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SOLAR WATER PUMPS

Technical Potentialities
International R & D Activities

Aus der Arbeit von gate

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TECHNICAL POTENTIALITIES
INTERNATIONAL R & D ACTIVITIES

S 1/4 9/78

German Appropriate Technology Exchange
Deutsches Zentrum für Entwicklungstechnologien
Centre allemand d'inter-technologie appropriée
Centro Alemán para Tecnologías Apropiadas

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SOLAR WATER PUMPS

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INTERNATIONAL R & D ACTIVITIES

S 1/4 9/78

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CONTENTS: Technical survey on the feasible utilization of solar energy for pumping.
Short descriptions of the R & D activities of the different institutions engaged in solar power utilization.

REMARKS: Even if there are some solar water pumps produced in small series one can say that all the obtainable pumps are in an experimental stage. Because of the high costs (see page 54) a widespread use cannot be recommended.
Construction manuals are not available.

QUESTION-AND-ANSWER-SERVICE

for "appropriate technologies"

The question- and-answer-service - a major service provided by GATE - supplies information, free of charge, on appropriate technologies. In performing this function, GATE is part of an international information and documentation system called SATIS (Socially Appropriate Technology Information System), in which ITDG (Great Britain), TOOL (Netherlands), ATOL (Belgium), VITA (USA), GRET (France) and SKAT (Switzerland) also participate.

The question-and-answer-service is made available to public and private institutions and selected persons in developing countries who are concerned with the development, adaptation, introduction and application of appropriate technologies. With this service GATE is aiming to supplement commercial private-enterprise activities by making a contribution to non-commercial technology transfer, particularly in the field of traditional, intermediate and alternative technologies.In addition to technology transfer from industrialized nations to developing nations, particular attention is given to cooperation between the developing nations themselves.

The activities of the question-and-answer-service are geared to the actual technological requirements indicated by the enquiries received from developing countries. At the same time, the demand for particular solutions is determined with the aid of a questionnaire distributed to institutions in developing countries dealing with situation-related solutions. Parallel to this, the questionnaire also makes it possible to ascertain solutions already available within these institutions. The question-and-answer-service relies not least on the documentation on newly-developed or traditional technologies supplied to it by such possessors of know-how.

When answering enquiries the question-and-answer-service uses documentation resources built up in this way. The information accumulated there on particular technological problem areas is - if frequently requested - combined to form "modules".

These answer packages, intended for dispatch, contain, where possible, technical descriptions and design drawings and are thus directly application-related, i.e. they provide an outline of technologies suitable for self-construction.The know-how of national research instititions and universities, with whom GATE works in close cooperation, is drawn upon to help answer specific enquiries, which can often be expected as feedback from the communication started with "modules".

In the event of enquiries dealing with typical problems encountered by a number of developing nations, but for which no suitable solution is available or can be obtained, GATE has the opportunity to suggest appropriate R & D measures to various sources of finance.

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WITH THE MODULES EDITED WITHIN THE QUESTION-AND-ANSWER-SERVICE WE AIM TO GIVE AND COMPILE INFORMATION ON VILLAGE-LEVEL-TECHNOLOGY. WE TRY TO STIMULATE THE DEVELOPMENT OF MAINLY RURAL AREAS WITH A STRONG EMPHASIS ON THE SELF-HELP CONCEPT.

BY NO MEANS DO WE INTEND TO PRESENT A SORT OF RECIPE FOR AN APPROPRIATE WAY OF DEVELOPMENT OR FINAL TECHNICAL SOLUTIONS WHICH WE CONSIDER TO BE THE ANSWER TO THE PROBLEMS CONCERNING THE QUESTION OF DEVELOPMENT IN RURAL OR SUBURBAN AREAS.

KNOWING WELL THAT INFORMATION IS THE FIRST STEP WHEN CHOOSING ACTIVITIES AND THAT - ESPECIALLY IN THE FIELD OF TECHNOLOGY - THERE IS A GREAT AMOUNT OF INFORMATION AVAILABLE, WE TRIED TO SELECT SOME OF THE SPECIFIC TECHNOLOGY NEEDS OF THE MAJORITY OF PEOPLE IN DEVELOPING COUNTRIES. THESE PEOPLE LIVE IN AREAS WITH A LACK OF WATER SUPPLY, SANITATION FACILITIES, APPROPRIATE HOUSING POSSIBILITIES, WHERE GENERALLY THE FOOD PRODUCTION IS LOW AND INEFFICIENT, THE ENERGY DEMAND IS NOT AT ALL MET AND THE MAJORITY OF PEOPLE IS ONLY PARTLY OR NOT AT ALL EMPLOYED.

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IN ADDITION, THE EXPERIENCE YOU HAVE GAINED AND INFORMED US ABOUT, MIGHT BE USEFUL FOR OTHERS. HAVING CONTACTS WITH MANY ORGANISATIONS IN DIFFERENT PARTS OF THE WORLD WE ARE IN A POSITION TO FORWARD YOUR IDEAS AND PROPOSALS IN THE FIELD OF TECHNOLOGY TRANSFER AND APPROPRIATE TECHNOLOGY.

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QUESTIONNAIRE

MODULE No. ________ DATE ________

1. How did you get this information?

   ○ I made a request at GATE and asked for it

   ○ Someone else gave it to me (Who was it? ____________________)

   ○ or:

2. Did you read the complete module?

   ○ yes, from the beginning to the end

   ○ only in parts

   ○ only the parts I was specially interested in

   ○ or:

3. What is your opinion about it?

   a) general understanding

   ○ difficult ○ just right ○ easy

   b) theory and basic knowledge

   ○ too much of it ○ just right ○ too few

   c) orientation to practical work

   ○ lacking ○ limited ○ just righ

   d) language, over-all presentation

   ○ appropriate for your needs ○ too complicated

   e) what else do you think is worth mentioning?

   (Please use back page for additional remarks and suggestions!)

4. Do you see any practical application for the received information?

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INTRODUCTION:

The first attempts of producing power, especially for pumping water using the solar radiation as an energy source, are rather old. As long as 65 years ago such a plant (37 kW) was constructed in Egypt. But because of the cheap oil and its simple use in diesel engines these experiments were not continued for a long time. Nowadays many countries are strengthening their research and development programs in the field of power generation from the sun. At present, there are existing different types of developed solar powered generators or pumps, but they are more or less in an experimental stage. The costs, which are higher by a factor of more then 20 to comparable diesel engines, are the main deterrent to the use of the solar powered pumps. Therefore, a widespread use of these plants can not be recommended until their prices will be reduced by improving the production technology. There are no construction manuals obtainable for any of those solar power plants.
The enclosed reports should give a short survey on the worldwide research and development activities to interested research institutions and politicians.

We will now have a look at the different solar water pump systems which can be seen as an application of the power generating plants.

In principle, a solar water pump is a conversion system with different single converters, which transforms the energy of the solar radiation to mechanical energy. This mechanical energy is used for driving a water pump.
Generaly three ways of energy conversion can be distinguished. Each single converter has his own energy losses and by dividing the output energy by the input energy you can get the efficiency η of the converter. The following figure shows a rough estimation of the total efficiency η_{tot} (as a product of the single η).

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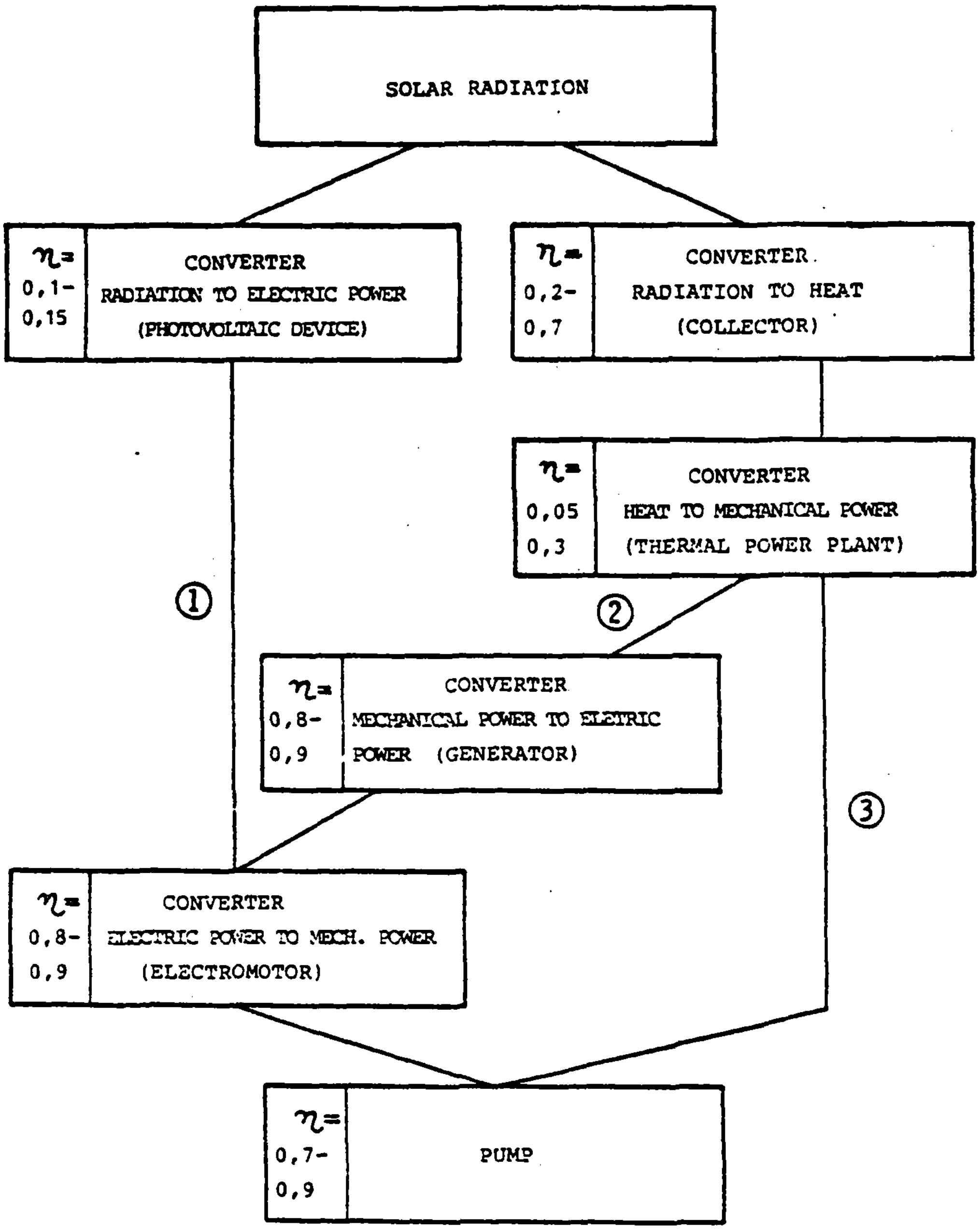

Total efficiency of the system:

η_{tot} =
① 0,06 - 0,12 (PHOTO-VOLTAIC DEVICE + ELECTROMOTOR)
② 0,004 - 0,15 (THERMAL POWER PLANT + ELECTRIC POWER)
③ 0,007 - 0,19 (THERMAL POWER PLANT IN DIRECT ACTION)

The efficiencies are very important for the characteristics of the plant, because they define the size of the collector area and therefore the costs of the costs of the total plant.

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION, VIENNA
Development and Transfer of Technology Series, No. 5:
Technology for Solar Energy Utilization (Excerpts) (pages 3-15, 35-44, 53-60)

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 (JEA), 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, "low 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.

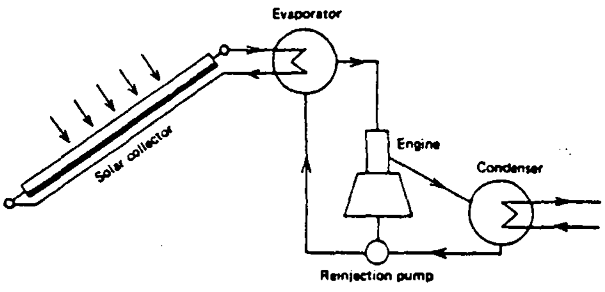

Figure 1. Low-temperature solar engine with working fluid evaporating in an evaporator heated with hot water from the solar collector

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.

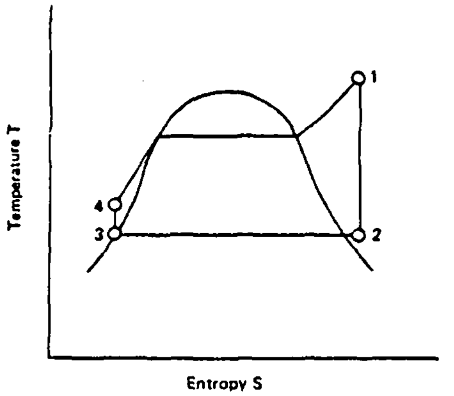

Figure 2. Ideal temperature-entropy diagram of the V-2 solar vapour engine

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.

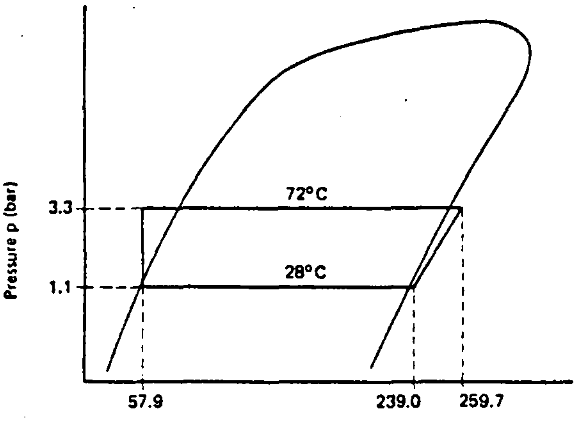

Figure 3. Pressure-enthalpy diagram of the V-2 solar vapour engine using Freon 11 as the working fluid (not to scale)

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.)

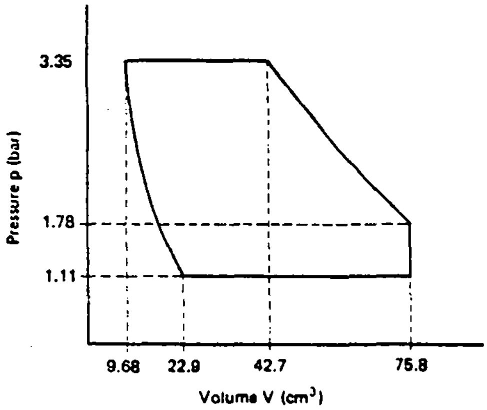

Figure 4. Pressure-volume diagram of the air inside the cylinders of the V-2 solar vapour engine

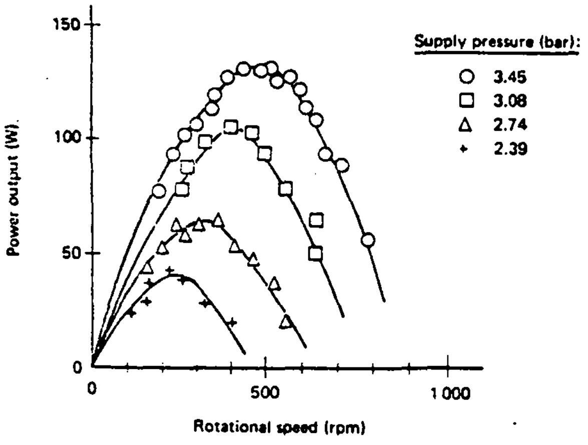

Figure 5. Power-speed curves for the V-2 solar vapour engine

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

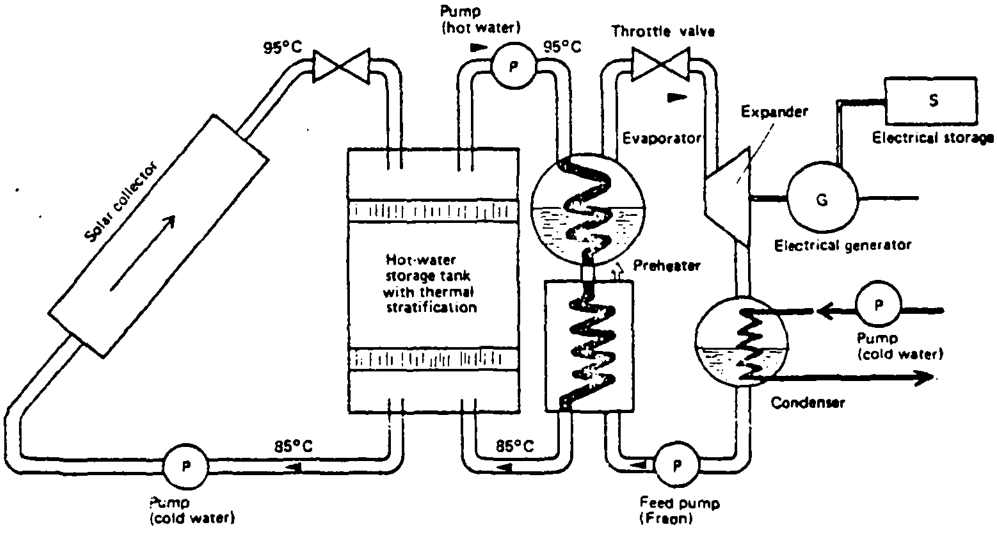

Figure 6. Schematic diagram of the MBB solar electric power plant

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 m^2 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 m^2/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 m^2. 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 m^2, 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 (m^2)	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/m^2)	*(Btu/ft^2)*	*(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.

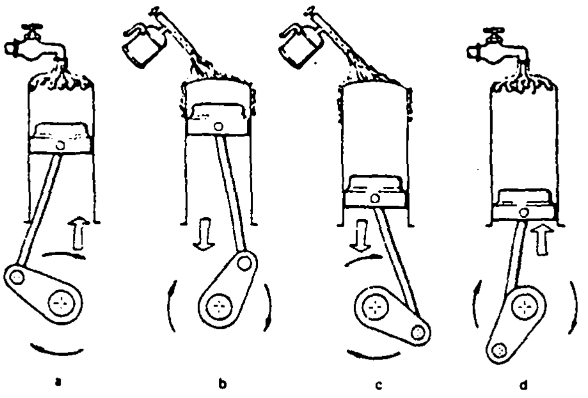

Figure 7. Simple representation of the operating principles of the Stirling cycle

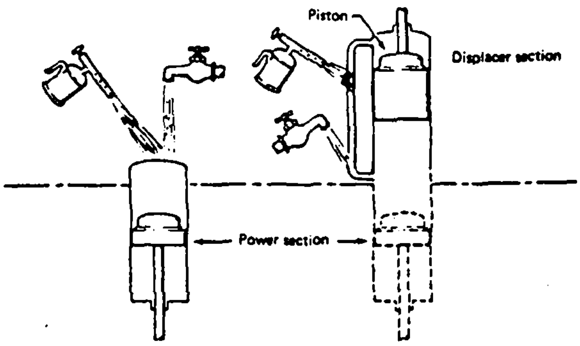

Figure 8. Simple representation of the displacer piston

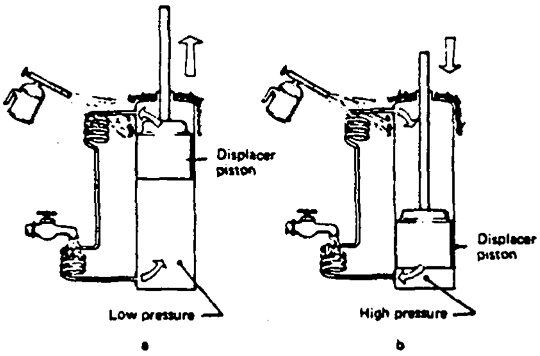

Figure 9. Action of displacer piston

The 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), 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

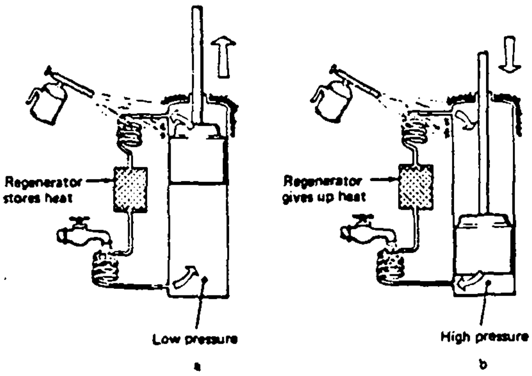

Figure 10. Action of regenerator

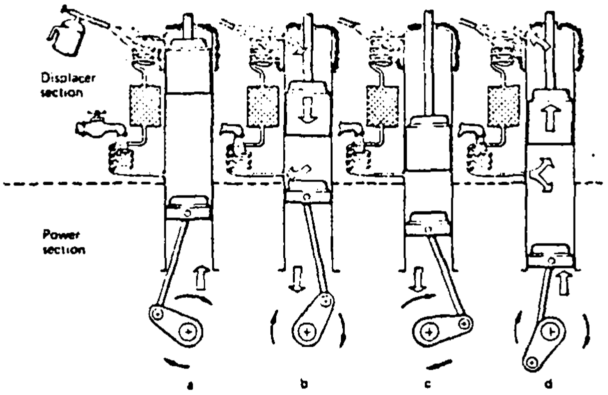

Figure 11. Stirling cycle complete with displacer section and regenerator

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

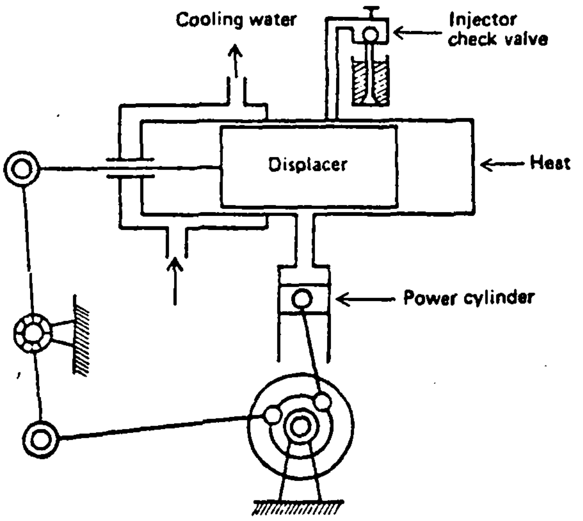

Figure 12. The Farber engine with air and water injection

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.

