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PROCEEDINGS OF THE SECOND SEDE BOQER SYMPOSIUM ON SOLAR ELECTRICITY PRODUCTION

25-26 FEBRUARY 1987

Editor

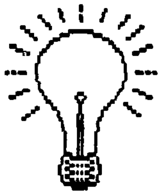
D. FAIMAN

Organized by:

The Applied Solar Calculations Unit
The Jacob Blaustein Institute for Desert Research
Ben-Gurion University of the Negev

Under the Patronage of

* The Israel Ministry of Energy and Infrastructure
* Ben-Gurion University of the Negev
* The Blaustein International Center for Desert Studies
* International Solar Energy Society (Israel Section)



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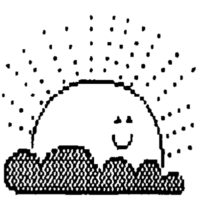

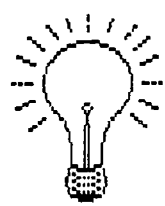

INTRODUCTION

By a happy circumstance, this second Sede Boqer workshop on solar electricity production coincided with the opening of the "Ben Gurion Sede Boqer Test Center for Solar Electricity Generating Technologies". The foundation stone setting for this facility, which was the chief stimulus behind the initiation of this annual series of workshops last year, took place November 19th 1985. Its dedication, however, honors the hundredth anniversary of Israel's first Prime Minister, a man who wrote [*]:

".....The mightiest source of energy in our world, the source from which all animal and vegetable life is nourished, and only an infinitesimal part of which is as yet utilized by the human race, is the sun."

".....but this energy can be transformed into an active, dynamic and electrifying force. Even after all the uranium and thorium deposits disappear from the earth, solar energy will continue to reach us in almost unlimited quantities, and our scientists and technologists must discover the most effective means for putting even a very small part of this tremendous energy to work for the growing and manifold needs of our variegated economy."

Indeed David Ben Gurion's more than passive interest in solar energy research was most poignantly recalled, for the benefit of those who attended this year's workshop, by Dr. Harry Tabor. "One day, years ago", according to this pioneer of solar research, "my work was disturbed by the unannounced arrival at my laboratory of Mr. Ben-Gurion and his entire Cabinet!" Dr. Tabor went on to recall how this event occurred at precisely the time (back in the 1950s) when oil had just been supposedly discovered in Israel! Well, the oil did not materialize and, alas, no other political leaders had the foresight to help develop solar technology to an extent that it might have alleviated a significant part of the oil crisis which came 20 years later.

But now, two decades later, with the painfull lessons of fluctuating oil prices and supply uncertainties vividly in our recent memories, we may take comfort in the fact that the Israel Ministry of Energy and Infrastructure has established the Ben Gurion test facility. Its opening comes at a time when, unencumbered by an *on-going oil* crisis, and armed with the experience of ten years of international effort to develop solar technology, it is now possible to perform side-by-side evaluations of the best that technology has thus far produced.

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[*] From Israel: Years of Challenge by David Ben-Gurion (Anthony Blond, London, 1964)

Naturally, mere system evaluation is not sufficient. Ideally there should be input from the scientific community on as broad a front as possible. It is towards this goal that the Applied Solar Calculations Unit established this series of annual workshops last year, and it is a source of considerable pride to us that scientific input has come this year from the international arena. Participation from abroad included two of our keynote speakers: Prof. Ari Rabl from Princeton University's Center for Energy and Environmental Studies, and Prof. Manual Collares Pereira from Portugal's Department for Renewable Energies at LNETI, Lisbon. In honor of our guests from abroad the language of this year's symposium was English.

As to the content of this year's symposium, we were honored to have the opening address delivered by Mr. Moshe Shachal, Minister for Energy and Infrastructure, who reviewed Israel's current energy policy. Mr. Shachal's presentation was followed by one from Dr. Nathan Arad, the Director General of the Ministry, who addressed us on the subject of Israel's involvement in energy R&D. Dr. Pinhas Gluecksterrn, the Ministry's Chief Scientist then presented an overview of the new test facility and its aims.

Three power-producing systems - the first that will be evaluated - were on display at the test site; photovoltaic systems belonging to the Israel Electric Corporation and to the Paz Oil Company, and a solar-thermal system belonging to the Luz Corporation. Each of these systems was reviewed in a series of presentations by the companies concerned, and in the same session the site's data aquisition system was described by its designer, Dr. Moshe Hirsch.

The more technical part of the symposium took the form of three invited 45-minute keynote lectures by prominent authorities in the field. Each such lecture was immediately followed by a 45-minute discussion session. The three areas reviewed were: High Temperature Solar Thermal by Prof. Rabl, Low Temperature Solar Thermal by Prof. Collares Pereira and Photovoltaics by Tel Aviv University's Prof. Joseph Appelbaum. In addition there was a poster session where presentations from academia and industry alike were on display and their authors were on hand to take questions.

This volume of proceedings contains the texts of the various keynote presentations, either in the written form kindly supplied by the authors or, where this was not possible, in a form reconstituted from the transparencies they showed. In addition, an edited text is appended containing the chief points that emmerged from the various (tape recorded) discussions. Lastly, extended abstracts are included to describe the contents of the various posters that were on display.

Finally, it is our pleasant duty to thank a number of organizations and persons, without whose help the symposium would not have been able to succeed.

Financial support is gratefully acknowledged from The Ministry of Energy and Infrastructure and The Blaustein International Center for Desert Studies.

Our use of the Ben Gurion Research Center's auditorium was due to the kind cooperation of its director, Prof. Ilan Troen. The beautiful flowers that decorated the hall were supplied by the Blaustein Institute's Controlled Environment Agriculture Unit thanks to the kindness of its Acting Head, Dr. Moshe Zeroni. The lectures and discussions were recorded due to the much appreciated efforts of Mr. Luuk Folkerts.

A fine evening of Israeli Folklore entertainment was provided by the folk dance group of the High School for Environmental Education, Sede Boqer (thanks to the school's Principal, Mr. Benzi Bar-Lavi, to the dance group and their trainer Mr. Hezi Za'arur), a song recital by young Shlomit and her mother Lorri (guitar) Za'arur (thanks to mother, daughter and Mrs. Aviva Cohen, Principal of the "Zin" Elementary School, Sede Boqer) and by June Hare with her delightful readings of extracts from the writings of David and Paula Ben Gurion.

Thanks are due to the various service departments of Midreshet Sede Boqer under its director Mr. Yossi Elihu, for providing dining facilities (Mr. Motti Abarjil) and sleeping accommodation (Mr. David Palmach - Head of the Sede Boqer Field School) for attendees at the symposium.

And during the entire two-day event, Ofra Faiman, Yocheved Gordon, Bosmat Ibbetson, Ruth van der Ley, Lilian Na'aman, Shula Zarmi and Judith Zemel were the most gracious of hostesses.

The Applied Solar Calculations Unit,
Sede Boqer,
May 1997.

THE SECOND SEDE BOQER SYMPOSIUM

ON

ELECTRICITY GENERATION FROM SOLAR ENERGY

Program

WEDNESDAY, February 25th 1987

12:00 - OPENING OF THE SYMPOSIUM (in the Axel Springer Auditorium of the Ben Gurion Research Archives - "A" on the attached map)

Chairman: PROF. LOUIS BERKOFSKY (Director, The Jacob Blaustein Institute for Desert Research)

1. Greetings in the name of Ben Gurion University of the Negev
   PROF. AVRAHAM TAMIR (Rector of the University)

2. Keynote Lecture: "Development of the Negev"
   MR. SHIMON PERES (Vice Premier and Minister for Foreign Affairs)

3. Keynote Lecture: "Israel's Energy Policy"
   MR. MOSHE SHACHAL (Minister of Energy and Infrastructure)

13:00 - Tribute to Ben Gurion's memory at his tomb ("B" on the map)

13:30 - Lunch Break (Midrasha dining room - "C" on the map)

14:30 - FIRST TECHNICAL SESSION OF THE SYMPOSIUM (Axel Springer Auditorium - "A" on the map)

Chairman: PROF. DAVID FAIMAN (Applied Solar Calculations Unit, Jacob Blaustein Institute for Desert Research)

1. Keynote Address by DR. NATHAN ARAD (Director General, (The Ministry of Energy and Infrastructure)

2. Keynote Lecture: "The Ben Gurion Solar Technology Evaluation Center: Goals and Programs"
DR. PINHAS GLUECKSTERN (Chief Scientist, The Ministry of Energy and Infrastructure)

15:30 - Progress reports on the first solar power-producing systems at Sede Boqer, presented by:

The Israel Electric Corporation.

Luz International Ltd.

The Paz Oil Company Ltd.

