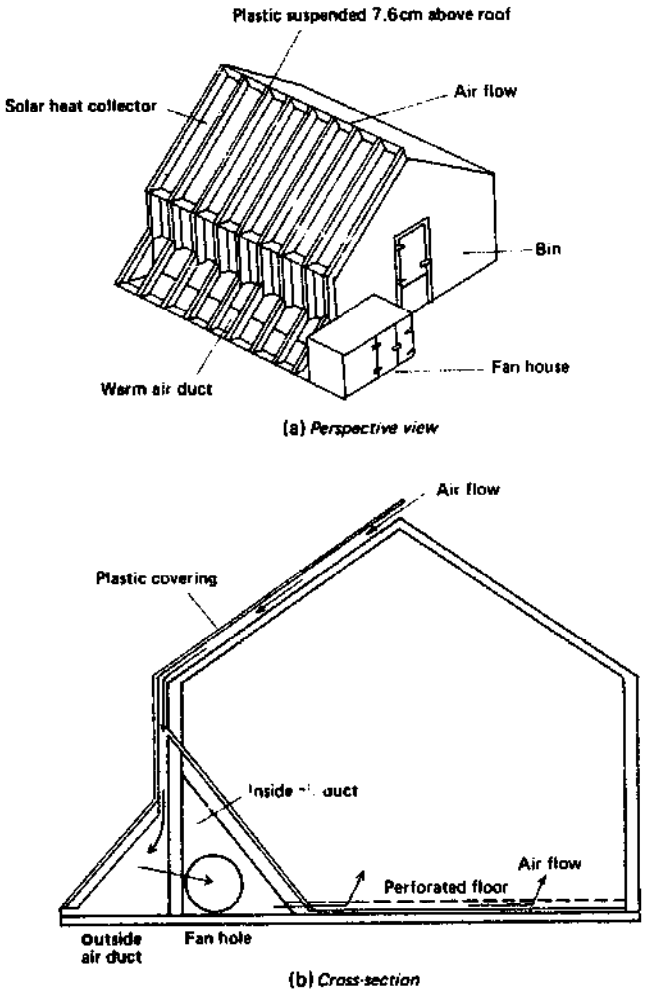


Figure 3. Solar supplementary heat drying bin

solar energy. A transparent plastic film is supported about 8 cm above the roof by stretching it over the framing members set edgewise. Air, drawn by a fan, enters the opening along the roof ridge and moves through the collector and down the south wall into the outside air duct. From there the fan pushes the warmed air into the inside air duct and through the grain by way of a perforated floor. The bin is designed to dry half its depth of shelled maize at one time (1.22 m). The fan should be able to deliver air at the rate of about 2 m^3/min for each cubic metre of corn to be dried, assuming the bin is full.

Large-scale solar agricultural drier (Barbados)[9]

The large-scale agricultural drier in Barbados was designed to dry feed for livestock, primarily corn. It operates in two stages handling 0.9 m^3 (770 kg) of freshly shelled corn per day. The first stage utilizes a mobile solar air-heated drying cart in which the moisture content of the freshly harvested corn is supposed to be reduced from 30% to 18% in the first day of operation. The corn is then transferred to an 18-m^3 capacity solar air-heated storage bin, where the moisture content is gradually reduced to the equilibrium moisture content of 13%. Particular attention was paid to the air-flow design so as to cause minimum pressure drop through all parts of the air heaters and drying chambers.

A centrifugal fan blows air through a diffuser duct into the solar field air-heated collector, which is 29 m long. The collector is fabricated from three plastic sheets—the top transparent, the centre a black mesh with 50% openings, and the bottom a layer of insulation sandwiched between two films, the upper one coloured black and the lower one, aluminium. The sheets are sealed along the long edges, and supported by tension straps every metre. The centre mesh rests on a rigid screen stretched between posts in the field. The collector is inflated on both sides of the tensioned layer and heats the air blown longitudinally through it. The end of the collector is connected to the mobile drying cart. The latter is insulated to reduce heat losses and fitted with air-flow dividers supporting a perforated drying floor. The fresh corn is loaded into the cart, which is covered by a sloping double-layered plastic roof.

When the moisture content has been reduced to the required level, the corn is fed into a blower and transferred to the storage-bin drier, where its moisture is gradually reduced to 13%. This drier is part of a farm building, one of the rooms being converted into a drying chamber, with a plenum chamber and perforated drying floor. The roof is used as a solar air-heater collector.

Solar timber-seasoning kiln (India)[10]

A solar timber drier was designed to increase the drying rate of timber as compared with the traditional air-drying method. This particular design makes use of large quantities of warmed air (up to 60°C) and permits rapid drying without undue degradation of the timber (cracks, warps).

The wood-frame structure of the kiln is oriented lengthwise on an east-west axis, the higher wall facing north. Except for the north wall, the whole structure is covered with two layers of transparent polyethylene film separated by an air gap; the north wall is sheathed with plywood. The roof faces south and is tilted at an angle of 0.9 times the latitude above horizontal (27°). The drying space in the kiln has room for about 3.5 m^3 of 25-mm planking. Inside the kiln, a false ceiling is installed above the wood stacks. A false north wall running the entire length of the kiln extends from the floor to the false ceiling and is

[9] Principal investigator: T. A. Lawand, Brace Research Institute, Macdonald College of McGill University, Ste. Anne de Bellevue, Quebec, Canada.

[10] Principal investigator: S. N. Sharma and Prem Nath, Wood Seasoning Branch, Forest Research Institute, Dehra Dun, U. P., India.

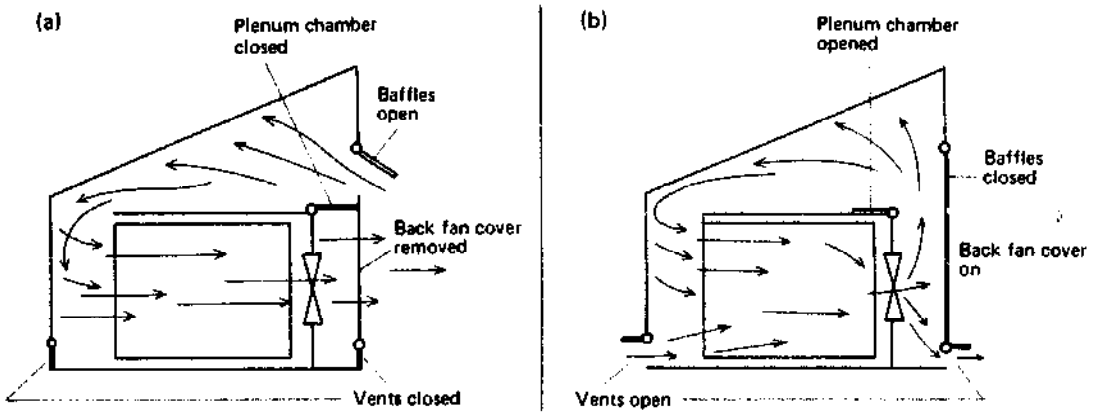


Figure 4. Solar timber-seasoning kiln working as *(a)* a single-pass forced-air drier; *(b)* recirculating air drier with partial venting

provided with a hole in its centre for housing the fan. The interior surfaces of the structural parts of the kiln (studs, pillars, false ceiling and wall, north wall, baffles and concrete floor) are painted black for maximum absorption of heat. The fan is driven by 0.75 kW reversible electric motor and is used for forced air circulation. The use of plywood baffles and movable partitions permits the drier to be used in either the single-pass or the recirculating mode (see figure 4).

BIBLIOGRAPHY

Akyurt, M. *and* M. K. Selcuk. A solar dryer supplemented with auxiliary heating systems for continuous operation. *Solar energy* (Elmsford, N.Y.) 6:4, 1962.

Akyurt, M., M. K. Selcuk *and* S. Akyurt. A continuous solar dryer. Paper prepared for the Conference of the Coopération méditeranéenne pour l'énergie solaire, Athens, October 1971. 4 p.

A two-pass solar air heater. *By* A. S. Satcunanathan *and others. Solar energy* (Elmsford, N.Y.) 15:1, 1973.

Bevill, V. D. *and* H. Brandt. A solar energy collector for heating air. *Solar energy* (Elmsford, N.Y.) 12:19-29, 1968.

Buchberg, H., D. K. Edwards *and* O. Lalude. Performance characteristics of rectangular honeycomb solar-thermal converters. *Solar energy* (Elmsford, N.Y.) 13:95, 1971.

Buelow, F. H. Drying crops with solar heated air. Paper prepared for the United Nations Conference on New Sources of Energy, Rome, 21-31 August 1961. (Solar energy: II, v. 5, p. 267 (S/17))
Sales no.: 63.I.39.

Close, D. J. Solar air heaters for low and moderate temperature applications. *Solar energy* (Elmsford, N.Y.) 7:3, 1963.

Davis, C. *and* R. I. Lipper. Solar energy utilization for crop drying. Paper prepared for the United Nations Conference on New Sources of Energy, Rome, 21-31 August 1961. (Solar energy: II, v. 5, p. 273 (S/53))
Sales no.: 63.I.39.

Dried Fruits Processing Committee. Grape drying in Australia. Melbourne, 1973 (CSIRO, ISBN-0-643-00054-4)

Ghosh, B. N. A new glass roof dryer for cocoa beans and other crops. Proceedings of the International Congress: The Sun in the Service of Mankind, Paris, 2-6 July 1973. p. 17.

Green, L. Solar heat for drying shelled corn. *Electricity on the farm magazine* (New York) 47:4:14-15, April 1974.

Gueneau, P. Une expérience de sèchage solaire du bois. *Bois et forêts des tropiques* (Nogent sur Marne, France) 131:69-78, 1970.

Gupta, C. L. Draft for action plan for solar drying. Pondicherry, India, Auroville Centre for Environmental Studies, 1973. (Occasional Paper No. 5)

Gupta, C. L. *and* H. P. Garg. Performance studies of solar air heaters. *Solar energy* (Elmsford, N.Y.) 11:25, 1967.

Ivory Coast. Ministry of Planning. Institute for Tropical Agricultural Products. See-saw sun dryer perfected by ITIPAT. Abidjan, 1966. 20 p.

Jordon, R. C. Low temperature applications of solar energy. New York, American Society of Heating, Refrigeration and Air-Conditioning Engineers, 1967.

Khan, E. U. The utilization of solar energy. *Solar energy* (Elmsford, N.Y.) 8:1:17-22, 1964.

Khanna, M. L. *and* N. M. Singh. Industrial solar drying. *Solar energy* (Elmsford, N.Y.) 11:2, 1967.

Lalude, O. *and* H. Buchberg. Design and application of honeycomb porous-bed solar-air heaters. *Solar energy* (Elmsford, N.Y.) 13:2, 1971.