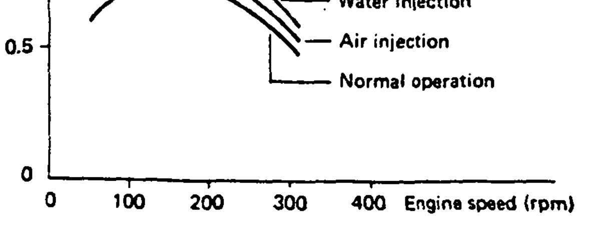

Figure 13. Power-speed curves of the Farber engine, showing the increase in performance obtained with injection

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

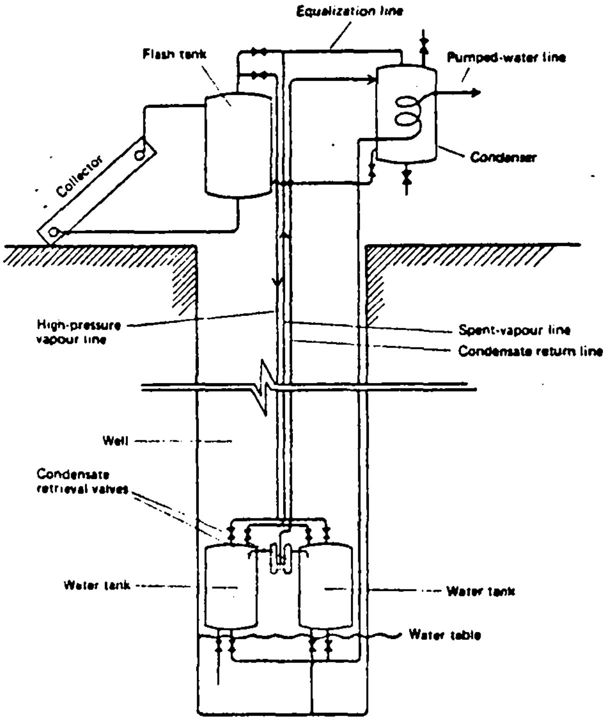

Figure 14. Solar water pump

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.

IV. INSTITUTIONS INVOLVED IN SOLAR ENERGY DEVELOPMENT

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Technical Assistance Bureau,
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Washington, D.C. 20 523

APPENDIX 4

External-Combustion Engines — Rankine and Stirling Engines as Small-Scale Power Sources for Developing Countries

Two types of external-combustion engines adaptable to a variety of heat sources are the Stirling- and Rankine-cycle engines. Both are based on modifications of the Carnot cycle, as illustrated in Figures 59 and 64, but thermal efficiencies are such that for operating temperatures below about 300-350°C, the Rankine engine is more efficient.

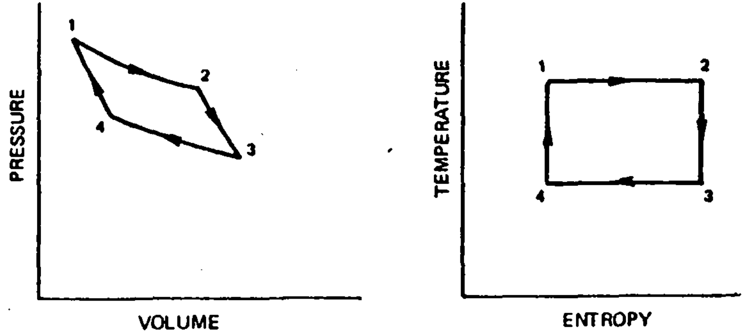
RANKINE ENGINES

The traditional example of a Rankine engine is the familiar steam engine, with thermal efficiencies of some 5-15 percent. This discussion, however, will be restricted to engines that are more useful on a smaller scale and that operate at temperatures in the range that can be achieved with solar collectors. For these lower temperatures, Rankine-cycle engines have been designed that use organic materials instead of water as the working fluid. The analysis that follows illustrates the type of system that would be associated with a solar-powered Rankine-engine-operated electric power plant.[1,2] It is based on current manufacturing capabilities for the individual components.

Introduction

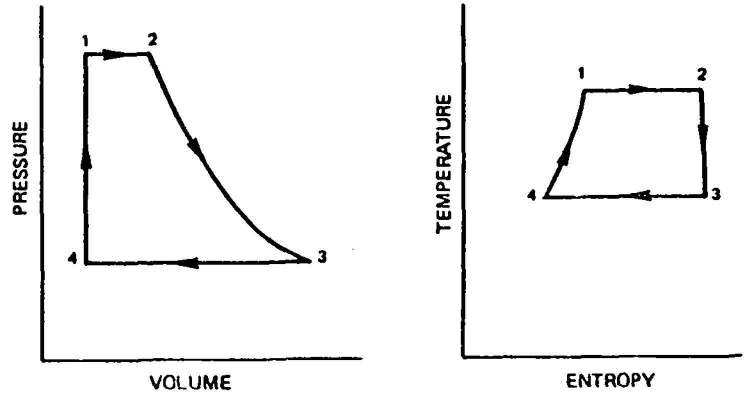
Figure 60 shows a schematic of a solar-powered organic Rankine-cycle engine loop. The system of the schematic indicates the engine driving an electric generator. However, the engine could just as well be driving a water pump or the compressor of a cooling system.

a. The Carnot cycle



1-2 Isothermal expansion (constant temperature)
2-3 Adiabatic expansion (constant entropy)
3-4 Isothermal compression (constant temperature)
4-1 Adiabatic compression (constant entropy)

b. The Rankine cycle



1-2 Boiler (heat input)
2-3 Engine (expansion)
3-4 Condenser (heat discharge)
4-1 Pump (compression)

FIGURE 59 The Carnot and Rankine cycles.

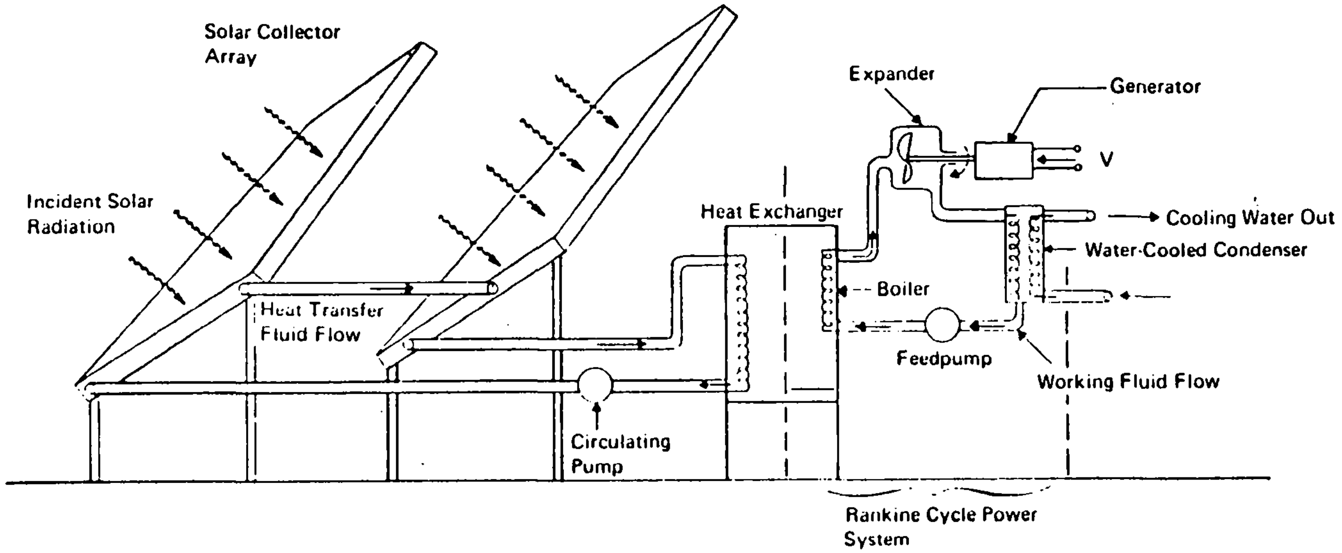


FIGURE 60 Solar-powered electric power plant. [Courtesy Arthur D. Little, Inc.]

Organic Rankine-cycle engines are particularly well suited for solar power application for a number of reasons:

- They have high thermal efficiency* even when operating with the low to moderate temperatures (180-400°F [80-200°C]) achievable with flat-plate collectors or collectors using low levels of focusing.
- The cost of components is low because of the use of common materials of construction (mostly carbon steel) and relatively uncomplicated mechanical components. This is potentially very important to developing countries because of the possibility of using local materials and labor.
- Organic Rankine-cycle engines have high reliability as a result of their sealed construction that protects them from the harmful effects of the surrounding environment (dust, moisture, etc.).
- Since the organic working fluids have very low freezing points, there are no problems associated with freezing.
- Finally, they are adaptable for use over a wide power range from 1-kW pumping systems to multimegawatt power stations.

System Description and Operation

The engine consists of four major components:

- expander
- boiler
- feedpump
- condenser.

During operation, a heat-transfer fluid (typically pressurized water) flows through the collector array and is heated to a temperature in the 200-400°F (100-200°C) range depending on solar-collector configuration, solar flux, and engine operating conditions. (This would entail a system capable of operating at about 235 psig [16.5 kg/cm^2 gauge].)

This hot fluid is then used to vaporize the working fluid of the engine in a heat exchanger; a number of common refrigeration fluids are appropriate for use in the engine loop. The hot, high-pressure, working fluid is then used to drive the expander of the Rankine-cycle engine. For higher-power-output applications (>100 kW) the expander will be a turbine. Lower-power systems can use positive displacement configurations such as reciprocating or vane-type expanders. After leaving the expander, the working-fluid vapor is

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*60-70 percent of the ideal cycle efficiency, given the heat input and rejection temperatures.

condensed and the liquid is then pumped back into the solar-collector heat exchanger, completing the cycle.

System Performance Estimates

An estimate of overall system efficiency depends on analysis of the efficiency of the major components.

ENGINE EFFICIENCY

The efficiency of the engine depends on both the ideal efficiency of the cycle under consideration (assuming 100-percent expander efficiency, etc.) and the actual efficiency of the major system components, such as the expander and feedpump. Tests by a number of firms for a range of component configurations indicate that with existing technology the following component efficiencies are obtainable:

- expander–70-85 percent
- feedpump–70-93 percent.

Engine performance calculated on the basis of an expander efficiency of 80 percent and a feedpump efficiency of 80 percent indicates that it is possible to achieve about 65 percent of the ideal Carnot efficiency when the engine is operated in its appropriate temperature range. The corresponding engine efficiencies, as a function of both heat-input and heat-rejection temperatures, are shown in Figure 61. As this figure indicates, heat-engine efficiency increases with increasing heat-input temperature and with decreasing heat-rejection temperature. The 120°F (~50°C) heat rejection temperature is considered to be typical of air cooling, 100°F (~40°C) of evaporative cooling, and 80°F (~30°C) of water cooling. The effect of condenser temperature is quite significant–particularly for systems operating with lower (200°F [~95°C]) heat-input temperatures–thus providing a strong incentive to use water cooling if water is available (such as for water-pumping applications).

ANNUAL COLLECTOR EFFICIENCY

Both focusing and non-focusing collectors can be used as the heat source for organic Rankine-cycle engines. Flat-plate (non-focusing) collectors are used here to illustrate the effect of thermal collector characteristics on overall system performance for the following reasons:

- Flat-plate collectors have the advantage of being capable of effective operation mounted in a fixed position. The collectors and their mounting structure are, therefore, structurally simple–an advantage for use in remote areas.
- Flat-plate collectors can utilize diffuse as well as direct radiation, making such a system appropriate over a wide range of geographical areas and varying climatic conditions.
- The technology of flat-plate collectors is advancing as a result of industry and government programs to develop solar heating and cooling systems (particularly in the United States).
- Organic Rankine-cycle engines can effectively use the low to moderate temperatures achievable with flat-plate collectors.

For estimating the performance of the collector/engine combination it is most realistic to use the *average annual* collector efficiency as a measure of collector performance rather than the efficiency at midday (i.e., high solar flux conditions) often referred to in the literature.

Calculated curves[2] for the annual collector efficiency in an arid region at 32.5° north latitude for a variety of solar collectors tilted in a fixed position (32.5° relative to horizontal) show that the collection efficiency can vary widely, depending on the collector configuration (Figure 62). All the curves assume selective coatings on the absorber plate. (A collector with a flat black

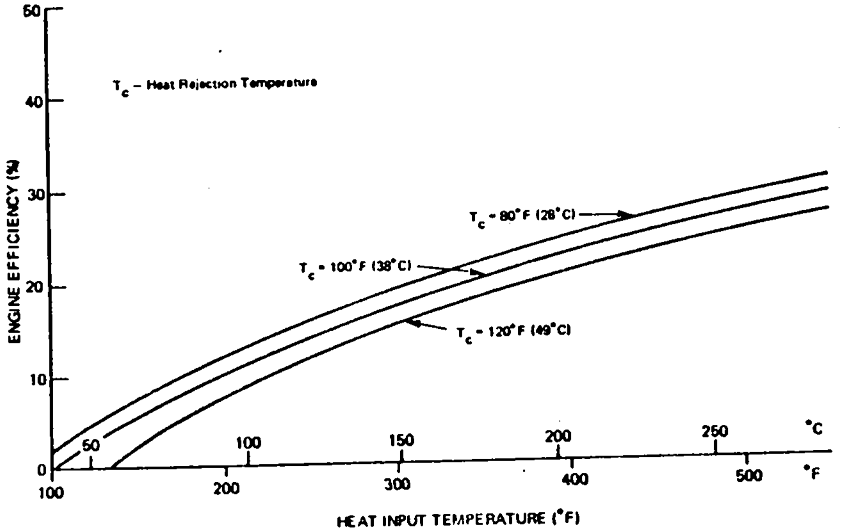


FIGURE 61 Heat engine efficiency as a function of temperature for an engine operating at 65 percent of Carnot efficiency. [Courtesy Arthur D. Little, Inc.]

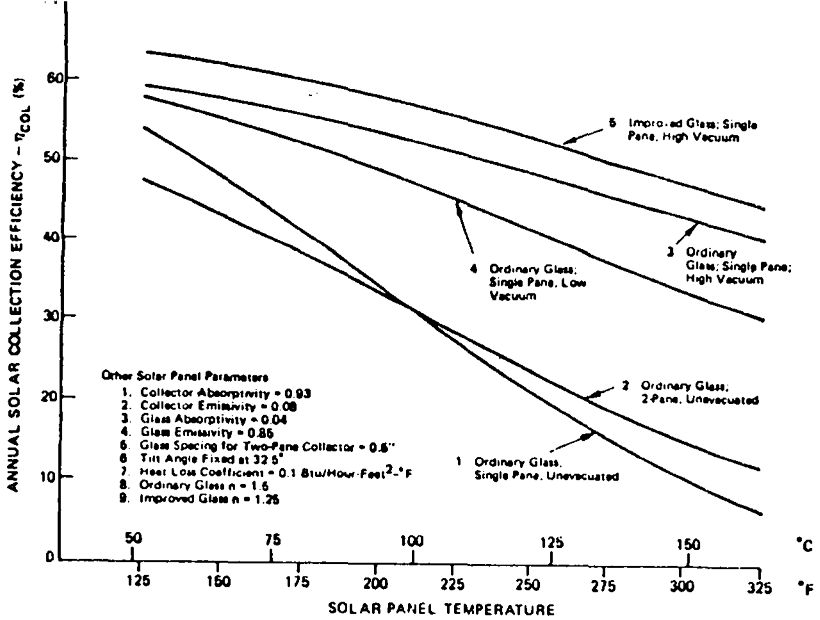


FIGURE 62 Annual solar collector performance as a function of collector temperature (for Yuma, Arizona). [Source: Bartoszek, *et al.*, Ref. 2]

coating and on two cover plates would have an efficiency level lower by approximately 10 percent than that indicated by Curve 1.)

As indicated, a large improvement in collector performance is achieved by using some form of convection suppression between the absorber plate and the cover plate(s) to eliminate heat transfer losses by convection. Figure 62 indicates the use of partial vacuum; similar results, however, may be obtained by using cellular structures (honeycombs).

Curve 5 indicates the improvement that would be achieved by using anti-reflective coatings or surface treatments on the glazing to reduce transmission losses. The benefits of anti-reflective coating would be even more pronounced for the lower-performance collectors typified by Curves 1 and 2.

SYSTEM EFFICIENCY

The overall system efficiency, which to a great extent determines the collector area requirements, is defined as:

$$\eta_s = \eta_e \times \eta_c$$

where:

η_s = overall system thermal efficiency
η_e = engine thermal efficiency
η_c = collector efficiency

Since increased collector temperature results in increased engine efficiency and decreased collector efficiency, there is an optimum operating temperature range for each engine/collector configuration. The variation in annual system efficiency is shown in Figure 63 for the collectors of Figure 62. The engine efficiency used in calculating these curves corresponds to the curve of Figure 61 with a condenser operating at 100°F (38°C).

As indicated, annual average efficiency levels are about 3.5 percent for collectors without some form of vacuum suppression and 6.5 percent to 9 percent if collectors using vacuum suppression are utilized. It should be noted that the peak efficiency of these systems under high flux conditions at solar

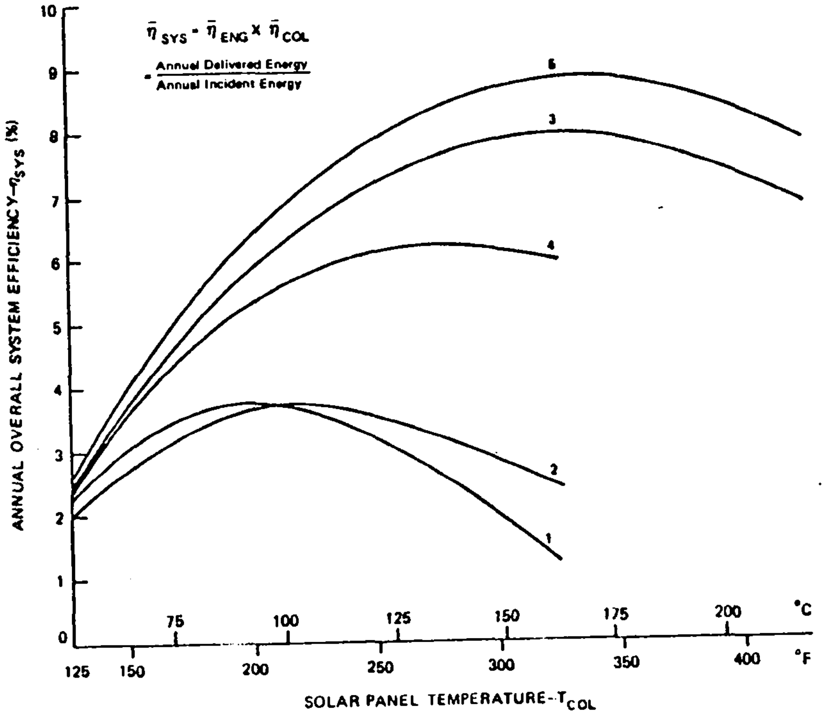


FIGURE 63 Annual overall system efficiency variation with collection temperature. [Source: Bartoszek, *et al.*, Ref. 2]

noon would be significantly (~50 percent) higher than those indicated in Figure 63. (These numbers are approximate; for a given design and application, it is possible to calculate more exactly what output can be expected.)

Comparison with Other Cycles

The heat generated in the solar collector array can, in principle, be used to operate any form of heat engine, including:

- Stirling cycle
- Rankine cycle (using water)
- Rankine cycle (using organic fluids)
- Ericsson cycle
- Closed cycle Brayton
- Hybrid cycle.

All of these engines have been suggested for use in solar thermal power systems. However, it is very difficult to operate gas-cycle engines (Stirling, Ericsson, Brayton) efficiently at the low temperatures (200-350°F [100-180°C]) associated with arrays of flat-plate solar collectors using low-level concentration, even though the ideal efficiency of the Stirling and Ericsson engines would be the Carnot efficiency. At these relatively low heat-input temperatures, the compression work in the gas cycle approaches the expansion work so that the net work output becomes very sensitive to the efficiency of the compression and expansion processes. Even with low operating temperature differences, the efficiency of the Rankine-cycle engines remains high (60-70 percent of the ideal Carnot efficiency). This is due to the fact that the pump work is a relatively small percentage of the expansion work.

If collector arrangements are used that can operate at elevated temperature levels (1,000°F [550°C] or higher) the engines based on gas cycles could, however, be very attractive and would merit serious consideration.

STIRLING ENGINES

Unlike the Rankine engines, Stirling engines are external-combustion heat engines that usually utilize air or other gases as working fluid. They are capable of operating on any source of heat such as sun, wood, coal, or field waste. Invented in 1816 by Robert Stirling, they were competitive with steam engines of the day, particularly with regard to fuel efficiency and safety. (Figure 64 shows the basic Stirling cycle.) In the early 1900s thousands were sold as coal-burning water-pumping machines that produced from 50 to 500 watts of delivered power at about 2 percent overall thermal efficiency.[3] These pumping engines used air at atmospheric pressure for a working fluid, and a cast-iron hot end. As a result, they were very large and heavy for their power. However, they were exceptionally quiet, durable, and easy to operate and maintain; they were displaced only by the advent of widely distributed electric power in the 1920s.[4]

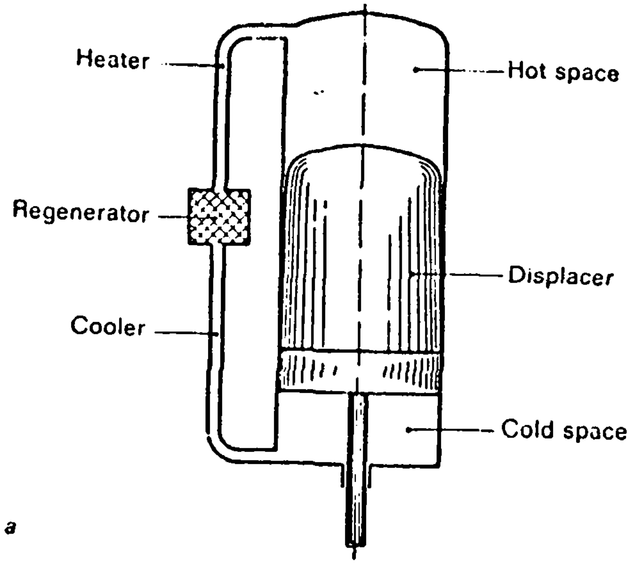
Toward the end of the Second World War there was launched an intensive development effort that has resulted in today's powerful, efficient, and quiet Stirling engines (Figures 65 and 66) intended for automotive use. In order for these large crank-type engines to come into commercial use, a number of very difficult design problems must still be solved.

As a result, and because of the nearly universal availability and very low cost of internal-combustion engines, the traditional crank-type Stirling engine remains in the development labs instead of on the road or in the field. No such engines producing more than a few watts of power are at present available on the market.

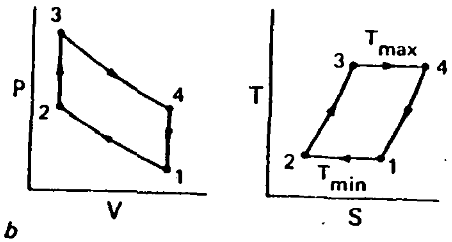
Free-Piston Stirling Engines

The practical difficulties of producing crank-type Stirling engines have led to the development of a great variety of free-piston linear-motion Stirling engines that, while they operate on exactly the same cycle as the crank machines (Figure 67), avoid many of their problems. Furthermore, their design makes the construction of small engines more easily achieved. Power is removed from these engines by various linear-motion pumps or alternators.[5] It should be emphasized that *all of these engines are under development* and are not yet commercially available in production quantities that would reflect a realistic manufacturing cost. These engines are under development in the United States under the sponsorship of the Energy Research and Development Administration (space power plant), the National Institutes of Health (artificial heart), and the American Gas Association (gas-fired air conditioner). Private groups are also involved in developing some of these devices.