16:30 - Coffee Break and Registration of Symposium Attendees (Lobby of auditorium "A" on the map)

17:30 - Keynote lecture: "High Temperature Solar Thermal Technologies"
PROF. ARI RABL (Center for Energy and Environmental Studies, Princeton University)

Discussion chaired by PROF. AHARON ROY (Dept. of Chemical Engineering, Ben Gurion University of the Negev)

19:30 - WINE & CHEESE PARTY (building "D" on the map)

22:00 - Lodging for those holding reservations (building "E" on the map)

THURSDAY, February 26th 1987

07:30 - Breakfast (Midrasha dining room - "C" on the map)

09:00 - SECOND TECHNICAL SESSION OF THE SYMPOSIUM (Seminar room of the Jacob Blaustein Institute for Desert Research - building "G" on the map)

Scientific Poster Session (Outdoors - weather permitting)

Chairman: PROF. YAIR ZARMI (Applied Solar Calculations Unit, The Jacob Blaustein Institute for Desert Research)

10:30 - Coffee Break

11:00 - Keynote Lecture: "Low Temperature Solar Thermal Technologies" DR. MANUEL COLLARES PEREIRA (Dept of Renewable Energies, LNETI, Lisbon)

Discussion chaired by DR. HARRY TABOR (The Scientific Research Foundation, Jerusalem)

12:30 - Lunch Break (Midrasha dining room - "C" on the map)

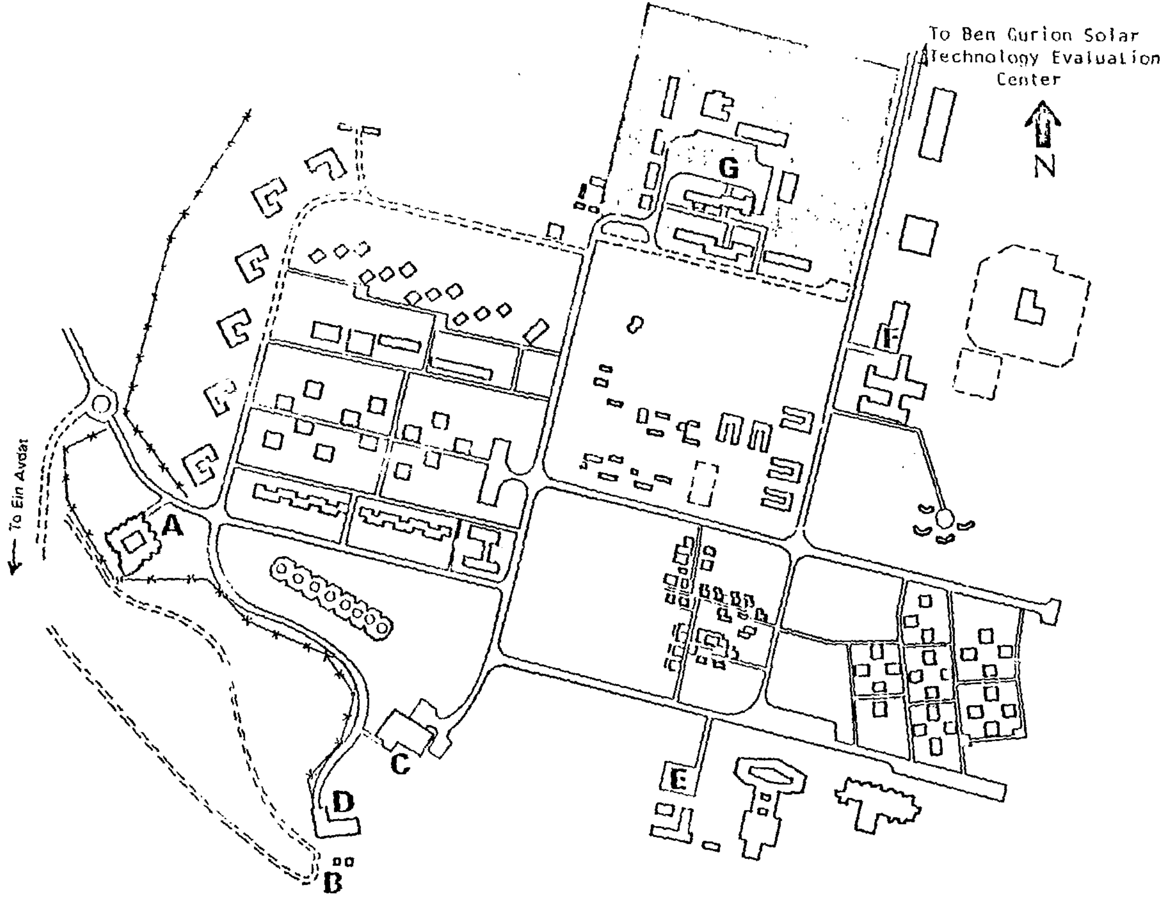
14:00 - THIRD TECHNICAL SESSION OF THE SYMPOSIUM (Seminar Room of the Jacob Blaustein Institute for Desert Research - building "G" on the map)

Keynote Lecture: "Subsystem Matching in Photovoltaic Power Systems" PROF. JOSEPH APPELBAUM (Faculty of Electrical Engineering, University of Tel Aviv)

Discussion chaired by PROF. JEFFREY M. GORDON (Applied Solar Calculations Unit, The Jacob Blaustein Institute for Desert Research)

15:30 - Coffee Break

16:00 - Summing-up Session chaired by PROF. DAVID FAIMAN (Applied Solar Calculations Unit, The Jacob Blaustein Institute for Desert Research)



SEDE BOQER CAMPUS

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(2) POSTER PRESENTATIONS [Extended Abstracts]

KEYNOTE ADDRESS

"Israel's Energy Policy: An Overview"

by

MR. MOSHE SHACHAL

Minister for Energy and Infrastructure

שר האנרגיה והתשתית
MINISTER OF ENERGY & INFRASTRUCTURE

SPEECH AT SOLAR ENERGY SYMPOSIUM, SDE BOKER, FEBRUARY 25, 1987

Distinguished guests, ladies and gentlemen:

The Solar Test Center which we dedicated today is named after a man who, in speaking of those who helped to build the State of Israel, once said:

"We are realists, because we believe in miracles."

The many problems which beset Israel when David Ben-Gurion became its first Prime Minister in 1948 were seen by some as insurmountable. Ben-Gurion, however, refused to yield the title of "realists" to those who saw only the very real difficulties that faced the new state. He understood that human will and ingenuity, guided by vision, are a force more powerful than the harshest reality.

The Negev was and is the symbol of Ben-Gurion's vision. Where others saw a barren wasteland, Ben-Gurion saw a challenge, an opportunity: in solving the problems of agriculture in a land without rain, of energy in a land without fuel, of development in a trackless desert, Israel would not only assure its own future, but could help others confronted with similar problems around the world.

"We are realists, because we believe in miracles." Ben-Gurion might have added that miracles have an affinity for those with a sense of reality, of practicality.

Ben-Gurion recognized and spoke of the importance of solar power at a time when this seemed almost visionary.
But he made sure to anchor his vision on a practical, even mundane level - as expressed, for example, in a household solar water heater, whose development he encouraged by placing it under the direct sponsorship of his own Prime Minister's Office.
Vision, which does not ignore reality, but confronts and eventually transforms reality--this is Ben-Gurion's legacy.

Today, nearly forty years later, what has become of this reality, and of this vision? If we look at Israel's energy situation, we see that these two poles of Ben-Gurion's thought are still very much relevant.

First, the reality. Israel has no coal, very little oil and gas. We must import about 97% of the energy we consume, and we pay for it dearly. In 30 years of searching for oil within the borders of this country, enough has been found to supply perhaps 1% of what our economy uses. Although we have oil shale, mostly in the Negev, it cannot be economically exploited on a wide scale at present.

The foreign currency that we expend for imported fossil fuels constitutes a significant part of our balance-of-payments gap. Since not all of the countries rich in fossil fuels are friendly to us, our dependence on imported fuel also poses a strategic problem.

We can console ourselves that we are not the only ones confronted by this reality. There are many other nations lacking coal and oil. Indeed, since the world's fossil fuel reserves are limited, we can say that Israel has already arrived at a situation which other nations must inevitably reach one day: a situation in which renewable, alternative energy sources are not merely a luxury but a necessity.

This, then, is the reality. It was Ben-Gurion's vision that this harsh situation actually presented an opportunity. By developing solar and other renewable energy sources, Israel could make a contribution to a worldwide goal--making solar energy practical. In a moment I will describe some of the forms this effort has taken, but I want first to briefly outline Israel's current approach to fossil fuels.

The two main problems with living on imported fuel are the economic cost and the strategic risk. Our goal is to reduce the economic cost to a minimum by buying and using fuel as efficiently as possible. We have tried to do this, not by

Government fiat, but by harnessing a much stronger force: the power of the market.

This policy is expressed in two main areas: pricing, and energy sector structure. By reducing or eliminating Government subsidies for energy products, we have exposed Israeli energy consumers to the realities of the world energy marketplace. Electricity prices, too, have been made to reflect real economic costs: since peak electricity costs more to generate, consumers are now asked to pay more, under a Time-of-Use tariff.

We have also tried to structure the energy sector so as to encourage efficiency. We have introduced a major re-structuring of the petroleum industry, aimed at increasing competition and reducing Government intervention. Israel's oil companies, which previously operated under a partial market-sharing arrangement, will now compete with respect to price and market share.

Israel's refineries will also face competition, since the oil companies will now for the first time be permitted to import refined products. The competition induced by these and other measures will, we believe, lead to greater efficiency in the energy sector.

Energy conservation is another way to reduce the price the economy pays for energy. We encourage conservation by funding projects that demonstrate the advantages of various energy-saving techniques, and by obligating major energy consumers to keep track of how they use energy.

These are some of the major ways in which we try to reduce the economic cost of living on imported energy. To reduce the strategic risk, we are diversifying our energy sources, emphasizing increased coal use.

As recently as 1980, Israel's coal consumption was negligible. Today, *more than half of our electricity comes from coal.* Industry, however, has been slower to take to coal. Still, by the end of the decade, coal will provide 30% of our total energy needs, and 70% of our electricity.

The measures I have described, though important, are overshadowed by one unpleasant fact: no matter how efficiently we use the fuel we import, we are still dependent on our suppliers. Our economy, our efforts at development, and our very future depend on the willingness of others to sell us energy at an affordable price. In this, we are in the same situation as many other nations, especially developing nations. In the past 15 years, many such nations have learned the hard way about how oil prices affect economic development.

Given this reality, it is clear why Israel and other nations have an interest in solar and other renewable energies. For Israel, which is as blessed with sunshine as it is poor in oil, solar energy is a potential alternative to the imported fuel whose cost casts a long shadow over our economy. Affordable solar energy could fulfill the vision of Ben-Gurion, by turning the Negev into an inexhaustible source of power to drive the Israeli economy.

But there is a catch to this vision. Solar power, for us, is still too expensive. Current solar electricity systems can generate power for about fifteen cents a kilowatt-hour. Peak power in Israel costs less than half of this--seven cents per kilowatt-hour.

Does this mean that the vision must be abandoned? Is solar energy, then, a luxury that only affluent nations can afford? We in Israel do not believe so. Solar energy is too important, its potential benefits are too great, to treat it as a luxury. We must hold on to the vision, but our efforts must be grounded in reality.