Lawand, T. A. A description of two simple solar agricultural dryers. Coopération méditerranéenne pour l'énergie solaire, December 1965. (Bulletin No. 9)

_____ A solar-cabinet dryer. *Solar energy* (Elmsford, N.Y.) 10:4:158-164, October 1966.

Löf, G. O. G. Solar energy for the drying of solids. *Solar energy* (Elmsford, N.Y.) 6:4, 1962.

Lukes, T. Research on the application of solar energy to the food drying industry. San Luis Obispo, Calif., California Polytechnic State University, October 1974. (NSF/RANN/SE/GI 42944/PR/74/3)

Maldonado, E. D. *and* E. C. Peck. Drying lumber by solar radiation in Puerto Rico. *Forest products journal* (Madison, Wisc.) October 1962, 487-488.

McLean, K. Principles of sun drying with special references to a see-saw dryer. Rome, Food and Agricultural Organization, 1972. 40 p. (Report AGS, SF/GHA7)

Peterson, W. H. Harness the sun to dry grain. *World farming* (Kansas City, Mo.) 1968, 36-37.

_____ Solar heat for drying shelled corn. *ASAE transactions* (St. Joseph, Mich.) 73:302, 1973.

Phillips, A. L. A solar energy method for reducing coffee drying costs. *Journal of agriculture* (University of Puerto Rico) 17:4:226-235, October 1963.

_____ Drying coffee with solar heated air. *Solar energy* (Elmsford, N.Y.) 9:4:213-216, 1965.

_____ Evaluation of a "mylar" plastic film as a surface for a solar heat collector. *Journal of agriculture* (University of Puerto Rico) 49:4:484-486, October 1965.

_____ Further observations on the use of solar energy for reducing coffee drying costs. *Journal of agriculture* (University of Puerto Rico) 49:2:272, April 1965.

Read, W. R., A. Choda *and* P. I. Cooper. A solar timber kiln. *Solar energy* (Elmsford, N.Y.) 15:4, 1974.

Roa, G. Natural drying of cassava. Ph.D. thesis. East Lansing, Michigan State University, Agricultural Engineering Department.

Roa, G. *and* H. J. Cock. Natural drying of cassava. Proceedings of the Third Symposium of Tropical Root Crops. Ibadan, Nigeria, December 1973.

Santa Barbara, Calif. Community Environmental Council. How to build a solar herb dryer. By I. E. Thomas and M. Zilles. 10 p.

Selcuk, M. K., O. Ersay *and* M. Akyurt. Development, theoretical analysis and performance evaluation of shelf type solar dryers. *Solar energy* (Elmsford, N.Y.) 2:81-88, 1974.

Shove, G. Low temperature drying of shelled corn. *Electricity on the farm magazine* (New York) 47:4:16-17, April 1974.

Solar Energy Products Co. Soloron air heater. Avon Lake, Ohio, 1974. (Brochure distributed at the International Solar Energy Society Meeting, 1974)

Un nouveau type de séchoir experimentée en Côte d'Ivoire. *Café, cacao, thé* (Paris) 13:1:57-64, 1969.

Whillier, A. Black painted solar air heaters of conventional design. *Solar energy* (Elmsford, N.Y.) 8:1, 1963-64.

Wilson, B. W. The role of solar energy in the drying of vine fruit. Paper prepared for the United Nations Conference on New Sources of Energy, Rome 21-31 August 1961. (Solar energy: II, v. 5, p. 296 (S/4))
Sales no.: 63.I.39.

Publications of the Brace Research Institute, Macdonald College of McGill University, Ste. Anne de Bellevue, Quebec, Canada

A survey of solar agricultural dryers. December 1975. 151 p.

Goldstein, O. Production drawing for solar cabinet dryer. June 1973.

Lawand, T. A. Description and construction cost analysis of a solar agricultural maize drying system in Barbados. December 1966. 65 p.

_____ How to make a solar cabinet dryer for agricultural produce. March 1966. 9 p.

_____ Solar driers for farm produce. Progress report. April 1963. 59 p

_____ The drying of maize in a solar cabinet dryer. January 1966. 8 p.

_____ The evaluation of solar agricultural dryers for the processing of surplus crops. Proposal No. 3. April 1969. 3 p.

_____ The operation of a large-scale solar agricultural dryer. February 1967. 11 p.

Nahlawi, N. The drying of yams with solar energy. July 1966. 16 p.

Nevot, M. A. Proyecto de un colector solar para desecar cereales. Agosto de 1966. 53 p.

Ward, G. T. Suggestions for corn harvesting, drying and storage trials in Barbados. September 1965.

The potential of solar cooking in developing areas

T. A. Lawand

Brace Research Institute, Macdonald College of McGill University, Quebec, Canada

Several traditional fuels have been used in developing areas for cooking. These include:

	Approximate calorific value	
	(MJ/kg)	*(Mcal/kg)*
Dried animal dung	9	22
Firewood	20	48
Charcoal	33	80
Coke	30	72
Kerosene, oil	42	10

Each of the fuels has a varying degree of cooking efficiency. It has been estimated in India that the effectiveness of dried animal dung as a cooking fuel is very low, about 1.4 MJ/kg (0.34 Mcal/kg). Not all fuels are as ineffective as this. In Senegal for example, it has been estimated that 1 kg of butane gas has the same heating effect as 24 kg of charcoal.

Another factor should be taken into account. The traditional method of preparing food, which is boiling it in a large pot on an open fire, a gas stove or an electric hotplate is in itself very inefficient.

Because of their high water content, most foods have a high specific heat, close to that of water (4 kJ $kg^{-1}°C^{-1}$). The higher the rate of heating the faster the food will be heated to the cooking (boiling) temperature. Then, except when water vaporization is essential to the cooking process, as in baking bread, the speed of cooking is practically independent of the heating rate as long as the temperature is maintained by a heating rate equal to the rate of thermal loss. Thus, the differences in the times required for cooking equal quantities of food on cookers having various capacities for heating are due mainly to the different lengths of the heating-up periods. Thus cookers with high heating rates may require almost the same amount of time for cooking foods that must be cooked for several hours as cookers with low heating rates.

The largest of the heat losses in cooking is usually the heat consumed in vaporizing water present in the food or added for cooking, nearly 2.5 MJ/kg. Next in importance are the convection losses from utensils and oven walls. These losses can be cut down by the use of covers on the utensils, and of insulation on the oven walls. Estimating an hourly convection loss (outdoors), at boiling-water temperature, of about 6.8 MJ per square metre of utensil, and a surface area of 0.1 m^2 per kilogram of container contents, the energy input for 1 h of food boiling, if one fourth of the water present is vaporized, would be distributed roughly as follows (%):

Heating food to boiling temperature	20
Convection losses from vessel	45
Vaporization of water	35

Although variation in the assumed conditions would materially alter this distribution, the figures would still show that most of the heat supplied in long-duration cooking is dissipated.

The whole question of the transference of energy from the heat source to the cooking pot needs to be re-examined in order to improve the efficiency of this operation. Until boiling occurs, the coefficient of heat transfer into the cooking pot is low because the liquid is relatively stagnant. Food often burns, hence the necessity of stirring not only to increase the transfer of heat but to avoid localized concentration of heat. The mechanism of heat transfer into the cooking pot, even the shape of the cooking pot, has a profound effect on the design of solar cooking devices. In developing solar cooking technologies, the classical inefficiencies found in existing systems should not be repeated, especially in developing countries, where cooking may account for as much as 80% of all energy used.

Solar cookers similar in capacity and size to classical cooking systems are needed. The rate of energy supply in conventional cooking systems, is fairly high, in spite of their inefficiency. Where electric or gas cooking is used, the normal burner supplies energy at the rate of approximately 1 kW and is capable of bringing 2 l of water to boil in about 10 min. Automatic ovens for roasting or baking may have an installed capacity of approximately double that. Therefore, a solar unit would have to have an energy delivery rate of roughly 1 kW to be comparable with existing systems. The alternative would be accepting longer cooking periods and

possibly cooking smaller amounts of food at one time. A solar collector area of about 2 m^2 would be necessary (at 50% collection efficiency) to give comparable normal cooking rates.

Several basic types of solar cookers have been developed to date. A brief review of the bibliography will reveal the degree to which researchers in developing areas have devoted themselves to this subject. In developed countries, except for groups interested in appropriate technological systems, most attention has been paid to small production units for use by campers or weekend travellers. These units, either collapsible umbrella reflectors or hot boxes, are designed to be portable and compact.

Three types of solar collectors exist:

(a) Solar hot box, an insulated solar cooker with double glazing, generally in a form of a box set out in the sun and oriented manually (figure 1). To increase efficiency, reflectors are often added that make it possible to obtain higher temperatures in the interior cooking chamber. One of the inherent disadvantages of this type of cooker is that cooking must be done in the open, a feature that is often socially unacceptable, particularly during periods of warmer weather;

(b) Parabolic reflector solar cooker that concentrates cooking rays on a focal point or area on which a cooking pot or frying pan is placed (figure 2). Again this process requires cooking outside. There is an even greater heat loss than with the hot-box cookers owing to convection from the wind. The reflectors can effectively concentrate only direct radiation, with the result that these units are less efficient in areas having high percentages of diffuse radiation;

(c) Detached solar collection and cooking chamber unit. In these units the heat-transfer fluid, whether water converted to steam or heat-transfer oil, is heated in a separate collector, whether of the flat-plate type, as is the case with the solar steam cooker, or the concentrating type, as is the case with some of the hot-oil heaters. The heated fluid is transferred to a separate, insulated cooking chamber, which can be located on the inside of the house where the cooking is done. In this way it can reduce the social inconvenience of external cooking. (See figure 3.)

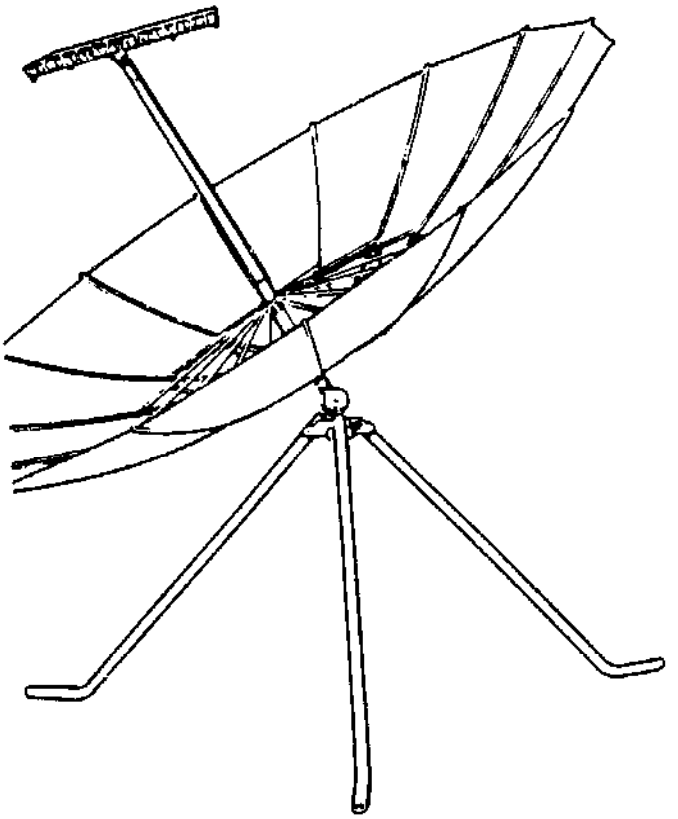


Figure 2. Parabolic reflector solar cooker, adjustable umbrella type

These systems have not been extensively field tested to date. Often the limiting technical factor is the transfer of heat into the cooking pot, though this factor is weaker in reflector cooking owing to the higher temperatures generated.