Figures 68 through 71 show several means of power extraction that are useful with linear motion engines. All of these have been built in prototype quantity and operated successfully. The inertia pump (Figure 68) is being developed in the United States for commercial use in a gas-fired air-conditioner system in which the free-piston Stirling engine (FPSE) drives an inertia pump that pumps Freon-12 around a conventional cooling cycle. When lower temperatures for food freezing are required, an even simpler machine can be used. In this, an FPSE heat engine drives an FPSE heat pump;



a



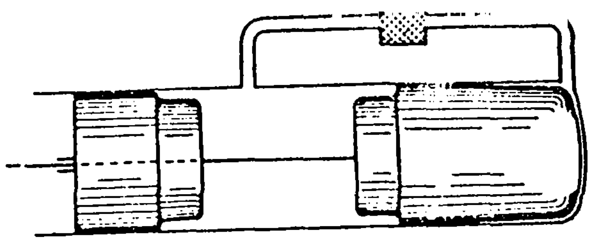
b

1-2 Isothermal compression at the lower temperature.
2-3 Heat input at constant volume, raising gas to upper temperature, increases pressure still further.
3-4 Isothermal expansion at upper temperature.
4-1 Gas cooled to lower temperature at constant volume.

FIGURE 64 The Stirling Cycle. [Courtesy Philips Research Laboratories, Eindhoven]
a. Principle of the displacer system.
b. The thermodynamic cycle.
c. Diagram of the cycle.

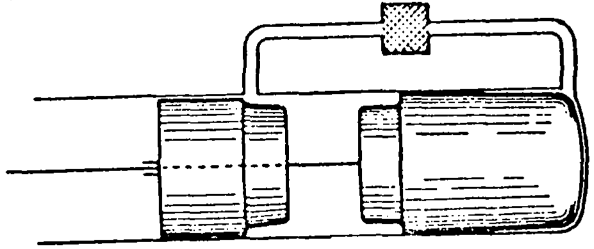
c

1



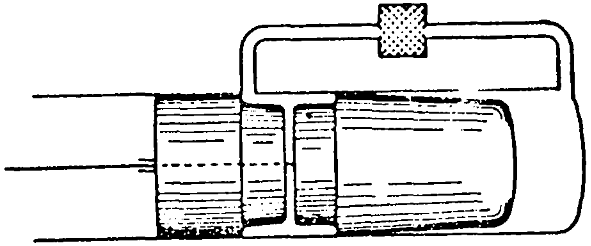
Piston at bottom dead centre. Displacer at top dead centre. All gas in cold space.

2



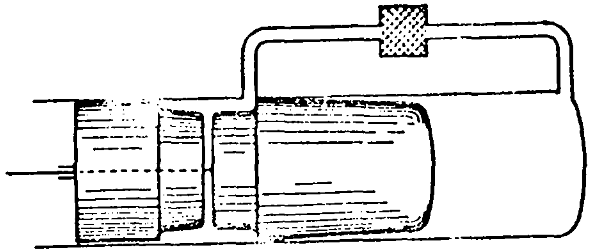
Displacer remaining at top dead centre. Piston has compressed gas at lower temperature.

3



Piston remaining at top dead centre. Displacer has shifted gas through cooler, regenerator and heater into hot space.

4



Hot gas expanded. Displacer and piston have reached bottom dead centre together. With piston stationary, displacer now forces gas through heater, regenerator and cooler into cold space, thus re-attaining situation **1.**

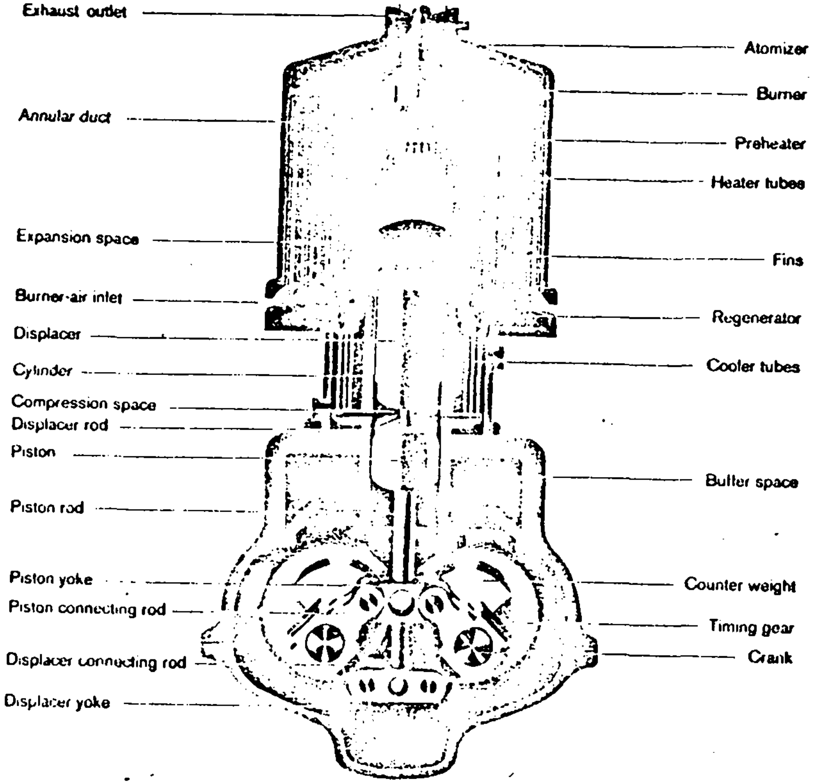


FIGURE 65 The Philips rhombic engine. [From: R. J. Meijer: 1970. *Philips Technical Review* 31:168-85]

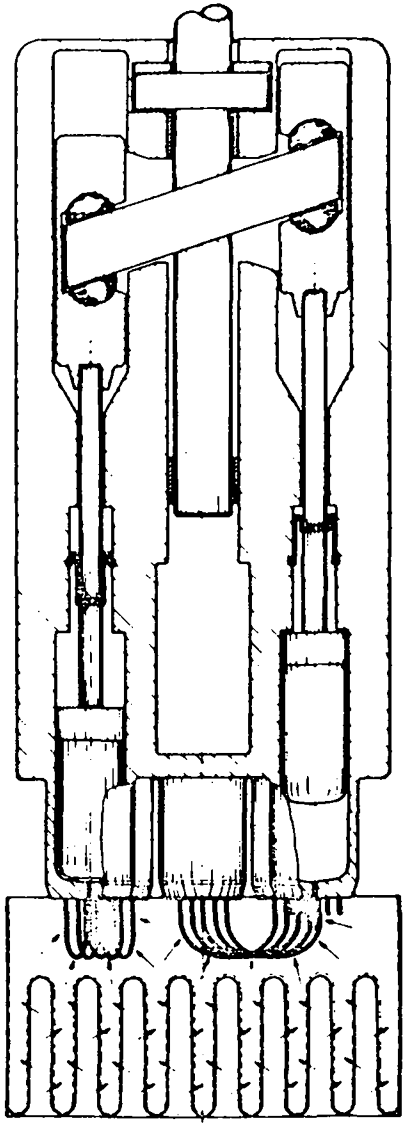
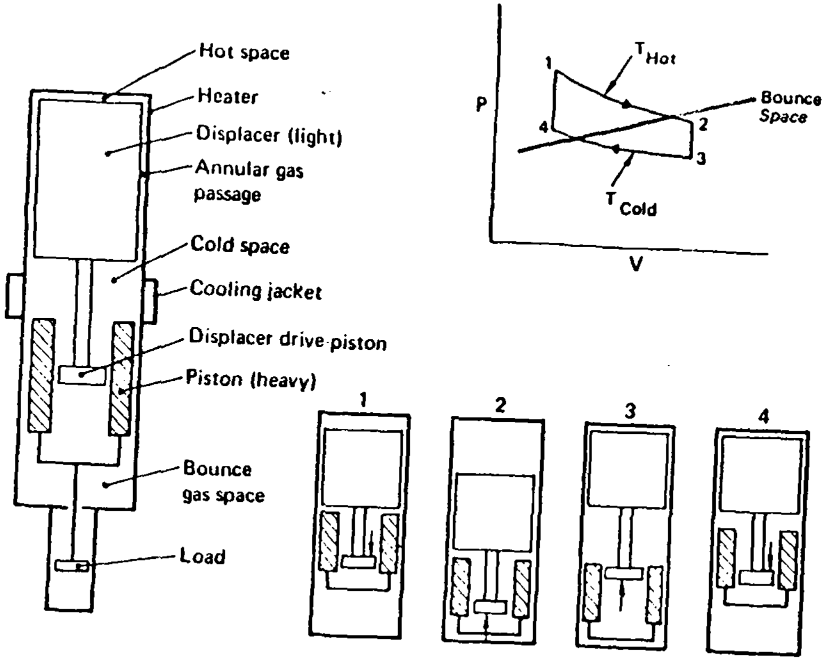


FIGURE 66 Swashplate Stirling engine. [From: R. J. Meijer. 1970. *Philips Technical Review* 31:168-85]

this combination is dynamically balanced and hermetically sealed, and as a result of its very simple construction, would probably be more reliable and less expensive than the engine/inertia pump combination.

A variant of the FPSE is the free-cylinder engine, illustrated in Figure 69, that operates from solar energy concentrated by a Fresnel lens.

A free-piston/linear-alternator engine is under development in the United



1-2 Working gas in hot space, working-gas pressure higher than bounce-gas pressure. Expanding gas drives displacer and piston down. *With a lower mass than the piston, the displacer accelerates more rapidly and soon contacts the piston* and both move together, compressing bounce gas.

2-3 Bounce-gas pressure greater than working-gas pressure. Pressure differential acting on displacer drive-piston, while bounce gas *is still being compressed by piston, moves displacer up, shuttling* working gas into cold space. Working-gas pressure drops rapidly.

3-4 Bounce-gas pressure drives piston up, compressing cold working gas.

4-1 Rise in working-gas pressure drives displacer down, shuttling cold gas into hot space. Working-space pressure rises rapidly.

FIGURE 67 Free-piston Stirling engine—principle of operation. [Adapted from Beale, *et al.*, Ref. 8]

States in a project supported by the Energy Research and Development Administration, *intended to result in a very long-life 1-kW space power plant heated by a radio isotope.* The linear-alternator machine may be made to operate on solar power, using either high temperature with a concentrating collector, or low temperature such as is available from a flat-plate collector. The use of a flat-plate collector to operate an FPSE diaphragm pump is illustrated in Figure 70. If the flat plate is used, condensing [illegible] rather than an ideal gas might be more appropriate, since they produce much *more work per cycle.*[6]

Diaphragm Engine

A particularly attractive variation for electric-power generation is shown in Figure 71.[7] This machine uses flexing diaphragms and springs, without any sliding fits or seals. The displacer is driven by the force transmitted from the cylinder to the displacer through the displacer support-spring, as the displacer oscillates at a resonant frequency determined by its mass and support-spring stiffness. Since the motion of the cylinder is 180° *out of phase with the*

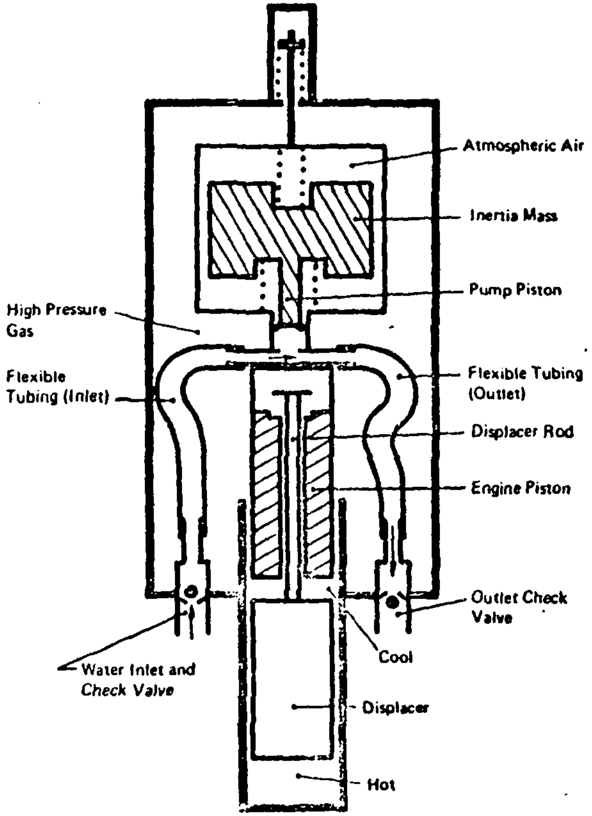


FIGURE 68 Free-piston Stirling engine inertia pump. [Source: Beale *et al.*, Ref. 8]

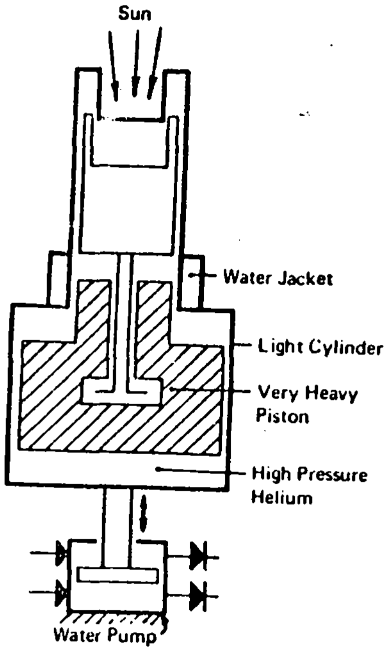


FIGURE 69 Free-cylinder Stirling engine. Power is taken from the cylinder, which moves in reaction to the motion of the heavy piston. [Source: Beale *et al.*, Ref. 8]

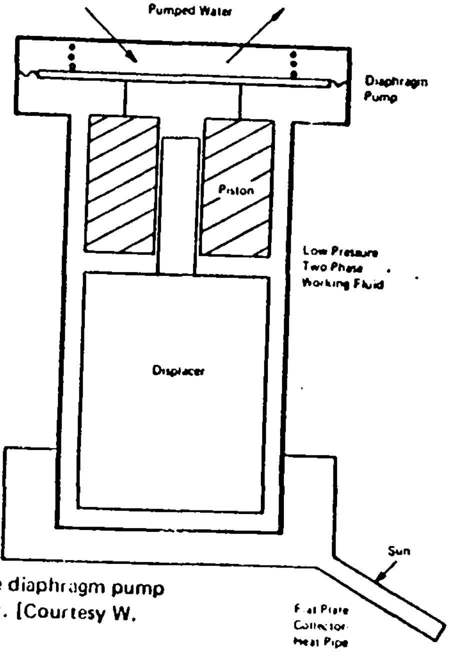


FIGURE 70 Free-piston Stirling engine diaphragm pump operated from a flat-plate solar collector. [Courtesy W. Beale]

diaphragm, a net energy input to the displacer is achieved. The present experimental models run at 110 Hz and produce about 25 W. Larger sizes are possible. Propane-heated and radioisotope-heated versions are operating. A propane-heated field-trial prototype is providing the electrical power for the UK National Data Buoy, and a similar machine powering a large marine light has been demonstrated commercially at the International Association of Lighthouse Authorities Exhibition at Ottawa in August 1975. This machine is being actively developed at the Atomic Energy Research Establishment, Harwell, England, and is now being offered commercially by two UK firms.[8]

Fluidyne Engine

One of the more recent variants of the free-piston Stirling engine is the "Fluidyne" pump being developed at Harwell.[12] This engine, illustrated in Figure 72, uses columns of fluid in tubes to displace the working gas (air) between the hot and cold regions, and also for extracting output power. This lends itself to direct integration in water-pumping systems.

At present, the following results have been achieved with some of the experimental Stirling engines of the type discussed here; better performance is expected with development.

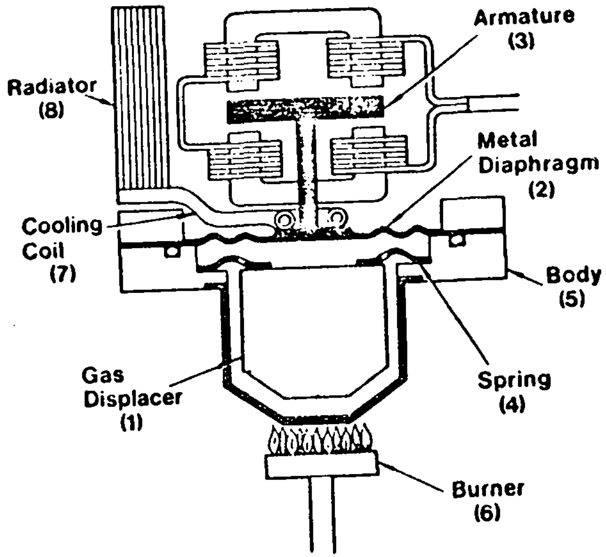


FIGURE 71 Harwell diaphragm engine. [Source: Harwell Bulletin No. 74/26]

Type of Load and Working Gas	Heat Source	Hot-End Temperature degrees C	Power Out	Thermal Efficiency	Reference
inertia Freon compressor (helium)	electric	650	2 kW	30%	9
inertia water pump (air)	electric	550	3 W	3%	9
linear alternator (helium)	electric	600	34 W	12%	9
linear alternator (air)	electric	500	3.6 W	4%	9
free cylinder water pump (helium)	sun (Fresnel lens)	450	6 W	3.5%	9
free cylinder water pump (helium)	electric	600	70 W	14%	9
Harwell diaphragm engine alternator (helium)	electric	594	37.5 W	16.9%	10
Harwell diaphragm engine alternator (helium)	propane	450	31.8 W	10%	11
Harwell diaphragm engine alternator (helium)	Sr^{90}	280	10.7 W	7.8%	10

A demonstration FFSE as shown hours without wear or performance degradation.[9] Critical components of the Harwell diaphragm engines have been operated for 2½ years without failure.[6] Two of these engines, one propane-heated and one radioisotope-heated, have each operated for more than 7,000 hours without wear or performance degradation.[8]

THE STATUS OF CURRENT TECHNOLOGY

There is as yet no significant commercial manufacture of Stirling engines. It is possible, however, to construct a 150-W output, free-piston Stirling engine

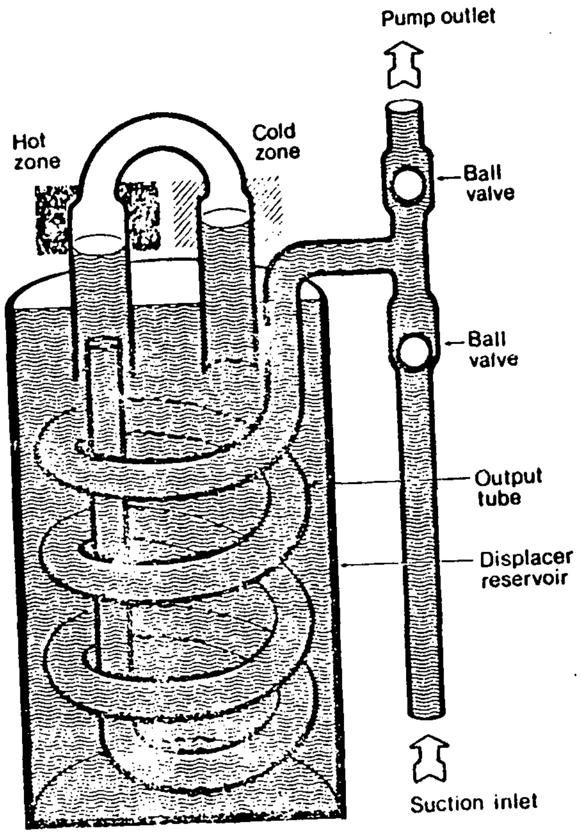


FIGURE 72 The Harwell "Fluidyne" pump. In operation, air is displaced between the hot and cold zones and the resulting changes in pressure force water up and through the pump, at the same time maintaining the rhythmic movement of the air. [Courtesy AERE Harwell]

weighing about 20 kg with all accessories, including power-output device (pump or alternator) and cooling system, with an overall efficiency of about 5 percent operating on solid fuels—or as high as 20 percent operating on bright sun with a Fresnel lens[9]—and costing approximately $100 as made in the United States. The performances and costs are approximations from present experience, and the costs may be lower if large numbers of engines are produced. The cost of the collector and tracker is not included, and is likely to be quite high (say $200 for a 100-W engine).

This machine could be expected to have a life of at least 4,000 hours and probably much more. The most likely failure modes would be corrosion of the hot end, and/or leakage of pressurized working fluid. It would be possible to repair it only at a central shop, but repair would be simple and cheap, probably requiring only replacement of the hot end and recharging. Internal moving components would operate on a gas film and should have no appreciable wear. Internal springs would be stressed only briefly during startup.

Whether the FPSE could be manufactured locally would depend on details of design. The only difficult operation is the very close fitting required on piston/cylinder and displacer rod. These might be designed for a hand-lapped fit, resulting in non-interchangeable matching pairs. Material throughout could be cast iron or steel if a low-temperature hot end is tolerated. Possibly a more desirable solution would be to use a relatively small amount of stainless steel for the hot end. This would greatly increase durability and might be less costly in the long run.

The diaphragm-type machine avoids the need for any sliding surfaces, so there is no wear and no close fits are required. Nevertheless, the present manufacturing costs of these machines in Great Britain are more than 100 times greater than the $100 estimate given for the 150-W FPSE. Furthermore, the diaphragm machines are much heavier for a given output than the FPSE machines. As with some thermoelectric and photovoltaic systems available commercially, the main present application of the diaphragm-type machine would be in situations where the ability to provide a few tens of watts of electric power, for a year or more without attention or refueling, is of great value.

RESEARCH AND DEVELOPMENT

Given the state of development of the free-piston Stirling engine, one would expect it to be commercially available in 5-10 years, if the demand warrants further commercial interest.

Further development of the diaphragm engine might also result in a device that would be available in 5-10 years. It is not only intrinsically extremely durable if properly designed and constructed, but also potentially very inexpensive in power levels below 100 W; the major cost is the alternator itself and the power diaphragm, which must be free of any flaws. It could be very largely assembled from pressings. Thus, if the potential market justified a substantial investment in design and tooling, there seems no reason why the cost should not be reduced to that of a small gasoline engine, if manufactured in equally large numbers.

The presently known technology would be adequate for power plants on the order of 100 W. For kilowatt levels of power, some work is needed to find designs of hot ends, solid-fuel burners, lenses, tracking mechanisms, and pumps appropriate for local manufacture in developing countries.

As a result of the active development programs being carried on for automotive, air-conditioning, artificial-heart, and space applications, rapid improvements in efficiency and durability of the Stirling engine can be expected, along with a reduction in costs.

USES OF THE STIRLING ENGINE IN DEVELOPING COUNTRIES

In view of the current state of development, there is little likelihood that Stirling engines will be used in developing countries to any great extent in the next 5 years. (The one possible exception is use of the large, slow, 1908-style engines discussed earlier, that could certainly be manufactured today in many developing countries.) If interest and demand in the industrialized countries result in manufacturing economies for the machines that exist in prototype form, some applications in developing countries may be possible in 5-10 years.