This means, first of all, introducing solar energy wherever it is affordable and practical. In Israel, we have had great success in doing this with solar water heaters.

Over 70% of Israeli homes now have such heaters. It is estimated that they reduce our national electricity bill by 6.5%. This is enough to make Israelis the world's leading consumers of solar energy, per capita. Here is proof that solar energy, if it can be made affordable, can be introduced on a mass scale.

Beyond this, our policy is to encourage a mix of solar research and development programs, some short-term and some long. One notable long-term program is the three-megawatt solar tower at the Weizmann Institute in Rehovot, part of a project which aims at converting solar energy to a storable and transportable form. It is a project that will put Israel in the forefront of international solar energy efforts, and which will enable us to co-operate with the most advanced countries in the field.

Somewhere between household solar water heaters and advanced solar towers are the systems that will be tested here at the Ben-Gurion Center. They are the fruit of an international effort, in which Israeli firms have played a leading rôle, to develop practical systems for generating electricity from solar power.

In testing and comparing these systems here at Sde Boker, we are tempering vision with reality.

Nor are our efforts limited to the solar electricity systems you have seen here. The solar pond power station at Beit HaAravah, the most advanced of its kind in the world, was connected to the national grid in 1984.

We have also sponsored research in other renewable energy sources, such as wind power and biomass. Wind turbines have been installed at three locations in the North, and surveys are under way to locate sites for more turbines, to help tap Israel's wind energy potential, which is estimated at 1,000 megawatts peak capacity.

Plants that produce steam or biogas from agricultural waste have also been built. To encourage the use of such alternative energy sources, we have set prices for the sale of electricity to the national grid by private producers.

An even more impressive confirmation of Ben-Gurion's vision is provided by the extent to which Israel's solar energy work has become of interest beyond our borders. This is especially true for many developing nations.

Developing countries have special reason to be interested in power generation from solar and other renewable sources. In the Third World, 1.7 billion people have no access to electric power. Those fortunate enough to have electricity must pay much more for it than those in the industrialized world--four to five times more, on average. The effect of this on development is obvious.

For developing nations, small electricity-generating systems based on solar and other renewable sources can be of great importance. In this respect and in others, I believe that Israel can be of real and immediate help to developing countries seeking to improve their energy situation.

Furthermore, I believe that an international fund should be set up to help third-world countries meet the energy needs which are so crucial to their development, and to help them progress towards a brighter future. This fund would be financially supported by the developed nations, and by oil-exporting countries. We in Israel support the concept of such a fund, and I personally am prepared to work actively for its realization.

Solar energy's potential impact on third-world development is another reason why solar energy must be viewed not as a luxury, but as a necessity. It follows that co-operation in solar research is also a necessity. To cooperate on such research not only saves time and money, but fulfills an obligation owed to the hundreds of millions of human beings for whom affordable power is the key to economic development and a better life.

Meetings like the one which we are having today are, of course, indispensable for promoting international cooperation. Next year, Israel will host its second world energy conference; the first was held in 1984. The theme of the conference, which will take place in June, 1988, in Tiberius , will be "International Energy Cooperation".

In solar power and in other areas of energy research, Israel is actively interested in co-operating with others in our region and in the world who can benefit from these energy sources. Such cooperation is based on a true commonality of interests, and as such can play a significant role in fostering peaceful relations between nations. We are actively pursuing the possibility of cooperating with our neighbors in solar energy and related areas.

In conclusion: I have tried to outline Israel's energy situation, and to show how our emphasis on solar and renewable energies was a virtue that grew out of necessity. Moreover, the necessities we have faced will, sooner or later, be confronted by many other nations. As we share in the problems, so we can share in the solutions.

Today we have taken one small step towards bringing the vision of affordable solar power closer to reality. I call on our neighbors, on our friends in the developing countries, and on our colleagues in every nation, to join hands with us in developing this source of power, which can be of such great benefit to so many. Thank you.

KEYNOTE ADDRESS

"Israel's Policy in Energy Research,
Development and Demonstration"

by

DR. NATHAN ARAD

Director General,
Ministry of Energy and Infrastructure

Israel's Policy in Energy Research, Development and Demonstration

Lecture by Dr. Nathan Arad, Director General, Ministry of Energy & Infrastructure at the Second Solar Electricity Symposium, Sde-Boker, February 25, 1987

It gives me a great pleasure to address the Second Solar Electricity Symposium of the Israeli Section of the International Energy Society, sponsored by the Ben-Gurion University of the Negev (the Blaustein International Center for Desert Studies), and the Ministry of Energy and Infrastructure. This is a festive occasion for us, as we have just inaugurated the Ben-Gurion Solar Electricity Technologies Test Center, which marks a major step forward in fulfilling the Energy Ministry's policy goals, aimed at applying modern solar energy technologies to Israel.

Let me review briefly our policy with regard to energy R&D

Energy R&D are means by which the Gov't plans to advance the objectives of our energy sector, using advanced scientific knowhow and technology. Our policy incorporates the frontier of knowledge - with a wide spread from the raw resource - all the way to the end user. In each of its phases, our policy examines and deals with aspects of basic research, importation and transfer of technology, its development and demonstration.

The Gov't R&D policy objectives are derived from the general energy policy objectives, which could be summarized in a concise way.

For one, our objective is to minimize the risks both strategic (i.e. - no supply) and economic (i.e. extreme and unexpected variations in the price of primary energy on the world market), which are derived from Israel being so heavily dependent on imported oil and coal.

Our second objective is to minimize the cost of energy from the national economic point of view.

Our R&D areas are therefore focussed on the following:

First, the promotion of research in those areas which Israel's scientific community possesses a relative advantage over others;

Second, the development of specific technologies aimed at the utilization of indigenous primary energy resources;

Third, improving upon existing available technologies and adapting them for local conditions, and upgrading them to a commercial level;

Fourth, the promotion and maintenance of centers of knowhow, in our institutions of higher learning, state owned companies, and industry;

Fifth, continuous monitoring of world development in these areas, through international cooperation, seminars, reviews and symposia, as this very symposium is an example.

The Ministry of Energy and Infrastructure, as a policy, appropriated at least 85 percent of its R&D budget to applied research and the demonstration of novel technologies that could progress to a commercial level in the short to the medium range, say 10 years.

Gov't support for R&D projects is weighed according to several criteria:

First, the potential of the project, if successful, to contribute to Israeli energy balance, both from strategic and economic considerations;

Second, the degree to which the proposed project contributes to the advancement of science and technology, relative to that already available, and its spin-offs.

Third, the chances of success;

Fourth, time span and development stages needed to advance the technology from the current stage, to the stage of commercial utilization;

Fifth, the required funds needed from the current stage to the stage of commercialization.

The criteria for funding R&D activities by the Gov't is based on the evaluation of the risks involved and on the proximity to commercial utilization.

The Gov't allows up to 100 percent funding to basic research activities and for the needed infrastructure for all R&D activities. The Sde-Boker facility, just inaugurated, is an example where Gov't funded all the needed infrastructure, such as civils, roads, fences, lighting, water, two-way electric connections, control and monitoring center.

National projects, with a potential of a substantial impact on the energy balance, and yet unprovable technology, enjoy up to 80 percent of Gov't funding, up to the demonstration stage. Gov't support of the development of the solar ponds in Beit-Ha'Arava, and the agricultural-waste-biogas-generation projects, are but two examples of exercising this policy.

Funding of up to 50 percent are provided for industrial development, including a pilot project.

Lastly, funding of up to 30 percent is provided to investors willing to invest the remaining 70 percent in projects aimed at demonstrating available technology, yet unknown and tested under real commercial field conditions in Israel.

Let me deviate for a minute from outlining our R&D policy and bring up two related points.

First, aiming at widespreading the commercial utilization of alternate energy projects, the Gov't provides a flat support of 15 percent of the investment needed in such projects, conditioned upon the availability of funds.

Second, starting back in April 1985, Gov't, in cooperation with Israel Electric Corporation, adopted a policy prescribing the conditions under which IEC is required to purchase electric power generated by private producers and the associated tariffs under which such electric power will be purchased by the IEC.

Both the 15 percent support to investors in the commercial utilization of alternate sources of energy, and the power purchase policies, proved to be very supportive to the advancement of our energy policy.

For the next ten years, the main thrust of our policy is aimed at the promotion of R&D activities in the following areas:

Oil Shale direct firing for the production of electricity. The demonstration project just approved and funded, with 50 percent Gov't support, is a co-generation plant with a boiler to produce 50 tons per hour of steam. The plant would supply low pressure process steam, and use a back-pressure turbine to produce approximately five Megawatts (MW) of electricity, to be sold to the electricity grid. The plant is scheduled for commissioning in 1989. By the year 2000 we may have additional two oil-shale fired plants, each producing 120 MW of electricity to the national grid.

We expect that the investment cost in 10 to 20 MW wind farms will be reduced to 600 to 750 dollars per kW installed, producing power at 4.5 cents per kWhr. We forecast that by 1990 wind farms will produce an aggregate of 15 MW, rising to 60 MW by the year 2000.

We expect that the investment cost in solar energy convertors for the production of electricity will be reduced to 1,800 to 2,400 dollars per kW, producing electric power at 6.5 to 9.3 cents per kWhr. This may be just competitive with grid peak power. We forecast the contribution of solar powered stations to reach a level of 5 MW in 1990, and 200 MW in the year 2000.