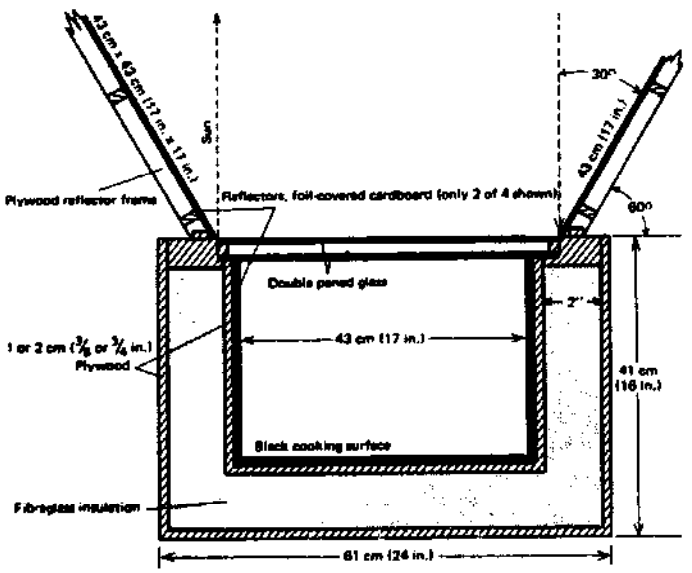


Figure 1. Solar hot box as a low-cost oven

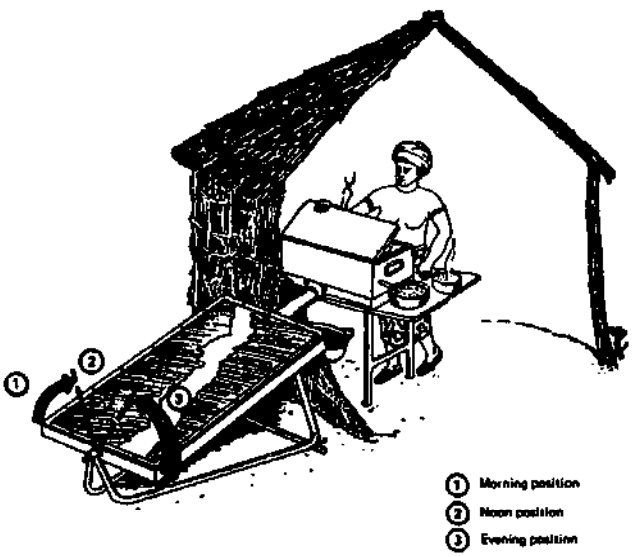


Figure 3. Solar steam cooker

COMPARATIVE COSTS OF COOKING WITH VARIOUS ENERGY SOURCES IN SENEGAL

	Butane (rechargeable reservoirs with gas burners)	*Electricity (urban areas)*	*Charcoal (urban areas)*	*Charcoal (rural areas)*	*Solar radiation (solar cooker with auxiliary butane burner)*	
					Model 1	*Model 2*
Capital investment ($)	19	15	10	10	150	200
Estimated life of equipment (y)	15	15	15	15	15	15
Annual capital recovery charge[a] ($)	2.64	2.09	1.39	1.39	20.86	27.81
Price of fuel ($/kg)	0.44	0.32[b]	0.10	0.06	0.44	0.44
Estimated annual fuel consumption (kg)	220	2 700[c]	1 750	1 750	44	44
Total annual fuel bill ($)	97.80	865	175	105	19.40	19.40
Annual maintenance cost ($)	1.90	–	–	–	22.88	30.38
Total annual cost ($)	101	867	176	106	66	81
Total annual cost if fuel price doubles ($)	198	1 732	351	211	85	100
Total annual cost if fuel price triples ($)	295	2 597	526	316	105	119

Note: All costs are calculated on an equivalent annual cost basis.

[a] Assuming 11% interest.

[b] In dollars per kilowatt-hour.

[c] In kilowatt-hours.

No comprehensive study of solar cooking technology has yet been made. It would be useful to collate all the existing information on cooking needs, available energies and similar types of problems so that it might be possible to determine what role solar cooking can play in meeting the energy needs of fuel-scarce societies. So many techniques have been developed that they need to be put into a compendium that can serve to assist societies in developing areas to either make use of these technologies or modify and adapt them to existing situations.

Programmes such as biogas conversion, which is actively being pursued in countries such as India, should be coupled with an investment in solar cooking technology, since the generated biogas has too high a potential to be wasted in cooking. It would be best used to generate mechanical shaft power or electricity, as has been demonstrated in India. Currently it must be used for cooking, since there are few alternatives.

Finally, with regard to economics: It was shown in Senegal that solar cooking with a smokeless wood stove as a back up (for the 10%-15% of the time when climatic conditions did not permit using solar energy) was far less expensive than using butane gas or charcoal. An example for Senegal is given in the table above, using two models of a solar cooker with an auxiliary butane burner. It is seen that making a capital investment in these units would in the long run be beneficial to the users.

BIBLIOGRAPHY

Abou-Hussein, M. Temperature-decay curves in the box-type solar cooker. Paper prepared for the United Nations Conference on New Sources of Energy, Rome 21-31 August 1961. (Solar energy: II, v. 5, p. 335 (S/75))
Sales no.: 63.I.39.

Alward, R., T. A. Lawand *and* P. Honley. Description of a large scale solar steam cooker in Haiti. Proceedings of the International Congress: The Sun in the Service of Mankind, Paris, 2-6 July 1973. P. 10.

_____ Une cuisinière solaire en Haïti. *Architecture concept* (Montreal) 28:312:2, March 1973.

Aprovechamiento de la energia solar en el altiplano Peruano. *Agronomia* (Monterrey, N.L., Mexico) 30:4, 1963.

Beason, R. G. Solar cooking turns practical. *Mechanix illustrated* (New York) July 1976.

Duffie, J. A. Reflective solar cooker designs. University of Wisconsin, Engineering Experiment Station. P. 9.

Duffie, J. A., G. O. G. Löf *and* B. Beck. Laboratory and field studies of plastic reflector solar cookers. *Solar energy* (Elmsford, N.Y.) 6:94-98, July 1962.

Duffie, J. A., R. P. Lappala *and* G. O. G. Löf. Plastics for focusing collectors. University of Wisconsin, Engineering Experiment Station. P. 9-13. (Reprint 327)

_____ Plastics in solar stoves. *Modern plastics* (New York) November 1957.

Food and Agricultural Organization, Nutrition Division. Report on tests conducted using the Telkes solar oven and the Wisconsin solar stove over the period July to September 1959. Paper prepared for the United Nations Conference on New Sources of Energy, Rome, 21-31 August 1961. (Solar energy: II, v. 5, p. 353 (S/116))
Sales no.: 63.I.39.

Ghai, M. L. Design of reflector-type direct solar cookers. *Journal of scientific and industrial research* (New Delhi) 12A:4:165-175, 1953.

_____ Solar heat for cooking. *Journal of scientific and industrial research* (New Delhi) 12A:3:117-124, 1953.

Ghai, M. L. *and* B. S. Phandher. Manufacture of reflector-type direct solar cooker. *Journal of scientific and industrial research* (New Delhi) 13A:5:212-216, 1954.

Ghosh, M. K. Sun cookers for villages. Paper presented for the All India Solar Energy Working Group and Conference, Indian Institute of Technology, Madras, November 1973.

Gupta, J. P. Studies on solar hot box. Paper prepared for the All India Solar Energy Working Group and Conference, Indian Institute of Technology, Madras, November 1973.

Jenness, J. R. Recommendations and suggested techniques for the manufacture of inexpensive solar cookers. *Solar energy* (Elmsford, N.Y.) 4:3, July 1960.

Khan, E. U. The utilization of solar energy. *Solar energy* (Elmsford, N.Y.) 8:1, 1964.

Khanna, M. L. Solar heating of vegetable oil. *Solar energy* (Elmsford, N.Y.) 6:2, 1962.

Löf, G. O. G. Recent investigations in the use of solar energy for cooking. *Solar energy* (Elmsford, N.Y.) 7:3, 1963.

_____ Use of solar energy for heating purposes: solar cooking. Paper prepared for the United Nations Conference on New Sources of Energy, Rome, 21-31 August 1961. (Solar energy: II, v., p. 304 (GR/16/(S))
Sales no.: 63.I.39.

Löf, G. O. G. *and* D. A. Fester. Design and performance of folding umbrella-type solar cooker. Paper prepared for the United Nations Conference on New Sources of Energy, Rome, 21-31 August 1961. (Solar energy: II, v. 5, p. 347 (S/100))
Sales no.: 63.I.39.

Neubauer, L. *and* G. Williams. Solar oven economy for farm homes. Paper presented to the annual meeting of the American Society of Agricultural Engineers, University of Nebraska, Lincoln, 1976. 12 p. (76-4021)

Performance of reflector-type direct solar cookers. *By* M. L. Ghai *and others*. *Journal of scientific and industrial research* (New Delhi) 12A:12:540-551, 1953.

Prata, Salgado. A cylindro-parabolic solar cooker. Paper prepared for the United Nations Conference on New Sources of Energy, Rome, 21-31 August 1961. (Solar energy: II, v. 5, p. 370 (S/110))
Sales no.: 63.I.39.

Sakr, I. A. Elliptical paraboloid solar cooker. Paper prepared for the International Congress: The Sun in the Service of Mankind, Paris, 2-6 July 1973.

Stam, H. Cheap but practical solar kitchens. Paper prepared for the United Nations Conference on New Sources of Energy, Rome, 21-31 August 1961. (Solar energy: II, v. 5, p. 38 (S/24))
Sales no.: 63.I.39.

Swet, C. J. A universal solar kitchen. Baltimore, Johns Hopkins University, Applied Physics Laboratory, July 1972. p. 23.

Tabor, H. Solar cooker for developing countries. Paper prepared at the annual meeting of the Solar Energy Society, Boston, Mass., March 1966.

Telkes, M. The solar cooking oven. New York University, College of Engineering, Research Division, January 1958.

Telkes, Maria *and* S. Andrassy. Practical solar cooking ovens. Paper prepared for the United Nations Conference on New Sources of Energy, Rome, 21-31 August 1961. (Solar energy: II, v. 5, p. 394 (S/101))
Sales no.: 63.I.39.

University of Florida. Solar cooking turns practical. *Mechanix illustrated* (New York) July 1976.