Stirling engines can be made to operate with either high-temperature sun-tracking collectors or with lower-temperature fixed collectors. The free-cylinder water pumps and the diaphragm linear alternator seem the most likely candidates for solar power.

Any of the Stirling engines mentioned could be designed to operate on solid fuel with power/volume ratio and efficiency dependent on the design of the heat exchangers. Solid-fuel stove/engine combinations can be devised to serve as heating or cooking units while providing electric power (Figure 73). These stoves could burn straw, dung, coal or any locally available fuel.

The free-cylinder engine with induction pump would have all its high-mortality components easily available, and its precision components completely protected from any possible contamination.

Another possibility would be to use an electric motor to drive a pump, and

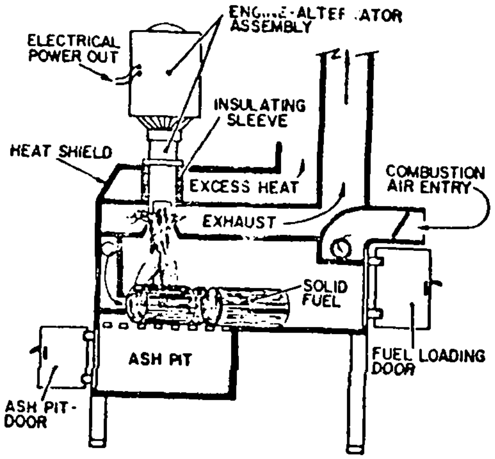


FIGURE 73 Combination wood stove/solid-fuel Stirling engine. [Courtesy W. Beale.]

use a Stirling engine, windmill, or other power source to maintain charge in a battery. This is a complex arrangement, but it has the advantage that many power sources can be used in parallel, and many uses can be made of the stored electric energy.

A third water-pumping alternative would be to use the 1908-style, large, slow, atmospheric engines. A modern design of these would have performance not less than the early 500-W 1-percent achievement. A possible advantage of this large and simple machine is that it requires lower tolerances and is more easily adapted to local foundry and machining capabilities than the more precisely finished high-pressure engines. It does, however, require far more metal for the same power. Another advantage of this rather primitive but appealing engine is its educational value. Its workings are obvious to the interested observer, which is not the case with the free-piston machines.

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TABLE 1. Some Candidate Materials for Terrestrial Solar Cell Fabrication

Material	Efficiency[a]	Status[b]	Type[c]	Commercial Availability[d] 0-5 years	Commercial Availability[d] 5-10 years
AlSb	(e)	experimental	III-V	no	perhaps
InP	.05	experimental	III-V	no	perhaps
GaP	.03	experimental	III-V	no	perhaps
GaAs (Al)	.16	experimental	III-V	perhaps	perhaps
GaAs ($Ga_xAl_{1-x}As$)	≃0.25	experimental	III-V	no	perhaps
CdS(Cu_2S)	.05-.08	advanced[f] development	II-VI	perhaps	perhaps
CdTe	.05-.06	advanced development	II-VI	no	perhaps
SiC	.03	experimental	IV-IV	no	unlikely
Si	.15-.18	commercial	elemental	yes	
ZnSe	(e)	theoretical possibility	II-VI	no	perhaps
$CuInS_2$	(e)	theoretical possibility	$II\text{-}III\text{-}VI_2$	no	unlikely
$CuInSe_2$	(e)	theoretical possibility	$II\text{-}III\text{-}VI_2$	no	unlikely
$AlInS_2$	(e)	theoretical possibility	$III\text{-}III\text{-}VI_2$	no	unlikely
Zn_3P_2	(e)	theoretical possibility	$II_3\text{-}V_2$	no	perhaps
Cu_2O	(e)	theoretical possibility	$II_2\text{-}VI$	no	perhaps

Photovoltaic Systems

Experimental and Prototype Systems

The categories of application of photovoltaic systems for terrestrial use include scientific tests and demonstrations, quasi-commercial or prototype commercial applications, and fully commercial applications.

Experimental or demonstration uses of solar cells began in 1955 when Bell Laboratories and the Bell Telephone Company installed a solar-powered, rural-telephone carrier system in Americus, Georgia.[4] The system was operated for about 6 months–as a technical demonstration and publicity effort. In 1973, combined photovoltaic (CdS) and thermal collectors were integrated into a laboratory/house at the University of Delaware[5] to explore the nature of residential solar electric/thermal systems connected to a local electric-utility grid. At the California Institute of Technology, scientists from the geology department are using surplus spacecraft solar panels (from Ranger and Mariner spacecraft), suitably modified for protection against weather, to power remote scientific geological stations in California and Mexico.[6] And the Mitre Corporation (McLean, Virginia) is developing a 1-kW solar electric/hydrogen system to demonstrate the use of solar-generated electricity combined with electrolytic hydrogen as a secondary energy carrier.[7] All of these applications have been largely scientific in nature; they have not involved exploration of near-term markets for photovoltaic applications, although the work at the University of Delaware will eventually lead to an evaluation of combined photovoltaic/thermal solar collectors for building applications.

Other experimental systems have been installed in the Chilean desert as a joint University of Chile/RTC (la RTC Radiotechnique-Compelec, France) project, in Iran (at Pahlavi University in Shiraz), as well as in France, Africa, the Soviet Union, India, Japan, England, and West Germany.

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[a] Efficiency of devices as measured under Air Mass Zero (AM0–see footnote, page 99) conditions of 1,400 W/m² incident solar radiation (i.e., with spectral distribution unmodified by atmospheric absorption or scattering–the characteristics of a space environment) and cell temperature approximately 23°C.

[b] "Experimental" refers to cells that have been fabricated in very small numbers under research laboratory conditions. "Advanced development" refers to devices that have been fabricated on a larger scale (many thousands of devices) under conditions that more or less simulate industrial production. "Commercial" refers to devices that are commercially available and technically suitable for use in rural communities.

[c] Roman numerals refer to the group in the periodic table to which each of the elements in the material belongs.

[d] The estimates of commercial availability reflect the opinions of a number of experts as reported in the recent open literature. As a result of the recent acceleration in funding for commercial development on such devices (mainly supported in the United States by the Energy Research and Development Administration [ERDA]), these estimates may prove to be conservative.

[e] Theoretical efficiencies of these devices are in the range of 10-20 percent under AM0 conditions at 23°C. These materials have been suggested by Loferski[3] as the prime candidates for further research for high-efficiency photovoltaic conversion.

[f] Although cadmium sulfide cells are actually commercially available, their operation is so unreliable and so poorly understood that in terms of rural use they should be considered to be in a state of advanced development.

FIGURE 15 Water pump powered by silicon solar-cell array. Illustration shows one of four panels required to power the ¼-horsepower motor that operates the pump. The array size is 36 X 39 in. (91.4 X 99 cm) and it produces 4 amperes at 12 volts DC. [Courtesy Spectrolab, Inc.]

Quasi-commercial or commercial prototype systems are those in which the initial installation was made in order to determine the operating economics of the system and to make a comparison with other available energy systems. Such applications have generally been in situations where there has been a need for remote power in the 1- to 100-W range and where the cost of replacement of batteries, transportation of fuel, or remote power lines was prohibitive. Such applications include, for example, remote radio beacons; radio, television, and microwave booster and repeater stations; and warning and navigational lighting on offshore oil platforms. A number of installations made on a prototype basis have led to commercial installations, following successful operation of the prototype.

Examples include the first remote solar-cell application in Japan, which provides power for a 150-MHz VHF repeater station on Mt. Shinobu,[8] and the *installations of Motorola solar-cell-powered telecommunications equipment* by the California Department of Forestry in the late 1960s.[6] In both cases, commercial installation followed the economic and technical success of the initial installations.

CURRENT TECHNOLOGY (AVAILABLE WITHIN 5 YEARS)

For purposes of this report, commercial systems are those that are produced as a regular product line by a company, and commercial applications are those in which such products have been purchased by some organization because the solar option was the most economical on an annual cost basis. The current commercial market for terrestrial photovoltaic systems could be characterized as one in which some combination of high reliability, low or no maintenance, zero fuel requirements, and noiseless operation, at power levels below 1 kWe (peak), justify, on an economic basis, the use of photovoltaic systems.

These characteristics of photovoltaic systems are not necessarily advantages over conventional power systems if transportation on foot, or by horseback, Jeep, helicopter, etc., for fueling and maintenance purposes to *remote locations* is easily available, if batteries can be purchased and installed

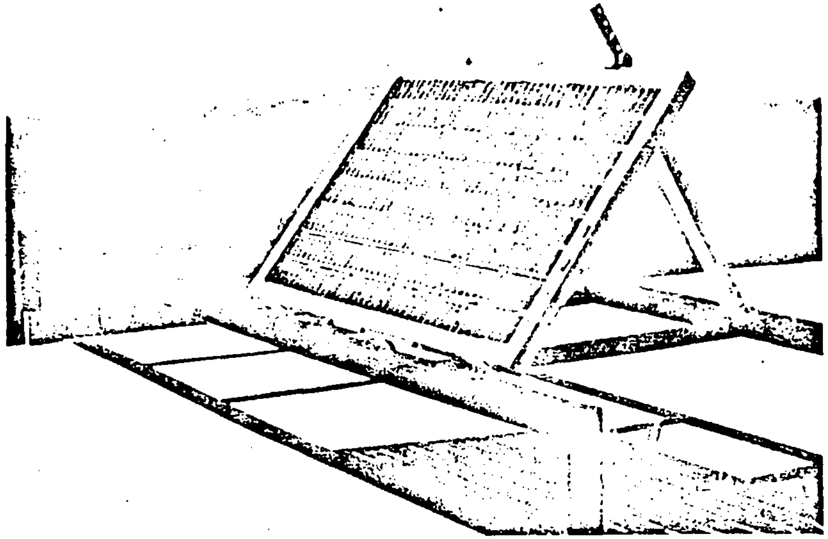

FIGURE 16 Silicon solar cells used for communications. (Photovoltaic panel used by the U.S. Bureau of Land Management to power a VHF radio repeater atop Jack's Peak, Nevada. The array size is 36 X 24 in. (91.4 X 61 cm) and it produces 2.5 amperes at 12 volts DC.) [Courtesy Spectrolab, Inc.]

each year, power lines can be laid, or noise insulation installed where required. Each of these has some specific cost for a given application and a geographic location. Hence, there are situations where the characteristics of photovoltaic systems translate directly into economic advantages. (An economist would say that in these cases the market is operating normally.)

In 1961, Kobayashi[8] reported that it was more economical, on a life-cycle cost basis, to provide remote power at levels up to 50 W by a solar cell/storage battery combination costing $130/peak watt than to run a power line 1 km. Today, Spectrolab, Inc., has sold over 100 systems for remote power for navigational and warning lights on offshore oil rigs in the United States.[9] Several states in the United States, including California, Nevada, and Oregon, are purchasing photovoltaic power systems for remote radio repeater stations and other similar applications; sailboat owners are purchasing solar arrays to keep batteries charged during long voyages; and the French are providing solar television sets in Niger (see below) for educational purposes. Small solar-powered radios were marketed by Motorola in the early 1960s and, at the extreme end of the luxury market, a West German company has recently introduced a solar-power (trickle-charged battery) electronic cigarette lighter for several hundred dollars! As mentioned earlier, the total world market for diverse commercial and spacecraft applications is roughly 100 kWe (peak) per year and, at present prices for photovoltaic arrays, it is expected to grow to perhaps 3 times that within 3 years.[10]

Of the various types of photovoltaic devices that have been manufactured, only silicon solar cells have become an established commercial product (Table 1). CdS cells have been used in space applications by the United States and France; GaAs cells were used by the Soviet Union in near-sun deep space probes. Nevertheless, silicon cells are the only devices that can be made reliably in quantity, are stable with time, and whose operation is sufficiently well understood to enable properties to be predicted and electrical characteristics to be designed in.

Commercial systems discussed in this section are available from manufacturers in the United States, Japan, West Germany, France, and England. Manufacturers will provide either individual silicon solar-cell modules appropriately encapsulated in rugged supports or complete systems including batteries and power-conditioning equipment.

Most of the devices and systems currently available have been developed and used for specific applications where conventional energy sources are not available, but the need for modest amounts of power is critical in terms of commercial or military operations. Thus, they are too costly for applications in rural areas of developing countries except where a specific and critical need might occur. A summary of some current manufacturers of photovoltaic arrays and an example of typical product data available are listed in Appendix 3 for the benefit of those concerned with use of such systems. Only a few typical examples will be mentioned here; the manufacturers themselves are probably the best source of information regarding practical applications in various locales.

Solar-powered signaling from remote stations in the United States. In 1973, the Tidelands Signal Corporation of Houston, Texas, fabricated a complete aid-to-navigation, warning-light system, including silicon solar arrays fabricated by Solar Power Corporation (Massachusetts), and installed the system on an offshore oil platform on the Texas Gulf coast. The lighting system consists of 1 2-mi fog signal and 4 5-mi lamps. Energy consumption is about 25 amp-hr/day x 12 volts = 300 Whe/day. Previously, this lighting system was powered by 40 1.2-volt, 3,300 amp-hr primary batteries. The total weight was 2,000 lb and these were replaced annually. The solar generator system incorporates 80 photovoltaic modules (1.5 W peak under AM1[*] illumination, 25°C) in a 4 x 5-ft (1.22 x 1.52-m) array. The information available implies a retail cost of roughly $20/peak watt and indicates that at such prices for a terrestrial array (sealed, ready to install), such arrays begin to compete with primary and secondary batteries in markets traditionally served by this hardware.[11] The report on this system claims that "solar cell/secondary battery systems clearly compete on a life-cycle cost basis, although the specific numerical details are not discussed."

The National Aeronautics and Space Administration (NASA) Lewis Research Center and the National Oceanic and Atmospheric Administration (NOAA) are cooperating on a project to design, fabricate, and install a number of solar power systems for remote atmospheric monitoring stations.[12,13] Two installations, one in Virginia (Sterling) and one in California (Mammoth Mountain), were built in 1973 and further installations are expected. As a precommercial application, solar arrays have been fabricated by NASA/Lewis using commercial solar cells in arrays made of modules containing 48 (6 x 8) circular silicon solar cells each and supplying 3 W (AM1) per module. The arrays at each installation contain 20 modules, for a peak power of 60 W, and are encapsulated in fluorinated ethylene propylene (FEP) sheets.

Solar-powered educational television sets in Niger. This example is one of the very few documented applications of photovoltaics in a developing country.[13] Although similar programs of educational television for use in outlying rural schools have been or are being instituted in other developing

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[*] The air mass ratio is the ratio of the distance light travels through the atmosphere to the length of the atmospheric path if the source were at the zenith. Thus, in this case, Air Mass One (AM1) implies that the sun is directly overhead.

countries (e.g., Ivory Coast, Brazil, India), none of these seems to have involved the use of solar cells as a power source.

Télévision Scolaire du Niger (TVSN) was created in 1966 as part of a program to upgrade the level of primary education in the country. This educational television system is intended principally for primary schools located in regions without electricity. Reception is assured through the use of television receivers especially designed to operate in climates of extreme heat or cold. These sets are transistorized, will receive at a wavelength of 61 cm (492 MHz), and are designed to operate on batteries supplying 35 W at 34 volts DC (±15 percent). With average battery life of 2,000 hours, it was calculated that one hour of television reception cost 1.38 francs per receiver.

In order to develop a more economical source of energy, the technical services of TVSN and the Office de la Recherche Solaire (Niamey) in 1968 installed an experimental solar panel to power the television set at a school near Niamey. The experiment demonstrated the practicality of providing solar-powered television reception in Niamey during the entire school year (October to June). After an applications study by the ORTF (Office National de la Radio-Télévision Française), six installations followed in 1972, and by 1973 some 800 students in 22 classes were receiving instruction via solar-powered television reception of broadcasts from the production center in Niamey.

As a consequence of the encouraging results of this experiment, the Government of Niger decided on the progressive establishment of a network of solar-powered television sets, with plans to reach 80 percent of the population with educational programs by 1985.[13]

Reliability (Lifetime and Maintenance)

Photovoltaic arrays have no moving parts, and the basic physical mechanism that accounts for the photovoltaic property has a lifetime measured in thousands of years for silicon. (That is, it is basically related to the rate at which impurity atoms, which form the p-n junction, diffuse through the crystal lattice, degrading the junction.) Techniques have been developed to encapsulate silicon solar cells in a clear silicone material that provides excellent shock insulation and protection from environmental effects. The closer such encapsulation approaches true hermetic sealing, the closer the lifetime of the device will approach that of the base material.

Such reliability may be critical if such systems, when they appear economically attractive, are to be rapidly and widely adopted. People are slow to put total reliance on innovations until a long period of testing and experience has gone by.[14]

In the case of suitably designed solar-cell arrays, the level of maintenance required to provide very high reliability (on the order of one failure per 15 years of operation) is probably both low and inexpensive. It principally involves protection of the transparent surfaces from extreme abrasion and periodic cleaning of the surface and perhaps the electrical connections. Modules could conceivably be developed for which maintenance would consist of only occasional cleaning. A number of photovoltaic systems have operated for close to a decade with no cleaning and with no observable degradation, despite such relatively dirty industrial atmospheres as the Cleveland Airport, for example.

Little labor is required for upkeep because of the low maintenance requirements of solar cells. Apart from skills and materials normally needed for battery maintenance, only a periodic cleaning of the solar array's surface with water—and perhaps soap and a cloth—is needed to maintain a solar-cell installation. Thus, there is no need for a supportive infrastructure for maintenance and repair, specialized training of maintenance personnel, or special tools, etc. (Compare this with the minimum tools, training, and access to spare parts required for the simplest internal-combustion engine/generator combination.)

Cost

The economics of the large-scale energy systems currently used in the industrialized nations (and to a considerably lesser extent in developing countries) differ substantially from the economics of small-scale energy systems that might be used in developing countries. In both sets of circumstances, however, the basic capital costs of various system alternatives must be established before any procedure to calculate final costs of energy delivered to the ultimate user can be employed. The costs of energy from a solar-energy conversion system include many factors beyond the capital cost of the solar conversion module. Capital or initial costs include, of course, the costs of the array modules, with support and orientation structures, plumbing (if forced cooling is used), and other elements such as batteries, inverters and other power-conditioning equipment, and hardware for local distribution of electricity. Additional capital investment costs include provisions for replacement parts, tools, materials for cleaning surfaces and inhibiting corrosion (where necessary), and possibly backup systems such as inexpensive internal-combustion engines plus generators, and occasional use of fuel. Other costs will of course include packaging and transporting the system elements to site, fees and tariffs for importation, and labor costs for assembly and operation of the system. Still additional costs include the development of a local infrastructure to handle replacements, training personnel to use the equipment, development and printing of instruction manuals, and possible additional costs associated with local institutional factors such as the need to monitor how much electricity each member of a settlement is drawing from the system. Other social costs might include payment to, or redirection of, people who make their living delivering kerosene or other fuels that are totally or partially displaced by the solar systems. A partial list of such cost elements is shown in Table 2.

Finally, as with any other proposed investment, the cost of capital and fixed charges will be an important factor in determining the cost of energy. In a photovoltaic system where the costs of the system operation depend primarily on the total capital investment in the delivered system, the interest rates applied to the loans will be particularly important, since the amortized cost of electricity will be almost linearly proportional to the interest rate.

The cost of a cell can be unambiguously expressed in terms of the cost per unit area of the finished device. The actual cost of energy produced in a working environment will depend on such factors as the efficiency of the cell as a function of temperature and of illumination intensity and wavelength, insolation patterns, and other environmental factors. Since the realistic applications of such cells will be in integrated modules, the final costs must be determined in terms of the performance of these modules and not of the cells alone. The current price for individual silicon solar cells is approximately $10,000 per peak kWe ($40,000-$60,000 per average kWe) and the cost of a completed array (with or without batteries and power conditioning, since these are relatively cheap) is $30,000-$70,000 per peak kWe ($120,000 and up for average power). Production of solar arrays or modules at prices more interesting in terms of rural use in developing countries (under $1,000 per average kWe) will depend on major cost reductions in the production of the semiconductor "blank" and its conversion to the finished cell, and in techniques for combining the cell and all of the necessary supports, contacts, connections, covers, etc., into the final module or array.

Of the various techniques currently under development, only one seems likely soon to result in cost reductions, in the cell blanks and finished cells, of sufficient magnitude to bring total costs below $1,000/kWe within 5 years. This is a technique, currently undergoing commercial development by Mobil Tyco Solar Energy Corporation (Waltham, Massachusetts), for the production of continuous silicon ribbon of high-enough quality (i.e., purity and freedom from lattice imperfections) to produce solar cells with conversion efficiencies in excess of 10 percent under standard conditions. The process is known as the EFG or Edge-defined Film-Growth technique. In this technique, a "seed" crystal of silicon is dipped in a bath of molten silicon and a film is pulled through a capillary die (Figure 17) to produce a ribbon. (A prototype array of cells fabricated from this material is shown in Figure 18.) Ribbons of 1-in. (2.54-cm) width with thicknesses down to .008 in. (0.2 mm) have been

TABLE 2. Cost Components for a Photovoltaic System

Capital Cost	Continuing Costs
Equipment	*Equipment*
Solar conversion modules including mechanical supports, heat transfer (active or passive), orientation mechanisms, concentrators, etc. Batteries	Replacement components for damaged system elements Replacement of batteries (3 to 5 years) and other elements due to corrosion and other forms of degradation, engines after 3 years
Power conditioning (inverters, voltage regulation, current stabilization, transformers, etc.)	Tools, manuals, etc., which are needed continuously and which break or wear out (or are stolen, sold, or otherwise made unavailable)
Local transmission and distribution components, including cables, plugs, and connections, switches and relays, etc.	
Transportation	*Maintenance and Operation*
Packaging for shipment	Labor for maintaining equipment, possible costs for night-time protection
Transport from sources to LDCs; (for those components not produced locally)	Labor for operating systems, including handling billings or other techniques for dividing up local support of the system
Internal transport	
Fees	*Capital Costs*
Import duties Taxes Hidden costs	Interest on capital borrowed to purchase systems
Local Support	*Local Taxes and Other Fees*
Spare parts Tools Manuals Training	Possibility of taxes or fees of various kinds imposed locally
Array Deployment	*Fuel*
Cost of land Labor and materials for deployment On-site structures for housing storage batteries, power-conditioning equipment, etc.	Fuel costs for backup system(s) that may be required to reduce risk of solar-system outages to acceptable levels

continuously pulled at rates of 1-1½ in. (2.5-3.7 cm) per minute, and with continuous lengths of up to 80 ft (24 m). It has been estimated that finished solar cells could be produced for the cost of $165/kWe (peak, AM1, 10 percent efficiency, .004 in. or 0.1 mm thick) or between $500 and $825 per kW average.[15] These estimates are based on anticipated reduction in loss of silicon during fabrication by a factor of 2, a further reduction—by a factor of 3—*in the amount of silicon used* (*as a consequence of the reduced thickness* of the wafer), and a factor of 3 reduction in the cost of the silicon itself as a consequence of the processing technique. In addition, the possibility exists of further significant reductions in cost by the use of solar collectors that would concentrate the light of a larger area onto the cell, thus effectively increasing the area of the solar cell. Figure 18 shows a prototype array of silicon-ribbon solar cells of the type being developed for commercial production.

