Wolfgang Palz

SOLAR ELECTRICITY

An Economic Approach to Solar Energy

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PARIS

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The Butterworth Group

United Kingdom	**Butterworth & Co (Publishers) Ltd**
London	88 Kingsway, WC2B 6AB
Australia	**Butterworths Pty Ltd**
Sydney	586 Pacific Highway, Chatswood, NSW 2067
	Also at Melbourne, Brisbane, Adelaide and Perth
Canada	**Butterworth & Co (Canada) Ltd**
Toronto	2265 Midland Avenue, Scarborough, Ontario, M1P 4S1
New Zealand	**Butterworths of New Zealand Ltd**
Wellington	77-85 Customhouse Quay, 1
South Africa	**Butterworth & Co (South Africa) (Pty) Ltd**
Durban	152-154 Gale Street
USA	**Butterworth (Publishers) Inc**
Boston	19 Cummings Park, Woburn, Massachusetts 01801

First published 1978 by United Nations Educational Scientific and Cultural Organization, 7 Place de Fontenoy, 75700 Paris, France and Butterworths, London

ISBN 0 408 70910 3 (Butterworths)
92 3 101427 7 (Unesco)

Library of Congress Cataloging in Publication Data

Palz, Wolfgang.
Solar electricity.

Bibliography: p.
Includes index.
1. Solar power plants. 2. Solar energy.
I. Title
TK1056.P34 621.47'5 77-3524
ISBN 0-408-70910-3 (Butterworths)
92 3 101427 7 (Unesco)

Typeset by Butterworths Litho Preparation Department

Printed in England at Chapel River Press, Andover, Hants

PREFACE

The growing demand for energy throughout the world has caused great importance to be attached to the exploration of new sources of energy; among the unconventional sources that have been studied, solar energy now holds out much promise. The scientific basis for the utilization of solar energy by man was acquired some years ago, but until recently it was not considered technologically feasible to make use of it on a large scale. However, the international congress, 'The Sun in the Service of Mankind' (Unesco, July 1973), focused international attention on recent advances in solar energy techniques which open up the prospect of supplying – in a convenient and economical manner – a significant part of man's energy needs before the end of the century. Already, small-scale applications are at work and steadily gaining new markets.

Along with the scientific and technological progress of recent years, which has brought the large-scale utilization of solar energy nearer, there has been a profound change in the economics of power production by conventional processes, and a growing awareness of their adverse environmental effects. Furthermore, there is a social need – especially in the developing countries – for techniques which permit decentralized power production in small, widely scattered communities; solar energy lends itself well to small-scale production in remote areas, and solar pumps can already be seen working reliably in many developing countries.

The General Conference of Unesco, at its 18th session, recommended that international action be encouraged in the field of fundamental scientific problems of energy, its production, conversion and transportation, giving special emphasis to the identification of areas where breakthroughs are needed to generate and use energy more efficiently from existing sources and to make large-scale energy generation feasible from renewable and clean sources such as nuclear fusion, solar energy, wind and tidal and geothermal sources. Following this recommendation, it was decided to review modern methods and practical possibilities of the various technologies for the use of solar energy.

The present book, based on a previous study prepared by the author at the request of Unesco, is the fruit of much labour and research. The latest achievements in the field are reviewed, including methods for the direct use of solar heat, thermodynamic conversion into mechanical and electrical energy, and the development and application of solar cells which convert light directly into electricity. The growing market for solar cells is expected to lead to mass production, which would open up further markets and make it possible to envisage large-scale power generation from this new source.

The book is written in a style which the non-specialist can follow without difficulty. It is hoped that this publication will provide useful information to students at all levels, and will also serve as an introduction to the subject for those who intend to devote themselves to the development of new sources of energy. Above all, it may be considered almost as a pioneering enterprise, dealing – as it does – with a subject hitherto little explored or explained.

The opinions expressed in this book are not necessarily those of Unesco or of the Commission of the European Communities.

ACKNOWLEDGEMENTS

The author expresses his gratitude to Mr. L. Crossby of the Unesco Secretariat for his collaboration in writing this book.

REVIEWERS

The author gratefully acknowledges many helpful discussions on the theory of the photovoltaic effect with Dr. Joseph Lindmayer, Rockville, Md., USA, and on solar heat collectors with Georges Alexandroff and Raymond Zaharia, Paris, France.

