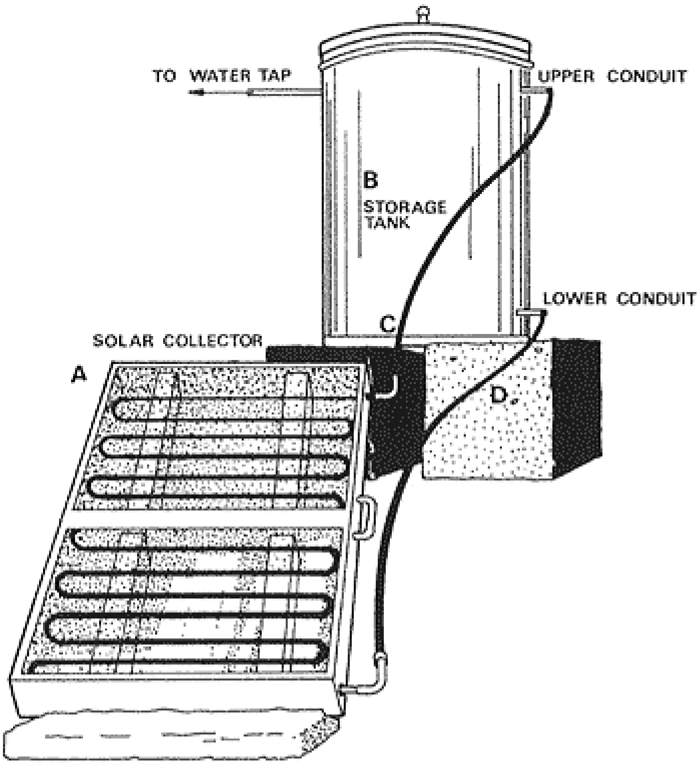
Solar Energy

Small scale applications in
developing countries

ISBN 90 70857 19 7



P. Vanderhulst
H. Lanser
P. Bergmeyer
F. Foeth
R. Albers

Table of contents

Chapter 1

Introduction

PURPOSE OF THIS PUBLICATION

This publication is aimed at people who are interested in finding out whether they can use solar energy for one or more applications in their daily lives, or in the lives of those with whom they work. This means that the authors have chosen to limit themselves to small-scale applications of solar energy. In other words, the reader will find nothing about large scale thermal power stations, solar heat for industrial processes, solar air-conditioning, etc.

Instead, thermal applications such as water heating, drying and cooking will be discussed, as well as electricity generation using small photovoltaic systems.

HISTORY

Solar energy has been used since time immemorial to dry agricultural products, to provide space heat in cold seasons or to create ventilation in homes, applications which are still used in many developing countries. More than two thousand years ago, Heron of Alexandria constructed a simple water pump driven by solar energy and in 214 B.C. Archimedes of Syracuse used concentrating solar mirrors to set fire m Roman ships.

The daily work of those complex and elegant solar collectors, the leaves of plants and trees, directly or indirectly provides our food, creates the cooking fuel for millions of households throughout the world, and has created all our fossil fuel reserves in the past.

This does not imply that there is nothing new in applying solar energy (solar photovoltaic cells are only a few decades old), but some historical insight helps to put things in perspective. People have been using and are still using solar energy technologies without even knowing the term, simply because it is useful and practical to them.

CHARACTERISTICS

At the present moment two methods exist by which sunlight can be converted into directly usable energy: conversion to warmth (thermal energy) and conversion to electricity (photovoltaic energy). In the first method, for example, sunlight is absorbed by a blackened surface, which then warms up. If air or water is passed alongside or through this warmed surface, it too will be warmed. In this way the warmth can be transported to wherever it is needed. For storage, an insulated chamber is usually employed, From which, for example, hot water can be drawn. This, in brief, is a principle of thermal conversion.
In photovoltaic conversion, sunlight falling onto a 'solar cell' induces an electrical tension; a number of cells combined in a panel are capable of generating enough current to drive an electric pump or to charge a battery.

LIMITATIONS

Whenever one is convinced that new solar technologies should be used by rural people, one should start by appreciating their own experience, looking at how they use their own resources and then find out together whether the new technology could be of any use to them and how it could be introduced. An important part of this process is a discussion of not only the advantages but also the limitations of the new technology.

The source of energy, solar radiation, is free, but the equipment needed to persuade the solar rays to do useful work can sometimes be expensive, usually requires maintenance and needs certain understanding of how things work.

It is a pity that there are so many examples in developing countries of solar energy equipment which has been 'dumped' into villages, without even asking if it could be of any use to the inhabitants. The ability of rural people to recognize immediately the benefits of a new technology, and to rapidly absorb it, is often underestimated. The first step For the introduction of any new technology should be the needs of the people for which it is aimed, and usually they know their needs much better than we do.

FLEXIBILITY

One of the beautiful characteristics of a solar equipment is that it can be made in varying degrees of perfection and in a wide range of sizes and costs. This implies that it can be of use for a wide social range as well, from the farmer who dries his grains, to a Minister of Agriculture who uses a solar water heater for his shower.

Let us make the example of solar drying, one of the oldest solar applications of mankind. The simplest solar dryer, at zero cost, is a black asphalt road on which people spread their grains to increase the natural (solar) drying process. The bamboo racks on which Thai fishermen put their fish are a little more sophisticated, but still represent a very cheap type of solar dryer. The solar timber kilns, which have been tested in many Asian countries, require much more care in design, can be quite expensive (although locally made) and are not meant for individual small-scale use. In Chapter 2 the reader will find more on the subject of solar dryers.

Solar water heating shows the same wide range of sophistication. On the one hand there is a blackened water tank which was used in Japan to heat bath water to fill the family bath at the end of the day. Or a cheap plastic tube filled with water which will heat up rapidly during a sunny day. Then there is the solar collector, such as discussed in Chapter 3, which can be made of locally available materials, and provides sufficient amounts of hot water for a small dispensary to save them collecting (or paying for) a large amount of firewood.

Solar cooking is one of the most debated applications, which is partly explained by the fact that making is one of the most important daily activities of every households in the world. Anyone who has cooked meals by himself knows that cooking energy by preference should be easy to handle, the power it produces should be easy to control, and the power should be available when the cook wants it. This is why gas cookers are so easily introduced, once people can afford it. Solar cookers have difficulty complying with these demands, which is why many rural households are not actually using them. In particular, the parabolic solar cookers, which are such nice toys for researchers and policy makers, have hardly been applied. The solar hotboxes are much better suited for their purpose, although Chapter 5 clearly warns that the users should be told that it is an additional cooking device.

Another example, at the other end of the technology scale, is the photovoltaic (PV) cell. They are applied in cheap solar calculators, in use throughout the world, but also the use of PV panels for street lighting, home lighting and for powering refrigerators in rural hospitals is increasing rapidly as discussed in Chapter 4.
A solar-powered telephone can be immensely useful for farmers wanting information about market prices or to arrange transport. These developments take place in spite of the fact that PV systems are (still) expensive, have to be imported, require care in handling, etc. In other words, people see a benefit in using them, and are therefore prepared to pay for it.

MORE INFORMATION

For those who require more detailed information references are presented and, if necessary, additional information can be provided by the TOOL Foundation in Amsterdam.

1.1 REFERENCES

- GATE, *Solar energy. Status report*, Vieweg, Braunschweig, FR Germany, 1986.

CHAPTER 2

Solar dryers

CONTENTS

2.1 INTRODUCTION

In contrast to water heating and the generation of electricity, crop drying utilizes the sun's energy directly.
Using solar energy to dry crops is nothing new in the tropics. Many edible, and even cash crops such as cocoa and coffee beans, have for decades been dried on racks placed in the sun.

2.2 PRINCIPLES OF DRYING WITH THE SUN'S WARMTH

Imagine a closed heated space in which a damp agricultural crop has been stored.
Two things happen:

- the crops is warmed by the heat from the stove of fire
- air around the heat source is heated up - whereby it can take up a great deal of moisture - and, rising, is continually replaced.

As the crop is warmed up, including the air between the plant fibres, the water it contains quickly evaporates. Pretty soon the air within and surrounding the crop is saturated with water vapour. Fortunately the air moving alongside, warm and unsaturated, can take up this moisture and transport it away. A small fan will of course help this process, but it is not strictly necessary.

At a certain moment the air in the room has taken up so much moisture from the crop that the windows suddenly mist up (though this will depend on the outside temperature); the air against the cold windows has been cooled to below the 'dew point'.
In this way the water in the crop is transferred to the window panes, where it can be wiped off, or allowed to fall into a gutter which leads outside the room.
If in this account 'heat source' is replaced by 'sun', a solar drier has effectively been described.
The 'cold window' (which works as a condensor) is sometimes encountered in indirect drying, where the warming of the air and the drying of the crop are separated, if the product has been stacked too high or too close together. See also paragraph 3.2.

Solar drying is a technique particularly suited to the warmer parts of the world, since:

- there is abundant sunlight.
- the air temperature is high and relatively constant over the whole year.