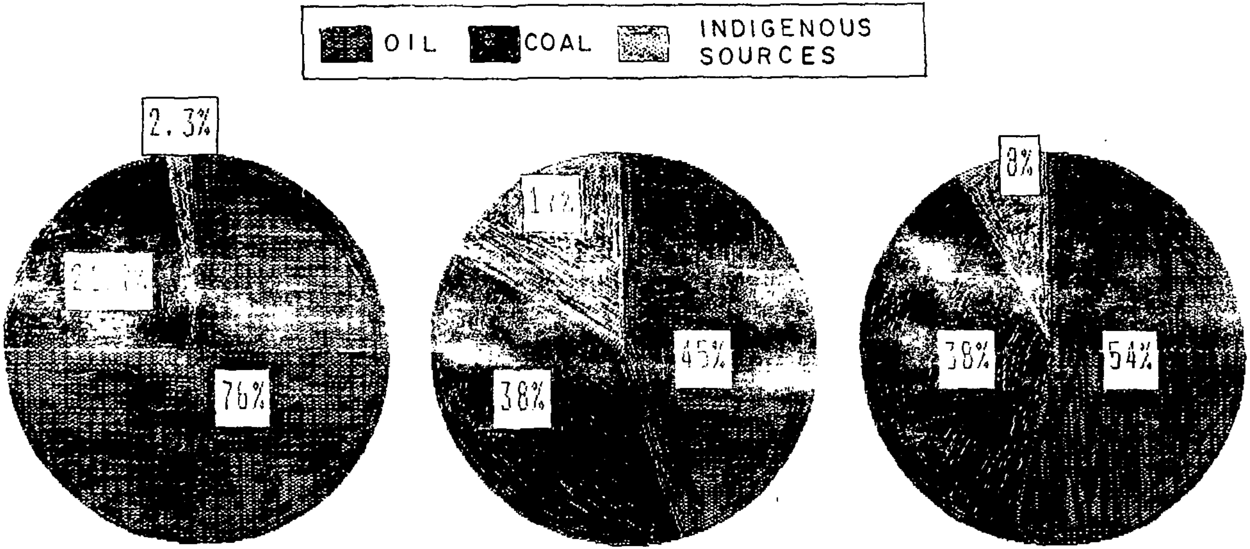
Some additional contribution of small hydro and biomass, both agricultural and city solid waste, may result in a total of 640 MW of power produced from alternate sources in the year 2000, thus providing approximately 9 percent of the electric power demand in that year, replacing 450,000 tons of imported oil equivalent.

Additional and no less important contribution will come from non-electric solar and biomass energy convertors. 1987 contribution of solar energy convertors for domestic water heating and some low pressure industrial use is estimated at 200,000 tons of oil equivalent. We expect this to double by the year 2000. The contribution of biomass projects to non-electric uses, is expected to be in the tens of thousands tons of oil equivalent in the year 2000.

Consistent with the policy just outlined in some detail, the Ministry of Energy and Infrastructure is striving to combine our human resources, professional skills and modest Gov't means in the best possible way to bring about a major impact on our energy balance by reducing our dependence on imported oil and coal. If successful in this policy, and under several assumptions regarding the price of oil and coal on the world market, the contribution of this effort may result in replacing some 900,000 tons of imported oil equivalent, or some 8 percent of our energy, to be provided from indigenous sources by the year 2000.

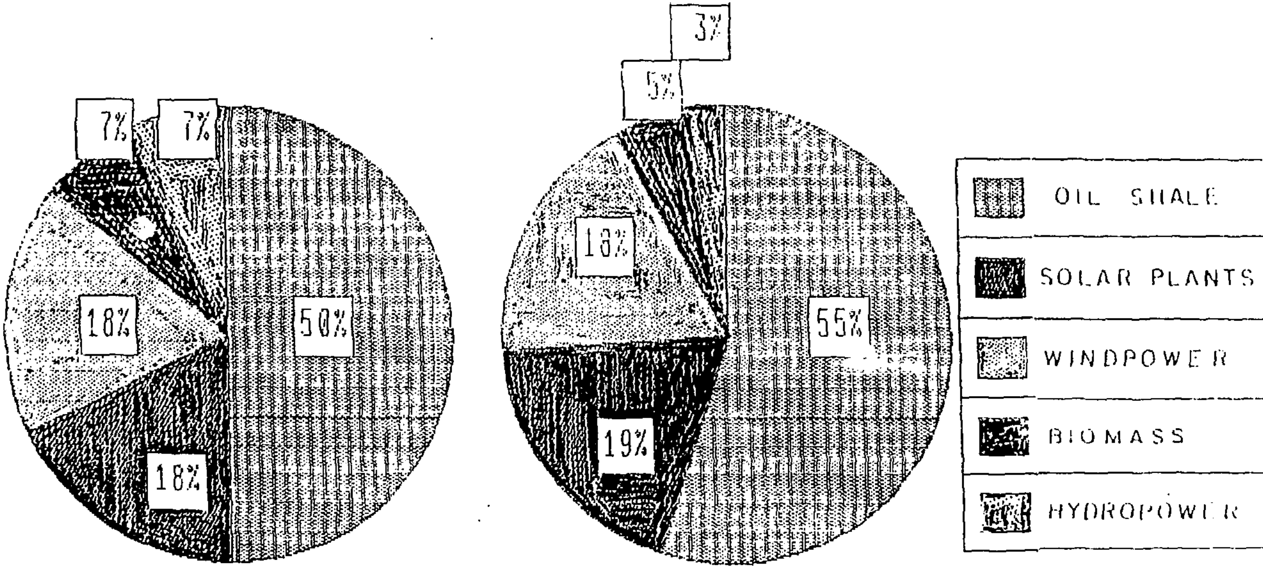
PRIMARY ENERGY SOURCES - 1985 AND 2000

Framework program - 1985



1985	2000	
	Upper limit scenario	Basic scenario
8.7 million TOE	13.6 million TOE	14.4 million TOE

ELECTRICITY PRODUCTION FROM INDIGENOUS SOURCES IN THE YEAR 2000



BASIC SCENARIO
640 MW
2.8 MILLIARD kWh
(10% of total)

UPPER LIMIT SCENARIO
1450 MW
6.6 MILLIARD kWh
(20% of total)

KEYNOTE ADDRESS

"The Ben Gurion Sede Boqer Test Center
for Solar Electricity Generating Technologies:
Goals and Programs"

by

DR. PINHAS GLUECKSTERN

Chief Scientist,
Ministry of Energy and Infrastructure

TEST CENTER RATIONALE

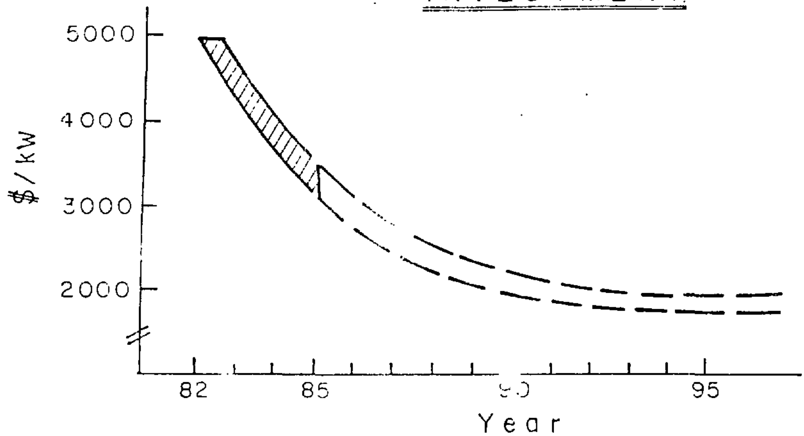
- 200 TO 500 MW OF (ISRAELI) SOLAR ELECTRICITY BY THE YEAR 2000 - ACHIEVABLE-IF FUTURE INSTALLED AND O&M COSTS ARE SIGNIFICANTLY REDUCED AND FUEL PRICE RELATIVELY HIGH.
- SOME SOLAR TECHNOLOGIES ALREADY POSSESS PROMISE TO REACH COMPETITIVENESS WITH CONVENTIONAL SYSTEMS.
- SOLAR TECHNOLOGY IS SITE ORIENTED.
- USING EXPERIENCE GAINED BY OTHERS:
  - SOMETIMES MISLEADING.
  - LACK COMMON REFERENCE.
  - DEFICIENT DATA.
  - QUESTIONABLE OBJECTIVITY AND RELIABILITY.
- PROOFING GROUND AT REAL FIELD CONDITIONS.

TEST CENTER RATIONALE (CONT.)

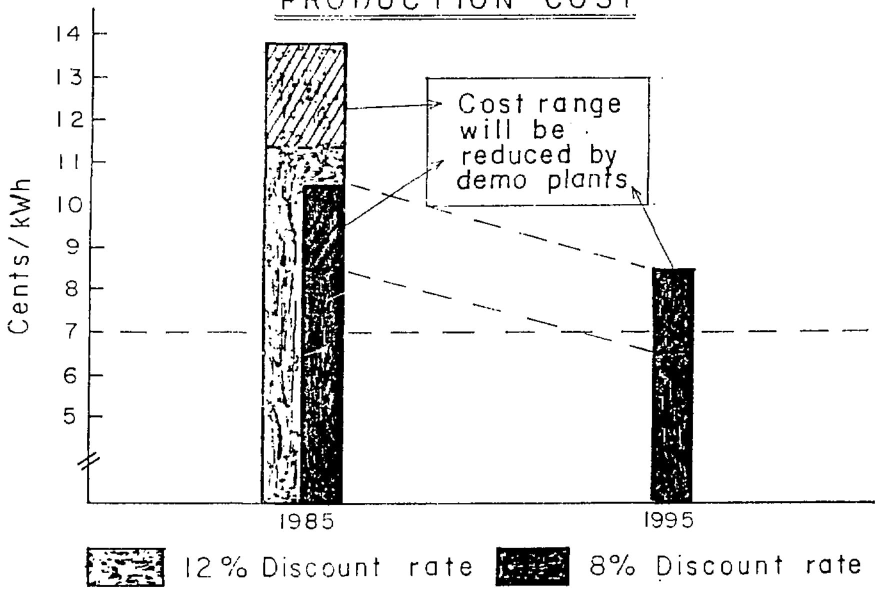
- ASSESSING RELIABLE PERFORMANCE PARAMETERS (EACH BY ITSELF AND COMPARED WITH OTHERS, SIDE BY SIDE).
- GENERATE COMMON INTEREST BETWEEN IMOE AND INTERESTED QUALIFIED ENTREPRENEURS.
- SHARING PROCESSED DATA AND EXPENDITURES.
- DEMO INSTALLATIONS OWNED BY ENTREPRENEURS-PERFORMANCE VERIFIED OVER LIMITED PERIOD.
- CONCENTRATE EFFORTS ON THOSE TECHNOLOGIES TECHNICALLY SOUND WITH PROSPECT TO ACHIEVE COMMERCIAL COMPETITIVENESS EVENTUALLY.
- TEST CENTER TO SERVE FOR MANY YEARS TO TEST - IMPROVE TECHNOLOGIES (PERFORMANCE, O&M COSTS).