For reviewing the manuscript the author is indebted to Dr. Rolf E. Glitsch, Paris, France; Dr. Albert S. Strub, Brussels, Belgium; Dr. Paul Leitz, Luxembourg; Dr. Dennis Curtin, Rockville, Md., USA, and John F. Jordan, El Paso, Texas, USA.

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INTRODUCTION

The prospect of converting solar energy on a large scale may seem an ecologist's dream, incompatible with the needs of a modern economy. Yet, until comparatively recent times, man relied entirely on the sun for his energy needs. Only in the nineteenth century, as a result of the prolific growth of industry in Western Europe and in the USA, did the extraction of fossil fuels become important. Today, man has become aware of the increasing dangers of pollution and the limited supplies of his present energy resources. The so-called energy crisis of 1973/74 flattened the growth rate curve of the economy in many countries, but the fuel fever was only abated, not cured. There can be little doubt that conventional fuel will become scarce and expensive towards the end of this century; advantage should therefore be taken of the remaining time to develop solar energy systems to an economic level at which they could take over at least part of the world's energy demand. The principal aim of this book is to review solar energy conversion processes and to assess their large scale potential for the future.

Unlike the agricultural economies of 200 years ago which utilized 'natural' solar energy, the advanced industrial societies of today need not only devices using solar energy in its natural state, but also apparatus to convert it into 'artificial' forms, capable of powering modern machines, and the means to store this energy so as to ensure a continuous supply.

Consumer needs are best illustrated by the demand for electricity, an 'invention' of the 19th century. Today, it would be difficult to envisage life without electricity and its innumerable applications, both in industry and the home. However, the development of solar electricity – in other words, the direct conversion of solar energy into electricity – offers the prospect of an unlimited and non-polluting supply. Thus, the large-scale utilization of solar energy in the future will not involve giving up the convenience of electric power.

Solar electricity cannot be found ready for use in nature. To obtain this new form of energy, man must invent and design appropriate conversion devices. Hence, for electricity the situation is different from solar heating or photosynthesis. The sun's radiation is transformed into heat or, if water is available, into organic matter by processes conveniently provided by nature. All man must do is to adapt the thermal conversion to his needs. This is particularly true of housing; ever since man started to build houses he has applied much skill to adapting the heating effect of the sun so as to achieve a comfortable temperature in his dwellings.

During the industrial period, the potential of solar energy has been increasingly neglected in architecture. The recent interest in the development of solar houses is a rediscovery of man's old concern, although the new approach is more technical, involving heat collectors, heat storage, and climatic control units. Nevertheless, it remains true that the use of solar energy in housing is essentially an architectural problem.

In contrast, the conversion of solar energy into electricity is a completely new challenge and it is therefore appropriate to focus attention on it in this book. Conversion by means of solar cells is only 23 years old; the unique impact of this new technology may be appreciated if one recalls that virtually all other inventions for solar energy conversion were made in the last century or long before.

After reviewing what has been achieved so far, this book looks to the future: the reader will find a broad survey of the prospects for the conversion and use of solar energy by all the known and presently foreseeable techniques. A general evaluation of the solar energy conversion processes, and particularly those intended for electricity generation, such as is attempted in this book, must necessarily include the costs and other economic aspects of use. The technical and economic problems associated with the large-scale use of solar energy that we are bound to explore are inseparable from each other; hence a purely scientific or technological view would be inadequate. The approach chosen in this book is to review in detail the technical designs and trade-offs in order to gain a comprehensive understanding of the current cost situation and the cost decreases that may be expected in the various competing systems. Attention is focused on technologies which, according to present knowledge, offer a real prospect of replacing a substantial fraction of the demand for the depleting fossil fuels. Less space is given to systems offering little promise in this respect, such as solar thermionic generators. Readers interested in these systems from a purely scientific point of view are referred to the physical literature.

The development of solar energy applications does not mean the beginning of a new economic world: on the contrary, the new energy systems must first win their place in the overall energy market, they must be made competitive with oil, coal or nuclear energy, whether for reasons of depletion of conventional resources, thermal or chemical pollution of the natural environment, greater independence from foreign suppliers, or simply lower costs. Hence, in order to situate the economics of solar energy vis-á-vis those of the conventional techniques, the book starts with a review of large-scale energy resources other than solar energy. Indirect solar energy resources such as water and wind power are included in this review.