Vita Union College Campus. Solar cooker construction manual. Schenectady, N.Y., June 1967.

Whillier, A. A stove for boiling foods using solar energy. *Sun at Work*. 10:1:9-12, January 1965.

Publications of the Brace Research Institute, Macdonald College of McGill University, Ste. Anne de Bellevue, Quebec, Canada

Alward, R. *and* O. Goldstein. Assembly drawings for the construction of solar steam cookers: 3 drawings. February 1972.

A study of the feasibility of establishing a rural energy centre for demonstration purposes in Senegal. August 1976. 380 p.

Cheng, K., H. Wong *and* O. Tanaka. Experimental study of a solar steam cooker. Project for the Department of Mechanical Engineering, Course No. 305-463A-464B, May 1973, 47 p.

Greenwood, C. Effect of heat input from solar cookers on the ascorbic acid content of peas. Final year project for the Department of Food Science, Course No. 344-490D. March 1974. 56 p.

Pons, M. F. *and* G. T. Ward. La cocina solar construide en Chucuito, Puno, Peru. Diciembre 1963. 22 p.

Sinson, D. A. Design and performance evaluation of a 6 ft X 4 ft parabolic solar steam generator and its application to pressure cooking. April 1964. 67 p.

Vickery, S. The effect of the sunbroiler on the ascorbic acid content of sweet peas. Final year project for the Department of Food Science, Course No. 377-490D. March 1974. 57 p.

Whillier, A. A stove for boiling of foods using solar energy. April 1964. 13 p.

_____ How to make a solar steam cooker. Rev. February 1973. 2 p.

_____ Preliminary report on solar stove for cooking by boiling. September 1963. 10 p.

Assessment of solar applications for technology transfer

Jyoti K. Parikh

International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

Introduction

As the intensity of solar radiation is low, a considerable amount of land is required for utilizing solar energy. Solar applications would therefore be more suitable for a rural environment where land is easily available rather than for urban areas. Conventional centralized energy systems have not yet reached the large rural population in many developing countries. Solar applications which contribute to the development of a decentralized energy system could lead to significant improvements in the economic productivity of rural areas.

According to United Nations[1] estimates, in 1970 the rural population of the world was 2.26 billion, 1.89 billion of whom were in the developing countries. The percentage of persons living in the rural areas of the developing countries is expected to decrease from 75% in 1970 to 59.2% in 2000. However, their absolute number will still be 2.92 billion, a substantial increase over the present number. Figure 1 shows regional rural population growth trends, as projected by the United Nations.[2]

The energy requirements of rural people, although extremely low, are largely met at present by locally-available non-commercial resources such as firewood, agricultural waste and dung. Nevertheless, government energy planners in most of the developing countries are concerned primarily with the development of large energy systems, appropriate for urban and industrial purposes. Although efforts are being made in most of the developing countries to expand rural electrification, its progress is slow because it is capital intensive, especially when it

[1] United Nations, Department of Economic and Social Affairs, "Selected world demographic indicators", 1975 (ESA/P/WP.55).

[2] *Ibid.*

Figure 1. Past and projected rural population of developing regions

involves connecting remote villages to the network. Thus, there is a need for developing decentralized energy systems for rural areas.

Scientists and technologists do come up occasionally with solutions for decentralized energy systems. When these are not adopted they generally complain about the difficulties of technology transfer, resistance from established interests etc. Though these obstacles are not to be underestimated, their claims about the relevance of their research and development are many times found not to be valid for actual adaptations in field conditions when all the facts are put together. Therefore, a careful appraisal of the difficulties of the transfer of technology is essential.

In this paper we consider first the issues that are important in assessing technology. Then some of the solar technologies are evaluated keeping these issues in mind. Since photovoltaic cells are very expensive at present, we have considered for this analysis only decentralized low-power thermal devices. In particular, solar pumping is evaluated in detail as a case study.

The algebraic expressions introduced here can be used for application to any country; numerical results are given for the specific case of India.

Issues involved in the technology transfer

Here "technology transfer" means the transfer of invention from a laboratory to the field. It has to be recognized that the users cannot run an experimental energy system. Due weight has to be given to the perfection of the invention and the development of required institutions, such as establishments to look after the problems of the user. The user's viewpoint could be classified into two categories: techno-economic and social, with the latter referring to the operating environment in which the technology has to be used. In general, the following points need to be considered.

Private and social benefits

The benefits, savings etc. are often calculated on national, state or village levels and not for the consumer who is going to use the technology. Though benefits at the national level, such as the saving of foreign exchange, curbing environmental degradation overall health effects etc. are important, they are meaningful only if the new technology is acceptable to the user. If the user does not benefit when an invention needs to be promoted for national or social purposes, he has to be compensated if he is to be induced to use it. That means that a national policy involving subsidies, financing facilities, tax rebates etc. has to be introduced to promote better technology.

Thus, the cost-benefit analysis should be done also from the user's point of view together with the analysis from the social viewpoint. One then identifies the loss, if any, that the user would have to incur and to what extent society might subsidize him in view of the indirect costs it would have to bear if the new technology were not promoted.

Comparison with other alternatives

The economic benefits to the user should be calculated keeping in mind the best possible alternatives open to him. For example, if the advantages of biogas plants are calculated by taking petrol or even coal as the alternative, they would appear substantial. But the comparison actually has to be made with the cheapest possible alternative, i.e. burning dung and purchasing fertilizer, if needed. The positive and negative aspects of both alternatives should of course be carefully weighed. Only then can one understand why certain innovations are not catching on. In addition, possible future developments of the existing alternatives should also be considered.

Scale of technology

Some technologies may turn out to be unsuitable in economic and managerial terms if the proper scale is not chosen. For example, in some situations many small solar pumps may be more expensive than a large pumping station. Yet the small pumps may be preferable when the management problems associated with the different scales are considered. Again, giving an example of biogas technology, an earlier analysis[3] shows that a community biogas plant may be more economical and socially desirable than family biogas plants.

Introduction of technology

The manner in which a technology is introduced determines its success. For example, groups which benefit less or are adversely affected may offer resistance. Besides, at the planning stage itself, problems of co-operation, maintenance and repair would have to be dealt with.

Compatibility with the environment

If an invention requires a change in life-style or is in conflict with the surroundings, it will face difficulties in its adoption. In such a case, the

[3] J. K. Parikh and K. S. Parikh, "The potential of bio-gas plants and how to realize it", Proceedings of UNITAR Symposium on Microbiol Energy Conversion, Göttingen, Federal Republic of Germany, 1976.

strength of the existing establishment of older technology should be carefully assessed, and the question whether society is ready for the change should be considered.

Acceptance of technology

An invention has to be appropriate for the kind of use for which it is meant. For example, as will be demonstrated later in this paper, there is a need to consider the manner in which pumps are currently used when designing a solar pump for agricultural purposes.

It is therefore necessary that a Government with limited resources should evaluate new technologies carefully so that only appropriate ideas are encouraged. The development of inappropriate inventions may waste precious scientific manpower and limited research funds and also cause a loss in the credibility of new technologies in general. Even though they made good sense, many new technologies have failed because of the neglect of simple, practical considerations. An attempt will therefore be made to analyse the difficulties of technology transfer for one of the applications of solar energy within the context of the above-mentioned criteria. Although the general framework of the analysis is applicable to any country, a case study of India is carried out.

Solar pumps

Solar pumps for irrigation purposes would be a significant application of solar energy for the developing countries, where 40% to 50% of GNP originates in the agricultural sector, for which water is an essential input. Table 1 provides data on energized pump-sets and their electrical energy consumption in India. About 9% of the total electricity consumption in India is accounted for by energized pump-sets alone, despite the fact that hardly 20% of the villages were electrified in 1967, as shown in table 2. The number of pumps required in the next two to three decades may be more than 10 million. Table 2 also

TABLE 1. PUMP-SETS AND ELECTRICAL ENERGY CONSUMPTION IN INDIA

Past and projected trends

Year or date	*Number of sets in operation*	*Consumption*			
		By pump-sets (10^9 kWh)	*Total (10^9 kWh)*	*Per pump-set (kWh)*	*Per unit of connected load (kWh per kW)*
1966/67	649 182	2.107	33.26	3 245	842
1967/68	847 357	2.585	36.76	3 050	814
1968/69	1 088 774	3.466	41.46	3 183	834
1969/70	1 342 006	3.770	45.02	2 809	738
1970/71	1 642 006	4.110	48.65	2 503	657
31 March 1974	2 444 599				
31 March 1979	4 022 790[a]				
Projections[b]					
1983	6.5×10^6				
1990	12.0×10^6				
2000	20.0×10^6				

Sources: India, Ministry of Irrigation and Power, *Ninth Annual Power Committee Report*, New Delhi, 1972; K. S. Parikh, *Second India Studies: Energy* (New Delhi, McMillan Press, 1976), p. 55.

[a] Target figure.

[b] Taking into account population growth and the need for additional food production consistent with the ground-water potential.

TABLE 2. ELECTRIFICATION OF VILLAGES IN INDIA, 1961-1973

Village population range (1961 census)	*Number of villages*	*Number of villages electrified on 31 March*				
		1961	*1966*	*1971*	*1972*	*1973*
< 499	351 653	3 986	10 265	31 518	39 730	46 665
500-999	119 086	4 306	9 787	26 436	32 602	37 880
1 000-1 999	65 377	5 918	11 567	25 715	27 971	31 586
2 000-4 999	26 565	5 458	9 441	17 036	18 326	19 922
5 000-9 999	3 421	1 319	1 963	2 674	2 753	2 913
> 10 000	776	560	647	702	712	729
Total	566 878	21 547	43 670	104 081	122 094	139 695

Source: Central Electric Authority, New Delhi, 1974.

shows that the rate of electrification for small villages of 500 inhabitants is much slower than that for the large towns. In view of the slow electrification of the rural areas, the importance of the agricultural sector, and the high projected pumping needs, solar pumps could play an extremely useful role.

Techno-economic considerations

In order for solar pumps to be acceptable, they should provide adequate pumped water and be cheaper than the existing alternatives or sufficiently convenient for farmers to be willing to pay a higher price.

A general framework for such a techno-economic comparison between any two alternatives is developed below. The symbols used in the calculations are these:

Capital cost	K
Discount rate	d
Discounted cost	C
Lifetime of pump	l
Number of pumps required for a period T of service	n
Annual maintenance cost	m
Price of fuel	p
Distance	s
Time	t
Amount of fuel used annually	q
Annual operating cost ($= m + pq$)	O
Efficiency	η
Operating time (hours per day)	h
Installed capacity	c
Collector area	A
Average daily solar radiation per unit area	S
Work done	W

When necessay, the subscripts s, e and d will be attached to the symbols to refer specifically to solar, electric and diesel pumps.

There are many ways in which the costs could be worked out, some of which are illustrated below. If electricity is available, the solar pump would have to compete with electrical pumps; if not, with diesel pumps.