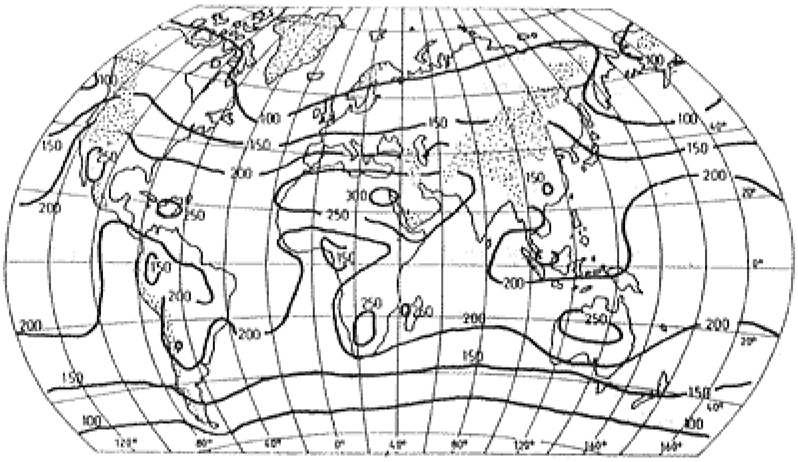


Figure 1. Annual mean global irradiance on a horizontal plane at the surface of the earth W/m averaged over 24 hours (Source: Budyko, 1958)

A high and stable air temperature is actually just as important as the sunshine itself, since it limits loss of generated warmth. It allows a simple solar drier to maintain the temperature of the drying crop during the day around 40°C.

Drying edible crops

The temperature within the solar drier is higher than that outside it. Consequently water on and in the product evaporates. The air takes up more and more of this moisture until a certain equilibrium is reached. Ventilation ensures that this saturated air is replaced with less saturated air, and so the product eventually dries out.
Drying is intended to evaporate and dispel the free water in a product, to make it unavailable to micro organisms. This water can also be bound, by adding salts (pickling) or sugar (preserving). Both techniques can also be used after drying.
Dried products attract moisture from the air, just as salt does. This moisture remains much freer - to micro organisms - than the moisture which was removed from the product; so even in conditions of relatively low humidity the product will rot.
This means that dried products must be given airtight packing unless the humidity is otherwise controlled, for example in a silo.
The level of dessication, i.e. the unavailability of free water, at which decay is stopped varies from product to product.

Table 1. Specifications for drying of agricultural products.
(Source: Herbert et al., 1984)

	Product	Humidity (water content %)	Drying temperature (°C)	Pre-treatment
	initial	final		
Corn	25	13	68-80	-
Beans	70	5	75	whitening
Onions	80	4	55	cutting
Yams	75	7	75	cutting
Potatoes	75	13	70	cutting
Manioc	62	17	70	cutting
Legumes	80	10	-	cutting
Peas	80	5	65	whitening
Bananas	80	15	70	cutting
Coffee	51	11	-	fermenting
Cacao	-	9	-	-
Cion	-	9	-	-
Copra	30	5	-	cutting
Peanuts	40	9	-	-

The warmth in the drier actually encourages rotting in products that are not yet completely dried. For this reason the speed at which the drying takes place is important. The fastest drying is brought about by strong ventilation with dry air.

Under such circumstances the difference between the internal and external temperature is less important than simply getting rid of the moisture as fast as possible. At a later stage the evaporation is less abundant, and much more temperature dependent. If the ventilation is now limited, the air in the drier will be warmed up, and the drying process improved further.

These considerations apart, the quality of the original product (its freshness and cleanliness) and of the drying air both exert a critical influence on the quality of the end product.

Forced drying using warm air circulation

Good ventilation is of crucial importance. It determines on the one hand the exchange of warmth from the absorbent surface to the air next to it and on the other hand the evaporation of the water on and in the product. A stronger ventilation leads to a lower average temperature but also to a more efficient overall transfer of warmth. This leads to a reduction in the relative humidity and improved drying.

Electric fans strongly increase the transfer of warmth to the drying air. This is especially true if the product is stacked close together, impeding the air circulation. It is important, therefore, to rack and shelve the products in such a way that the air circulation is impeded as little as possible. Forced air circulation is only worthwhile if sufficient solar energy can be taken in by the drier; this supposes a large enough (with regard to the mass to be dried) and efficient enough absorbent surface (for example, porous materials), and special glass for covering.

If these factors are not taken into account, the temperature within the drier will not be much higher than that outside it - which of course does not promote efficient drying, and certainly not at the last drying stage. Forced air circulation becomes economic in larger installations drying 50-100 kg per day or more. In non-forced air circulation, or natural ventilation a site is chosen which makes best use of prevailing winds, the air inlet and outlet being oriented accordingly, or a chimney is added to improve the draught.

2.3 THE PRINCIPLE OF THE FLAT-PLATE COLLECTOR WITH COVER

Physical description

The principle underlying the solar collector is that 'visible light' falling onto a dark object is converted into tangible warmth. The colour of the object does not in fact need to be black; it is rather the absorptive qualities of the material which determine the effect. A painted plate can be warmed, but so can a suitable fibrous material such as charred rice chaff.

The cover is of secondary importance, but still has a decisive influence on the total working efficiency; it prevents the created warmth from being blown away and also limits the warmed-up objects' heat loss through reradiation. Moreover it allows a controlled airstream over the warmed objects, which would not otherwise be possible.

To exploit the warmth in the heated objects or surface a medium (water, air) is directed alongside which takes up the warmth and takes it to wherever it is needed. When air is used, it can pass under the collector, above it, or through canals embedded within it. It can be a 'forced' or a 'natural' current. The various possibilities are examined in paragraph 3.2.

In drying, the relative and absolute humidity are of great importance. Air can take up moisture, but only up to a limit. This limit is the absolute (= maximum) humidity, and is temperature dependent.

In practice, however, the air is very rarely fully saturated with moisture. The degree of saturation at a given temperature is called the relative humidity and is expressed as a percentage of the absolute humidity at that temperature.

If air is passed over a moist substance it will take up moisture until it is virtually fully saturated, that is to say until absolute humidity has been reached.

However, the capacity of the air for taking up this moisture is dependent on its temperature. The higher the temperature, the higher the absolute humidity, and the larger the uptake of moisture.

If air is warmed the amount of moisture in it remains the same, but the relative humidity falls; and the air is therefore enabled to take up more moisture from its surroundings.

If fully-saturated air is warmed and then passed over the objects to be dried, the rise in absolute humidity (and the fall in relative humidity) allows still more water to be taken up.

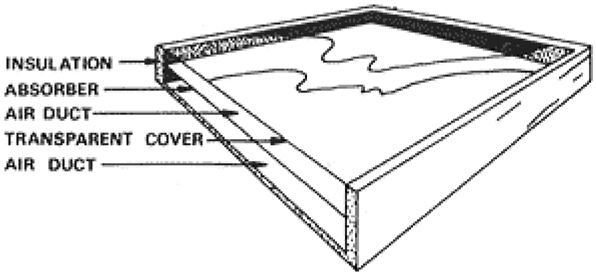


Figure 2. Simple solar dryer

Basic technical details of the drier

Every solar drier is constructed using the same basic units, namely:

a. A transparent cover which admits sunlight and limits heat loss (glass or plastic)

b. An absorbent surface, made dark in colour, which takes up sunlight and converts it to warmth, then giving this warmth to the air within; this can also be the product that needs drying itself

c. An insulating layer underneath

d. An air intake and an outlet, by which means the damper air can be replaced with fresh drier air

These four elements can be modified if necessary, and/or other elements added, for example a fan or a chimney.

2.4 DIFFERENT DESIGNS AND CONSTRUCTIONS OF SOLAR DRIERS

Basic types and their applications

In choosing a certain type of drier account must be taken of the following six criteria:

- the use of locally available construction materials and skills
- the investment of the purchase price and maintainance costs
- drying capacity, holding capacity
- adaptability to different products
- drying times
- (fall in) quality of the end product

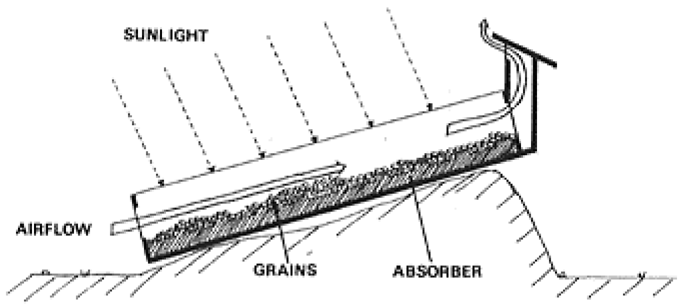


Figure 3. Solar drier directly employed

Solar driers can be constructed out of ordinary, locally available materials, making them well suited for domestic manufacture.

Solar driers can be divided into two categories:

1. driers in which the sunlight is directly employed; warmth absorption occurs here primarily by the product itself.
   These are further divisible into three sorts:
   - traditional drying racks in the open air
   - covered racks (protecting against dust and insects)
   - drying boxes provided with insulation and absorptive material
2. driers in which the sunlight is employed indirectly (see fig. 4). In this method, the drying air is warmed in a space other than that where the product is stacked. The products, then, are not exposed to direct sunlight. Various sorts of construction are possible; this design can also be provided with powered fans in order to optimise the air circulation.

Advantages and disadvantages of the various designs

Direct drying

Tradition open-rack drying enjoys four considerable advantages:

- it demands a minimum of financial investment
- low running costs
- it is not dependent on fuel
- for certain products the drying time is very short

On the other hand the products are exposed to unexpected rain, strong winds and the dust they carry, larvae, insects and infection by, amongst others, rodents.