Next, because the suitability of a given conversion system – especially if it employs a concentrating device – depends on the geographical region, the site, and local meteorological conditions, the available solar energy resources in different parts of the world are described.

Although the application of solar energy to the heating and cooling of houses is marginal to the theme chosen for this book, the major technical and cost elements of this somewhat simpler field are summarized so as to provide the reader with a comprehensive understanding of the whole solar energy picture. Finally, the conversion of solar radiation into electricity is described in greater detail. Solar electricity is particularly appropriate to the advanced economies of modern times, which have a remarkable capacity for the development of sophisticated technology. A comprehensive analysis is presented of the broad spectrum of conversion processes, based either on thermodynamic conversion usually involving a turbine or similar device, or the photovoltaic cell or solar cell. Attention is focused on the prospects of these techniques to produce an important part of the world's energy needs.

Two specific problems are discussed at the end of the book: first, the physics of the photovoltaic effect, and secondly, market considerations of solar energy for small-scale applications, particularly in remote areas.

Despite the innumerable steps that have been taken all over the world during the last year or two to make solar energy a reality and of which only a few examples can be mentioned in this book, despite also the rapid progress now taking place in the field, it is felt that this book will provide the non-specialized reader with criteria that will enable him to evaluate the confusing variety of systems he is confronted with; and moreover to establish his own guidelines for estimating the prospects of development. Therefore, attention is focused on the physical principles that provide the most appropriate and evolution-free tool for analysis. The method employed is essentially descriptive and avoids mathematical formulae wherever possible. All the basic knowledge needed for an understanding of the phenomena is presented.

In short, this book is designed to give an introduction to the broad field of solar energy, addressing in depth the more sophisticated conversion methods for the production of electricity, and covering the physical and technological aspects as well as the cost problems. On the other hand, there is no intention to provide a complete catalogue of all development projects, for in the present fast-moving phase of development, a solar energy encyclopaedia would be obsolete as soon as it was written.

CONTENTS

CHAPTER 1

ENERGY OVERVIEW

1.1 THE EVOLUTION OF POWER DEMAND

Only two hundred years ago, man derived his sources of energy almost exclusively from the sun.* At that time, four or five generations back, wood was in general use for heating, and animals were used for transport. Both these kinds of power are provided – directly or indirectly – by photosynthesis, the process by which plants are able to utilize part of the sun's energy to convert carbon dioxide and water into combustible substances and food. Other forms of energy derived from the sun were wind and water power, the best known applications being windmills and watermills.

The consumption of fossil fuels was insignificant until the eighteenth century. This is a surprising observation because all the fossil fuels have been known since antiquity. The Mesopotamians used petroleum, and Alexander also knew of it, as reported by the Greeks. Oil was used for lighting and asphalt (a Greek word) was employed as a construction material. The American Indians also knew of petroleum. As regards coal, we learned from Marco Polo that the Chinese used it 2000 years ago. The Greeks used coal, too, especially in bronze foundries. In Europe, coal mining is reported from the 12th century onwards. Throughout the Middle Ages and afterwards, coal was used mainly in smithies and foundries. Some old names (e.g. the town Zwickau; the French term *la houille* from the blacksmith Hullos of Liège) are related to coal. Natural gas has also been known for a long time, especially in India and the Middle East, where it played a rôle in religion.

The trend away from solar energy and towards the utilization of fossil energy resources started slowly in the nineteenth century and has continued and intensified ever since. The exploitation of coal on a large scale started about 1820. The beginning

* 'Solar energy' means all energy that has *recently* originated in the sun. It includes direct and intermediate forms of solar energy such as water power or hydroelectricity, wind, products of photosynthetic processes (fuel wood and working animal feed), organic wastes, ocean thermal gradients and others. Although coal, oil and gas result from photosynthesis that occurred millions of years ago, they are called fossil fuels and not solar energy. The difference is that solar energy is renewable, whereas fossil energy is not.

of the large-scale use of oil dates back to 12th August 1859 when oil was found accidentally in a borehole in Pennsylvania. But why did fossil energy, which had been known for so long, suddenly become the energy favourite in the nineteenth century? The answer is that this important development in man's history resulted from the appearance of a new kind of demand: energy was needed for the engines which were developed during the unique period of scientific and technical progress that occurred at the end of the nineteenth century in the 'industrialized' countries. The development of engines increased productivity and – together with advances in other fields, such as the discovery of synthetic fertilizers, vaccines and antibiotics – made possible a tremendous population growth. To gain an idea of the dynamics of power consumption growth – largely uncontrolled in the past, but now on the verge of being regulated – it is worth while to recall how, step by step, the flow of inventions which resulted from more and more systematic research opened the way for new applications and increased the demand for energy.