ELECTRIC POWER PRODUCTION BY SOLAR PLANTS

INVESTMENT



PRODUCTION COST



TEST CENTER OBJECTIVES

- ASSESS TECHNO-ECONOMICAL VIABILITY OF DEMO TECHNOLOGIES.
- ENCOURAGE QUALIFIED PARTICIPANTS (INFRASTRUCTURE, O&M SERVICES, DATA PROCESSING-PLUS LIMITED GRANT).
- SHORTEN TIME AND REDUCE EXPENDITURES-TO GAIN RELIABLE DATA FOR IMPROVEMENT (OR OTHERWISE).
- ACHIEVE MAX. FLEXIBILITY TO EXCHANGE COMPONENTS.
- GENERATE GOOD ATMOSPHERE AND ESTABLISH MEANS TO ASSIST PARTICIPANTS IN PURSUING THEIR GOALS.
- CHOOSE THE RIGHT POWER RATING - LARGE ENOUGH AT REASONABLE COST TO BOTH PARTIES.
- GENERATE COOPERATION AND SHARING OF DATA AMONG PARTIES - PUBLISH RESULTS (IMOE).

TEST CENTER OBJECTIVES (CONT.)

- ESTABLISH A RELIABLE DATA LOGGING AND PROCESSING SYSTEM - TO MONITOR DEMO INSTALLATIONS PERFORMANCE.
- ENCOURAGE LOCAL INDUSTRIES TO PARTICIPATE - COLLABORATING WITH LOCAL AND/OR FOREIGN KNOWHOW.
- INCREASE COOPERATION WITH DEVELOPED AND DEVELOPING COUNTRIES - KNOWHOW AND PROJECTS.
- CONTRIBUTE TO ISRAEL'S BALANCE OF PAYMENTS.
- EXPORT.

MAJOR SITE FEATURES

- 5 ACRES AVAILABLE (INITIAL PHASE) FENCED AND SECURED, INCL. LIGHTING POSTS.
- NORTHERN PART: GENERAL SERVICES.
- EASTERN PART: SOLAR THERMAL.
- W. .TERN PART. PHOTOVC.TAIC.
- UNDERGROU.D PIPING, POWER CABLES, MEASUREMENT (MONITORING) WIRES FOR DATA TRANSMISSION TO CONTROL ROOM - TO ACCOMODATE ANY DEMO FACILITY.
- FULLY EQUIPPED, ON-LINE, METEOROLOGICAL STATION (INSOLATION, WIND, TEMP., RELATIVE HUMIDITY, ETC).
- WATER AND ELECTRICITY INTERCONNECTIONS WITH THE REGIONAL NETWORKS.

MAJOR SITE FEATURES (CONT.)

- WATER CONDITIONING.
- ELECTRICAL MAIN SWITCHBOARD (TWO-WAYS).
- WATER AND FUEL TANKS.
- BACK-UP DIESEL GENERATOR.
- ACCESS FROM THE SDE BOKER CAMPUS.
- CONTROL BLDG. WITH: CONTROL RM., INSTRUMENT RM., INSTRUMENT LAB., CONFERENCE RM., KITCHENETTE, LAVATORY, GUARD RM. - MOSTLY AIR-CONDITIONED.
- COMMUNICATIONS: TELEPHONES, COMM. MODEMS.
- RE-USE OF COOLING TOWER REJECT FLUIDS BY APPLYING APPROPRIATE DESALTING TECHNOLOGIES.

CRITERIA FOR PARTICIPATION

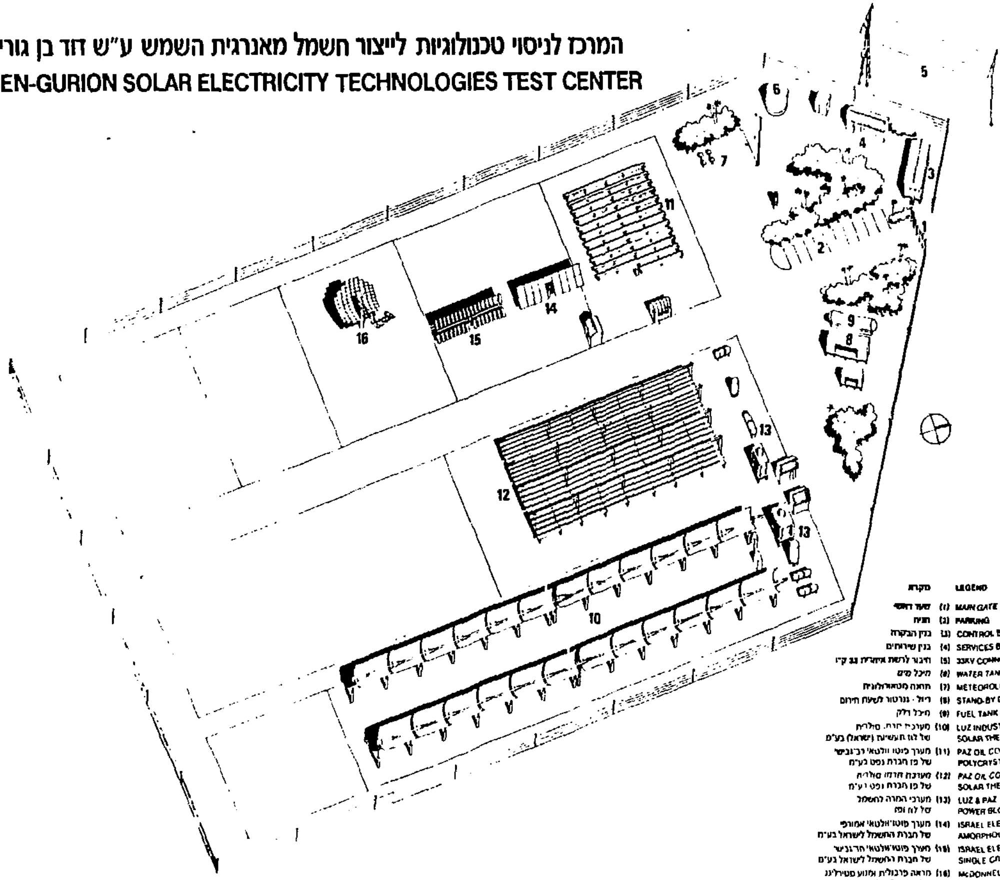
- ANY LOCAL AND FOREIGN PARTY POSSESSING APPLICABLE TECHNOLOGY.
- TECHNOLOGY SHOULD BE PAST THE APPLIED RESEARCH STAGE.
- EACH DEMO FACILITY WILL BE TEST MONITORED FOR 2 YEARS PERIOD.
- AVAILABLE FEATURES (BY IMOE)
    - COMPLETE INFRASTRUCTURE.
    - O&M SERVICES.
    - COMPUTERIZED DATA LOGGING AND PROCESSING.
    - LIMITED FINANCIAL SUPPORT (GRANT).
- EACH PARTICIPANT SHOULD POSSESS TECHNICAL CAPABILITIES TO UNDERTAKE IMPLEMENTATION, PROVIDE GUIDANCE, BACKUP AND ADVANCED MAINTENANCE.

CRITERIA FOR PARTICIPATION (CONT.)

- FOREIGN PARTIES SHOULD COLLABORATE WITH A LOCAL COMPANY.
- PERFORMANCE DATA WILL BE CERTIFIED AND DOCUMENTED (BY IMOE).
- EACH PARTICIPANT MAY RETRIEVE ANY DATA FROM ITS DEMO FACILITY BY COMMUNICATION MODEM.
- IMOE WILL CARRY ALL RUNNING COSTS TO BE (PARTIALLY) COMPENSATED FROM SALES OF GENERATED ELECTRICITY TO IEC.