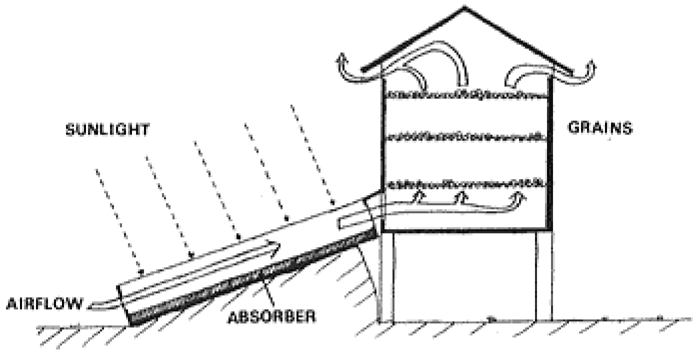


Figure 4. Solar drier indirectly employed

Moreover, certain sensitive products can become overheated and eventually charred. Dried fruit so spoiled necessarily loses its sale value.

Commercially available driers often appear to be economically unfeasible. Specifically, not enough product can be dried fast enough to recoup the outlay. Larger (combined) installations are more cost-effective but call for sophisticated management if the input and output of products is to be held at a controlled, and high, level. They are also fitted with artificial heating (fires) and fans.

Indirect drying

The advantages if the indirect system are that:

- the product is exposed to less high temperatures, whereby the risk of charring is reduced
- the product is not exposed to ultraviolet radiation, which would otherwise reduce the chlorophyll levels and whiten the vegetables.

However, its use demands some care. Faulty stacking of the product to be dried can lead to condensation; rising hot air in the lowest layers becomes saturated, but cools so quickly as it rises that the water condenses out again in the upper layers: see also paragraph 2.1.

This problem can be overcome by

- stacking the product less high
- stacking it less close together
- a larger collector, higher working temperature, faster circulation of more air, or
- a deeper collector, the same working temperature and speed of circulation but more volume.

The higher cost and the complexity of the indirect method drier are also disadvantages.

Technical design

A drier which operates optimally is usually the result of a number of adjustments whose value is established by trial and error and simple drying tests.

It is therefore important that if a solar drier is bought or made, these adjustments can be made.

A summary of these adjustments is given below.

With regard to temperature regulation:

- the available sunlight is dependent on the season and the location and limited to 4-7 kW. hr/day/m . The absorbent area can be effectively increased by directing extra sunlight onto it with reflectors. The angle of the absorber is also specified by the latitude. Take care that the collector is facing the sun and that it is out of shadow as far as possible.
- it is a simple matter to insulate the drier better and thereby raise the degree of heat absorption (and air warmth uptake). The wall of a covered drier - which the sun cannot pass through - is better replaced by insulating material which lines the box and is painted black.

The heat collector of an indirect drier can be improved by:

- enlarging the absorptive capacity
- reducing heat loss, by means of insulation and keeping hot-air-glass contact to a minimum.

This is usually only worthwhile if the airflow has been artificially increased.

In the absence of a forced ventilation, the chimney-effect is crucial. The difference in height between the air intake and outlet largely determines the draught and therefore the 'natural' ventilation. A chimney will help provided that:

- it is wide enough; if it is too small it will obstruct the draught.
- it is warm enough.

The air must not cool - this causes a reverse airflow! A wooden chimney is suitable. A chimney less than 40 cm high will in this case suffice.

Despite the many experiments carried out in almost every tropical area, it still appears to be impossible to design the 'ideal' solar drier. Depending on the building materials used, the products that need drying, and the season in which the drying must take place, the 'ideal' dryer will take many forms.

Solar energy storage

Excess heat generated during the hottest hours of the day can be stored by passing the air through, for example, a container full of stones. This only works in forced circulation systems, as the stones cause considerable pressure loss in the airflow. Storing solar warmth in this way allows the excess heat generated by oversized collectors to be used again during the night for more drying.

Such an installation makes it possible to control the air temperature in the drying room, and thus to ensure that the different drying stages work well (for example, for sowing-seeds). In the first drying stage higher temperatures are allowable because the considerable free water still present in the product.

2.5 PRACTICAL TIPS

For the transparent cover, glass is the suggested material, but it is often difficult to obtain and rather expensive. Plastic offers a reasonable alternative. It is less radiation-efficient, but often enough more readily available. If plastic is stretched over the collector it will sag. Dust and rain can collect in the hollow. This can be remedied by fitting a supporting rib across the collector along its longest axis. If this is fixed slightly higher than the edges of the collector the plastic cover will slope down slightly on either side of the rib. Take care that there are no air leaks at the rib ends.

Dust on the cover reduces its efficiency, and should be removed as often as possible.

If the collector is strongly tilted, this favours the airflow and therefore promotes good heat transfer.

However, the further it is tilted below the sun the less sunlight it receives. For this reason the indirect dryers are often better in practice.

Watch out for excessive surrounding air humidity, for instance during misty early mornings! It is vital that the drier is only set into operation (by opening the air intake and outlet) after the mist has risen and the air humidity has fallen. Otherwise there is a risk that in the weak early morning sunshine the product, instead of being dried, attracts condensation.

In drying grain whose capacity for germination must remain, such as sowing-seeds, the maximum temperature is limited to around 40 C.

2.6 REFERENCES

- Brace Research Institute, *A survey of solar agricultural dryers*, Quebec, Canada, 1975.
- Arbeitsgemeinschaft für Entwicklungsplanung, *Devices for food drying*, GATE, Stuttgart, FR Germany.
- ILO, Solar drying: *Practical methods of food preparation*, Geneva, Switzerland, 1986.

CHAPTER 3

Warming water with solar energy

CONTENTS

3.1 INTRODUCTION

In this chapter we will examine the heating of water by means of solar energy. This has several applications; we consider the distillation of dirty water, the heating of clean water and the sterilization of water and of medical instruments.
Each of these applications makes specific demands on the design of a solar-energy installation. Nevertheless the basic principle of solar heating remains the same in all cases. The general introduction contained a summary of the principle; in the first section the technical details will be examined. Where possible, for each application we specify whether the installations are commercially available or whether they are suitable for do-it- yourself construction.

3.2 TECHNOLOGY

Collector

A surface faces the sun's rays and absorbs them, converting the radiation into warmth. The temperature of this surface, the so-called absorber, therefore rises. Every object placed in the sun exhibits this effect to a greater or lesser degree. A black surface shows the greatest rise in temperature; it absorbs about 90% of the sun's incident radiation and reflects very little.
The warmed absorber would however give its warmth to the surroundings again, if we take no further action. A heat-insulating layer can be brought against the underside of the absorber. The upper surface can be covered with a transparent screen of glass or ultraviolet-resistant plastic. In this way a sheet of air above the absorber is formed which also acts as an insulator. For the absorber's warmth to be employed it has to be conveyed away; if water channels are built into the absorber a heat exchanger has been made; if water is passed through, it takes the heat from the absorber.
These components, the absorber, the insulation and the screen are finally built into a closed container provided with connections for the supply and removal of the water. The whole thing is called a collector.

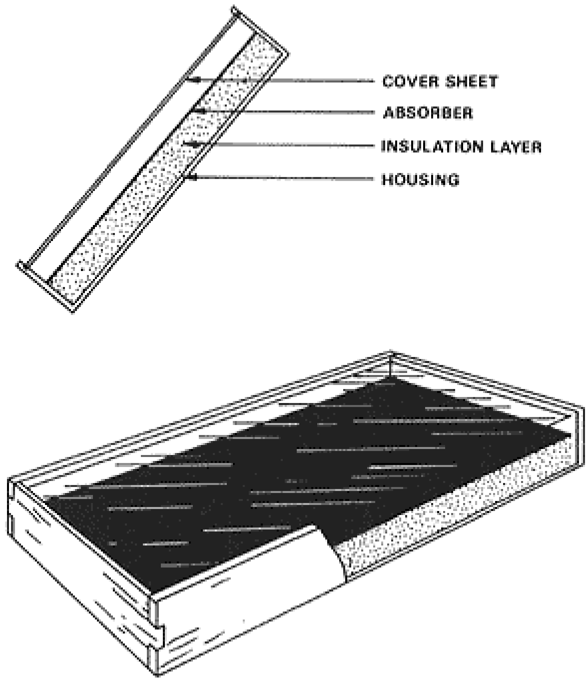


Figure 5. Solar collector schematic (Source: Deuss, 1987)

Besides this type there is a 'concentrating collector', in which the sun's rays are concentrated before falling onto the absorber. In principle, this type of collector can generate much higher temperatures. However, it has several disadvantages compared with the flat plate collector.
In the first place this type operates only under 'direct' illumination. Only those rays coming directly from the sun are effective; much 'diffuse' radiation, scattered by cloud, mist or dust, has little effect. The proportions of direct and diffuse radiation depend on the climate, the season and frequently also the time of day. The flat plate collector makes use of both direct and diffuse radiation. The use of the concentrating collector is therefore much more exacting.
In the second place the concentrating collector must be moved continuously to face the sun. There are mechanisms which make this possible but they are expensive, delicate, difficult to obtain and anything but maintenance-free.
Thirdly, a concentrating collector can easily inflict burns.

For these reasons we shall pay no more attention here to the concentrating collector.

Storage

The second important component in a solar energy water warming installation is the storage. The purpose of this is to bridge the intervals between the collector's supply and the user's demand for warm water. If the warmed water is held in an insulated tank, then in principle it is made available in the evening and the following morning. In the following applications we shall encounter heat-storage in various forms.