Apart from the windmill and water wheel, the first mechanically driven engine which came into widespread use was the steam engine. The first primitive version of the steam engine was invented in 1706 by the Frenchman Papin, then working in Germany. The efficiency of this engine was far too low – it was 75 times lower than that of engines built 200 years later – and only in 1768 (Watt in England) did an operational steam engine become available. Practical applications of the steam engine developed slowly: the first steam-powered ship went into service in 1807, the first railway in 1825. The first steam boilers burnt wood, but there was a progressive change to coal.

The development of modern electrical machines followed the discovery by the Dane Oersted in 1819 of the reaction between a magnetic needle and a current-carrying wire. In 1831, Faraday added the principle of magnetic induction. The first electric generator following Oersted's invention was built by Pixii in 1832 in Paris. In the three following decades attempts were made, especially in France (the 'Alliance machine', 1863) to use these generators for electrolysis and electric lighting, and in lighthouses, but the machines proved to be too inefficient. The breakthrough came in 1867 when Siemens and Wheatstone almost simultaneously discovered that the dynamo could be made self-exciting through the residual magnetism in the soft iron cores of the electromagnets. These generators were further improved by the Belgian Gramme. Finally, it is said that the first power station was built by Edison in 1882 in New York. It had a power of several kilowatts. This milestone marked the start of a second phase of industrialization in which electric power became important. In 1902, the first year for which national statistics for electricity are generally available, the installed capacity in the then most advanced countries as regards electrification was as follows:

USA	3000 MW
Germany	1400 MW
UK	500 MW
France	370 MW
Spain	200 MW
Sweden	100 MW

For comparison, the capacity installed in the European Economic Community (EEC) in 1972 was 225 000 MW.

Around 1862, Otto built his four-cycle internal combustion engine which made possible the development of the modern automobile and the aeroplane and greatly stimulated the demand for a new type of fossil fuel, namely oil.

Another major step in the progress of mechanical power was the development of turbines, the principle of which had been described by Leonardo da Vinci. In the 18th and 19th centuries a number of scientists worked on turbines and the first engines were built. Modern hydraulic turbines were invented by the American Francis (1849) and the Austrian Kaplan (1912). The steam turbine was invented in 1884 by the Englishman Parsons and the Swede de Laval. The gas turbine dates from 1850.

The turbine provided the basis for the invention of the jet engine around 1930 (Sir Frank Whittle). The first jet aeroplane was successfully flown in Germany (the He 178 in 1939).*

Finally, man discovered nuclear energy. The first studies on radioactive materials were initiated in France and England at the end of the last century. But it was only in 1938 that Hahn in Germany achieved the first artificial fission of uranium atoms; in 1942 Fermi built the first nuclear reactor in Chicago. Despite the early hopes of rapid development, this energy source occupies only a small part of the energy picture in the mid-seventies.

The evolution of power consumption that resulted from all these inventions may be studied, and the future technical development and industrialization of a number of countries may be foreseen by taking the case of the United States of America, for which the most comprehensive statistics are available. *Figure 1* gives a somewhat schematic view of the exponential growth of power consumption in the USA between 1850 and 1970.

In 1850, the USA relied almost completely on renewable solar energy in the forms of fuel wood, animal feed, and wind and water power. Coal accounted for only 7% at that time, although 70 years had passed since the invention of a practical steam engine. In absolute terms, the consumption of solar energy has remained remarkably constant until the present time, but as a fraction of total consumption it has fallen to 6%. However, during the second half of the last century, the forms in which solar energy was used underwent a fundamental change. The use of wood as a fuel constantly diminished, whereas hydroelectricity became more and more important. The lower part of *Figure 1* brings out the evolution of the non-fossil prime movers and the appearance of electricity.[1] In the other industrialized countries, the trend was similar. In 1972, in the EEC, not more than 4% of total consumption originated from indirect solar energy, i.e. hydraulic reserves and fuel wood.