It should be noted that at the current stage of development, because of the concentration of lattice dislocations in the ribbon, it is not yet possible to obtain these hoped-for efficiencies (10-20 percent) under standard conditions in solar cells made, by direct diffusion, with silicon ribbon. Such efficiencies have been obtained, however, when an epitaxial layer of silicon is grown on EFG ribbon and the junction is then formed in this layer.*

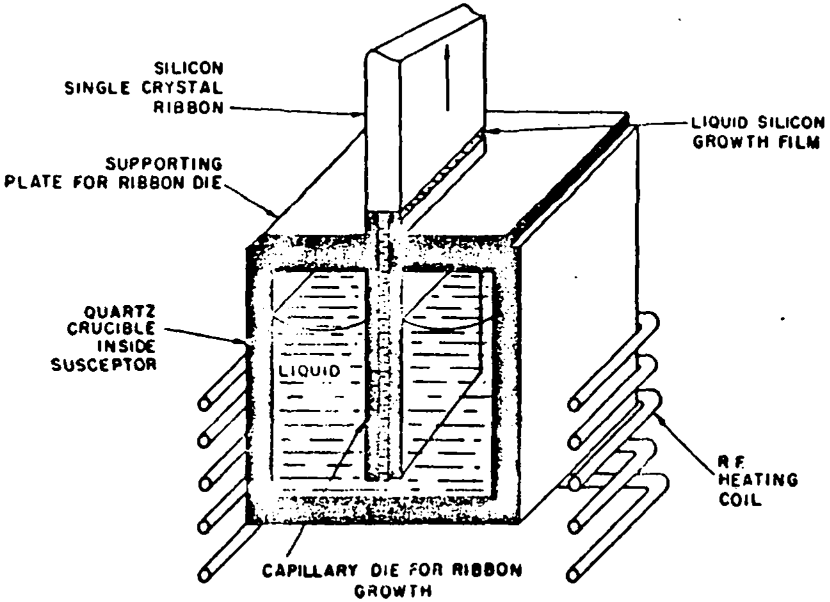

FIGURE 17 Schematic of solar-cell silicon ribbon growth (EFG—"Edge-defined Film Growth") from capillary die. [Courtesy Mobil Tyco Solar Energy Corporation]

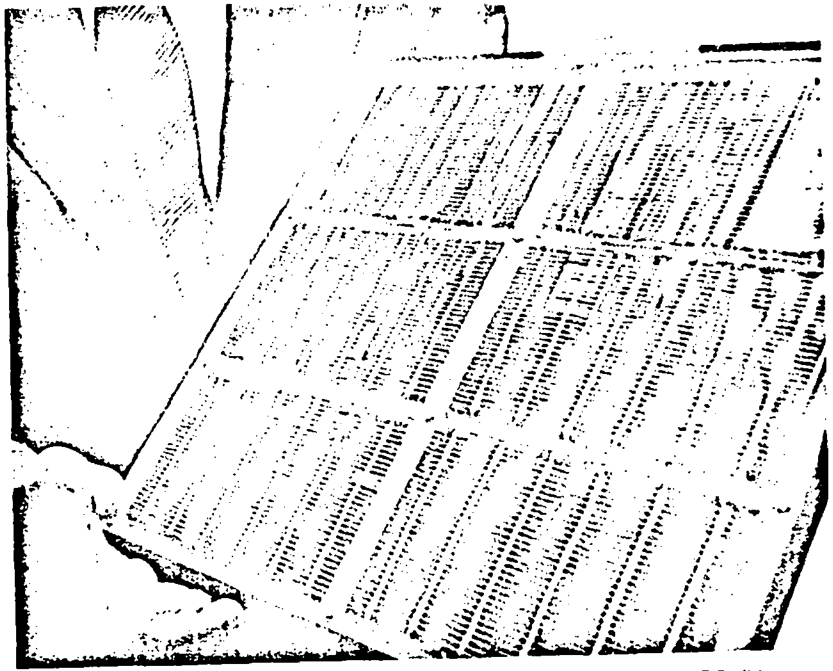

FIGURE 18 Terrestrial photovoltaic array (prototype) fabricated from EFG ribbon silicon. [Courtesy Mobil Tyco Solar Energy Corporation]

Other techniques for the development of low-cost manufacturing processes for production of silicon solar-cell arrays have been explored in considerable detail by Wolf.[17] Among those being examined, for example, is generation of polycrystalline silicon sheet by rolling or extrusion followed by sheet recrystallization by floating zone regrowth.

RESEARCH AND DEVELOPMENT

Although the development of silicon-cell solar arrays at prices under $1,000/kWe average was discussed in the previous section, it is really difficult

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*In work recently reported, for example, a conversion efficiency of 10 percent was obtained with an EFG-ribbon cell on which a 30-μ layer of silicon had been epitaxially grown, while a conversion efficiency of only 6.2 percent was obtained with a cell made from ribbon alone.[16]

to predict whether such a price breakthrough will occur within the next 5 or 10 years. It seems likely that by 1985 such arrays will be available for about \$500/kWe average, but the likelihood of their availability any sooner depends on worldwide interest in, and commercial demand for, such systems.

Integration of solar cells and optical concentrators has been explored in the past. The potential advantage resulting from the reduced cell area needed for a given electrical output might mean a reduction in cell needs by a factor of 4-10; it seems, therefore, that work in this field might usefully be encouraged to compound the savings from new fabrication techniques. This would be the case especially in situations where cooling water is available to keep the silicon temperature from rising beyond the point where the cell efficiency is seriously impaired. (At 200°C the theoretical maximum efficiency is reduced to about 5 percent from a theoretical limit of about 22 percent at 25°C.)

In the case of materials other than silicon, there are some interesting candidates from which highly efficient solar cells might be commercially manufactured within 10 years (Table 1) but, again, whether a sufficient price breakthrough will occur to make them reasonable power sources for developing countries is hard to say. Gallium arsenide is particularly interesting in that, because of the nature of its bandgap, incident sunlight is absorbed at a depth of about 1-2 μ (compared to 100-200 μ for silicon), which makes it possible to use much less material per device than with silicon, thus perhaps compensating for its higher cost. Furthermore, because of its electronic properties, GaAs has a higher theoretical efficiency than silicon, its bandgap (1.35 eV) is closer to the optimum for sunlight (average photon energy $\simeq$1.5 eV) than is silicon's (1.1 eV), and it can operate efficiently at higher temperatures, thereby making the potential use of concentrators more promising.* Thus, the combination of factors–thinner wafers, smaller areas, and higher efficiencies (as high as 19.1 percent with a concentration factor of 1735)[18]–makes gallium arsenide a material that could compete with silicon as a source of efficient solar cells. However, its accessibility in terms of cost depends strongly on how much further research and development are stimulated by worldwide demand.

PHOTOVOLTAIC SYSTEMS IN DEVELOPING COUNTRIES

The attractiveness of a photovoltaic system to a developing country will depend on the economic significance of that application to those who have to pay for and maintain it. In some cases, this may be some agency of government, a donor agency such as the U.S. Agency for International Development (AID), or an international agency such as the United Nations Development Program (UNDP) or the International Bank for Reconstruction and Development (World Bank). In others, it will be the local inhabitants themselves. A detailed analysis of the value of various energy-related or energy-derived (specifically electrical energy) services in various cultural and geographic environments is required before a useful assessment of the potenial market for solar power systems can be made (unless the cost of these systems drops to the point where it is the cheapest alternative available for large-scale power generation). The nature and size of various markets in developing countries will depend on the delivered cost of the photovoltaic systems as well as on the value of electricity-derived services. Part of the required analysis would be an economic assement of the value associated with the following features of photovoltaic systems:

- High reliability;
- Low maintenance requirements;
- Zero fuel requirements;
- Intermittent output without storage, continuous output with storage; and
- Modularity (when one piece of the system goes out, the rest can continue to function, which is not the case with generators).

Reliability and maintenance have already been discussed. Photovoltaic systems share total independence of fuel requirements with all other alternative-energy technologies discussed in this report; the intermittent nature of their output–without storage–is another characteristic shared with many of these technologies. The modularity of photovoltaic systems, however, is unusual and worth special attention.

The modular nature of photovoltaic systems permits the users to gain experience with a relatively small investment. This is a crucial aspect of rapid diffusion of an innovation.[14] When large investments in innovations are required, they may never be adopted due to the lack of opportunity to test them at an acceptable level of financial risk. Systems can grow as the affluence of the local community grows, and system elements could be designed to permit the development of local "grids" as neighboring systems grow and eventually become contiguous. Loads can grow with supply, meaning essentially full amortization of the investment. Finally, a modular power system means that one or a few photovoltaic elements can fail and the system can continue to operate. Replacements can be obtained at the most convenient and least expensive time.

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*Although there are many other direct bandgap materials, besides GaAs, that could be considered as candidates for similar reasons, more industrial effort has already been devoted to investigations of gallium arsenide than to any of the others.

Conversion of solar into mechanical or electrical energy: Indian experience

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The total area of land under cultivation in India is about 143 X 10^6 ha, of which 30%, or 43 X 10^6 ha, is irrigated. Of this irrigated area, 23 X 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 X 10^6 ha, of which 6 X 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

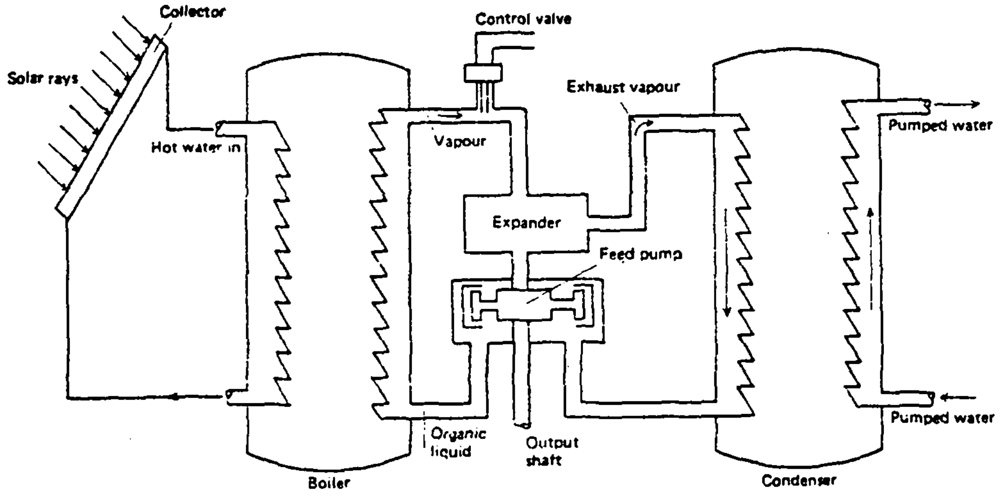


Figure 1. Diagram of Abhimanyu solar water pump

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/m^2 (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.

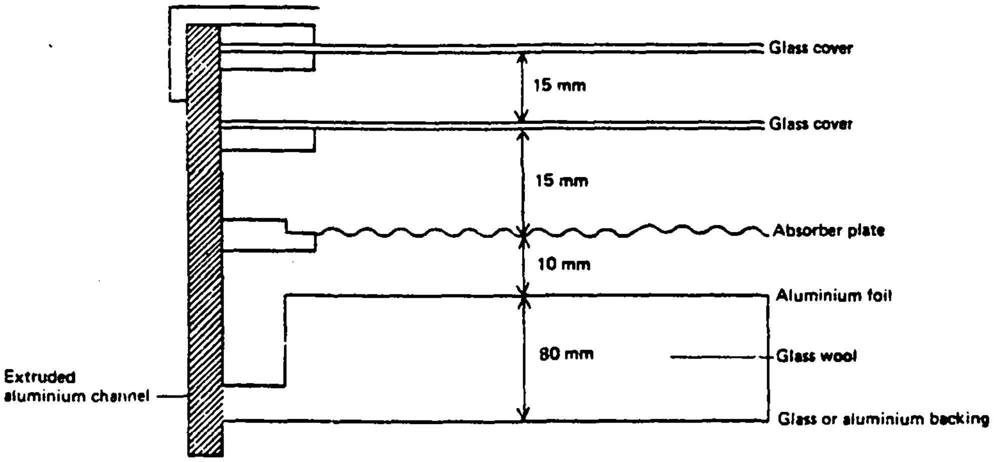


Figure 2. Cross-section of a collector assembly

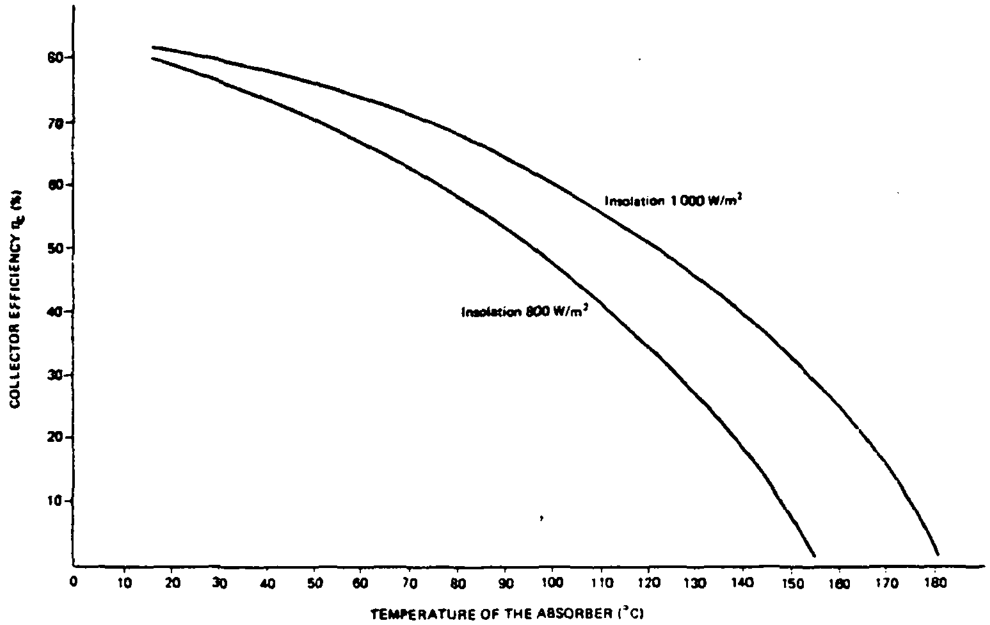


Figure 3. Efficiency of the collector chosen for the Abhimanyu pump

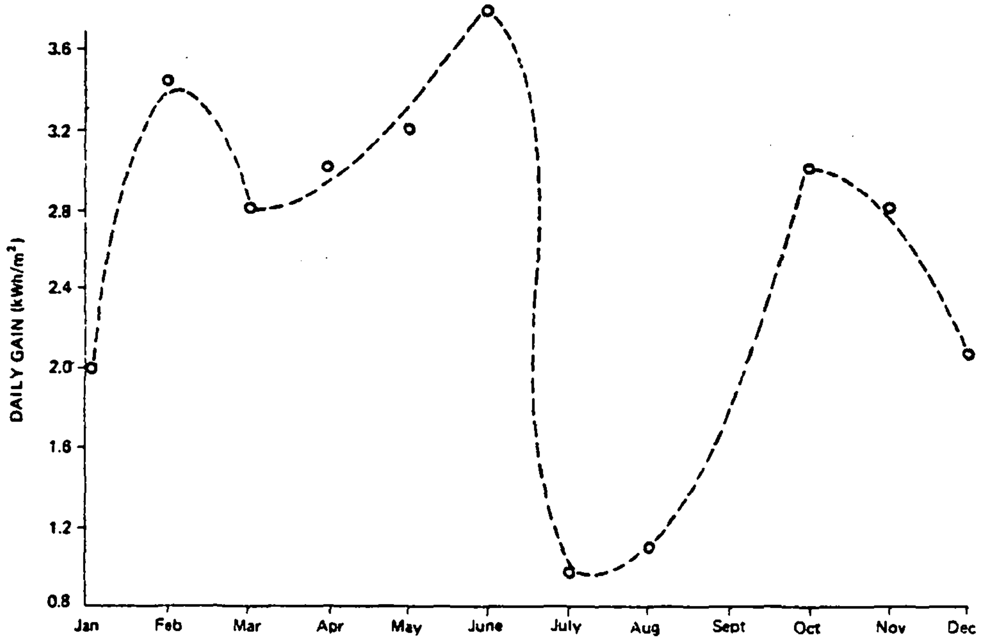


Figure 4. Annual variation of the daily useful gain in energy by a typical collector operating at 90°C

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

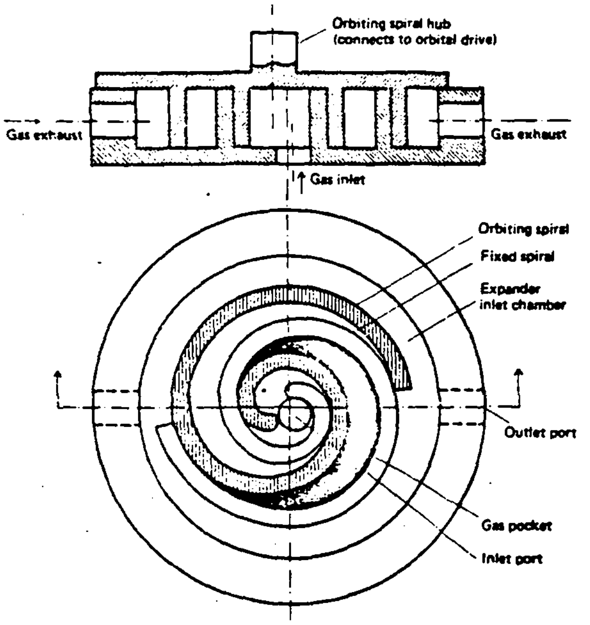


Figure 5. Typical spiral expander configuration

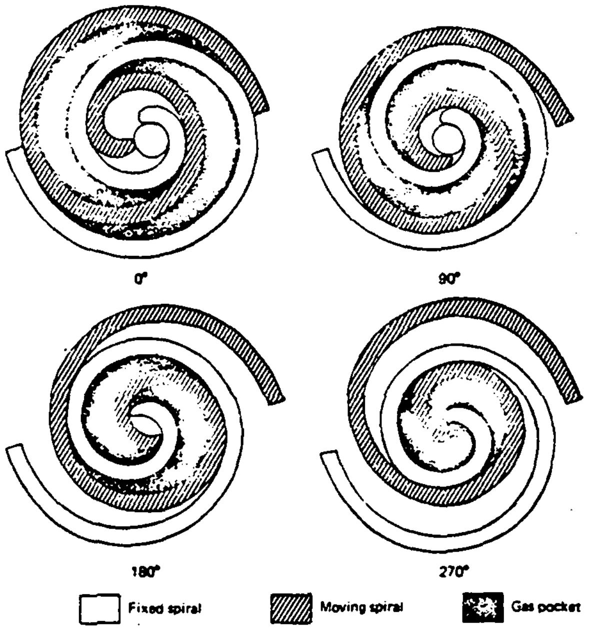


Figure 6. The positive-displacement rotary machine operating as a compressor, at different phases of the orbit of the moving spiral

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.

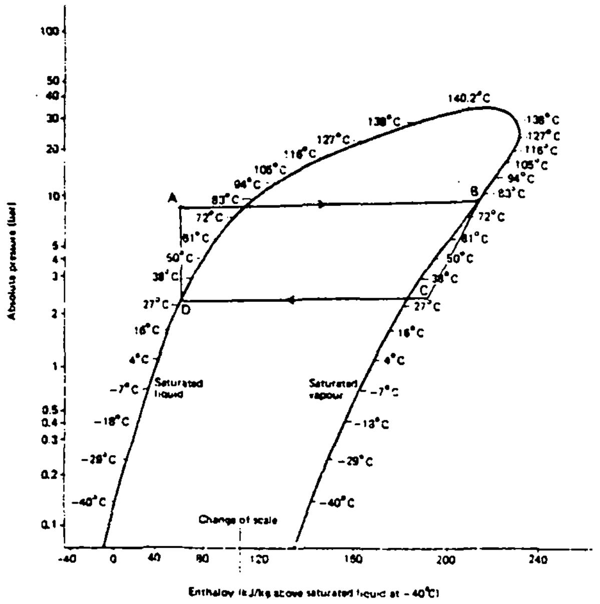


Figure 7. Engine working cycle

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 X 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.