Average annual cost per unit of installed capacity

It is assumed that the annual cost of the loans made to finance the installation would be equal to half the rate of the interest d (discount) plus the operating costs. Neglecting inflation, but taking depreciation into account, the following equation is obtained:

$$K_s\left(\frac{d}{2}+\frac{1}{l_s}\right)+m_s = K_d\left(\frac{d}{2}+\frac{1}{l_d}\right)+q_d p_d(s,t)+m_d \quad (1)$$

A similar expression has been derived by Takla.[3] However, such an expression does not consider the different availabilities at night of the two alternatives being compared. Before this problem is considered, an exact formula for the discounted cost instead of the approximate form (1) will be given.

[3] See article by Assad Takla, p. 7.

Discounted cost for a given period of service

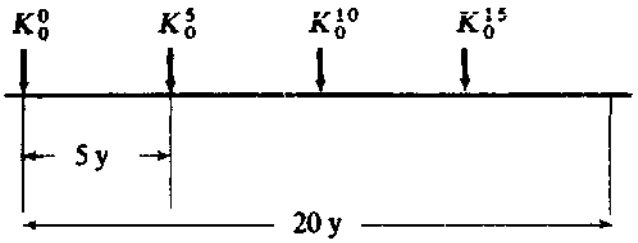
The discounted cost of installing capacity in the initial period for any option would be as follows:

$$C = K + \sum_{i=1}^{l} \frac{O_i}{(1+d)^i} \quad (2)$$

In order to compare solar and diesel engines, they must provide service over the same period T, since the lifetimes of the options may be different. The period T is chosen so that

$$n_s l_s = n_d l_d = T \quad (3)$$

Thus, if the lifetimes of the solar and diesel engines are respectively 20 y and 5 y one would require four diesel engines to provide the same service as one solar engine, with a new investment every 5 y which would have to be discounted on the initial period:



A general formula for discounting an investment every l years over the period $T = nl$ is

$$C = \sum_{j=1}^{T/l}\left(K + \sum_{i=1}^{l}\frac{O_i}{(1+d)^i}\right)\frac{1}{(1+d)^{(j-1)l}} \quad (4)$$

On the other hand, without storage capacity the solar pump cannot be operated for the same length of time each day as the diesel pump. In using the formula, the work that would be done by both these pumps in a day has to be taken into account. The following two cases are considered.

Slow rate of pumping. In some areas the rate at which water recharges may be slow, and hence there may be an effective limit to the rate at which water can be pumped. In this case, we have to compare two pumps of the same capacity. Since the solar pump can be operated for only about 6 hours a day and the diesel pump for 18-20 hours it means that the two pumps cannot be compared. In fact, the solar pump without adequate storage may not be considered a feasible option in this case.

Comparison of equivalent work. A solar pump works with an average efficiency of η_s for h_s equivalent hours of full capacity (see figure 2) where

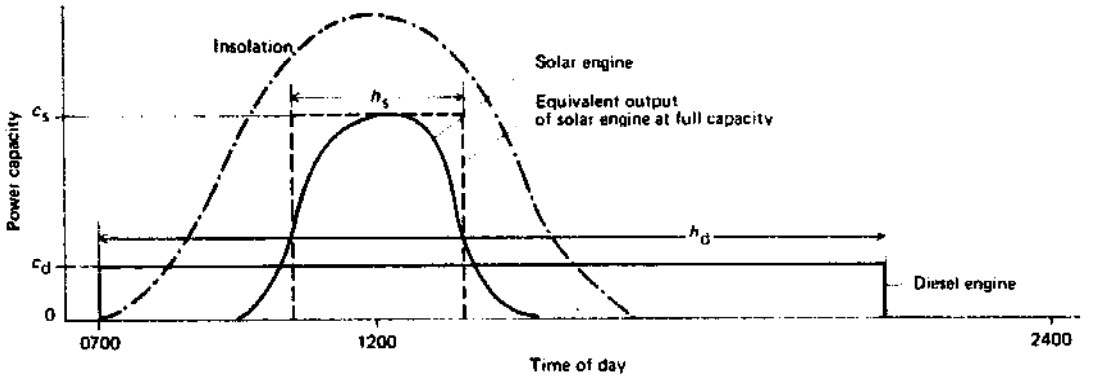


Figure 2. Diurnal variation of insolation and of the output of solar and diesel engines

an average daily solar radiation per unit collector area of S is available. The collector area required for the installed capacity c_s is A. The daily work done is

$$W_s = \eta SA \tag{5}$$

The diesel pump, on the other hand, can operate for a much longer time, say h_d hours. This may mean higher consumption of fuel but better utilization of the installed capacity, which is denoted by c_d. The daily work done in this case is

$$W_d = h_d c_d \tag{6}$$

Stipulating that

$$W_s = W_d \tag{7}$$

we have

$$\eta_s SA = h_s c_s = h_d c_d \tag{8}$$

Here $\eta_s = \eta_c \eta_p$, where η_c and η_p are the efficiencies of the collector and the pump respectively. Equation (8) makes it possible to determine both the value of c_s for equivalent work and the required collector area.

Numerical comparison between the alternatives

Having developed a general framework for a techno-economic comparison, the alternatives open to a user will be compared. In doing so, various elements of uncertainty should be considered, such as possible efficiency improvements, the cost of solar pumps, the escalation of diesel prices etc.

Present design and feasible technical improvements

Low-temperature pumps operating only on temperature differences will not be considered because the technology is not yet developed enough to give the required output, and because the main concern is a pump for agricultural needs. Instead, consideration will be given to an engine-driven pump, such as the one shown in figure 3.

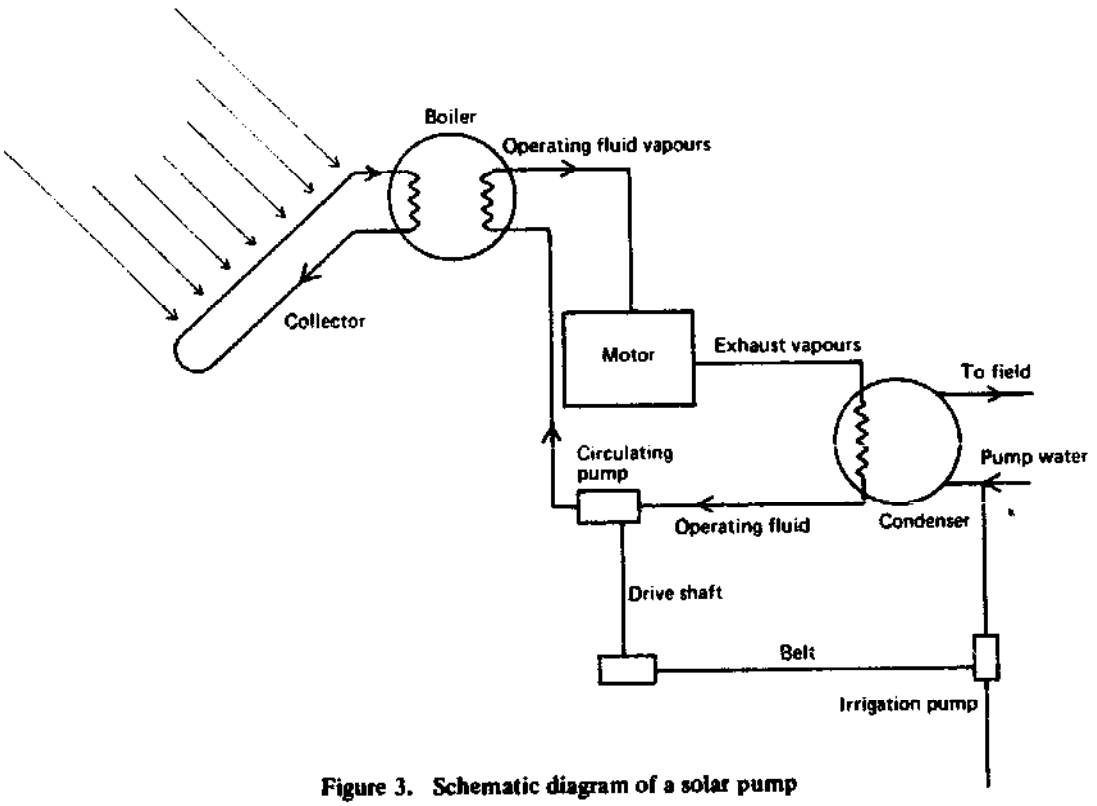


Figure 3. Schematic diagram of a solar pump

If a manual tracking system operating with concentrators utilizing Fresnel lenses is developed—a realizable goal—and other improvements in the design of solar engines and collectors are made, we can expect an efficiency of 10% in the near future.

Numerical values

To the advantage of the solar pump, it will be assumed that electricity is not available in the region, and that the alternative is to use a diesel pump. Considering the data in table 1, it seems that on the average, a farmer's requirements are met by a pump of $c_d = 4$ kW running 1 000 hours a year. A solar engine and a diesel engine required to drive such a pump will be compared. The lifetimes l_s and l_d are 20 y and 5 y respectively. The capital cost K_d is about 6 000 rupees ($600) for a 4-kW diesel engine ($K_d/c_d = 150$ $/kW). Further assumptions are: $O_s = m_s = \$50$; $m_d = \$50$ plus cost of lubricant ($20) = $70, and $p_d q_d = \$150$, giving $O_d = \$220$.

Operating conditions in the field are such that pumps have to run 18-20 or even 24 hours a day. A diesel engine can be run round the clock, whereas a solar engine without storage may be run for only 6-9 hours a day. Using equation (7), we find that the capacity of the solar engine would therefore have to be 2-3 times that of the diesel engine. These two possible capacities, with three scenarios of oil-price escalation—annual increases of 0%, 5% and 10%—were therefore considered.

Equation (4), with $d = 10\%$, was used to calculate discounted costs at constant (current) dollars; only price increases over and above inflation were taken into account. The results of the analysis are summarized in table 3.

The market price per unit capacity, of a solar pump is 15 000-20 000 $/kW. From table 3 it is seen that a reduction in price by a factor of 25 to 70 is required before a solar engine would be economically acceptable for driving an irrigation pump. If the pump is only to be used for obtaining drinking water, then it can be of the same capacity as the diesel pump and may run only 4-6 hours per day. From the table, it is seen that a price reduction by only a factor of 10-20 is required in this case.

Validity of assumptions

Most of the assumptions made in the above analysis are quite generous to the solar engine, as can be seen from the following considerations.

Technical assumptions. A solar engine with a lifetime $l_s = 20$ y is not yet available. Moreover, a solar engine with twice the capacity of the diesel engine would also require a hydraulic pump, driven by the solar engine, of twice the capacity of that used by the diesel engine. This additional cost of the hydraulic pump for the solar engine is not considered in the calculation.

The present analysis assumes an operating time $h_s = 6$-8 h without storage. So far, no solar engine has achieved $h_s = 8$ h even with storage. The engine designed by the National Physical Laboratory (India) has $h_s = 4$ h with storage. Storage requires additional collector area as shown in equation (5), the costs of which should also be included.