Today, if we wish to increase the share of direct solar energy in overall power consumption, the example given by our great-grandfathers cannot be followed. An irreversible change has occurred, and there can be no doubt that the harnessing of solar energy for future needs requires, first and foremost, difficult technical development work and an industrialization effort. Anything less would lead back to a primitive civilization.

Since the non-reversible resources will be depleted in the long run, no country can rely on them indefinitely. This explains the growing interest, even anxiety to develop new energy sources other than fossil fuels.

* A kerosene-air mix is ignited in a combustion chamber. As the gases expand they turn the blades of a turbine rotor. A shaft coupled to the rotor leads to the air intake at the front of the engine and drives a compressor which forces more air into the engine. After the gases have passed the turbine blades they expand through an exhaust nozzle, thereby increasing their velocity for the final drive.

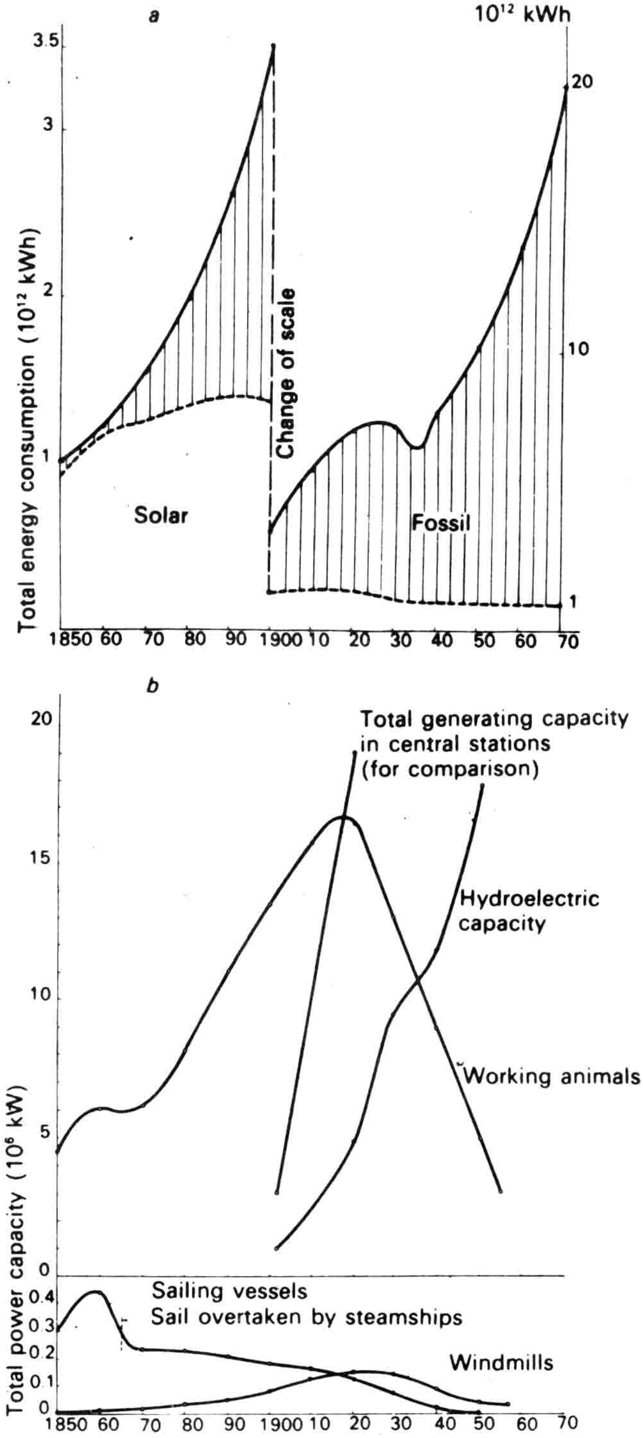

Figure 1. The evolution of the energy and power scenario in the USA from 1850 to 1970 (a) consumption of solar and fossil energy (b) power capacity of the main non-fossil prime movers