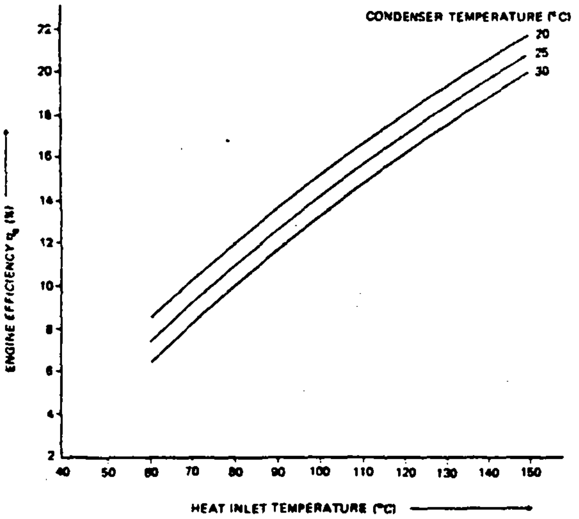


Figure 8. Engine efficiency against inlet temperature at different condenser temperatures

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

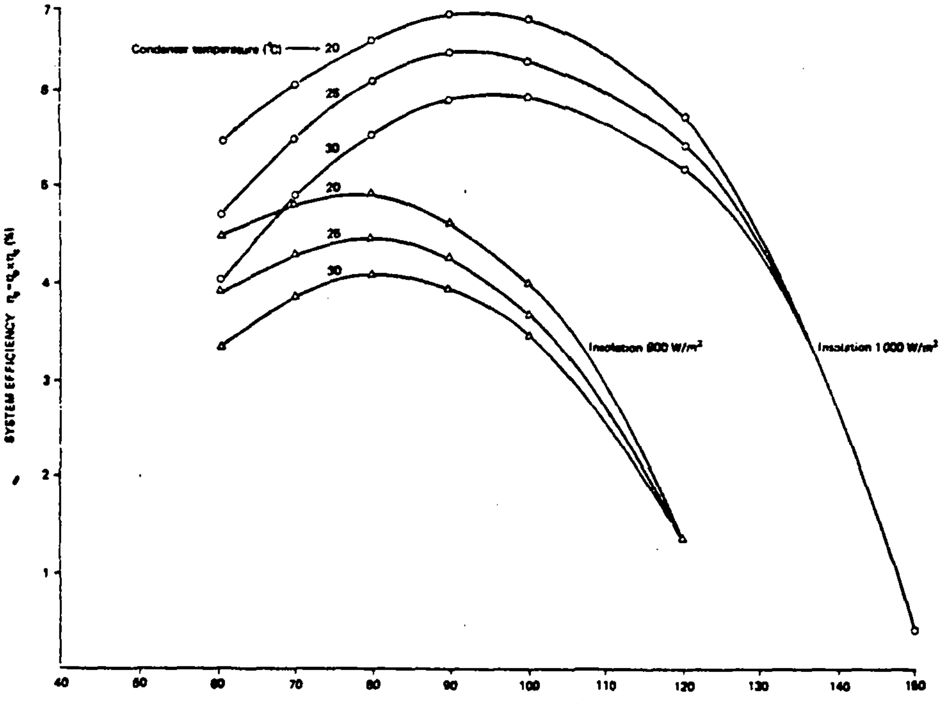


Figure 9. Variation of system efficiency with collector temperature at insolations of 800 W/m^2 and 1 000 W/m^2

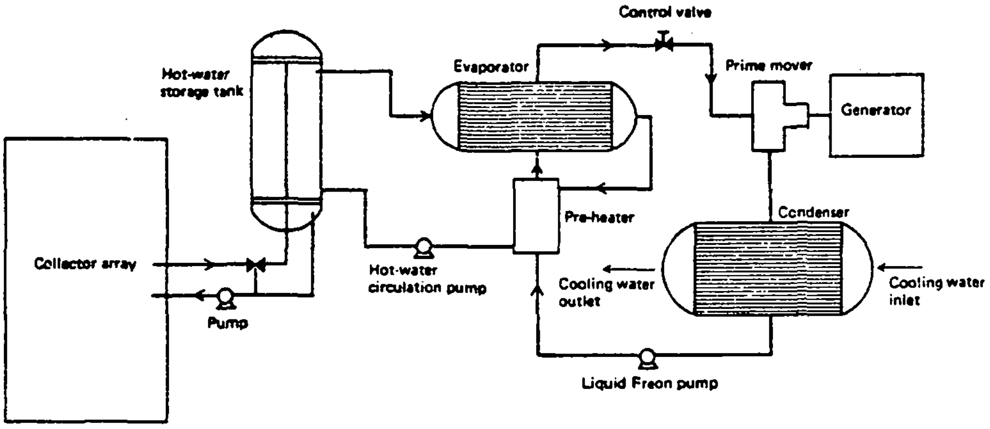


Figure 10. Diagram of a 10-kW power station

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.

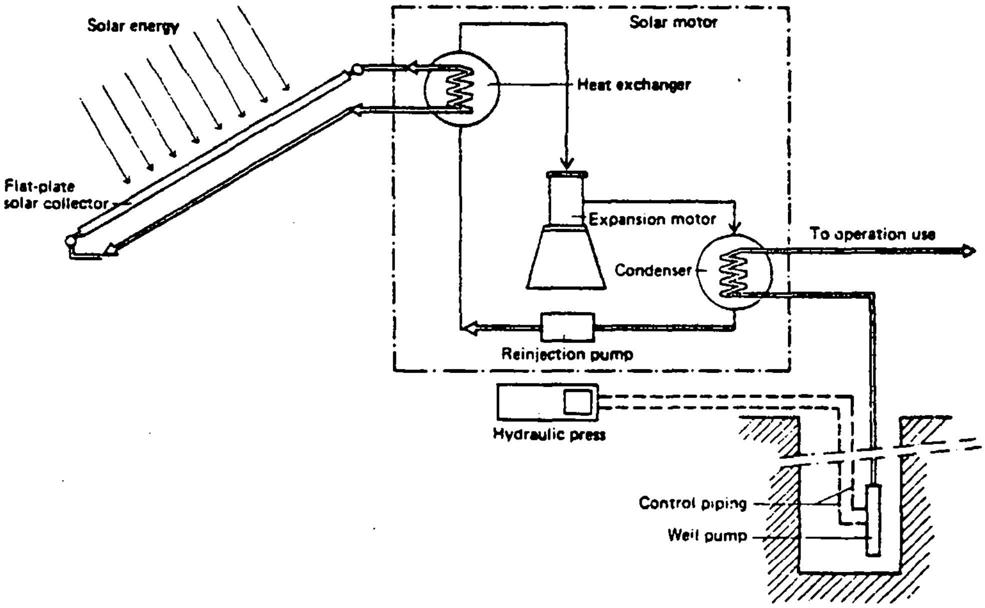


Figure 1. Schematic diagram of a solar pumping station

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)	High investment Discontinuous supply (storage tank required) More extensive civil engineering
Solar radiation *(cont.)*	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	

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.

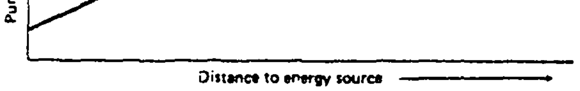


Figure 2. Cost of pumping water using various forms of energy as a function of the distance to the energy source

DORNIER SYSTEM

Solare Pumpe

Bei der Nutzung der Solarenergie zum Betrieb von Arbeitsmaschinen steht die solare Pumpe an vordester Stelle. Besonders für die Entwicklungsländer, die vorwiegend in den Trockengürteln der Erde liegen, werden einfache Pumpen zur Bewässerung und Trinkwasserversorgung benötigt. In diesen Ländern bietet sich aufgrund der hohen Sonneneinstrahlung der Pumpbetrieb mit Hilfe von Solarkollektoren an. Trotz des großen technischen Aufwandes, der bei der Nutzung der Solarenergie für Arbeitsprozesse notwendig ist, müssen die Pumpanlagen den Einsatzbedingungen entsprechend so einfach und zuverlässig wie möglich ausgeführt sein.

Unter diesen Gesichtspunkten werden derzeit bei Dornier verschiedene Konzepte untersucht:

- Verwendung von konzentrierenden, nachführbaren Solarkollektoren in Verbindung mit einer kleinen Dampfmaschine, die einen Generator antreibt. Die vom Generator erzeugte elektrische Energie wird zum Betrieb einer Wasserpumpe und des Nachstellmotors der Solarkollektoren genutzt. Bei der auf den werkseigenen Testgelände in Friedrichshafen aufgebauten Demonstrationsanlage gibt der verwendete Generator bei einer Umdrehungszahl von 500 U/min etwa 500 W ab.
- Verwendung einer Dampfpumpe, die direkt mit dem in konzentrierenden und nachführbaren Solarkollektoren erzeugten Dampf angetrieben wird. Der Stellmotor der Solarkollektoren wird von Solarzellen mit der notwendigen Energie versorgt.
- Verwendung von Pumpen mit einfachen Membranen oder Federbälgen, die in Verbindung mit Flachkollektoren (z. B. mit dem Dornier-Wärmerohr-Solarkollektor) Druckluft erzeugen, welche in einen Brunnenschacht über entsprechende Vorrichtungen (z. B. durch Ausdehnung eines Gummikörpers) das Wasser nach oben drückt. Bei der Untersuchung der hierbei denkbaren verschiedenen Möglichkeiten wird besonders auf die Verwendung einfachster Maschinenelemente für die Pumpanlage geachtet.

Das von Dornier angestrebte Entwicklungsziel der genannten Projekte ist die Bereitstellung solarer Pumpanlagen mit zufriedenstellendem Wirkungsgrad bei vertretbarem technischen Aufwand, die zumindest teilweise auch in den Entwicklungsländern selbst hergestellt werden können.

Solar pump

The solar pump ranks high on the priority list in the use of solar energy to operate machines. For developing countries situated in the arid zones of the Earth in particular, simple pumps are required for irrigation purposes and fresh water supply. Because of the high amount of insolation in these countries, pump operation by means of solar collectors seems obvious. Despite the complex technological requirements for use of solar energy in working processes, the pump installations must be as simple and reliable as possible corresponding to the conditions of use.

With these constraints in mind, Dornier currently examines various concepts:

- Use of concentrating, tracking solar collectors together with a small steam engine driving a generator. The electrical energy produced by the generator is used to operate a water pump and the adjusting motor of the solar collectors. The pilot plant installed on Dornier premises in Friedrichshafen has a generator with an output of roughly 500 W at 500 rpm.
- Use of a steam pump directly operated by the steam generated in concentrating and tracking solar collectors. The adjusting motor of the solar collectors receives its energy supply from solar cells.
- Use of pumps with simple membranes or bellows which, together with flat collectors (e. g. the Dornier heat pipe solar collector) generate compressed air which lifts the water in a well by means of suitable installations (e. g. expansion of a rubber ball). The evaluation of the different possibilities is concentrated on the use of the simplest machine elements for the pump installation.

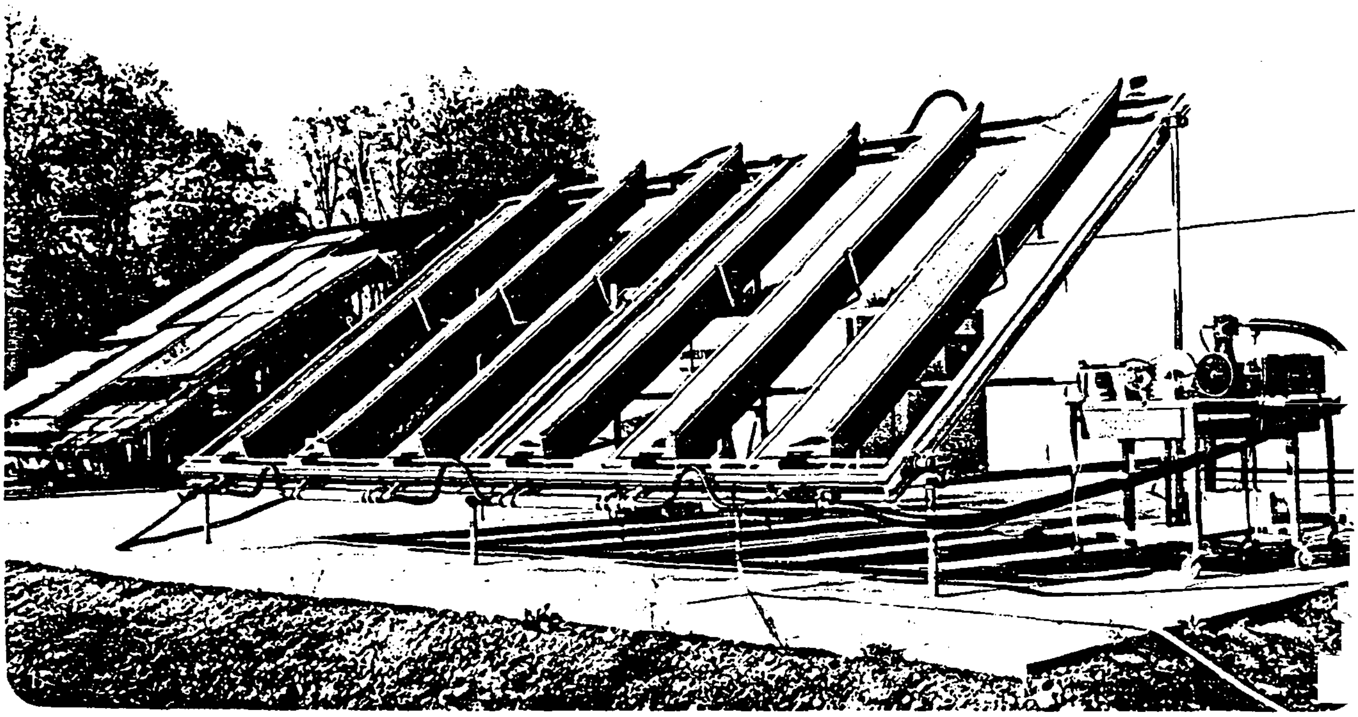
Dornier's development target for the projekts enumerated is to make solar pumps with a satisfactory efficiency and technological complexity available which can be partly built in the developing countries.

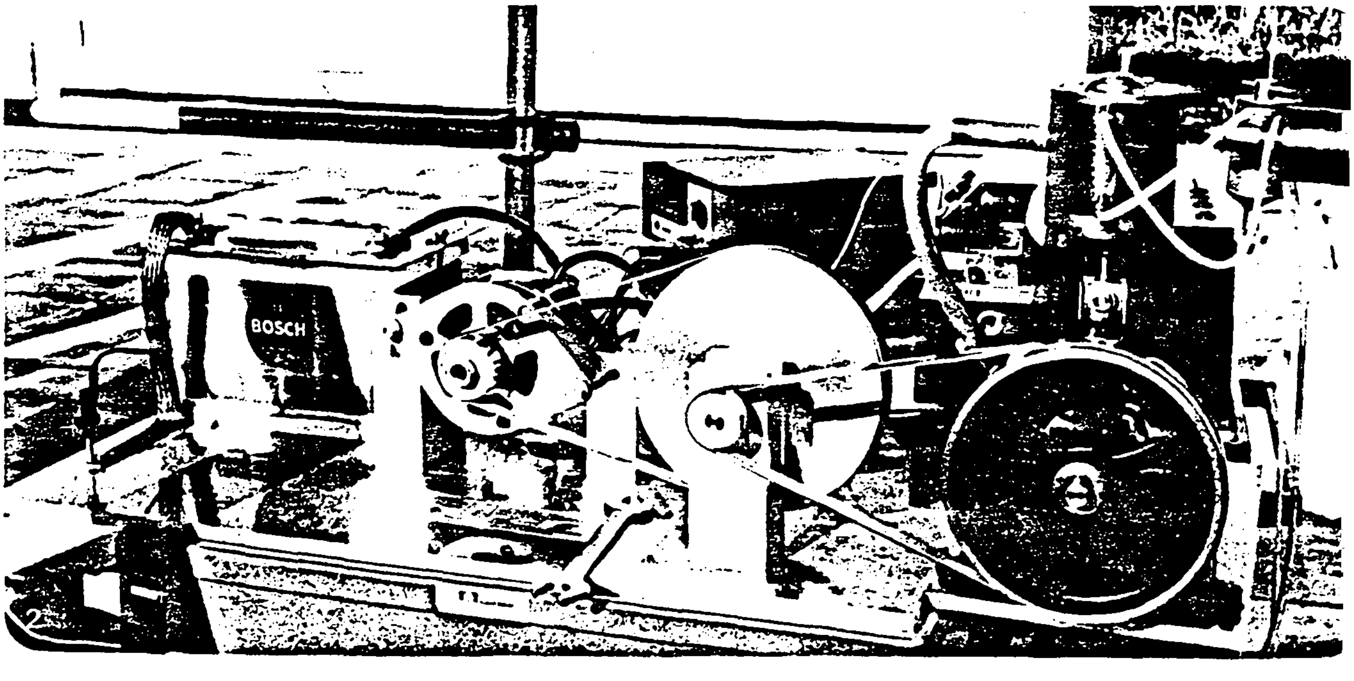
Bild 1: Demonstrationsanlage mit einem konzentrierenden, nachführbaren Solarkollektor

Bild 2: Versuchsaufbau mit einer Dampfmaschine und einem elektrischen Generator

Fig. 1: Demonstration plant with a concentrating tracking solar collector

Fig. 2: Test set-up with a steam engine and an electric generator





Entwicklung und Bau einer einfachen, mit Solarenergie angetriebenen Pumpe

Klaus Speidel
Dornier System

Übersicht

Verschiedene Möglichkeiten zum Bau einfacher, mit Sonnenenergie angetriebener Pumpen wurden untersucht. Beim Einsatz von Flachkollektoren ist ein Zwischenträgermedium notwendig, welches nicht mit dem Trinkwasser in direktem Kontakt kommen darf. Einfachsysteme, aufgebaut nach dem Verdrängungsprinzip, und Systeme mit Ausnutzung der Entspannungsarbeit wurden untersucht. Aus Wirtschaftlichkeitsgründen wird ein Antriebssystem mit Entspannungsprozeß vorgeschlagen. Die notwendige Dampfmenge soll durch Direktverdampfung auf der Kollektorseite erfolgen.

1. Zielsetzung

Ziel dieser Arbeiten ist die Entwicklung und der Bau einer einfachen solarbetriebenen Pumpe, die auch ohne hochentwickelte technische Infrastruktur in Entwicklungsländern größtenteils herstellbar ist. Der Einsatz der Pumpe ist im wesentlichen zur Deckung des Trinkwasserbedarfs kleiner, entlegener Dorfgemeinschaften gedacht. Dies bedeutet, daß bereits relativ kleine Pumpenleistungen genügen.

Ein Prototyp einer derartigen Anlage soll nun gebaut werden, nachdem in einer ersten Phase unterschiedliche Konzepte untersucht wurden. Dieser Prototyp soll etwa folgende Spezifikationen erfüllen:

- Pumpenleistung ca. 100–200 W bei Kühlwassertemperaturen von ca. 25° C
- Selbstanlauf des Pumpensystems an jedem Sonnentag
- weitgehende Wartungsfreiheit
- einfacher Aufbau des Systems
- Reparaturfreundlichkeit

2. Systemkonzept

Prinzipiell lassen sich zwei Systemkonzepte unterscheiden:

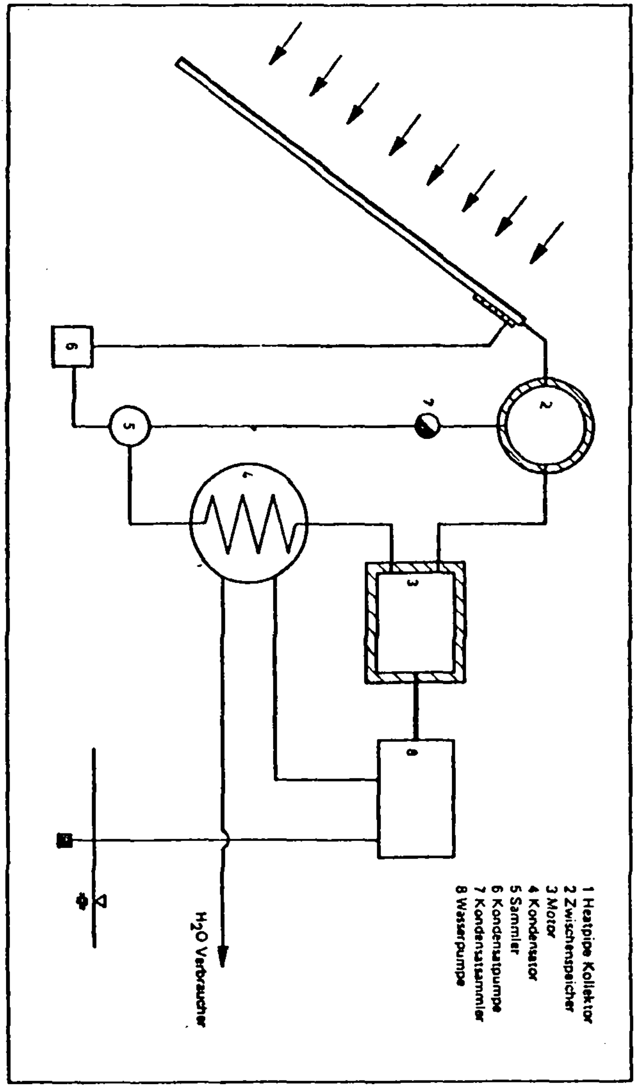
- offene Systeme
- geschlossene Systeme

Offene Systeme arbeiten mit der Methode der direkten Kontaktnahme mit Wasser und Kreislaufmittel. Als Bauelemente dienen im wesentlichen mehr oder weniger große Tanks, die durch Aufheiz- und Abkühlvorgänge bei entsprechender Verschaltung und Steuerung die Pumpenleistung erbringen. Für Bewässerungssysteme mögen solche Pumpen mit Einschränkung einsetzbar sein, nicht jedoch für die Trinkwasserversorgung.

Geschlossene Systeme arbeiten nach dem Prinzip der absoluten Trennung von Pumpenwasser und Kreislaufmittel und eignen sich daher für den geplanten Einsatz. Aus diesem Grunde ist hier der Bau dieses geschlossenen Systems vorgesehen.

Zur Realisierung gibt es unterschiedliche Prinzipien, die im folgenden z. T. erläutert werden sollten. Grundsätzlich, wie auch bei allen anderen Solarenergienutzungssystemen, besteht auch hier die Notwendigkeit, die Wirkungsgrade der Einzelkomponenten zu optimieren. Die Sonnenenergie wird zwar kostenlos geliefert, jedoch bedeutet jegliche Nutzung den Aufbau von Aggregaten mit mehr oder weniger hohen Investitionskosten, die die Wirtschaftlichkeit des Systems wesentlich bestimmen. Schlechte Wirkungsgrade auf der Aggregatseite bedeuten entsprechend höhere Investitionskosten auf der Kol-

Abb. 1: Funktionsschema Solare Pumpe



lektor- und Systemseite. Insofern ergibt sich eine gewisse Problematik bei der Suche nach einfachen Systemen, die aber doch höhere Wirkungsgrade aufweisen sollen.
Es wurden verschiedene Konzepte untersucht, die jeweils mit verschiedenen Vor- und Nachteilen behaftet sind. Da die Energieübertragung in allen untersuchten Fällen über ein Zwischenmedium erfolgen muß, wird folgendes Gesamtsystem zur Realisation vorgeschlagen (s. Abb. 1):

- Die einfallenden Sonnenstrahlen erwärmen den Heatpipe-Kollektor [1], in welchem sich das Kreislaufmittel befindet. Der Heatpipe-Kollektor wirkt hier als Verdampfer.
- Das verdampfte Kreislaufmittel wird zum Antrieb des Motors verwendet, welcher direkt mit der Wasserpumpe gekoppelt wird.
- Nach Arbeitsabgabe wird das Kreislaufmittel kondensiert und über eine Kondenspumpe in den als Verdampfer eingesetzten Heatpipe-Absorber zurückgepumpt.