3.3 APPLICATIONS

Water distillation

The simplest application of a thermal solar energy installation is in the distillation of water. The solar distiller purifies water by first evaporating and then condensing it.
Distilled water contains no salts, minerals or organic impurities. It is not, however, aseptic, as is sterilized water; of which more later. Distilled water can be used for: drinking water, applications in hospitals, battery water, and so on.
Such an installation is suited to areas where water is ample but polluted, salty or brackish; naturally, there must also be abundant sun. Finally, glass or UV-resistant transparent foil - the most important materials in the construction - must be available and affordable.
A reasonably functional solar distiller is able to produce an average of four litres of distilled water per day per square meter of working surface.

The operation of the distiller will be described with reference to Fig. 6.

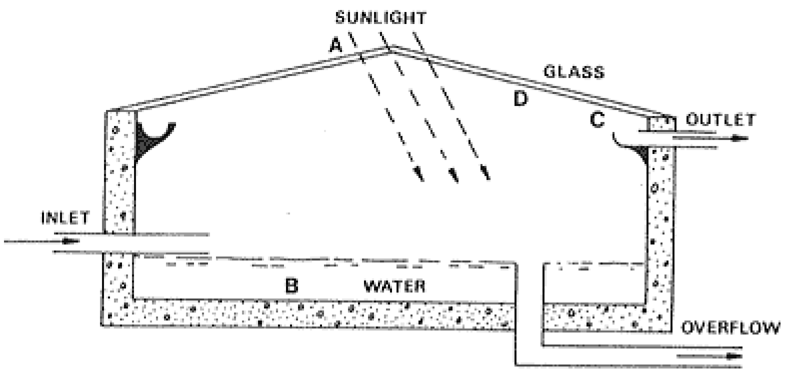


Figure 6. Solar still: simplified cross-sectional diagram

The radiation (A) falls through the glass or plastic screen (D) onto the absorber. In this case the absorber is a tray or basin filled with dirty water (B). Just as in the flat plate collector's absorber, this absorber works best if the basin is black. This is especially important if the water is clear; turbid water absorbs well enough on its own. The absorbed radiation, then, warms the basin and, gradually, the water. To reduce heat loss to a minimum it is vital to insulate the sides and bottom of the basin; if the basin rests on a dry surface this actually forms a reasonable insulation.
The water warms and then evaporates, leaving the impurities behind. This vapour (C) condenses on the underside of the screen (D) when this has a temperature appreciably lower than that of the water and the water vapour. This will certainly be the case if wind is cooling the screen, or the outside temperature falls as night falls. The condensate runs along the sloping screen and into a collecting gutter. To prevent the condensate from falling back into the water, the screen must be filled by at least 10 degrees from the horizontal. The whole distiller must be made as airtight as possible, to prevent loss of vapour. To achieve the best results the dirty water must be daily replaced by more water. Setting the whole distiller at a slight angle makes this straightforward.

It will be clear from this description that this distiller lends itself well to independent construction. More information on the various forms of construction are available from the WOT (1).

Solar boiler

Slightly more complex than the distiller is the solar boiler. This consists of one or more flat plate collectors and a insulated storage tank, and is designed for use as a water heater for hospitals, laundries, kitchens, showers, and so on.
A solar boiler with a collector surface of 3 to 4 m² and a storage capacity of 200 litres can provide 300 to 400 litres per day of water between 40þC and 60þC in temperature.
The yield is naturally dependent on the amount of sun and on a judicious use of the installation.
The conditions for the useful application of such a solar boiler are: one, a spot in direct sunlight as close as possible to the point of water use, and two, the straightforward supply of (unheated) water. If a water mains system is available, this of course offers the best solution.
Finally, the collector surface area and tank volume demand for warm water. The yield already mentioned, 300 - 400 litres per day at 40 - 60þC for a collector of 4 m and a 2001 tank, can be used as a guideline. If more water is drawn off, its average temperature will fall.

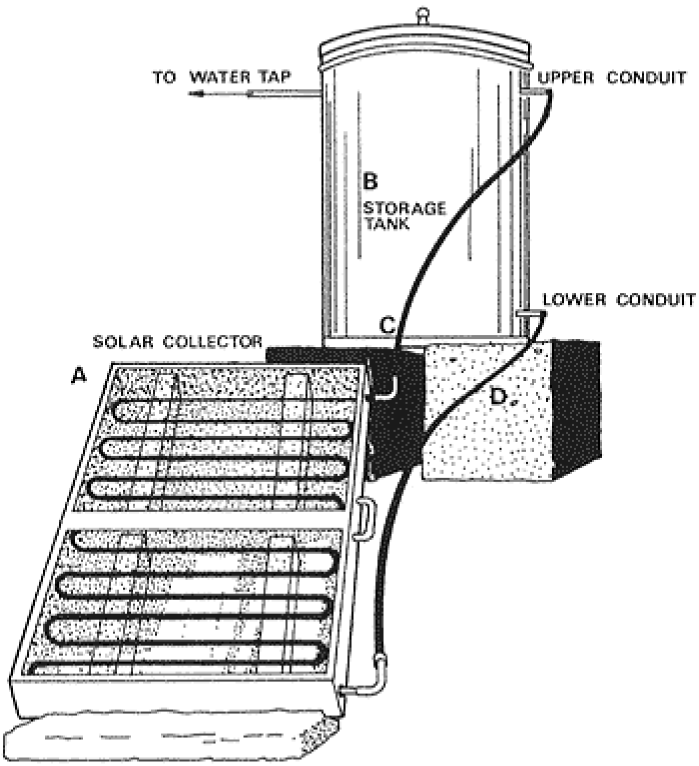


Figure 7. Solar collector of 1.6 m²

The operation of the solar boiler will be explained with reference to Fig. 7. The collector (A) is constructed according to the principles already described in paragraph 3.2. The collector is fixed at an angle to the horizontal which approximates to the degree of latitude of the location itself. The panel faces south if the location is in the northern hemisphere, north if in the southern. The storage tank (B) is so arranged that its lowest point is about 40 cm above the highest point of the collector. The warm water outlet (C) connects the higher outlet of the connector to the top of the warm water tank; a cold water supply pipe runs from the bottom of the storage tank to the lower part of the collector. The cold mains water supply also runs into the bottom of the tank, and the warm water draw-off pipe is fixed to the top of the tank. If the tank is now filled with cold water it will pass via (D) into the (lower) collector. If the sun shines the water will warm up and will pass via (C) to the top of the tank. This happens on its own, because warm water moves upwards.

The sun therefore generates a circulation of water between the collector and the tank, called 'natural circulation' or 'thermosyphon'. No pump is needed. The water in the tank gradually warms up until it is drawn off and cold water comes in to replace it. If the storage tank is well insulated, the water remains warm into the evening and even the early morning. The nice thing about this self-starting system is that it is practically maintainance-free.

The construction of a solar boiler calls for more skilled work than is needed to make a solar distiller. Still, a solar boiler is suited to local production. An excellent handbook, in English, containing many practical tips and illustrations has been compiled by Bart Deuss. Step by step he describes the construction of the so called zig zag collector. He makes use of a special toolset developed by the Dutch firm Zonnevang (2), shown in Fig. 8. If, after studying the abovementioned handbook, it is decided against home construction of the collector, the same firm sells ready-made examples made especially for the tropics. Connecting a prepared oil drum to this form a storage tank is then comparatively easy.
It is also possible to make the principle tools (like a pipe bender) by your- self. More information on this can be obtained via the WOT (1).

Figure 8. Solar collector manufacturing tool box (Source: Zonne-energie Nederland BV)

Solar disinfector and sterilizer

It is possible to reach higher temperatures using solar energy than were quoted for the solar boiler. For most applications of the solar boiler these higher temperatures are not needed, however, if water has to be disinfected, or medical instruments sterilized, higher temperatures are required, and can be achieved using solar energy. The apparatus is considerably more complex and is not well suited to local construction.

Figure 9: Autoclave plant with portable sterilizer (Source: SUNICE)

Here we would like to refer to a water disinfection unit developed by EEG-International (3). The unit has a maximum capacity of eleven litres per hour of disinfected water and can reach a temperature of 95þC. It also makes use of natural circulation between collector and tank; when the tank water reaches the desired temperature, a thermostatically-controlled tap opens and the contents of the tank pass into a separate reservoir.

The Danish firm SUNICE (4) manufactures an 'autoclave plant'. This generates steam at a temperature of about 130þC. A portable autoclave can be connected to it, in which medical instruments can be sterilized.
According to the manufacturer, the contents of the autoclave are sterilized within 25 minutes - including deactivation of the most resistant bacteria, such as Clostridium tetani, and the virus for Hepatitus B. Fig. 9. shows a photograph of the steam-producing unit and the free-standing sterilizer.
The firm also makes a vaccine cooler also powered by solar collectors, as opposed to the vaccine cooler powered by photovoltaic cells which shall be described in another chapter.

3.4 REFERENCES

(1) Working Group on Development Techniques
P.O.box 217
7500 AE Enschede
The Netherlands
tel. +31 53 489 2845
fax. +31 53 489 2671

(3) EEG-International
Postbus 238
6600 AE Wijchen
The Netherlands

(2) Zonnevang
Strijpsestraat 41
5616 GL Eindhoven
The Netherlands
Tel: 40 523993

(4) SUNICE Ltd.
Hovedvagtsgade 6
DK-1103 Copenhagen K
Denmark
Tel: 45 1 322471 Telex 19655 sunsal dk

- Bachman A., *Solar water heaters in Nepal. Installation manual*, SATA, Kathmandu, Nepal, 1979.
- Deuss B., *Zig zag collector. Manual on the construction of u solar water beater*, TOOL/BACIBO, Amsterdam, The Netherlands, 1987.
- Streib J., *Hot water from the sun. How to construct your own solar panel*, FAKT, Stuttgart, FR Germany, 1989.