If adequate storage were to be provided so that the solar engine could be run with $h_s = 18$ h, the capacity of the solar engine need not be larger than that of the diesel engine. The break-even cost per unit capacity of such a solar engine, including the costs of collectors and storage, can be as high as 1 180 $/kW.

Economic assumptions. Although an electrical pump provides a cheaper alternative, the cost

TABLE 3. COST COMPARISON OF SOLAR AND DIESEL ENGINES IN PUMPING SERVICE

Item	*Annual increase in price of diesel oil* 0%	5%	10%
Discounted costs of diesel engine, $T = 20$ y		($)	
Capital cost	1 348	1 348	1 348
Operating cost	1 872	2 543	3 825
Total C_d	3 220	3 891	5 173
Less discounted operating cost of solar engine	(425)	(425)	(425)
Total break-even discounted capital cost of solar engine	2 795	3 466	4 748
Break-even cost per unit capacity			
In irrigation service		($/kW)	
$C_s = 2C_d = 8$ kW	349	433	593
$C_s = 3C_d = 12$ kW	233	289	395
In drinking water service only			
$C_s = C_d = 4$ kW	698	866	1 186

comparison has been made with a diesel pump. Since the analysis is concerned with a solution which could be adopted nation-wide, the question of the unavailability of diesel fuel in individual remote areas has not been considered. These areas might find the solar pump useful in the near future, especially for drinking water, as it may be the only feasible technology. However, we do consider the case of an eightfold increase in diesel fuel prices (10% annual increase) over 20 years relative to other prices, which are kept constant in the analysis.

However, if the solar pumps are manufactured in the developing countries, they could be cheaper than current quotations. For example, the pump developed in the laboratory in India[4] has a material cost of 1 200 $/kW. However, much progress is to be expected; and it remains to be seen what the costs of a commercial solar pump would be in the developing countries.

Operational problems of solar pumps

Given a solar pump which is of comparable cost to the other alternatives, it may be asked what are the other factors that need to be considered. Among those that have been ignored in the analysis above are climatic variations, the desired pumping pattern and the availability of land for collector installations.

Climatic and local variations

The intensity of solar radiation changes from month to month. The efficiency of utilization depends on the radiation intensity, the temperature, the cloud cover etc. In table 4, monthly variations of solar radiation, utilization efficiency and utilizable solar energy are given for two places, namely Nagpur, Madhya Pradesh (central India), and Jodhpur, which is in the western region near Rajasthan Desert. The table shows that in Nagpur the utilizable energy drops by a factor of 5 between the months of May and August. In fact, these are the months when water is required for cultivation. The reason why the solar radiation drops is that it rains in this period. In case the rains are delayed and it is nevertheless cloudy, the installed solar pump may not be useful, unless the collectors also collect diffuse radiation and the water requirements are met.

Pumping pattern

In hot regions, some of the farmers may prefer to pump during the evening or night-time so as to save loss of water due to evaporation. In such cases, storage may be essential.

Availability of land for solar collectors

The collector area required for a pump of certain capacity working a given number of hours a day is obtained from equation (8):

$$A = h_s c_s / \eta_s S$$

This could mean a collector area of 100 m^2 for a 4-kW pump.

In the developing countries, farms are small in size and an average farmer may not be willing to allocate even a small portion of extra agricultural land for the collectors when the area involved exceeds that required for alternative pumps. If the collectors are placed in such a way that sunlight for crops is

[4] See article by V. G. Bhide, p. 55.

TABLE 4. ANNUAL SOLAR RADIATION VARIATION AND TYPICAL EFFICIENCIES IN TWO INDIAN CITIES

		Nagpur			*Jodhpur*		
Month	*Number of days*	*Average daily radiation (MJ/m^2)*	*Utilization efficiency (%)*	*Total energy availability (MJ/m^2)*	*Average daily radiation (MJ/m^2)*	*Utilization efficiency (%)*	*Total energy availability (MJ/m^2)*
January	31	19.3	88	530	17.2	84	450
February	28	21.3	83	500	20.1	84	470
March	31	23.9	76	560	23.4	77	560
April	30	25.5	72	550	26.4	78	620
May	31	26.4	70	570	28.5	83	730
June	30	20.1	40	240	28.5	73	620
July	31	16.7	23	120	22.2	48	330
August	31	15.9	23	110	20.1	43	270
September	30	20.1	51	310	22.6	54	370
October	31	20.9	69	450	21.3	84	550
November	30	20.1	87	520	18.4	91	500
December	31	17.6	84	460	15.9	88	430
TOTAL	365			4 920			5 000

Source: The data on radiation and utilization efficiency are adapted from G. O. G. Löf, J. A. Duffie and C. O. Smith, *World Distribution of Solar Radiation* (University of Wisconsin, Solar Energy Laboratory, July 1966).

obstructed, then it may not be a preferred alternative unless the farmer is willing to grow certain types of vegetables which can be grown in the shade under the collector and other crops on the remaining land.

Other factors

Some other factors to be considered when developing a solar pump are these:

(a) Compatibility of possible peak load with the quantity of water required, i.e. the amount of water pumped in comparison with its requirement over a day;

(b) The availability of spare parts and necessary services and the availability of skills for repairs;

(c) Compatibility of water-table with the possible capacity of the presently available pump (however, if the rate of water recharge is small, the pump would have to run at low speed and continuously).

Summary

For the large and increasing rural population in the developing countries, decentralized solar energy applications would be quite relevant. An especially important application could involve the solar pump, in view of the additional food required to support growing populations. In India, the number of energized pump-sets may in the coming decades increase from 2 million to 20 million.

Crop yields depend primarily on the availability of water at certain periods of the year. A solar pump would therefore have to be designed to meet irrigation requirements under all possible field conditions. That means that a solar pump must have a higher capacity to do the same amount of work than a diesel pump. The foregoing analysis, which takes into account fuel price escalation, shows that the break-even cost of a solar pump is in the range 250-600 $/kW. The current cost of a solar engine is higher by a factor of more than 20. However, this cost could come down if the engines were manufactured by developing countries. If the engine is installed for obtaining drinking water, then six to eight hours of running time per day may be sufficient, and hence it could therefore be of the same capacity as the diesel engine. In this case, the break-even cost could be 1 200 $/kW. (Of course, if neither diesel nor electricity is available in some remote area, a solar pump might be the only solution.)

Moreover, even when economic solar pumps are developed, other factors based on climate, geography and the local, social and institutional environment must also be considered. For a successful transfer of technology, what is developed must be appropriate for the intended purpose.

Annexes

I. RECOMMENDATIONS OF THE EXPERT GROUP MEETING ON THE EXISTING SOLAR TECHNOLOGY AND THE POSSIBILITIES OF MANUFACTURING SOLAR EQUIPMENT IN DEVELOPING COUNTRIES*

A plan of action by UNIDO

I. Preamble: The Expert Group recognized that solar technology is a multidisciplinary area of activity with continued potential for successful economic applications in both industrialized and developing countries. Therefore, with due regard to the activities of UNIDO in the encouragement of applied R and D, manufacturing promotion and technology transfer in the field of solar technology is applicable to the needs of the developing countries, the Expert Group also recognized the fast growing technological advances in this field in industrialized countries and some developing countries, and the Expert Group places a great importance on UNIDO's capabilities of assisting developing countries through continued up-to-date sources of knowledge and effective assessment of fast growing technology.

Recommendation 1: Therefore, the Expert Group recommends that UNIDO establish an "Advisory Group on Solar Technology" on an honorary basis. Such an Honorary Advisory Group shall consist of selected eminent technical personnel in solar technology, both from industrialized and developing countries, and shall act as the "focal point of reference and technical contact" for UNIDO. Each member of the Advisory Group will be requested to advise UNIDO in his individual and honorary capacity in a technological information dissemination system. The Advisory Group at the request of UNIDO, will meet on an *ad hoc* basis to discuss specific technical problems, assist the UNIDO secretariat and also be available to render short term Expert Consultancy Services in the field when requested by UNIDO. Such field services shall be based on a non-conventional financial basis, with a token recognition fee only.

II. Preamble: The Expert Group is of the strong opinion that solar technology, in terms of scientific and theoretical principles, is well established. However, it is the transformation of scientific principles into technological hardware which is still under intensive work in industrialized and a few developing countries. For example: *(a)* Only collectors (flat plate and small concentrated type) and water heaters are commercially available; *(b)* the simple water distiller stills, simple dryers and cookers have been successfully manufactured but have not yet been taken up on an industrial production basis primarily due to need for market development and extension; *(c)* the pump system, space heaters (household, industrial, recreational, etc.), driers, compact cookers, solar generators, multi-stage distillers and intermittent low temperature absorption refrigeration systems have been successfully designed and fabricated by a few manufacturers and Institutions (any judgement on large scale manufacturing possibilities/investment promotion could be given only after field trials with emphasis on reliability and performance analysis); *(d)* the refrigeration system (solid absorbers: calcium-chloride and others) and air-conditioners are still in the prototype stage and require further R and D work and field testing of prototypes; *(e)* the central power station system is in the conceptual stage and has a great future potential; *(f)* solar cells for space application have been successfully designed, manufactured and used in selected industrialized countries. However, transformation of the same to large scale terrestrial usage requires further technological work to reduce costs. Solar cells, however, hold a great promise to all countries.

Therefore the work of UNIDO in the promotion of solar technology and eventual manufacturing programmes should be geared up to different levels of "State of the Art" and future potential.

Recommendation 2: In order to promote the concept of solar technology and its potential to the developing countries, UNIDO should collect available information and make it available to all developing countries and Institutions in industrialized countries. In addition, UNIDO should launch a programme for preparation of the specific technical manuals (sources of information, State of the Art, etc.) and also organize workshops and initiate fellowships (training) for the benefit of developing countries.

Recommendation 3: UNIDO should assist developing countries, at their request, in negotiating with foreign manufacturing firms for local manufacture of well-established commercial products, with emphasis on assessment of technology, suitability for local application, performance evaluation through local testing and commercial/techno-economic negotiations in manufacturing. It is recommended that at the request of the developing country, UNIDO become the active adviser in all such negotiations with a view towards achieving a most satisfactory agreement with due consideration to the interests of the developing countries.

Recommendation 4: UNIDO should actively associate with the programmes of development of selected R and D Institutions of industrialized countries and also of selected developing countries, with reference to products that have been fabricated but require further testing. In this connection, UNIDO shall act as an active partner in twinning of Institutions in industrialized and developing countries and assist in installation of such prototypes in developing countries through testing and techno-economical evaluation. Assistance in transformation of the test prototypes to "commercial manufacturing prototypes" is also necessary. UNIDO shall also assist the Institutions of developing countries in securing

*As they appear in the report of the Meeting (UNIDO/IOD.73), except for correction of obvious errors in spelling and grammar; the report was not formally edited.

such a technology and in manufacturing promotion. In this connection, UNIDO at the request of developing countries, should depute appropriate experts to assist the Governments in formulating such an integrated programme and also assist in the effective realization of the same.