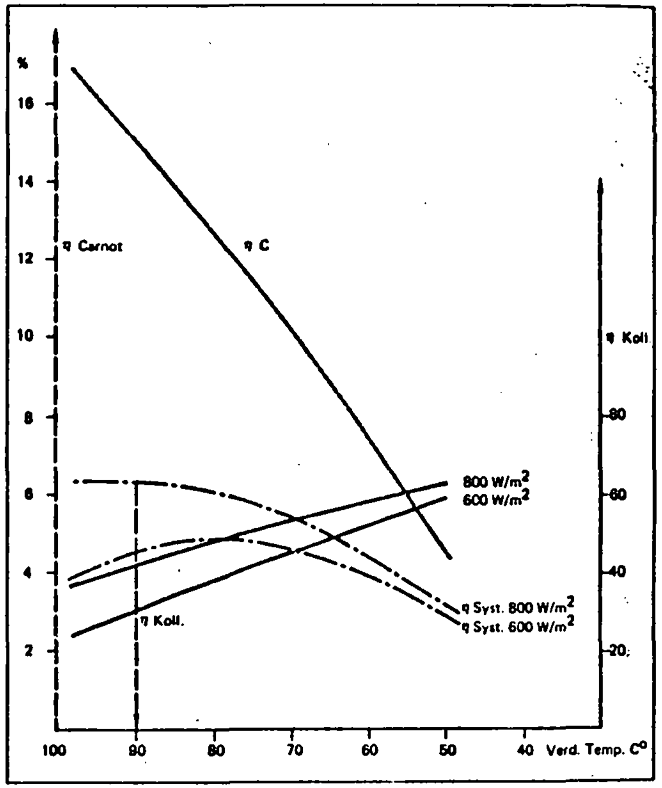
Damit ist der Kreislauf geschlossen. Das gepumpte Wasser wird z. T. zur Kondensation des Kreislaufmittels verwendet, wodurch es geringfügig erwärmt wird.
Der konstruktive Aufbau des geplanten Systems unterscheidet sich von den Systemen üblicher Bauart insbesondere in einem Punkt: der Kollektor wird nicht als wasserdurchflossener Kollektor ausgeführt, sondern in der Bauart als Heatpipe-Absorber. Dies hat insbesondere folgende Vorteile:

- Direktverdampfung des Kreislaufmittels im Absorptionssystem, damit Vermeidung von Wärmetauscher mit Temperaturverlusten.
- Selbstanlauf des Systems vereinfacht, da keine Umwälzung von Wasser im Kollektorsystem.
- Schnelleres Anlaufen des Gesamtsystems durch geringe Wärmekapazität des Kollektors.

3. Thermodynamische Betrachtungen

Ausgangspunkt der thermodynamischen Betrachtung ist die Festlegung der Arbeitstemperaturen des Kreislaufes. Die Kondensationstemperatur ist vorgegeben durch die Brunnenwassertemperatur, die mit ca. 25° C anzunehmen ist. Um die Baugröße des Kondensators in vernünftigen Grenzen zu halten, wird die Kondensationstemperatur auf etwa 35° C festgelegt. Die Verdampfungstemperatur hängt vom eingesetzten Kollektor und dessen Kennlinie ab. Mit zunehmender Verdampfungstemperatur fällt der Kollektorwirkungsgrad, der Prozeßwirkungsgrad jedoch steigt. Diese beiden Kriterien bestimmen im wesentlichen den Wirkungsgrad des Gesamtprozesses und somit lassen sich optimale Arbeitstemperaturen ableiten. Aus Diagramm 1 sind diese Abhängigkeiten dargestellt.
Definiert man den Carnotprozeß (zur vereinfachten Betrachtung) als Prozeßkriterium und übernimmt aus Messungen den Kollektorwirkungsgrad, so läßt sich zeigen, daß bei einer Einstrahlung von 800 W/m² die optimale Arbeitstemperatur des Verdampfers bei 90° C liegen soll.
Dieser Wert wurde für alle weiteren Betrachtungen als optimierter Wert angenommen. Der so ermittelte maximale Wirkungsgrad des Gesamtsystems liegt bei ca. 6,4%. Legt man als theoretischen Vergleichsprozeß den bei Dampfmaschinen üblichen Rankineprozeß zugrunde, so liegt der maximale theoretische Wirkungsgrad des Gesamtsystems bei ca. 5,8%. Als Arbeitsmittel wurde für diese Betrachtung R11 angesetzt.
Der Arbeitsprozeß selbst ist in Diagramm 2 wiedergegeben (auch hier wurde R11 als Umlaufmittel gewählt).
Darin bedeuten:

1–2: Vorwärmung und Verdampfung im Heatpipe-Absorbersystem
2–3: Expansion und Leistungsabgabe
3–4: Kondensation
4–1: Pumpen des Umlaufmittels



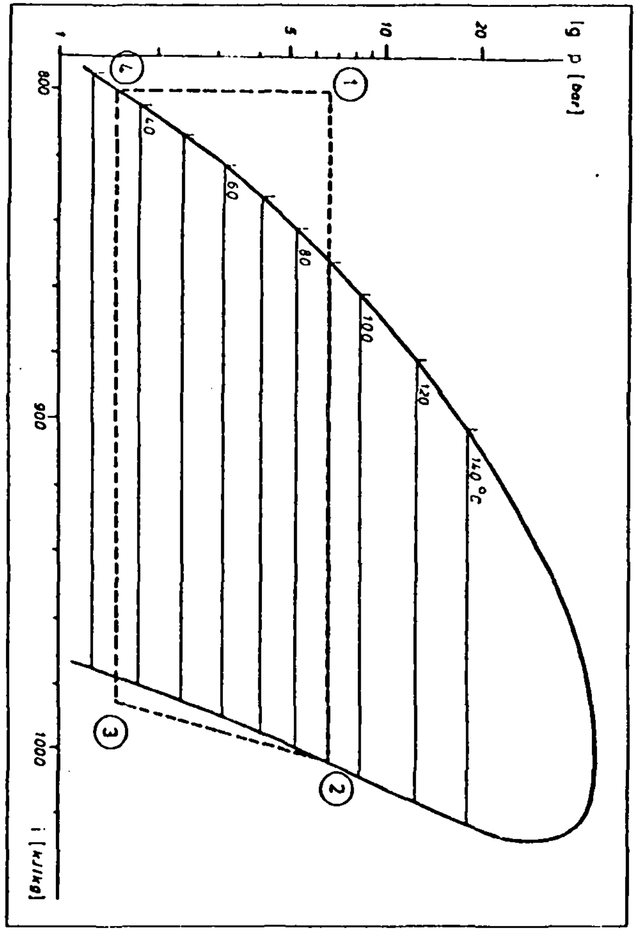
Diagr. 1: Optimierung Prozeßtemperatur

Die maximale Arbeit des Systems (bezogen auf 1 kg Dampfmenge) läßt sich errechnen zu:

$$L = \int v \, dp = i_2 - i_3 \qquad (1)$$

abzuziehen ist die Kondensatpumpenleistung

$$L_k = \int v' \, dp = v' (P_1 - P_4) = \Delta i_k$$



Diagr. 2: Prozeßverlauf für R 11

Bei üblichen Dampfprozessen mit höheren Temperaturen ist die Kondensatpumpleistung fast zu vernachlässigen, bei diesen Prozessen fällt sie zwar nicht allzu sehr ins Gewicht, muß aber berücksichtigt werden.
Der thermische Wirkungsgrad des theoretischen Prozesses nach CLAUSIUS-RANKINE errechnet sich demnach zu (mit R11 als Kreislaufmittel):

$$\eta_{th} = \frac{L}{i_2 - i_1} \qquad (3)$$

und beträgt in diesem Fall 13,8%.
Eine genaue Berechnung des realen Wirkungsgrades ist nicht möglich, da neben der konstruktiven Gestaltung und Ausführung des Motors weitere schwer abschätzbare Parameter mit einfließen. Unter Berücksichtigung dieser Verluste (am Kollektor, Motor, Prozeß und an der Pumpe) ergibt sich ein geschätzter Gesamtwirkungsgrad von

$$\eta_{ü} = \text{ca. } 1{,}4\% \text{ (bei 800 W/m}^2\text{ Einstrahlung)}$$

für optimale Verhältnisse im Auslegungspunkt des Gesamtsystems. Der mittlere Wirkungsgrad bei sich verändernden Einstrahlungsbedingungen und veränderlichem Pumpenbetrieb wird etwa bei 0,8–1,2% angesetzt. Dies bedeutet, daß für den Auslegungspunkt eine Leistung von ca. 8 W/m² Kollektorfläche erbracht wird. Für eine Pumpe von ca. 100 W Leistung ist demnach ein Kollektorfeld von ca. 12,5 m² erforderlich.

4. Motorkonzepte

Das Herz der Gesamtanlage ist der Motor, dessen Bauweise nach verschiedenen Kriterien beurteilt werden muß. Einerseits ist eine einfache Konzeption gefordert, andererseits muß der Wirkungsgrad des Motors so hoch sein, daß der im Punkt 3 genannte Gesamtwirkungsgrad in etwa erreichbar ist.

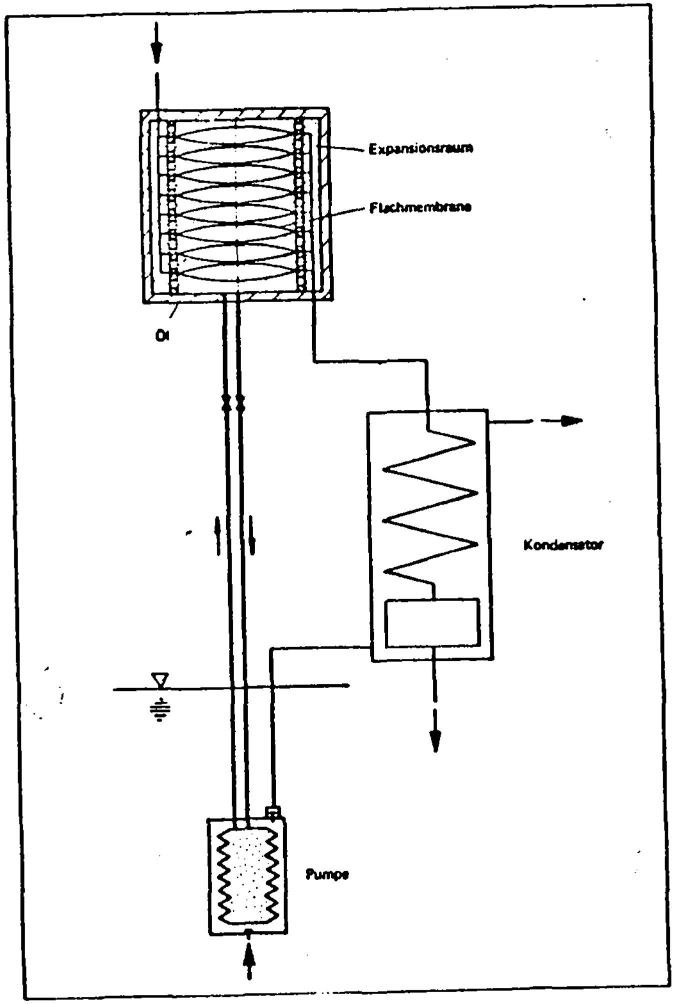


Abb. 2: Solare Pumpe mit Flachmembran (tiefliegende Unterwasserpumpe)

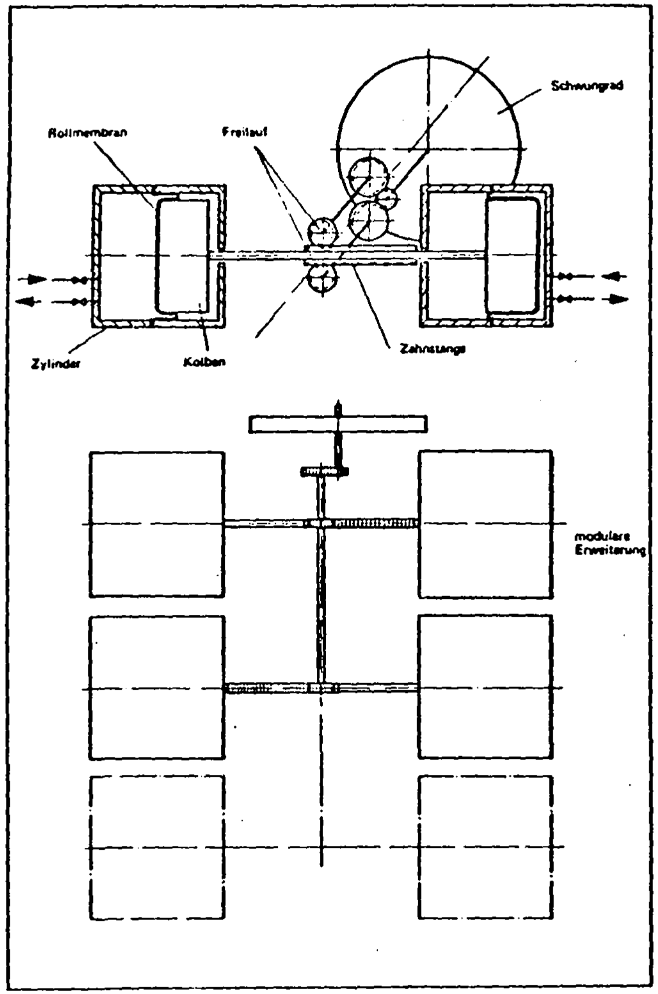


Abb. 3: Antriebssystem Zylinderbauart mit Rollmembran (mit Rotationsumsetzung)

Von den verschiedenen Möglichkeiten der konstruktiven Gestaltung und Ausführung wurden zwei Systeme näher betrachtet, da sie die Spezifikationen voraussichtlich am besten erfüllen können.

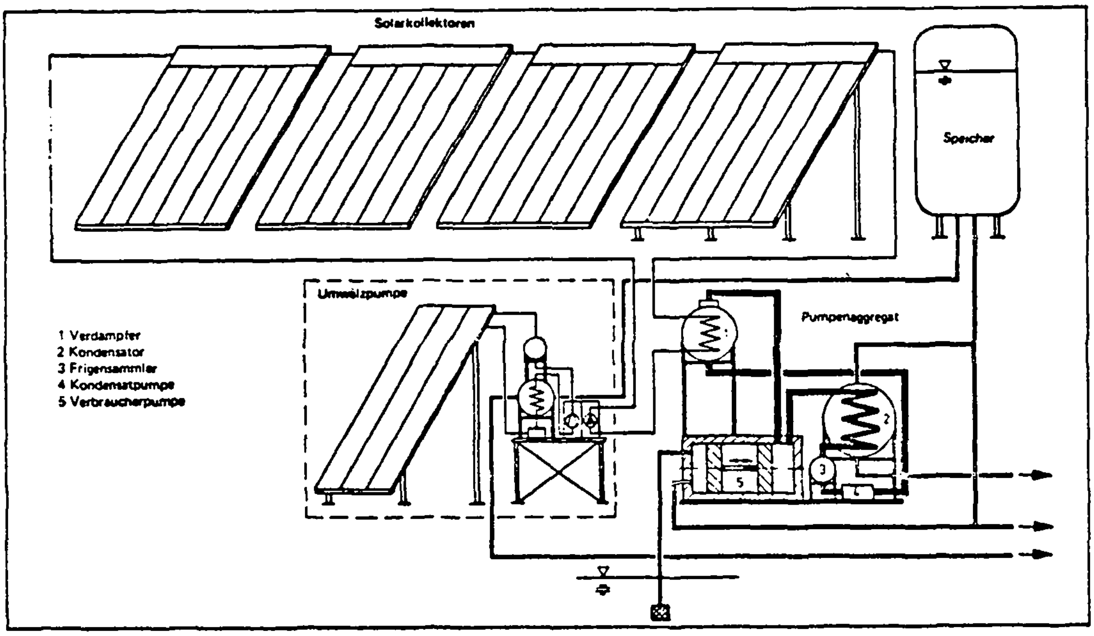
- Flachmembranmotor mit gekoppelter Pumpe (s. Abb. 2)
- Rollmembranmotor in Zylinderbauart mit Rotationsumsetzung (s. Abb. 3).

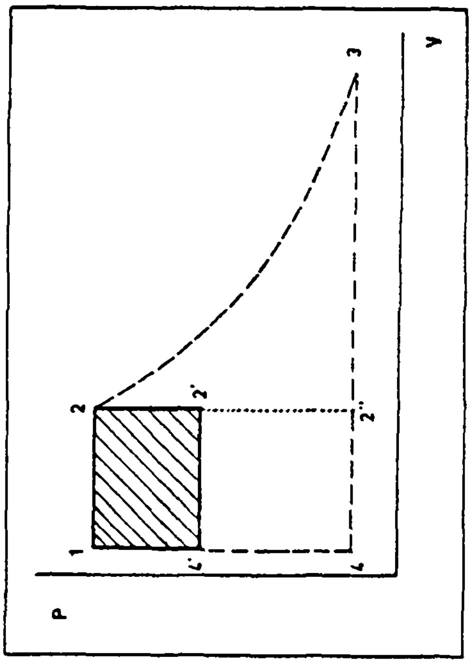
Als wesentliches Element des Flachmembranmotors dient eine Flachmembrane, die als ringförmiges Element in mehrfacher Ausführung aufeinander liegend aufgebaut wird. Das einströmende Freon bewirkt eine Volumenvergrößerung der Membrane, so daß Öl aus dem gefüllten Expansionsraum in die Pumpenmembran gedrückt wird und durch Verdrängerarbeit Wasser fördert. Nach der Expansion wird das Freon in den Kondensator geleitet. Das Öl wird durch den statischen Druck des Wassers auf die Pumpe in den Expansionsraum zurückgedrückt.

Eine weitere Möglichkeit der konstruktiven Gestaltung von Solarantrieben wird in der Verwendung von Rollmembranen als Trennung zwischen Freon und Umgebungsluft gesehen. Rollmembranen sind bekannte Bauelemente in der chemischen Industrie und werden sowohl bei Steuerungselementen als auch bei Antriebselementen erfolgreich eingesetzt. Diese Verwendung von auf dem Markt vorhandenen und erfolgreich getesteten Elementen bietet sich in diesem Falle besonders an. Rollmembranen wurden seit Jahren entwickelt und sind für verschiedene Zwecke geprüft und verwendungsfähig. Eine Untersuchung hat gezeigt, daß ihr Einsatz für diesen Zweck sinnvoll erscheint. Grundsätzlich bietet die Verwendung von Rollmembranen folgende Vorteile:

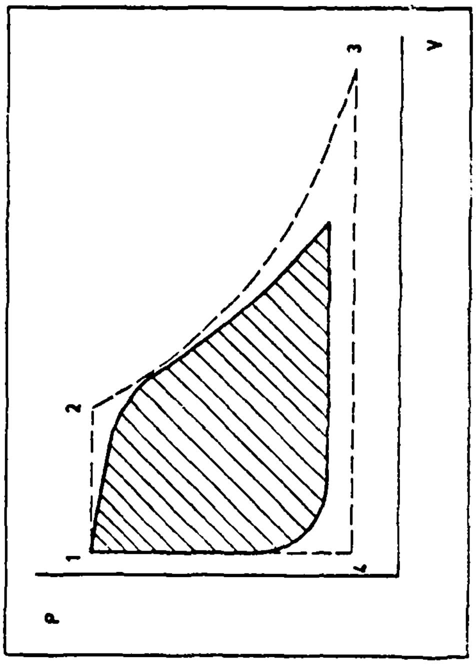
- Bau von Kolbenmaschinen ohne den sonst üblichen Genauigkeitsaufwand beim Bau von Motoren
- Relativ kleiner Totraum des Zylinders und damit guter Wirkungsgrad

Abb. 4: Solare Pumpe für große Leistungen





Diagr. 3: P-V Diagramm für Flachmembranmotor



Diagr. 4: P-V Diagramm für Rollmembranmotor

- Umsetzmöglichkeit der Arbeit in Rotationsenergie, und damit flexible und bessere Nutzung der dargebotenen variablen Leistung

Bei der Beurteilung der beiden Einfachsysteme interessiert zunächst die Thermodynamik der Systeme. Während das Zylindersystem wie eine Dampfmaschine betrachtet werden kann, sind beim Flachmembranmotor einige andere Berechnungen notwendig. Durch die für diese Zwecke relativ große Inflexibilität der Flachmembrane ist es nicht möglich, einen echten Entspannungsprozeß zu gestalten, so daß diese Maschine als reine Verdrängermaschine arbeitet, mit den bekannten Nachteilen. Da für die Pumpe eine gewisse Förderleistung vorgeschrieben ist, vermindert sich die theoretisch mögliche Arbeit nochmals. Diese Vorgänge sind an Hand der p-v-Diagramme 3 und 4 näher erläutert. Die schraffierte Fläche zeigt die bei beiden Systemen gewinnbare Arbeit bei gleichen Verhältnissen. Aus dieser Betrachtung ist zu entnehmen, daß das Prinzip des Rollmembranmotors wesentlich vorteilhafter erscheint. Außerdem gibt es weitere Kriterien, die den Bau eines Rollmembranmotors bevorzugt erscheinen lassen, die hier nicht näher erläutert werden sollen.
Selbstverständlich muß klargestellt werden, daß Systeme mit Rollmembranen nicht für alle Leistungsbereiche einsetzbar sind, ebenso wie alle anderen einfachen Systeme. Leistungen bis zu ca. 0,5–1 kW lassen sich durch die modulare Erweiterung des Grundmoduls erreichen. Geht man zu höheren Pumpleistungen (ab 1–10 kW) und man verlangt dieselben Spezifikationen für dieses Pumpensystem (insbesondere selbständiges Anlaufen), so ist eine Kombination zweier Pumparten denkbar (s. Abb. 4): das Einkreissystem als Einsatz für die Wasserumwälzung und das Zweikreissystem für das Pumpenaggregat. Dieses System würde ohne elektrische Starthilfe auskommen und würde bei entsprechender Bauart keine elektrischen Einrichtungen benötigen.

Literatur:

[1] Beschreibung Heatpipe-Kollektor siehe:
H. Gehrke, Solarhaus Dornier, RWE, Forschung aktuell, 1976, Umschau Verlag;
B. Dietrich und H. Gehrke, Wohnhaus mit Versuchsanlage zur Nutzung von Sonnenenergie, Elektrowärme International, Bd. 33 (1975) Nr. 11, S. A275/A277.

Assessment of solar applications for technology transfer

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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

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[1] United Nations, Department of Economic and Social Affairs, "Selected world demographic indicators", 1975 (ESA/P/WP.55).

[2] *Ibid.*

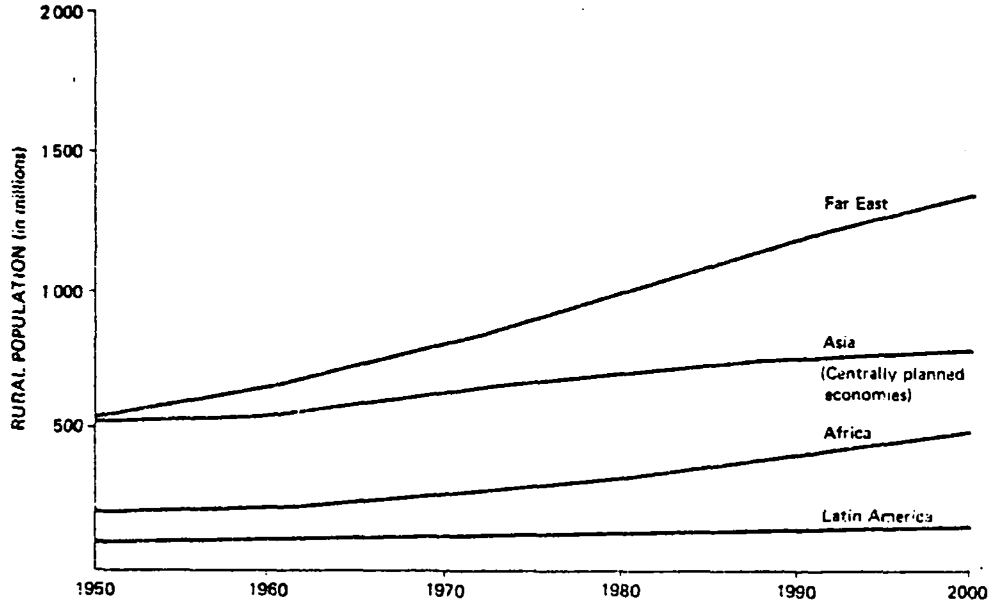

Figure 1. Past and projected rural population of developing regions

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

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[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.