CHAPTER 4

Cooking with solar energy

CONTENTS

4.1 INTRODUCTION

Cooking by means of solar energy started in the '70s in response to the growing shortage of firewood resulting from chronic deforestation. A solar cooker needed no wood - just sun! With this in mind, dozens of research institutes developed solar cookers.
There are several types. The most important is the solar cooking box, which will be described in more detail in the last section. To start with we will look at another type that enjoyed much attention in the past - the parabolic model.

However, first of all something will be said about problems that may be expected in the introduction of solar cookers; it has become clear that several projects in which solar cookers were introduced were failures because insufficient account was taken of the local population.

4.2 SOCIAL ASPECTS

The social aspects of solar cooker introduction schemes can cause important problems, as cooking with solar energy differs radically from other cooking methods. Because of this, solar energy offers only a supplement to other energy sources, and can never provide a 100' replacement. Besides this, buying a solar cooker will cost a lot of money.
In practice it is hard to explain that a technique with a limited application can still be economic. The applications are limited because:

- the sun does not always shine
- not all meals can be prepared in a solar cooker.

To begin with the sunshine: many people cook at dawn or dusk. A solar cooker cannot, therefore, be used. It is often difficult and sometimes impossible to change these cooking habits. Someone who walks an hour to the fields to spend all day there is not going to come home at midday to cook and eat. On sunless days the cooker is also useless.

Not all meals can be prepared in a solar cooker. The more important the meal is, the worse this problem becomes. The cooking box has two serious drawbacks: it cannot be opened during the cooking, to stir a meal or to add ingredients; and food cannot be fried or roasted in it. In the cooking box that will here be described the temperatures are not high enough.
There are models which allow for frying and roasting, but they are complicated and less convenient. A cooker using a parabolic reflector is less of a problem but this can heat only one pan at a time.

The purchase price is a problem for the poorer groups especially; the cost recovery time varies widely according to local circumstances and in many instances can be as long as two or three years. The apparatus must therefore be made to a high quality, using accordingly expensive materials.
The image of the cooking box also plays a part. In areas where the 'modern, western life' is in demand, such a simple appliance may be rejected for vague reasons even when it is economically acceptable.

Finally a few remarks concerning its use. The cooker must obviously be so sited as to receive full sunlight. Children at play can easily damage a solar cooker so it also has to be out of their way; in towns, a flat roof is sometimes a suitable place.
The different appliances can be heavy or awkward to move; facilities for an eventual repair should be nearby.
Lastly, the users have to learn how to handle the cooker. The cooking technique is so unfamiliar, especially for the cooking box, that guidance during its introduction and afterwards is vital. If its users are at a loss to know how to use it, it quickly falls into disuse.

The problems outlined above are not intended to discourage the introduction of a solar cooker, but to illustrate that careful planning and preparation are a more than usually important aspects of the introduction of this technique.

4.3 THE PARABOLIC SOLAR COOKER

The parabolic or concentrating solar cooker reflects the sun's rays in such a way that these are converged onto a small area. In this area a dark metal cooking pot is fixed. Because of the small size of the area of convergence there is room for only one pot. It can be warmed up between 150and 350þC; enough to fry. See Fig. 10.

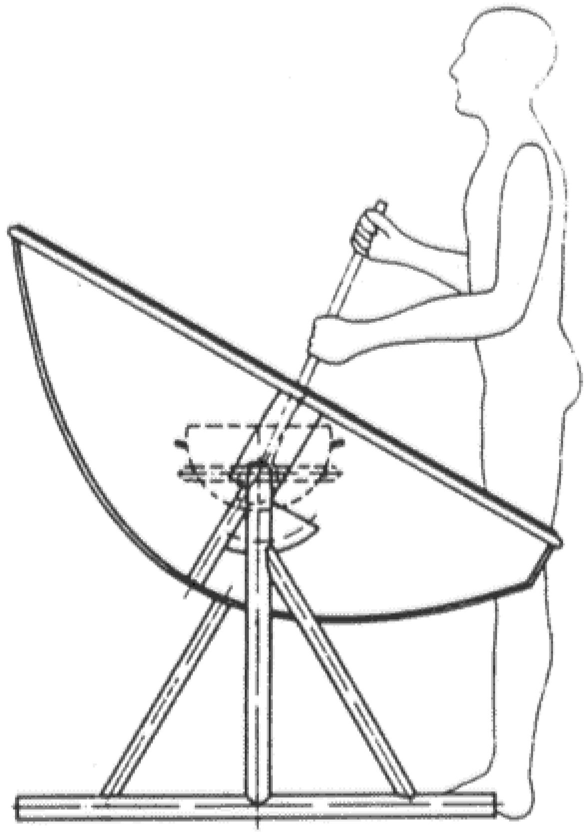


Figure 10. Parabolic solar cooker

However, the design does suffer some serious disadvantages. The reflector has to be realigned as often as every ten minutes, because the sun's movement shifts the convergence point accordingly. This means continual attention during cooking. Another disadvantage is the higher temperature - carelessness can result in burns - and the disagreeable reflections of light. Besides the problems of its use, the construction of such a parabolic reflector poses difficulties. The reflecting surface's curve must be extremely precise; this exactness is not always achieved. The apparatus is, moreover, often sensitive to wind.

All in all the parabolic solar cooker suffers considerable technical drawbacks. These are partly obviated by the solar cooking box described below.

4.4 THE COOKING BOX

The cooking box works on the principle of the retention of warmth. The box must be well insulated, so as to retain the energy that shines into it; for this reason the box cannot be opened during cooking. If this should happen, the loss of heat will considerably slow down the preparation of the meal. This limitation also means that meals that need to be prepared step by step are unsuited; so an effective menu plan, prepared beforehand, is viral.
A cooking box is easy enough to make on one's own; the following introduction looks at what comes into such construction.

The highest attainable temperature depends largely on the design. The more sophisticated it is, the higher the temperature. The simplest example of such a cooking box is shown in Fig. -11. It is a box, with double walls of wood or of metal, and a lid comprising two layers of glass. Insulating material fills the space between the double walls. This simple version can reach a temperature of 50 to 70 degrees above the outside temperature.

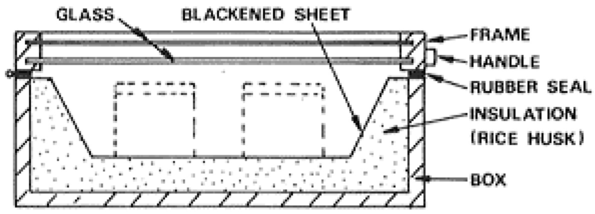


Figure 11. Simple cooking box

An excellent and long-lasting insulation material is rock wool, but in most developing countries this is either unavailable or very expensive indeed.

Other insulating materials include cotton, wood shavings, coconut fibre and straw.

These materials do not need to be packed densely in, or scattered loosely; firm pressure is enough. The material must be very dry and it must remain so; for this reason a metal inner box is preferable to a wooden one which is comparatively difficult to make watertight.
It is advisable to paint the bottom of the inner surface of the cooker matt black. The sides can be painted reflective (shining). As this is to obtain the best possible absorption of the sun's rays, a matt paint is most important, and a matt dark blue works better than a shiny black.
It is advisable to have outward-tapering walls rather than upright ones, as these prevent shadowing the interior; and high temperatures are more likely if the whole box is shallow.

The food to be cooked is placed, in a matt black pan, in the box. The pan may be made of thin metal; this often gives the best results, but such pans are not too strong. The pan should be covered with a lid, to prevent condensation forming on the glass and to speed the cooking. The cooking time in such a cooking box is considerably longer than normal.

The temperatures reached by the design shown in Fig. 11. would be too low for many cooking purposes. Filling the box with one or more reflectors can appreciably raise the maximum temperature. An example of a cooking box filled with a reflector is shown in Fig. 12. The reflector increases the amount of incident light, whereby higher temperatures are attained more quickly.

However, the use of reflectors also has its disadvantages:

- The box must be aimed at the sun more frequently
- The construction becomes a little more complex
- The reflector makes the cooker more expensive
- The cooker is less stable (gusts of wind)
- The more reflectors are used, the more these disadvantages will prevail

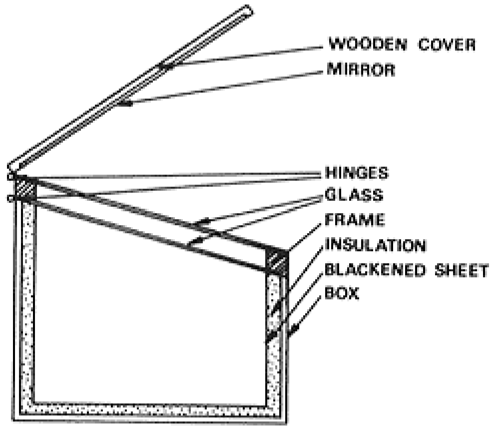


Figure 12. Example of a solar cooking box with reflector

The reflector can be made from various materials. Ordinary mirrors can be used, and are good reflectors, but they are expensive and fragile. Aluminium foil is an alternative but is hardly durable; plastic containing a layer of aluminium, sometimes sold under the name Mylar, is longer-lasting.
Lastly, a simple reflector can be made from a polished aluminium sheet. In most instances it provides an adequate degree of reflection.