Recommendation 5: UNIDO, through active association with selected R and D Institutions of industrialized countries shall assist R and D Institutions of developing countries in keeping informed about the activities in the conceptual stage and of activities which have a great potential future.

III. Preamble: The Expert Group—taking into account the required level of technological infrastructure, the continuous technological changes that are taking place and the need for adaptation of technologies and prototypes through field testing, as well as laboratory analysis, adaptation, negotiation for local manufacture and local entrepreneurship development—attaches a great importance on technology transfer from industrialized countries as well as co-operation among developing countries.

Recommendation 6: The Expert Group recommends that UNIDO assist all interested developing countries at their request to establish or strengthen appropriate national Institutions with emphasis on applied R and D, evaluation of technologies, negotiations on manufacture and local entrepreneurship development. The work programmes should take into consideration the local needs, level of technology, product priority and potential, and operate on the basis of technology transfer from Institutions of industrialized countries, with emphasis on co-operation among developing countries, with a view towards developing local capabilities. In this connection, UNIDO shall assist the developing countries in making judicious decisions with respect to programmes on solar technology development: R and D, institutional, investment promotion and manufacturing promotion.

Recommendation 7: In order to *(a)* promote co-operation among developing countries, *(b)* mobilize technological and financial resources, *(c)* promote the concept of self-reliance, and *(d)* utilize effectively the technological accomplishments and capabilities of selected developing countries for the benefit of other developing countries, it is recommended that UNIDO strengthen appropriate existing Institutions in selected developing countries (which have technological, industrial and infrastructural capabilities) and transform the same into "Solar Energy Centres of Excellence" with the objective of developing an applied R and D programme for the benefit of other interested developing countries. Therefore, the Expert Group recommends that UNIDO ascertain the interest of selected potential developing countries in being associated in this programme, to become one in the nucleus of the activities within the framework of co-operation among developing countries, and assist the local Institutions to develop an integrated work programme of applied R and D, assessment of technologies, and evaluation of prototypes and products, disseminate technological information and techniques, train technical personnel from other developing countries and promote entrepreneurship development. Such "Centres of Excellence" should also make available prototypes and designs and technologies to other developing countries, engage in co-operative evaluation and develop a programme for eventual local manufacture of appropriate products with due emphasis on relevant technology. In this connection, UNIDO should also develop a co-operative programme between two such "Centres of Excellence". It is also strongly recommended that UNIDO activities promote co-operation and transfer of technology to such "Centres of Excellence" by Institutions and manufacturers from industrialized countries.

IV. Preamble: The Expert Group is of the strong opinion that practical use of solar energy has become a reality and that the world today has entered this threshold. It is a technology with great potential and it is of great benefit to the needs of developing countries. The work will require applied R and D, technology assessment, prototype field analysis, assessment of reliability of products, including techno-economic and cost analysis, development of manufacturing technology, entrepreneurship promotion and eventual local manufacture. Therefore, the Expert Group is of the opinion that UNIDO should take leadership and initiative and develop an integrated programme of action.

Recommendation 8: It is recommended that UNIDO develop an integrated short term and medium term action programme for the benefit of developing countries. In this connection, it is recommended that UNIDO develop a co-operative programme with Institutions and manufacturers in industrialized countries as well as in developing countries. Special emphasis is to be paid to co-operation from other United Nations organizations and agencies, as well as appropriate intergovernmental and non-governmental organizations.

Recommendation 9: It is recommended that the Governments of developing countries give sufficient priority on initiation of a programme of action in the field of solar technology. This may require allocation of a solar technology programme to an existing appropriate Institution and provision of relevant finances and technical manpower and development of a practical work plan. In addition, it is also recommended that the Governments, through existing meteorological Institutions, initiate the necessary steps for collection of appropriate data, with a view towards assisting and guiding a solar technology programme.

Recommendation 10: It is recommended that UNIDO take an active role with the Governments of industrialized countries on the concept of initiation of appropriate integrated activities through UNIDO for the benefit of developing countries. In this connection, the Expert Group strongly urges that UNIDO initiate a programme to secure financial contributions from industrialized countries for integrated solar energy projects and initiate meaningful and effective plans of action.

Recommendation 11: As finances are most important for initiation of any solar technology programme, it is recommended that Governments of developing countries earmark appropriate finances for such an activity. In addition, it is also recommended that UNIDO initiate a programme to secure appropriate contributions (financial and in-kind (physical facilities, technology, etc.)) within the framework of co-operation among developing countries.

II. CURRENT IEA PROJECTS IN SOLAR ENERGY

In November 1974, the International Energy Agency (IEA) was established. Its members are Austria, Belgium, Canada, Denmark, Germany, Federal Republic of, Ireland, Italy, Japan, Luxemburg, Netherlands, New Zealand, Spain, Sweden, Switzerland, Turkey, United Kingdom of Great Britain and Northern Ireland, and the United States of America. Norway and the Commission of the European Communities participate as observers.

IEA consists of several committees, one of which is the Committee on Energy Research and Development. The Solar Energy Expert Group within this Committee has developed five co-operative projects in solar heating and air cooling of buildings and solar radiation measurement and analysis. In November 1975, the IEA Governing Board approved projects in seven new technological areas, including solar power systems, wind energy, ocean thermal energy and biomass conversion. Five of the projects undertaken are described below.

Project 1. *Development of solar heating, cooling and hot-water supply systems*

The objective of project 1 is to organize co-operation among the participating countries in two areas: The first area covers modelling and simulation of solar heating, cooling and hot-water supply systems in order to calculate their thermal performance. The second covers measuring and reporting the thermal performance of the systems and reporting on their durability and cost. This work is expected to provide a basis for the cost-benefit optimization of such systems.

The successful completion of this project will have the following results:

- Information on an evaluation of existing computer programs for calculating thermal performance of systems
- A standard international procedure for measuring thermal performance of systems
- Information on thermal performance, durability and cost of existing and, especially, new systems
- A procedure for designing the most economical systems

Project 2: *Development of components for solar heating, cooling and hot-water supply systems*

The objective of project 2 is to accelerate the development of the components of solar heating, cooling and hot-water supply systems by reviewing and exchanging information on continuing and new development programmes in the participating countries.

The viability of solar heating, cooling and hot-water supply systems for commercial application depends upon the effectiveness of the key components. Major R and D efforts are, accordingly, being undertaken in participating countries to improve performance and durability and to reduce the costs of the key components.

The key components of the solar heating and cooling system that will be included in this project are:

- Solar collectors
- Thermal energy storage
- Solar air-conditioning
- Other major components, as appropriate

Project 3: *Performance testing of solar collectors*

The objective of project 3 is to develop and use standard test procedures to rate the performance of a broad class of collectors for heating and cooling applications.

The collector is a key component in a solar energy system. Many collector designs with a broad range of qualitative differences are known. Performance testing to rate the technical and economical potential of the component collector is urgent. Therefore, standardized methods must be used to determine the efficiency or the energy output of a collector and to predict its reliability and durability. It is expected that performance rating can be achieved by specifying a few characteristic qualities, such as optical, thermal, and mechanical properties. A performance test procedure must allow one to measure or to state these properties. The interim test procedure (NBSIR-74-365) proposed by the National Bureau of Standards (NBS) of the United States is a first step in this direction. This test procedure is already used or under consideration in many member countries as a basis for further development. The difficulties inherent in the NBS procedure are due to a restriction in environmental conditions that permits testing in climatic regions such as in central Europe only during a few weeks of the year. These problems may be solved by applying simulators, i.e., by applying artificial suns and reproduceable climatic conditions in climatic chambers. The applicability of simulation is a main goal of this project.

The successful completion of all the tasks will *(a)* yield reliable data for system design; *(b)* provide engineering advice in collector design; and *(c)* provide a basis for quality standards. Thus, the test procedures must be scientifically correct, sufficiently accurate and as simple as possible.

The goal of the research work is to reduce performance testing to the evaluation of a set of characteristic parameters that define the optical, thermal and mechanical properties. To achieve this goal, four tasks have been identified:

- Development of recommended test procedures to determine outdoor thermal performance
- Development of recommended test procedures to determine indoor thermal performance

Development of recommended long-term outdoor and accelerated indoor test procedures to determine mechanical performance

Concise documentation of the results in a collector reference book

Project 4: *Development of an insolation handbook and an instrumentation package*

The objectives of project 4 are *(a)* to compile and distribute a handbook on insolation and related weather measurements for solar energy applications and *(b)* to design, build, test, evaluate and recommend a portable, low-cost insolation and related weather data instrumentation package to be used for measurements at the site of a solar energy system, both before and during its operation. This instrumentation package will provide essential data in a suitable format for many studies on solar energy application and system designs. It will also be used to gather data for system or subsystem performance evaluations.

A significant and well-developed body of knowledge and experience in insolation and related weather measurements exists in national meteorological centres throughout the world. This knowledge, however, needs to be summarized, and used in the many developing national solar energy programmes. The handbook to be developed as part of this project is designed to meet that need.

Each country, anticipating the future significant use of solar energy, should have the means to measure solar radiation and related parameters in all of its climatic regions, and in areas where population or industrial growth is forecast or at potential solar energy utilization sites. In addition, the design and evaluation of solar energy systems and components requires certain data on solar radiation and weather. The instrumentation package that is one of the subjects of this project will be designed to provide that data within the constraints of low cost and portability.

The successful completion of this project will *(a)* provide a valuable data resource—the *Insolation and Related Weather Measurements Handbook*, drawn together by international experts and disseminated to IEA member countries, *(b)* significantly facilitate the understanding of the insolation and weather aspects of systems tests and demonstrations in the participating countries and *(c)* provide for a more effective and usable exchange of information on the performance of these systems, which will permit each participating country to fill in the gaps in its own national programme with the experience and results of activities in other countries.

Project 5: *Use of existing meteorological information for solar energy application*

The objectives of project 5 are *(a)* to determine the quantitative relationship between measurements of solar radiation and other meteorological parameters and *(b)* to develop an internationally uniform system of presentation of solar radiation data to facilitate the calculations for utilizing solar energy.

The project will concentrate on two major tasks: *(a)* to advise on methods of estimating the solar radiation incident upon a horizontal or an inclined surface by means of solar radiation measurements or other meteorological data and *(b)* to improve the quality of current and past records of solar radiation and to make them available in standardized form.

III. SOLAR ENERGY INFORMATION SYSTEMS*

General

Ideally, an information system in the solar energy field should provide for the following functions:

Support of R and D, by ordered dissemination of information on past and current research results

Technology transfer, by providing repackaged research and development results in a form suitable for direct application

Planning data, for example on climatic parameters, but also including cost and economic data, standards, legislative and regulatory aspects, etc.