המרכז לניסוי טכנולוגיות לייצור חשמל מאנרגית השמש ע"ש דוד בן גוריון

BEN-GURION SOLAR ELECTRICITY TECHNOLOGIES TEST CENTER



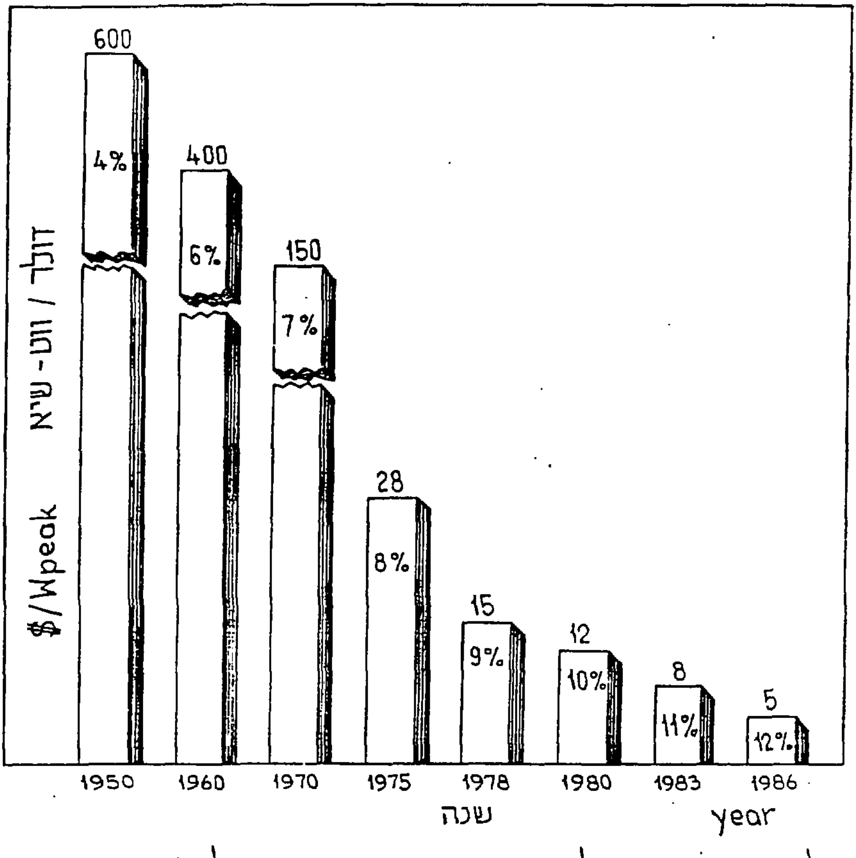
מקרא		LEGEND
שער ראשי	(1)	MAIN GATE
חניה	(2)	PARKING
בנין הבקרה	(3)	CONTROL BUILDING
בנין שירותים	(4)	SERVICES BUILDING
חיבור לרשת ארצית 33 ק"ו	(5)	33KV CONNECTION TO REGIONAL NETWORK
מיכל מים	(6)	WATER TANK
תחנה מטאורולוגית	(7)	METEOROLOGICAL STATION
דיזל - גנרטור לשעת חירום	(8)	STAND-BY DIESEL-GENERATOR
מיכל דלק	(9)	FUEL TANK
מערכת תרמו-סולרית של לוז תעשיות (ישראל) בע"מ	(10)	LUZ INDUSTRIES (ISRAEL) LTD. SOLAR THERMAL SYSTEM
מערך פוטו וולטאי רב-גבישי של פז חברת נפט בע"מ	(11)	PAZ OIL COMPANY LTD POLYCRYSTALLINE PHOTOVOLTAIC ARRAY
מערכת תרמו סולרית של פז חברת נפט בע"מ	(12)	PAZ OIL COMPANY LTD SOLAR THERMAL SYSTEM
מערכי המרה לחשמל של לוז ופז	(13)	LUZ & PAZ POWER BLOCKS
מערך פוטו-וולטאי אמורפי של חברת החשמל לישראל בע"מ	(14)	ISRAEL ELECTRIC CORP. LTD AMORPHOUS PHOTOVOLTAIC ARRAY
מערך פוטו-וולטאי חד-גבישי של חברת החשמל לישראל בע"מ	(15)	ISRAEL ELECTRIC CORP. LTD SINGLE CRYSTAL PHOTOVOLTAIC ARRAY
מראה פרבולית ומנוע סטירלינג של מקדונל דגלס מערכות אנרגיה בע"מ	(16)	McDONNEL DOUGLAS ENERGY SYSTEMS INC PARABOLIC DISH & STIRLING ENGINE

INVITED PRESENTATION

"Photovoltaics Research at
The Israel Electric Corporation"

by

DR. DAN WEINER
The Israel Electric Corporation



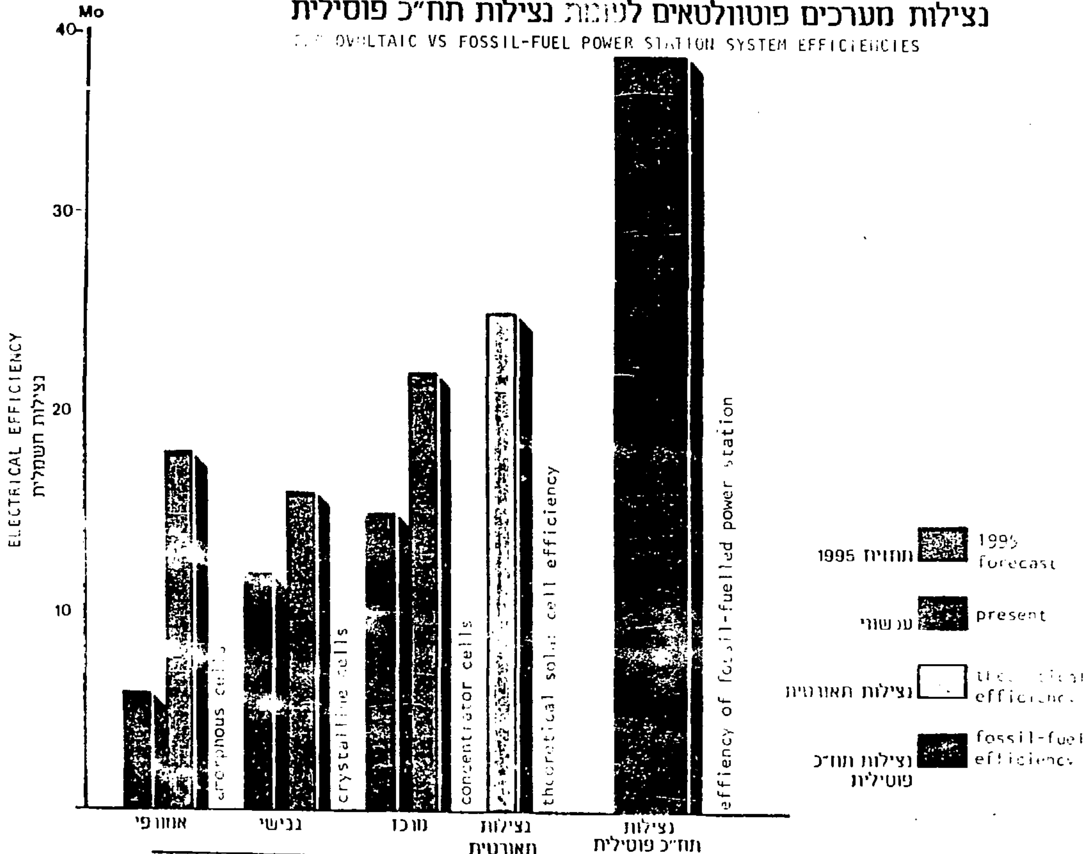
עלות בסיסית של תאים גבישים ב - דולר / ווט - שיא

לאורך השנים 1986 - 1950

PASIC COST OF CRYSTALLINE CELLS ($/Wpk) DURING THE PERIOD 1950 - 1986

נצילות מערכים פוטוולטאים לעומת נצילות תח"כ פוסילית

PHOTOVOLTAIC VS FOSSIL-FUEL POWER STATION SYSTEM EFFICIENCIES

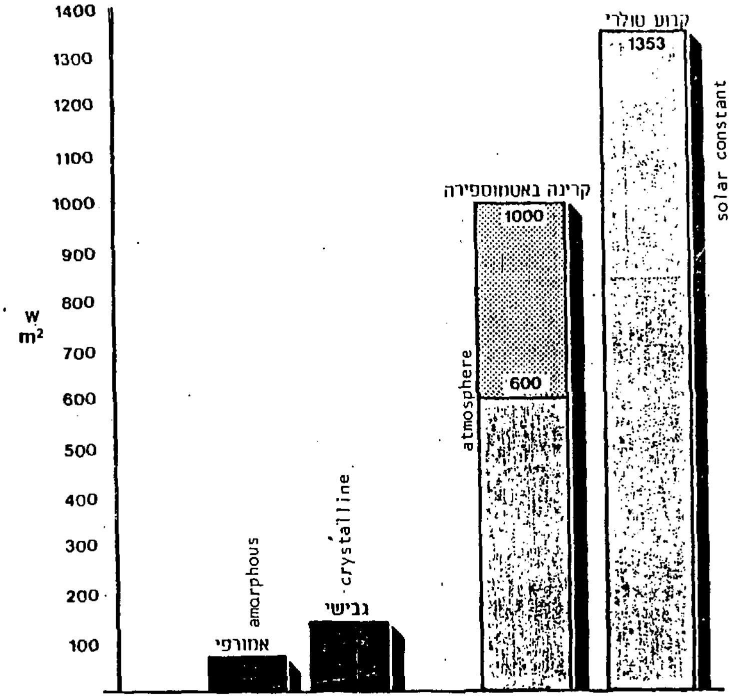


מערכת "התקע המצדיע"

חברת החשמל לישראל

POWER DELIVERED BY PHOTOVOLTAIC CELLS RELATIVE TO AVAILABLE RADIATION

הספק מופק של תאים פוטוולטאיים לעומת רמת הקרינה



מערכת "התקע המצדיע"

חברת החשמל לישראל

Sede Boqer

ADVANTAGES OF 2-AXIS TRACKING

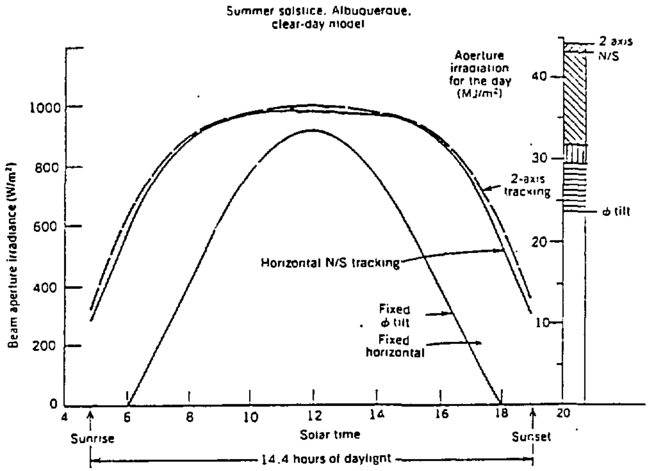


Figure 4.24 Aperture irradiance for different fixed and tracking aperture configurations for Albuquerque, NM on June 22.