4.5 CONCLUSION

Cooking with solar energy remains a fuel-saving technique which can provide definite help in situations of fuel scarcity. Solar cookers and especially cooking boxes can be successfully locally made.
However, the introduction of a new way of cooking results in radical changes in the rhythm of life in a community. Many projects failed because of disregard for these social aspects, or because mistaken priorities meant that insufficient attention was paid to the problems of introduction.
In fact, intensive guidance during the introduction period is of crucial importance.

4.6 REFERENCES

- Hoda M.M., *Solar Cookers*, Appropriate Technology Development Association, Lucknow, India 1979.

CHAPTER 5

Electricity from the sun

CONTENTS

5. 1 INTRODUCTION

In a solar cell light is converted into (electricity by means of the so called photovoltaic (PV) effect. PV is still enjoying large research and development efforts in order to produce more efficient and cheaper solar cells.
But solar electricity is already economically feasible compared to other energy sources for a number of applications.
In the past, inadequate system design and sizing of system components has led to unfavourable experiences. However in recent years PV has proved to be reliable if sufficient attention is paid to the design.

In this chapter a closer look will be taken at those situations in which PV comes into consideration. Next the technology of the solar cells and other components of a PV-system will be discussed. Subsequently some characteristics of a PV-system are discussed and some attention is paid to those aspects which are important in designing a system. Finally some interesting applications will be examined.

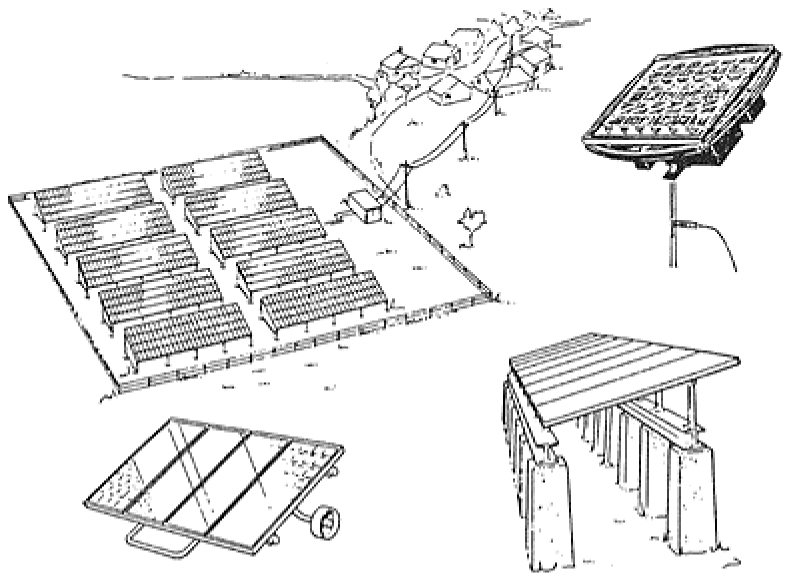


Figure 13. Some solar panels (Source: ATOL, 1980)

5.2 THE CASE FOR PV

In rural areas and at remote locations solar electricity is an energy source which can be a good alternative to other energy sources. At the moment PV is used mostly for small appliances such as refrigerators, telecommunication and navigation equipment. Nevertheless in California (USA) a large PV plant has been built which feeds the grid. In general however the use of PV in large projects and grid connected applications is too expensive to be of interest. When a grid is available, a connection with the grid is generally preferred to the installation of a PV-system. When the reliability of the energy supply is crucial PV can offer a solution. This is for instance the case in vaccine refrigeration. When the vaccine temperature becomes too high, the vaccine can no longer be used for immunization. In many developing countries the performance of the grid is very poor, so PV might even be of interest in areas where a grid is available. The alternatives include back-up generators, accumulator batteries and other renewable energy sources.

The production of solar cells requires high technology. Only a few developing countries, i.e. India and Brazil, have production facilities for solar cells. Most countries can produce only the non-PV-system parts.

Another obstacle for the use of PV in developing countries is the high initial investment cost. Nevertheless PV has some specific advantages which make it attractive for the developing world:

- PV can be used for very small appliances, where other sources, for instance diesel, are operating far below their nominal capacity and are therefore relatively expensive
- thanks to the modular character it is easy to enlarge a system to provide more energy or add more applications to it
- PV has no moving parts, therefore repair is almost never needed and the maintenance requirements are moderate
- when well designed a system operates very reliably
- no fuel is needed

The design of a PV-system, modules together with modules storage and electronic equipment, has to be carried out very carefully. Many of the unfortunate experiences with PV were related to a bad system design. PV can be very reliable as has been demonstrated in telecommunication projects where PV was chosen specifically because of its reliability, the same applies to buoys along the rivers and coasts. Even in The Netherlands with its small amount of sunshine and its large electricity grid, newly installed buoys are all PV powered.

5.3 SOLAR CELLS

Solar radiation can be converted directly into electricity using semiconductor devices, which are known as photovoltaic (PV) cells. The most commonly used material is silicon. By diffusing phosphorus or boron into the silicon it is possible to create p- and n-type silicon, each with its own electrical characteristics. A thin silicon wafer is divided into two layers. Both layers are provided with metallic contacts.
When sunlight falls upon the solar cell a part of the light is absorbed. The energy of the light releases electrons inside the silicon. When both sides of the cell are connected an electric current will start flowing.
The size of the current depends upon the intensity of the incoming radiation. Not all the energy of the light is converted into electrical energy.

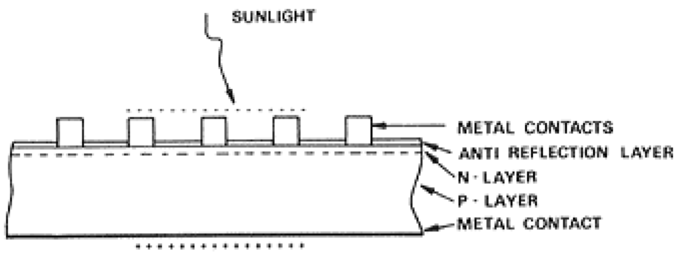


Figure 14. Schematic cross view of a silicon solar cell

There is a number of semiconductor materials from which solar cells can be made. Until recently the most commonly used was mono-crystalline silicon. At the moment poly-crystalline and amorphous silicon are becoming more important. Table 2 gives the theoretical and achieved conversion efficiencies for a few types of solar cell materials.

Table 2 Efficiency of solar cells under standard irradiation (at sea level) for several semiconductor materials. The theoretical efficiency and the achieved efficiencies under laboratory conditions and in industrial production are given.

		Photovoltaic efficiency of solar cells (%)			
	theoretical	achieved in laboratory	achieved in industrial production	
Monocrystalline silicon	25	21	13	
Polycrystalline silicon	23	17	11	
Amorphous silicon	24	14	9	
GaAs	28	24	-	
CuInSe	22	14	-	
CdTe	28	13	-	

Instead of falling directly onto the flat plate modules, the sunlight can be concentrated first by the use of lenses or mirrors. The concentrated sunlight can be focussed on a solar cell, which increases the efficiency of the cell. In this way a record efficiency of 31% was recently achieved for a silicon-gallium arsenide tandemcell. This method enables a reduction of the costs of the array but on the other hand extra costs are incurred by the lenses; the system as a whole also becomes more complex. The technology for concentrating sunlight is still under research and is not commercially available.

Monocrystalline silicon

Monocrystalline silicon solar cell technology is based on the semiconductor technology used in the transistor and integrated circuit industry.
Using monocrystalline silicon wafers solar cells can be manufactured with a conversion efficiency of 13 - 15%. The conventional processes employed to obtain single crystal wafers are slow and very energy and material consuming.

Polycrystalline silicon

Monocrystalline silicon is gradually being replaced by polycrystalline silicon (sometimes also called semicrystalline silicon). Polycrystalline silicon can be produced at lower costs.
The efficiency of polycrystalline cells is 1 to 2% lower than the efficiency of monocrystalline. However combined with the use of cheaper silicon feedstock material, large cost reductions compared to conventional production methods are expected.

Amorphous silicon

Another option to reduce the costs of the cells is the use of amorphous silicon solar cells. These cells are very thin, and thus use very little material.
Amorphous silicon has made considerable progress. The first cells were produced in 1974. In 1985 the market share already had reached 30%. Commercial applications have been found in pocket calculators, watches and battery chargers.
One of the problems of amorphous silicon at the moment is the degradation of the cells. The cell efficiency decreases when light is falling upon the cell, especially during the first months of operation.

Other materials

Besides silicon other materials are under research for use as solar cells. CuInSe2, CdTe and GaAs look very promising in the long term, but in the coming years large-scale application of these types of cells is not expected.
The same applies to stacked solar cells. In these structures two or more cells with different characteristics are combined in order to utilize as much of the solar energy as possible.

5.4 BALANCE-OF-SYSTEM

All components of the system together, besides the modules, are called the balance-of-system (BOS). The composition of the balance-of-system depends on the kind of application and on the location of the PV-system.

The balance-of-system may comprise:

- array support structure
- connections/wiring
- power conditioning
- energy storage.

We will have a closer look at several elements of the balance-of-system.