The survey has so far concentrated on the support-of-R-and-D role, as probably being the most important at this early stage, when several countries are still in the programme planning stage. Nevertheless, in the long term the other information system functions are at least of equal importance. At present, most of the countries for which data have been obtained are not yet in a position to implement information systems in technology transfer and planning data in solar energy, although there are plans for such activities and in one case (the USA) these plans are in the early implementation stages.

The concept of a total information programme is also being discussed, particularly in the USA; such a system is designed to perform multiple functions, ranging from the traditional R and D support role through technology transfer to information aimed at local authorities, public utility organizations and even the general public, to promote the use of solar energy as a means of conserving or replacing other energy resources.

Even in the area of R and D support, however, the results of the survey so far obtained show that in most countries the situation has not yet crystallized to the point at which the special needs of the scientists and engineers active in the field have been assessed and a database constructed to meet the needs. The information resource in general is scattered throughout a wide variety of journals and laboratory reports, and except in the USA and possibly in the Federal Republic of Germany, is not yet being organized for easy access.

Scope and coverage—the information resource

Solar energy, from a scientific and technical information point of view, is a sub-field of energy as a whole, and like energy information generally is "transdisciplinary", i.e. the information required by a project team engaged in an R and D project is to be found in many of the sub-disciplines of physics, engineering and other sciences. For project planning, access to meteorological and possibly geological information will be required, and for planning and assessment work, resource data and economics will also be necessary.

It follows that while subdivisions of the field may be useful for the purpose of classifying documents, the total stock of information cannot and must not be divided into isolated blocks, one relating to power systems, another to heating and cooling applications, a third and fourth to solar thermal and photovoltaic conversion methods, etc. A database relevant to solar electric power generation cannot be uniquely identified as a separate entity distinct from that for any other area of research, development or application. Indeed, in many analytical and assessment studies in solar energy using, for example, systems analysis or technology forecasting techniques, access to other areas of energy information might be required in addition.

The scope and coverage of scientific and technical information in solar energy is well illustrated by the following solar energy category definition in the current ERDA Energy Information Database subject category listing.

"Information on conversion of solar radiation to useful amounts of electric energy, the use of solar energy for heating and cooling, or any other use of solar energy that might contribute to the total energy budget. Information relating to all technical aspects of the design, research and development, manufacture, testing, and operation of solar cells and solar collectors are included. Also included is information on materials with indicated utility in solar cells or solar converters."

Size and characteristics of the database

Taking the above definition of scope and coverage, there are probably some ten thousand relevant articles, reports and monographs, mainly in the English language, which constitute the basic information resource. This probably does not include much material from Eastern Europe and the USSR, and may not include literature published in Japanese. Also, there may be an (unknown) quantity of material produced by individual firms but not published or otherwise made available for dissemination: the estimate certainly includes a high proportion of results from work done by industry under government agency contract, in the case of material originating in the USA. It can be expected that the proportion of so-called "non-conventional" literature (i.e. laboratory and contractor reports, which do not appear as formal publications) will be high, as is usually the case in mission- or application-oriented R and D fields. For example, in atomic energy the ratio of non-conventional to conventional literature is 1:5. The growth-rate of scientific and technical literature relevant to solar energy is increasing: a reliable estimate is that additions will reach a figure of 200 per month in 1976.

*Excerpted from *Small Solar Power Systems;* (appendix pp. 175 ff.).

R and D information in Europe

Sources available

The survey of scientific and technical information activities in the IEA European member states is far from complete, but a source of information frequently mentioned was that contained in the computer files of the RECON (Remote Console) interactive information system operated by the Space Documentation Service of the European Space Agency, which can be accessed through a data network, ESANET. Nodes of this network are located in Denmark, France, the Federal Republic of Germany, Italy, the Netherlands, Spain, Sweden and the UK. Access is, however, possible from other countries using normal dialled telephone connections. Some twelve computerized information databases are available for interrogation, of which the following have been identified as having some solar energy content:

NASA (aerospace and related technologies)
INSPEC (applied physics)
METADEX (metallurgy, etc.)
ENGINEERING INDEX (general engineering)
Government Research Abstracts (NTIS–technology)

All the above, except INSPEC, are US products. The occasional useful reference could also be found in other files available over the network, e.g., World Aluminium Abstracts, Nuclear Science Abstracts, and Chemical Abstracts Condensates.

Because this information resource is available to users in most of the European IEA member states, it is of some importance to estimate the probable relative coverage of the subject in these files, as compared with the total national solar energy database.

While it could be argued that the total database does not yet exist, the nearest approximation to it is the content of the Solar Energy Bibliography produced by ERDA, which now contains approximately 10 000 items. The total relevant content of the ESANET databases probably amounts to something over half this number, but no exact estimate can be made without a detailed overlap check, which is costly and time consuming. Nevertheless, the existence of the ESANET resource and its general availability within Western Europe is a valuable asset to R and D work in that area. It does not, however, contain information on current research. With regard to future growth it may be that coverage of the subject from these databases may tend to deteriorate somewhat owing to the fact that as the US solar energy programme grows, much of the resulting material will appear on the ERDA database (ERDA contractor report, etc.) in preference to the other databases. While non-ERDA solar energy material, where appropriate, will appear in the Engineering Index database, and NTIS will presumably maintain its present coverage, the problem would best be solved if the new ERDA database were available for interrogation over ESANET.

Turning to non-computerized sources, contacts in the IEA member States were asked to indicate what journals and other publications they found useful. Replies so far received are insufficient to permit conclusions to be drawn. The general impression is, however, that useful information is dispersed over so many publications that classical literature searches yielding a satisfactory percentage of the material relevant to a problem is a major difficulty even for those users with access to major libraries.

So far only two attempts to create a specialized energy database with a significant solar energy content have come to light during the survey, both in the Federal Republic of Germany, one at Jülich and the other at Karlsruhe. The latter centre is the German focus for input to INIS and is therefore the centre of German information services in the atomic energy field. It is understood that this activity is being extended to cover the whole energy field. The Jülich solar energy databank is in the planning stage.

R and D information in the USA

Introduction

The present position can best be understood in relation to the development of the ERDA Energy Information Database (EEDB). This is a computer database composed of all items reported in ERDA Research Abstracts, which covers all publications reporting ERDA-sponsored research, Energy Abstracts for Policy Analysis (also an ERDA publication), the ERDA input to INIS in nuclear science and engineering and non-ERDA non-nuclear material appearing in the publication Energy Abstracts. This latter is a sub-set of Engineering Index but specializes in all engineering disciplines related to energy. Thus, both ERDA and non-ERDA material in the field of solar energy is included in EEDB. Material of non-US origin is acquired by exchange agreements. It is understood that EEDB will replace Nuclear Science Abstracts in July 1976. Solar energy information originating before the creation of EEDB arose from many sources apart from the published literature (the NASA and NSF programmes for example), but it is believed that all this material is included in a Solar Energy Bibliography published by ERDA Technical Information Center.

Organization

The implementation of the ERDA scientific and technical information programme is the responsibility of the Office of Public Affairs. The Technical Information Center at Oak Ridge, Tennessee, is responsible for all ERDA technical publications and creation of the database. The ERDA database is

available for interrogation within the USA over the ERDA (formerly AEC) RECON network, serving ERDA centres and main contractors. The central node of the network is also at Oak Ridge in the Oak Ridge National Laboratory.

Solar energy content of EEDB

The subcategories of solar energy included in EEDB are as follows:

Resources and availability
Heat storage and rejection
Site geology and meteorology
Economics
Environmental aspects
Solar energy conversion
Photovoltaic conversion
Thermionic conversion
Thermoelectric conversion
Photosynthetic conversion
Photovoltaic power plants
Solar thermal power plants
Orbital power plants
Tower focus power plants
Linear parabolic power plants
Ocean thermal gradient power plants
Solar radiation utilization
Space heating and air-conditioning
Cooking
Furnaces
Distillation
Drying and curing
Desalination
Water heating
Heat engines
Solar collectors and concentrators

Other databases

Computer databases containing relevant materials are NASA, NTIS, and COMPENDEX (Engineering Index). The solar energy category of EEDB will, it is understood, contain material from these files. Pre-1976 relevant information from these files has been included in TIC's solar energy bibliography.

A bibliography on solar thermal energy is published by the Technology Applications Center at the University of New Mexico. It contains about 4 000 items and is being updated. The extent to which its contents are included in the TIC Bibliography, which has wider scope, is not precisely known, but this ought to be nearly 100%, since sources are much the same. There is no computer tape service.

IV. INSTITUTIONS INVOLVED IN SOLAR ENERGY DEVELOPMENT

Australia

Committee on Solar Energy and Research
Australian Academy of Science
P.O. Box 216, Civic Square
Canberra, ACT 2606

Austria

Austrian Solar and Space Agency
Garnisongasse 9
A-1090 Vienna

Brazil

University of Campinas
Caixa Postal 1170
Campinas, São Paulo

Canada

Brace Research Institute
Macdonald College of McGill University
Ste. Anne de Bellevue HOA ICO, Quebec

France

Centre National de la Recherche Scientifique
15 quai Anatole France
Paris

Centre National de la Recherche Scientifique
Laboratoire de l'Energie Solaire
B.P. 5
F-66120 Odeillo-Font-Romeu

Ecole Nationale Supérieure des Arts et Métiers
151 Boulevard de l'Hôpital
Paris 13e

Laboratoiries d'Electroniques et de Physique Appliquée
3 avenue Descartes
94 Limeil-Brévannes

Laboratoire de Physique des Solides
1 Place Aristide Briand
F-92190 Meudon-Bellevue

Germany, Federal Republic of

Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt
Pfaffenwaldring 38-40
D-7000 Stutigart

Greece

National Council for Energy
Athens

Nuclear Atomic Energy Commission
Athens

Physics Laboratory
University of Patras
Patras

India

Central Salt and Marine Chemicals Research Institute
Gijubhai Badheka Marg
Bhavnagar 364 002

Birla Institute of Technology and Science
Pirlani
Rajasthan

Mali

Laboratoire de l'Energie Solaire du Mali
B.P. 134
Bamako

Netherlands

Institute of Applied Physics
1 Stieltjesweg
Delft

Stichting TOOL
P.O. Box 525
Eindhoven

University of Technology
Delft

Niger

L'Office de l'Energie Solaire
B.P. 621
Niamey

United States of America

College of Engineering and Applied Sciences
Arizona State University
Tempe, AZ 85281

Solar Energy Application Laboratory
Colorado State University
Fort Collins, CO 80523

Solar Energy and Energy Conversion Laboratory
College of Engineering
University of Florida
Gainesville, FL 32611

Previous issues in the UNIDO *Development and Transfer of Technology Series* (DTT) cover the following topics:

No. 1 National Approaches to the Acquisition of Technology (ID/187)

No. 2 UNIDO Abstracts on Technology Transfer (ID/189)

No. 3 The Manufacture of Low-cost Vehicles in Developing Countries (ID/193)

No. 4 Manual on Instrumentation and Quality Control in the Textile Industry (ID/200)