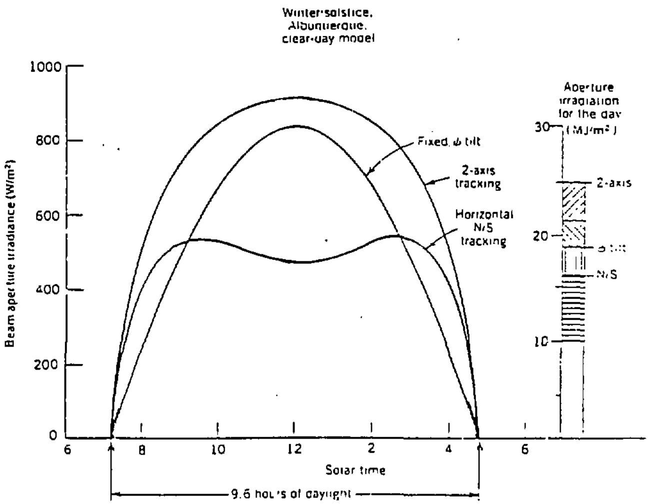
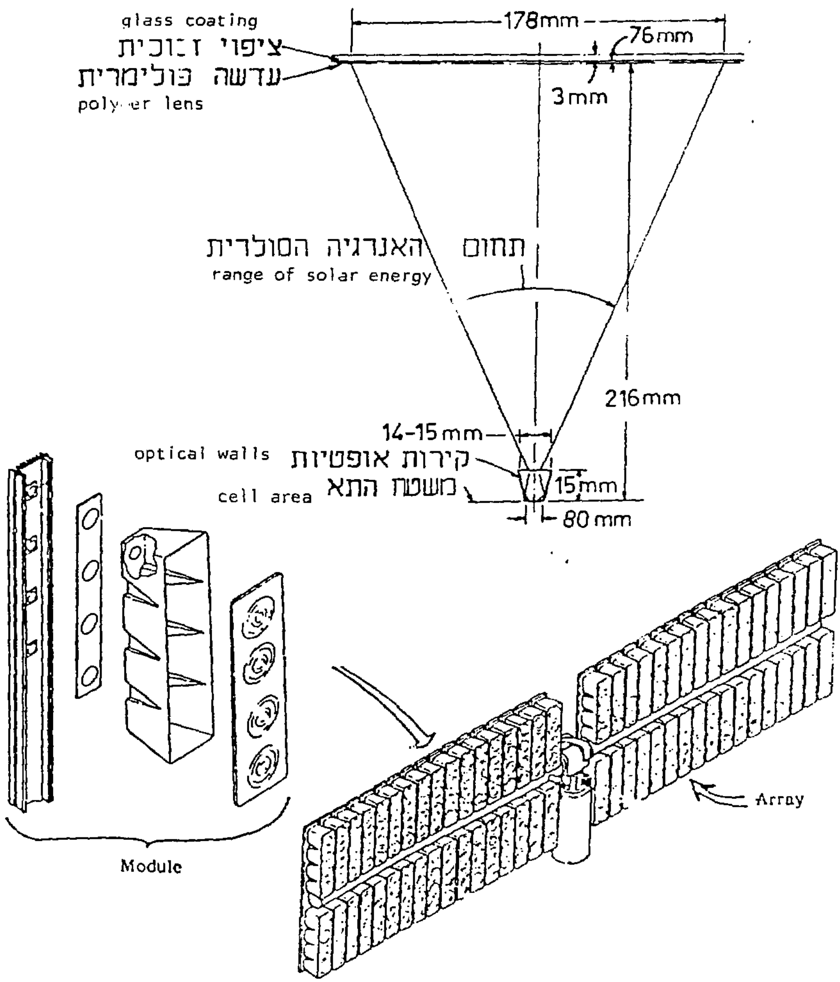


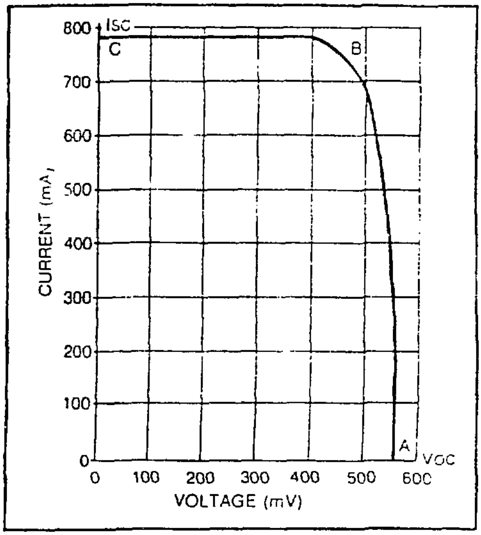
Figure 4.25 Aperture irradiance for different fixed and tracking aperture configurations for Albuquerque, NM on December 22.

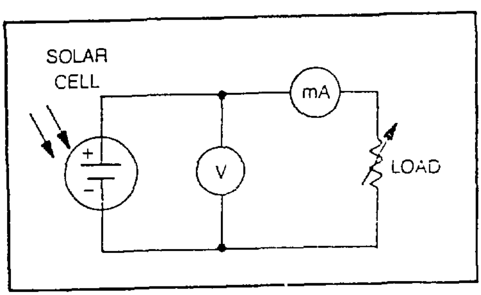
After: W.B. Stine & R.W. Harrigan, Solar Energy Fundamentals and Design (J. Wiley $ Sons, New York, 1985).

IEC's CONCENTRATOR SYSTEM



A TYPICAL I-V CURVE AND ITS MEASUREMENT

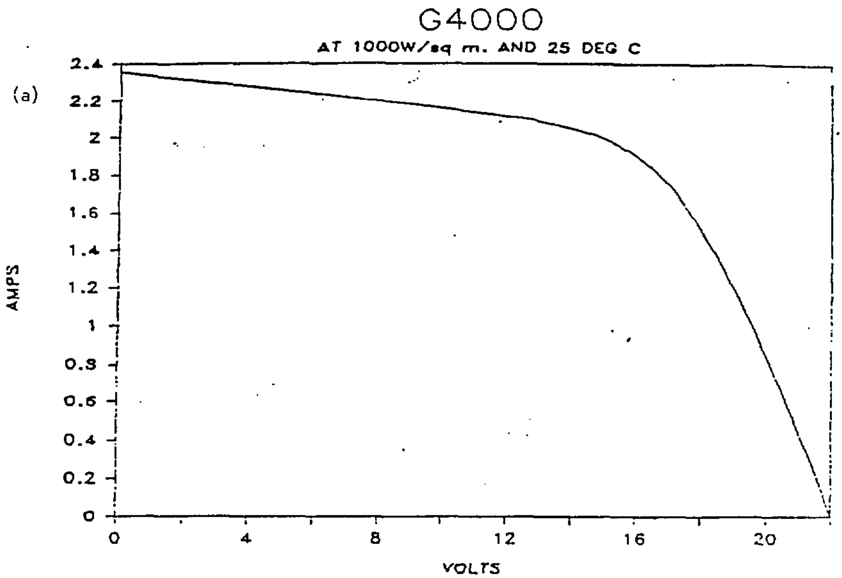




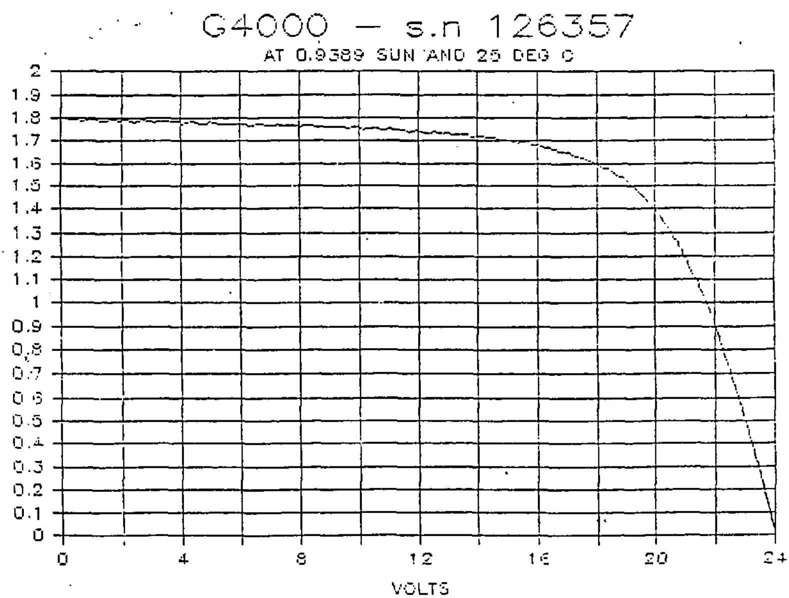
G4000 IV Curve

I-V CURVES FOR AMORPHOUS MODULE AS (a) ADVERTISED, (b) MEASURED

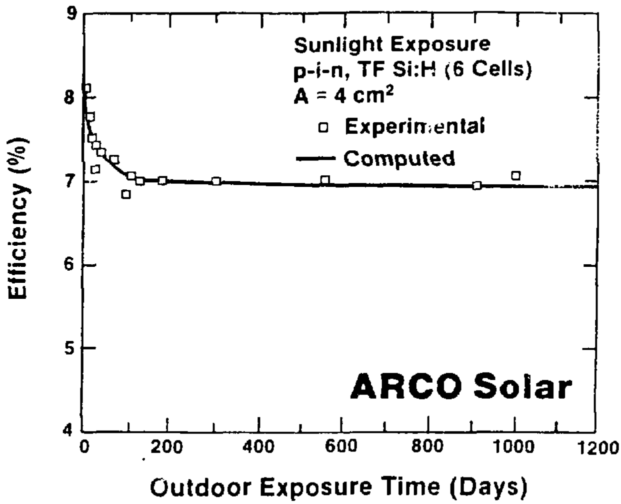
(a)



(b)



OBSERVED DEGRADATION OF AMORPHOUS PHOTOVOLTAIC CELLS WITH TIME



Time dependence of cell efficiency under normal sunlight. (From H.S. Ullal et al., 17th IEEE PV Spec. Conf., 1984, and D. Willett et al., MRS Conf., April 1986.)