Discounted cost for a given period of service

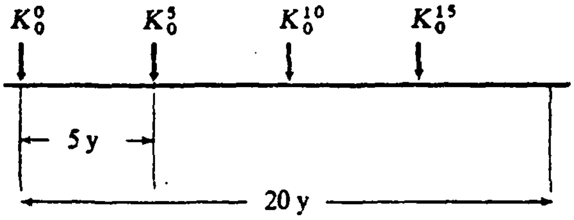
The discounted cost of installing capacity in the initial period for any option would be as follows:

$$C = K + \sum_{i=1}^{l} \frac{O_i}{(1+d)^i} \quad (2)$$

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

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[3] See article by Assad Takla, p. 7.

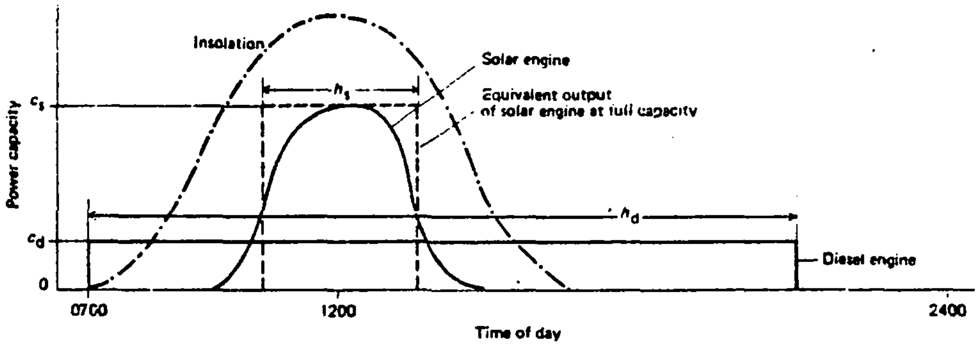

Figure 2. Diurnal variation of insolation and of the output of solar and diesel engines

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

$$W_s = \eta SA \qquad (5)$$

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

$$W_d = h_d c_d \qquad (6)$$

Stipulating that

$$W_s = W_d \qquad (7)$$

we have

$$\eta_s SA = h_s c_s = h_d c_d \qquad (8)$$

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.

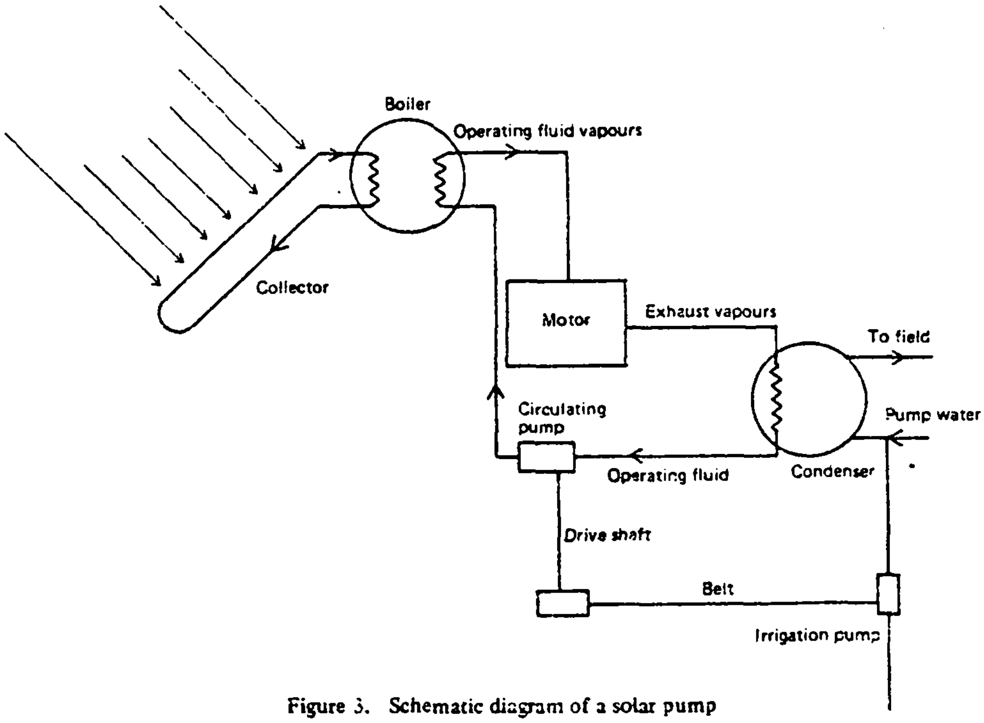

Figure 3. Schematic diagram of a solar pump

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

	Annual increase in price of diesel oil		
Item	*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	1 136

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

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).

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[4] See article by V. G. Bhide, p. 55.

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.

INTERNATIONAL COLLEGE ON APPLIED PHYSICS

INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

FOURTH COURSE ON SOLAR ENERGY CONVERSION

6 - 24 September 1977

SOLAR WATER PUMPING

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(excerpts)

PRACTICAL SOLAR ENGINES WITH THEORETICAL RANKINE CYCLE

There have been many designs of small engines aimed at producing power for water pumping(10,16-19). A unit employed in several developing countries is manufactured by Sofretes of Montargis, France, and is shown schematically in Figure 9. The system includes the following components:

a. Flat plate solar collectors to heat water
b. A heat-exchanger or evaporator to transfer heat from the hot water to the working medium and evaporate the latter.
c. The expander which consists of a reciprocating engine.
d. A condenser which is cooled by the pumped water.
e. A feed pump which is directly connected to the engine
f. The water pump which consists of a hydraulic press connected directly to the expander's shaft, water as the transfer fluid, and the pump itself, mounted in the well.

A unit which has been functioning in Dakar, Senegal, has the following characteristics(18):

The motor effective speed, 80 to 90 rpm, water temperature leaving the solar collector, 65 to 80°C.

Water temperature in the well, 28 to 30 °C. Pumping capacity and lift, 8 to 10 liters per minute and 13 to 14 meters, respectively, corresponding to a power of about 21 watts. The overall efficiency of the solar pump, less than 1%.

Another unit operating in Niger has the following specifications(19):

Collector surface 60 m^2
Pumping capacity and lift, 6 to 7 m^3/hr, and 12 meters, respectively corresponding to a power of about 200 watts
Duration of operation, 4 to 6 hours/day. $\eta_{tot} \simeq 0{,}003$

Dornier-System GmbH Postfach 648 D 799o Friedrichshafen West Germany	low temperature Rankine cycle, power output 1 kw (water-delivery) closed system	Prototype-trial stage in Germany. Production in India in preparation

Solar thermal water pumps.

Great efforts are being made in most of the developing countries to expand electrification. Its progress is slow, because it is capital intensive, especially when it involves connecting remote villages to the network. Thus, there is a great need for developing decentralized energy system for the rural areas.

Dornier System is working since several years on this field and some of these developments are solar electricity production units and solar water pumps. One of the objectives of the developments is to enable an economic operation of solar powered water pumps.

To provide remedial measures in this field, the Federal Ministry for Economic Cooperation (BMZ) jointly with the Federal Ministry for Research and Technology (BMFT) is promoting a research and development project which will be carried out by Dornier System GmbH

Solar energy is delivered free of charge, but the conversion of low heat into mechanical energy means investments costs. These costs are the higher the lower the total efficiency of solar systems is. Therefore such system will be optimized to enable an economic operation.

the activities on the field of thermic cyles showed, that a lot of improvments are possible such as:

- the direct evaporation of the working fluid within the collecting field. Several types of such direct evaporating collectors have been developed and will be tested. Using this method, a higher total system efficiency (more than 40 %) is possible; at the same time the total investigation costs decreases. Simultaneously a quicker start of the system can be realized. Even at low insolation the system will start within a short time.

- vapor machine without lubrication. For small power units (about 1 kW) we use a double acting eypansion machine with an automatic preheating before starting.

- automatic start ans stop of the system. A special developed control system enables the automatic start of the system if enough vapor is produced. If the pump stops e.g. by shading of the collector field, than the vapor valve closes and the next start begins only if enough solar energy could be collected.

These improvments made it possible to reach a higher total efficiency.

It has to be well recognized the definition of the total efficiency. To speak about that means the multiplication of all component efficiencies such as collector-, cycle- (including heating losses and all internal consumers) motor-, mechanical- and water pump efficiency.

The objective of the solar pump development program is to lift up this total efficiency in the range of about 5 %.

That means following partical efficiencies:

- Rancine cycle efficiency	20 %
- collector efficiency	55 %
- motor efficiency	75 %
- cycle efficiency	85 %
- mechanical efficiency	95 %
- water pump efficiency	85 %

An 1 kW solar pump was designed and starts operating in the beginning of 1979. A smaller power output is possible with this system by reduction of the collector aerea.

Such systems will be proposed for the desired application in India, Mali, Philippines and Sudan.

Our system specification was mainly orientated to cpacity ranges and delivery heads, where it can scarsly be replaced by animal or human power (about 1 kW and 20 m delivery head).

If water pumping can be done by animal or human power it will be very difficult to reach on economic operation of those systems, independant of solar pump types.

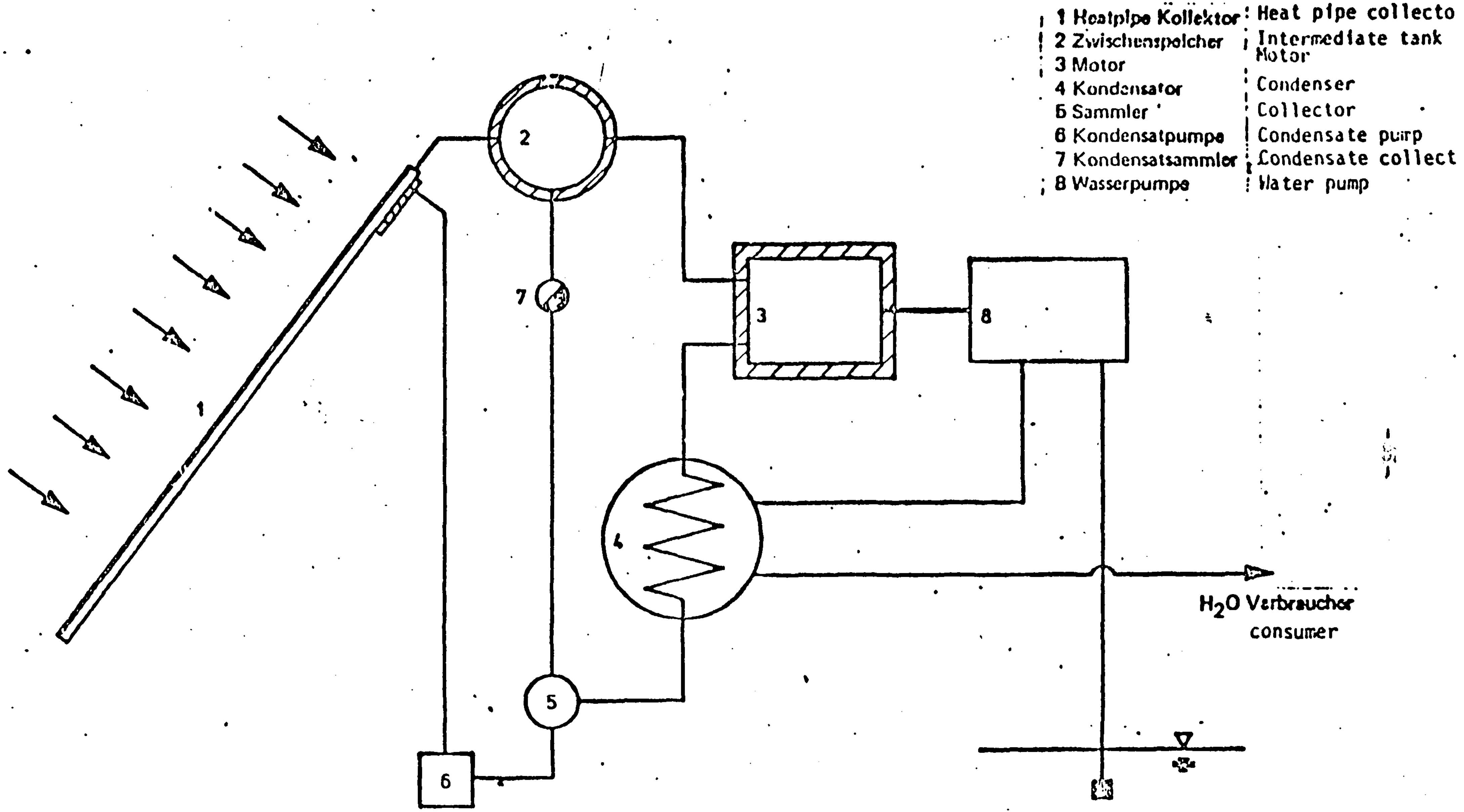
1. SYSTEM DESCRIPTION

The function sceme of the offered solar power pump is shown in Fig. 1. The working fluid (Freon 11) will be vaporized within the collecting field (1) and led over an intermediate tank (2) to the motor (3). The motor is directly coupled to the water pump (8) which pumps the water to the condenser (4) and to the consumer. The liquified working media will be refilled over the condensate collector (5) and the condensate pump (6) to the evaporator (collector).

Specification of the system

- motor, working without lubricating oil
  capacity range about 100-1500 W;
  internal efficiency about 70 % at 1000 W
- collecting field (flat plate collector) working as an evaporator; Collecting aerea of about 20 m^2, collector efficiency at designed point about 40 %
- system capacity
  about 300 W at 0,8 kW/m^2 insolation (hydraulic power)
- automatic start-stop control of the system
- Working temperatures:
  steam input about 85 °C
  Condense-temperature 30° if 25 °C cooling water is available
- amount of pumped water at design point approximately
  6 l/s

All components of the working cycle are designed for a cpacity of 1 kW net hydraulic output. That means, that an enlargement of the capacity is possible only by enlargement of the collecting aerea and change of the water pump.



DORNIER SYSTEM

Bild 1: Funktionsschema Solare Pumpe

Fig. 1: Functional diagram of a solar pump

2. COMPONENT DESCRIPTION

The main components of the system are:

- collecting field, prepared for direct evaporation
- motor,
- water pump
- auxiliary equipment

Collecting field

The designed collector is a flat plate collector with a double glass couvering. Each collector module (see Fig. 2) consists of 6 heat-pipes designed as flat plate collectors. On the top of each heat pipe the working fluid will be vaporized in a separate heat-exchanger. The vapor will then led to the storage tank. Each module has a length of 5,6 m and a width of 1,25 m.

Motor

The especially for solar application designed motor is a double-acting piston machine as shown in Figure 3. This machine is directly coupled over a flywheel to the water pump. This machine is working with low piston speed and was designed to operate without lubricating oil.

Water pump

A double-acting piston water pump was chosen to enable higher efficiencies. The internal efficiency is about 85 %. This pump is directly connected to the motor.

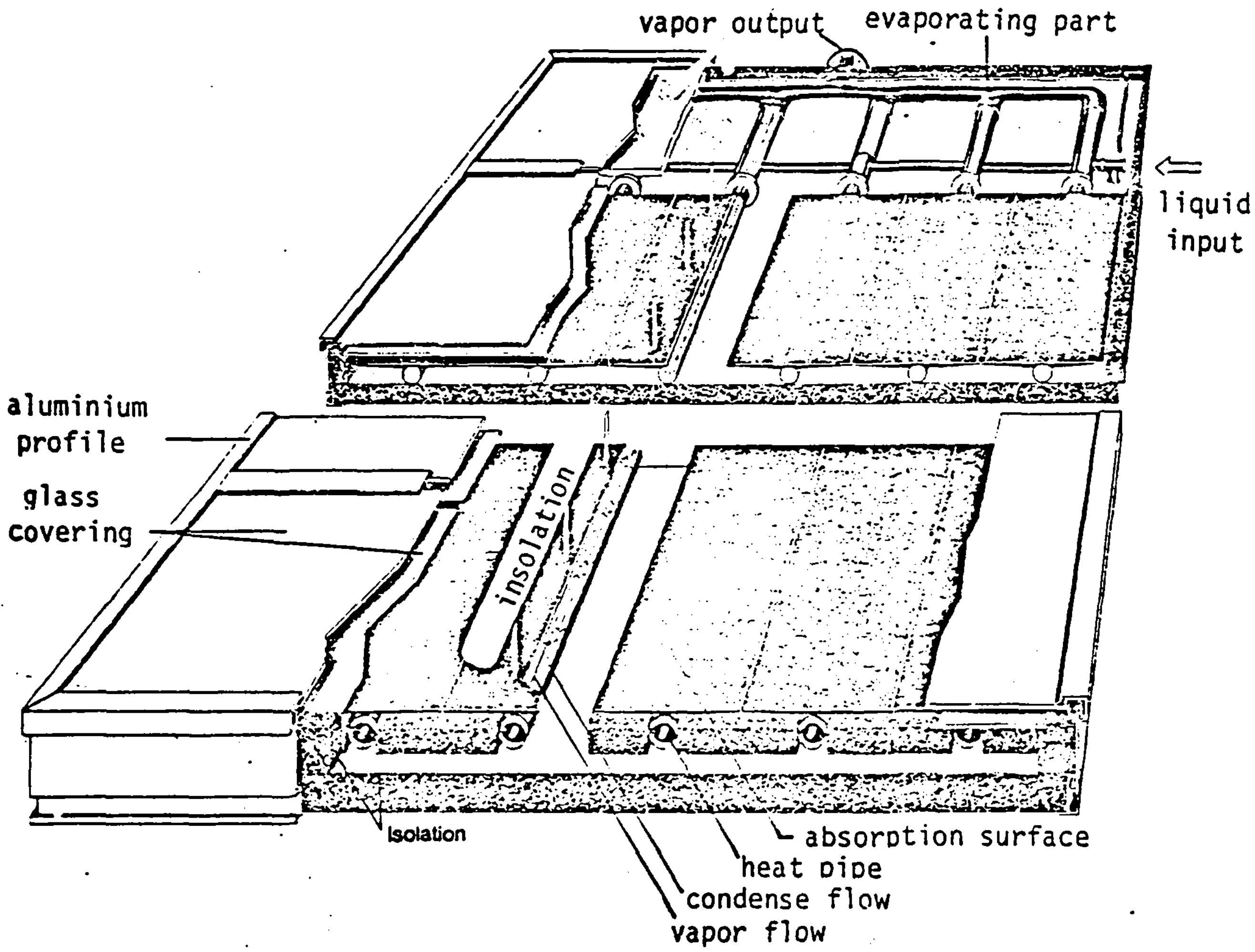


Fig. 2 Evaporator design

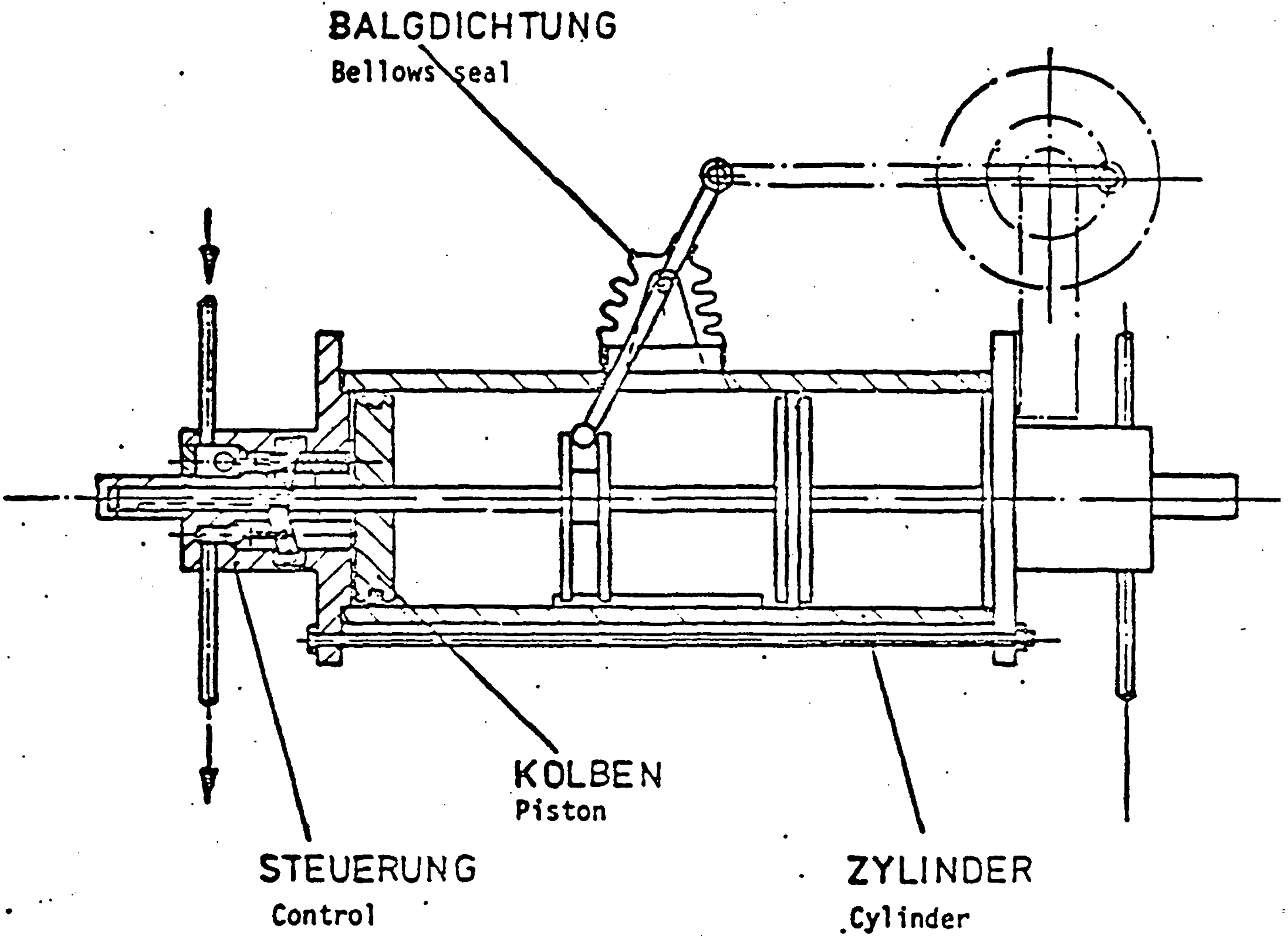


BILD 3 : DOPPELWIRKENDE EXPANSIONSMASCHINE

Fig. 3: Double-acting expansion machine

Auxiliary equipment

To drive this closed cycle autommatically following auxiliary equipments are foreseen besides others:

- automatic start-stop valves
- condenser
- condense pump
- connecting pipes and different valves .

The total system exclusive the evaporator, which is integrated in the collector aerea, is mounted in one rack.