Array support structure

The solar-cell modules rest on a array support structure. The array support structure is generally made out of aluminium or steel struts, resting on a concrete foundation. Research is being done to develop low cost constructions of wood and bamboo.
Another way of reducing costs is to mount the modules on the roofs of buildings. At the moment only limited experience with this kind of construction has been gained.
At present most systems have fixed arrays. In case of a tracking system it must keep the modules in an optimal orientation towards the sun. There are several options.

- Seasonally-adjusted tilt. A few times a year the arrays can be adjusted to the elevation of the sun.
- Single-axis or two-axis tracking. A drive mechanism keeps the modules in the direction of the sun during the whole day. The array structure can rotate in one or two directions.

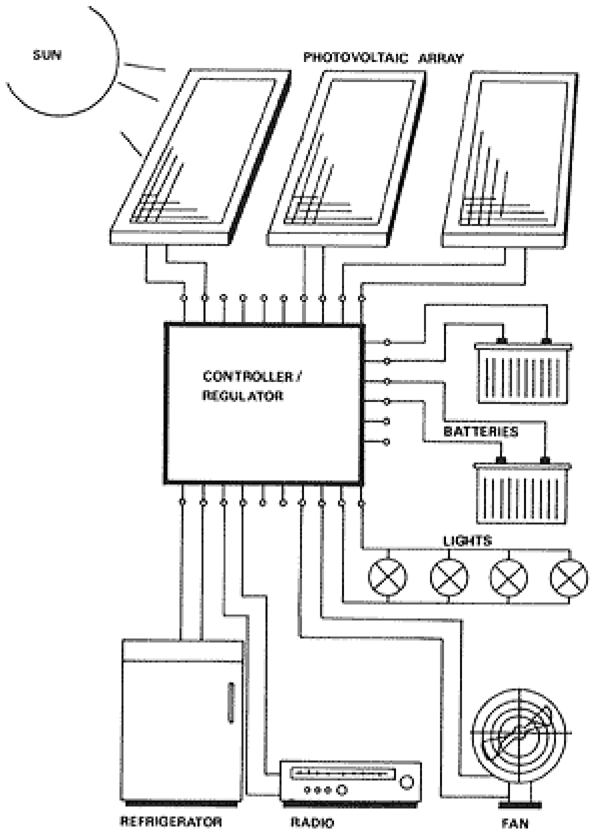


Figure 15. Schematic of PV-system for household electrification (Source: Solar Energie Technik)

Power conditioning

The power conditioning can be composed of the following elements:

- controllers
- maximum power point tracking
- DC-AC converters
- interface between the PV-system and the grid
- electronic protection of the system.

The maximum power point tracking ensures that at any given moment, with any given amount of sunlight and any given cell temperature the maximum power is extracted from the modules.
In general electricity is supplied as AC (alternating current). Therefore a lot of equipment has been developed for AC-application. The PV modules, however, supply DC (direct current)-power. The consequence is that a choice has to be made between the use of DC-apparatus, not available for all appliances, and the installation of an inverter to convert DC into AC. To connect a PV-system with the grid, a special interface is needed including a DC-AC inverter.
To obtain the highest possible system efficiency it is important to lose only small amounts of energy in the power conditioning. At the moment an efficiency of 95% is possible. When the system is not working on full power the efficiency of the power conditioning does fall; sometimes only about 70% efficiency is left. The cost of the power conditioning depends on the need for AC or DC-voltages.

Energy storage

If electrical power is required when the sun is not shining or if there is a short peak demand, for instance to start an electric motor, some form of energy storage is needed or a back-up supply from a diesel or gasoline generator must be provided.
When a PV-system is used to pump up water, in many cases the choice will be to store water instead of electricity.

Several types of storage batteries are available; the lead acid battery is the most common, but Nickel-Cadmium (NiCd) batteries are also suitable.

The operation of the batteries requires much attention during the design of a PV-system. In a battery a certain amount of energy can be stored: this is the capacity of the battery. Lead acid batteries can only be discharged to 30% of the total capacity. From a technical point of view deeper discharge is possible, but the lifetime of the batteries then decreases dramatically. Moreover the total capacity of the battery will decline.
Batteries can also be overcharged. This also has a bad influence on the performance of the battery.
To keep the state of charge of the battery within the allowed range a battery controller can be used. This controller is part of the power conditioning.
A NiCd battery has a better performance. Its design makes it impossible to overcharge or discharge the NiCd-batteries to deeply. Also 100% of the capacity can be used. However NiCd batteries are at the moment (1989) two to three times as expensive as lead acid ones.
Many different batteries are available. A distinction can be made between open and closed batteries. The hermetically closed batteries need no refilling, because the water can not evaporate. Therefore closed batteries in general require less maintenance than open ones.
For uses in developing countries it is often better to transport the battery and the acid apart, so the battery will not age during the often lengthy transport time. When air mail is used, it is not even permitted to transport ready-to-use batteries. Because of safety precautions battery and acid have to be transported separately.
The number of charge/discharge cycles specifies the lifetime of the battery. Another factor of importance to the lifetime is the temperature in which the battery has to operate. The higher the temperature the shorter the lifetime. Here too NiCd has better characteristics than lead acid.

5.5 PV-SYSTEM CHARACTERISTICS

Lifetime

Since PV-systems have been used only relatively shortly for terrestrial applications, there is little experience on the lifetime.
The lifetime of the modules which are commercially available at the moment (crystalline silicon) and of the power conditioning is expected to be about 15 years. A longer lifetime is thought to be not unlikely.
Batteries have an expected lifetime of five to ten years at a temperature of 25þC. When operating at higher temperatures the lifetime is shortening. At 40þC the lifetime of a lead-acid battery reduces to about one third of the lifetime under standard conditions, while the lifetime of a NiCd battery reduces to about three quarters.
Failures which can occur in the modules are broken connections, cracked solar cells and corrosion. Moisture penetration is the biggest problem in the long term.
Apart from the possibility of sudden failure, the performance of the cells will slowly decline over the years, but this effect is relatively small. Bad connections between the modules and the other components of the system can reduce the performance of the system as a whole.

Most systems have a battery controller to prevent the batteries against over-charging and excessively deep unloading. There are many controllers on the market that are not properly designed and may cause system failures.

Modularity

PV-systems can easily be scaled to the electricity demand. A single module provides enough energy to light one house, a number of modules can provide enough energy for an entire medical centre. A new system could begin with one or two modules for the most urgent purposes. The system can be expanded when more applications are envisaged, or demand grows, or when additional funds become available. The original system in the mean time does not need to be replaced.
When the expansion does take place the composition of the whole system, modules, storage and power conditioning, must be taken into consideration, in order to maintain an optimal performance.

Maintenance and reliability

Because a PV-system does not have moving parts and therefore no mechanical wear, maintenance requirements are minimal. The necessary maintenance comprises:

- cleaning the collector surface
- electrical check on the modules; the wiring/connections and the power conditioning
- visual inspection of the modules for broken cells or surface, humidity, electrical connections, and so on
- visual inspection of the mechanical connections and the supporting structure, especially on corrosion,
- repairing or changing broken parts,
- maintenance and repair of the batteries.

Apart from the battery maintenance and (possibly) the collector cleaning a yearly service should be sufficient.

Cost

The most important cost factor is the initial investment. These costs are high compared to other energy sources. However, the costs over a life time are more favorable for PV. Because no fuel is used, the only costs after the installation are the maintenance costs. To make a real comparison, therefore, between different energy sources, all the costs during the life of a system have to be reckoned with.
The high initial investment is a large obstacle to the application of PV in developing countries. It is sometimes suggested that PV has no costs after the investment. But in general that is not true. The batteries need to be replaced every few years. While the price of modules is declining, the batteries are a cost factor which is becoming more and more important.

5.6 IMPLEMENTATION

Designing a PV-system requires care if disappointment in the performance of the system is to be avoided. The most important aspect is the amount of sunlight. The irradiation varies during the year and is also dependent on the latitude and the weather (climate). On a clear day in the tropics with the sun shining directly overhead the irradiation might exceed 1000 W/m ; on cloudy days this will be less.
The number of solar cells needed depends on the demand for energy and the amount of sunlight in the same period. The use of energy storage might be necessary to overcome cloudy days or just to overcome the night.
The sizing of the batteries is of crucial importance, whereby there has to be reckoned with the worst season concerning the irradiation and allowance made for the worst season for sunlight.
The energy demand has to be looked at very carefully. Because of the high investment costs of PV and batteries it is important to reduce the demand as much as possible by the use of energy efficient apparatus, for instance TL-lights, and to try to fit the demand to the amount of solar radiation during the day.

5.7 APPLICATIONS

Vaccine refrigeration

Vaccines require refrigeration during transport and storage. Many vaccines are not resistant to heat. The cold chain therefore has to be reliable in order to make vaccination a success.
When the performance of the grid is poor as is the case in many developing countries, or there is no grid at all, a kerosene or bottled gas (LPG) powered refrigerator can be used. However their performance is also frequently inadequate for vaccine refrigeration.
PV refrigerators have therefore an important role in the vaccination programmes of rural areas in developing countries.
The World Health Organization (WHO) is one of the most experienced organization in this field. They have tested and evaluated PV refrigerators of over SO types for 12 suppliers in 30 countries. As a part of their Expanded Programme on Immunization (1), product information sheets are published in which test results are given for those refrigerators approved by the WHO.
At the moment there are about 1000 PV refrigerators installed throughout the world. At least 20 companies can supply PV refrigerators for vaccine storage.

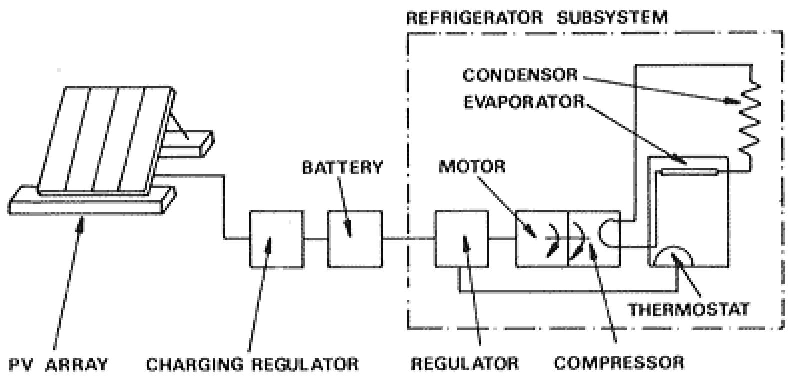


Figure 16. Schematic of photovoltaic refrigerator system (Source: McNelis 1988)

System

In figure 16 a schematic diagram of a photovoltaic refrigerator is given.

The power supply for the refrigerator comprises a photovoltaic array and a battery for storage. The PV array charges the batteries via a charge regulator, to prevent the batteries from overloading and underloading. Via a regulator a DC-motor is powered. The motor is generally directly coupled to the compressor, which is responsible for the cooling inside the refrigerator. The regulator is used to keep the motor within the power range and to prevent overdischarge of the batteries. A thermostat is used to regulate the motor to keep the temperature inside the refrigerator at a constant level.

The World Health Organization (WHO) has outlined several specifications for refrigerators used for vaccine cooling:

- Continuous operation must be guaranteed during the lowest periods of insolation in the year. If other applications, such as lights, are included they should operate from a separate battery set.
- Five days of continuous operation must be guaranteed when the PV array is disconnected and the batteries are fully charged.
- The supplier is required to give a warranty for the replacement of any failing component. The minimum period is to be ten years for the PV array, five years for the batteries and two years for the other components.

Besides these three specifications the WHO has several technical specifications for the modules, the battery set, the freezer, the voltage regulator and the instrumentation. They have also prepared a list of essential spare parts for each of ten installed systems.

The refrigerators are available with capacities of 3.6 to 200 litres. For a village with 150 births a month, space for packed vaccines is necessary, but other medicines may be stored in the refrigerator too. It is important that the refrigerators are capable of freezing ice packs. These are used in transporting vaccines from the health centre to the field for immunization.
Not all DC-refrigerators can be used for vaccine storage as some suffer from internal temperature variations. These are only suitable for domestic purposes.

Telecommunications

Applications for PV-powered telecommunications have been found in a wide range, from small systems (one module, one battery) in health care communication projects to large systems operated by governments, public companies and private companies. PV is a commercial option in areas where the reliability of the power supply from the grid is poor or where there is no grid available.

System

A PV-powered telecommunication system comprises a PV array, a power conditioning unit, a battery storage unit and the telecommunication apparatus. The power conditioning can vary from a simple voltage regulator to controllers that optimize system performance. The system can also include equipment for remote control and monitoring.

Battery chargers

In developing countries a large number of batteries are used for radios, cassettes, flashlights and other applications. Often non-rechargeable batteries are used. Sometimes batteries can be recharged or car batteries (lead acid) are used. People often have to travel long distances to a charging station to reload these batteries.
A battery charging station on PV is a very simple system. Only PV-modules are needed. Storage of energy is not necessary. To charge one battery in one day a module of about 200 Wp is needed.
In several countries PV charging stations have proven to be a profitable option for local traders. A charging station can be part of a larger system by which the owner can earn some money to offset, for instance, his own battery costs.

Lighting

Electric light is an important improvement in the quality of life in areas, especially when compared to kerosene lights. Electric lighting is therefore one of the first uses for electricity in homes and other buildings. Because lighting does not need a lot of energy, in many cases extending the grid is too expensive. The use of PV as an energy source can be of help.
PV-lighting can be used for domestic and community buildings, such as schools and health centres. PV is also used as an energy source for streetlights (security) and tunnel lighting.

Water Pumping

Solar pumps are used to pump water from boreholes or from surface waters for rural drinking water supply and for irrigation. The use of PV for pumping should be considered in sunny locations for a not too large water demand in regions where the supply of fuel is inconvenient. When the local wind regime is sufficient a wind pump is usually more attractive than a PV pump.
There have been many problems in applying solar pumps in developing countries, but they have been overcome. More than 5,000 pumps are operating at the moment throughout the world. The guarantee of satisfactory performance depends on reliable data on insolation, water resources, water demand and well characteristics. The proper design of the whole system is complex, not least because of the many types of pumps available.

5.8 REFERENCES

(1) Expanded Programme on Immunization
World Health Organization
1211 Geneva 27, Switzerland

- Davidson J./Komp R., *The solar electric home. A photovoltaics how-to handbook,* AATEC Publications, Ann Arbor, USA, 1984.
- Derrick A./Francis C./Bokalders V., *Solar photovoltaic products. A guide for development workers*, Intermediate Technology/The Beijer Institute/Swedish Missionary Council, London, United Kingdom, 1989.
- McNelis B./Derrick A./Starr M., *Solar-powered electricity. A survey of photovoltaic power in developing countries*, Intermediate Technology/Unesco,London, United Kingdom, 1988.

Appendix

General recommendations for PV-system projects

1. PRE-FEASIBILITY STUDY

Such a preliminary study should contain the following items:

- Energy consumption patterns of the potential users, with special emphasis on electricity consumption presently and in the near future, based on peoples' expectations and income levels.
- Economic and financial comparison of alternative renewable energy and conventional (diesel generator sets) options. In such comparisons non-financial arguments should also be discussed.
- System sizing study based on present and expected energy consumption figures, solar radiation figures and system specifications.

2. SELECTION OF MANUFACTURER/SUPPLIER

When this pre-feasibility study results in a positive recommendation the next step is the elaboration of the design and selection of manufacturers/suppliers.
In cases where substantial amounts of money are to be spent on equipment, tendering is worthwhile. As a rough estimate, tendering becomes interesting when the procedure costs less then 5 to 10% of the sum involved.
Tendering in such cases has the following benefits:

- it ensures product quality, if well carried out;
- it ensures proper sizing of the equipment by setting specifications on performance which are less than specified by the manufacturer/supplier;
- it can ensure proper installation and commissioning of the equipment.

On the other hand tender preparation has considerable costs. To give some indication, even for small projects at least one man-month should be considered.

For all PV-system projects quotations of at least three manufacturers/suppliers should be called for. In the competitive business of PV-systems, unit prices might not vary so much, but secondary conditions such as guarantees and after-sales service could show interesting differences.

A very strong argument in the selection of a particular manufacturer/supplier is their already existing market share in the region and the presence of a local agent of such a company.

In the final agreement of delivery of goods the following points should be covered:

- point of delivery of goods and price at delivery;
- storage costs at point of delivery per day;
- type of packing: number of crates, quality of crates (for sea and air transport) and list of contents per crate;
- payment procedures of the order and expiry date;
- calculations on sizing of each independent system and assumptions made for such calculations;
- manuals on the installation, operation and maintenance for each independent system and system component;
- specifications of each system and system component and applied rules and standards, including tolerable operating conditions: all system components should be suitable for operation in the humid tropics and marine conditions: battery regulators, lighting armatures, switches, division boxes should be drip-water proof;
- guarantees and after-sales service: conditions for guarantees and financial consequences should be specified: transport of defective components, on-site repairs, etc.;
- spare parts list for a two years' operation period.

Caution should be exercised with respect to the transport of the equipment a complete insurance for goods and transport should be arranged.

3. TRAINING OF USERS

Training of the system users should be provided in advance of or at installation. This should ensure proper use and awareness of the systems' limitations.
Subjects which should be dealt with are:

- applications for PV-systems and its scope;
- basic working principles of the PV-systems: discussion of the functions of the system components;
- operation and maintenance requirements;
- some practical trials to show the effect of shading on the output: effect of battery depletion etc.

4. INSTALLATION OF PV-SYSTEMS AND TESTING

If the organisation which purchases the equipment claims to be experienced in its installation a list of successfully installed PV-systems might be provided as demonstration of competence. However care should be taken that the organisation which installs the system gets the assurance of the manufacturer/supplier that the guarantees and after-sales service conditions are still valid when the system is installed by others.

If possible, training of the organisations' employees by the regional agent of the manufacturer/supplier is strongly recommended. Checking major Dutch manufacturers/suppliers on this point shows that one gives special training on installation, while the other trust in the instruction manual and will send replacements of defective components free of cost, once analysis has shown that the defect falls within the guarantee regulations.

When the system is tested after installation, the assistance of an independent party has proven most helpful in ensuring that the system functions according to the manufacturers' specifications. Such independent sources of expertise could be a university or technical high school department which deals with renewable energy systems.

5. MONITORING OF PV-SYSTEMS

In each PV-system project a monitoring phase should be included. This monitoring of the system can be carried out by the development organisation or by the users. Preference should be given to the users: it will then directly provide a feed-back to the users themselves. The development organisation should stimulate the monitoring as it can derive useful data from it.

6. REFERENCES

- Oelert G./Auer F./Pertz K., *Economic issues of renewable energy systems. A guide to project planning*, GTZ, Eschborn, FR Germany, 1987.