INVITED PRESENTATION

"Luz Technology:
Status and Future Development"

by

DR. YEHUDA CHARATS

Luz International Ltd

L U Z T E C H N O L O G Y

STATUS AND FUTURE DEVELOPMENT

(Prepared for the Technical Symposium of February 25th 1987)

INTRODUCING THE SOLAR AGE

Man has long been a passive benefactor of the sun's warmth and energy, but serious attempts to harness its energy have consistently failed to achieve commercial viability. As the need for a clean, inexpensive energy source has become more pressing, significant technological breakthroughs were necessary in order to make solar energy a practical alternative to conventional power.

In a few years of research, design, and technical application, Luz International Ltd. has successfully introduced the "solar age" - an age when clean, renewable energy from the sun has become a cost-efficient source of electric power.

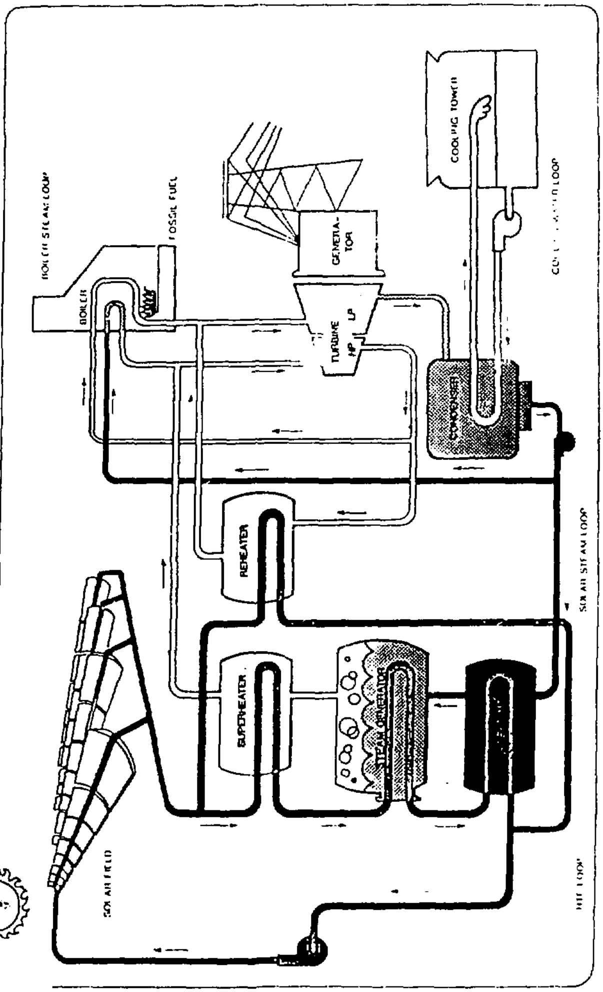
Today, Luz is the world's most experienced and successful producer of solar thermal power stations, with 100 Megawatts of solar power already on the power grid of the Southern California Edison utility company, and another 480 Megawatts to be added by 1992. Producing a significant percentage of all of the solar-generated power throughout the world, Luz has made solar energy competitive with that of conventional fossil fuels, a welcome development for a world which must face the environmental effects of power production and the prospect of dwindling fossil fuel resources.

EXPERIENCED SOLAR POWER PRODUCER

Four operating Solar Electric Generating Systems (SEGS) in Southern California currently produce electricity for a total of 50,000 homes at peak hours of electricity demand. The first Luz SEGS system, SEGS I, was installed in Daggett, California within thirteen months, under a power-purchase agreement with Southern California Edison, and began producing 13. 8 MW in December 1984. One year later, in December 1985, SEGS II went on line under a similar contract, supplying 30 MW of electricity to the local power grid. At the end of 1986, two more 30 MW systems, SEGS III and SEGS IV, went on line in Kramer Junction, California, as work began on the installation of the next two 30 MW systems, SEGS V and SEGS VI, due to become operational in late 1987.

Luz has signed a total of nineteen power purchase contracts with Southern California Edison, and the remaining fifteen 30 MW power plants will be built in the Mojave Desert area by 1991. All Luz systems are privately owned.

THE LUZ SYSTEM - SEGS VI



LUZ SOLAR TECHNOLOGY

The Luz SEGS systems are designed for efficient collection of the sun's direct radiation through a field of distributed parabolic trough collectors (the solar field), and transformation of the collected energy into high temperature saturated steam through a steam generator. The steam is then superheated and used to operate conventional power generation equipment (the power block). The system is designed to operate most of the time in a solar mode. However, for selected hours during inclement weather and during the winter months, natural gas is burned in a supplementary boiler to produce the steam that generates electricity

The solar field. The solar field, the system's most unique element, is based on modular solar collector assemblies (SCA's), interconnected through a system of insolated pipes. These assemblies, comprised of parabolic trough reflectors, concentrate the sun's rays on a unique heat collection element positioned at the focal point of each reflector. The heat collection element is a metal pipe, enclosed in a vacuum-sealed glass pipe, through which flows a heat transfer fluid. The fluid, which heats up to a temperature of 350-400 degrees centigrade, circulates through the solar field and is pumped through a heat exchanger to produce steam. The steam is then superheated and used to drive a turbine generator, producing electricity.

Electronic tracking and control. The reflectors within each SCA are designed to independently track the sunlight on a single axis through a sophisticated three-stage electronic control system. This includes a positioning system, which tracks the sun throughout the day and enables the SCA to be moved as it follows the sun; the LOC, or local microprocessor, which acts together with the positioning system to track the sun and control the SCA's position; and the field supervisor, the central computer which coordinates the operations of the entire system.

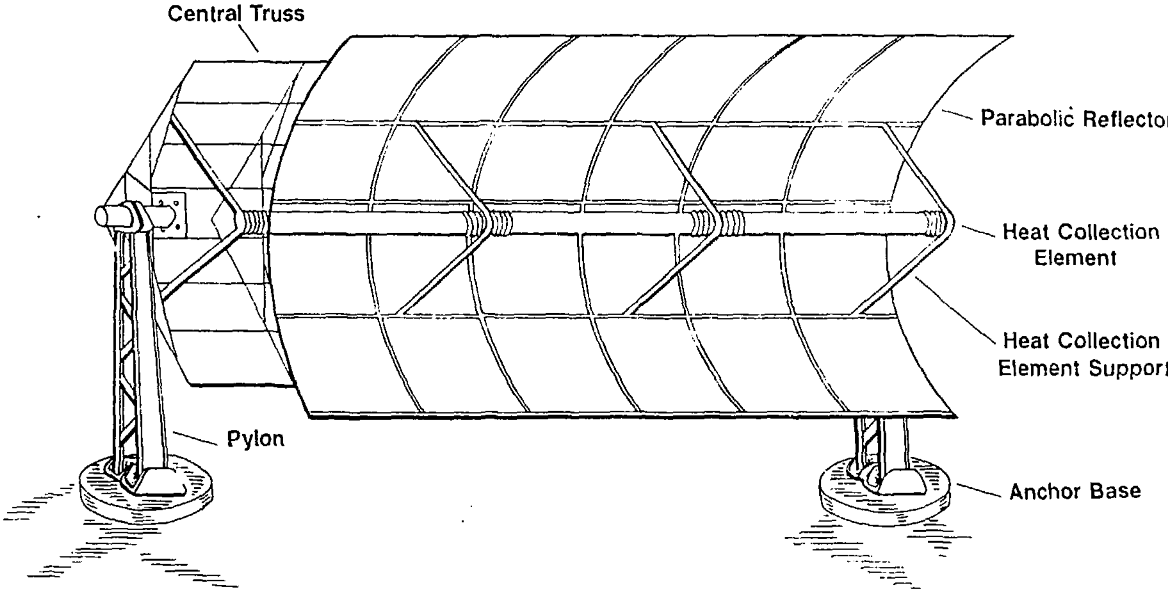
FUTURE DEVELOPMENT

Currently Luz is using its LS-2 design - the 2nd collector generation. However, the development of the LS-3 generation is now in its advanced stage, and it will be implemented in SEGS VI and VII, both of which will become operational at the end of 1987.

Luz will introduce major improvements for these two projects. The first will be the use of a new structural design and a higher working temperature. The second will be the introduction of a reheating steam turbine which can use the higher temperature to produce electricity much more efficiently.

TYPICAL SECTION OF AN LS-3

SOLAR COLLECTOR ASSEMBLY



LUZ INTERNATIONAL LTD.

LS-3

For the third time in over three years, Luz engineers have developed a new generation of Solar Collector Assembly (SCA), which increases system efficiency and reduces system costs by some 20%. Luz System 3 (LS-3) will be the cornerstone for future solar fields.

The LS-3 collector is based on a new metal support system. This new system, called the Central Truss, will replace the current torque-tube support, resulting in substantial savings in metal parts. The truss design will also allow a significant increase in the distance between pylons, and this will result in further cost savings on the foundations.

The LS-3 parabola is larger than its predecessor, LS-2, with an aperture of 5.77 meters. The larger mirrors help raise the working temperature of the system from 350 degrees centigrade to 390 degrees. The more efficient LS-3 system needs a smaller number of SCA's, which in turn require proportionally fewer components such as flexible hoses, drive systems, local computers, communication cables, and sun sensors.

Past Experience. The new SCA represents an engineering design based on the results of extensive experience in the operation of solar power stations, as well as a series of long-term experiments on parabolic strength and rigidity. The large glass parabolas and their metallic supports are required to be able to withstand winds of up to 67 km/hr (including irregular wind gusts) while retaining their geometric structure and efficiency. Any wind velocity above that speed will signal the parabolas to invert into a "stow" position.

*Sputtering

The operation of power plants at higher efficiency levels necessitates an increase in working temperatures. Until recently, temperatures were limited due to use of the electroplated selective coating of the heat collection elements, which remains stable only up to certain temperatures. To overcome this limitation, Luz engineers developed a new type of selective coating, which will be produced using a high-vacuum sputtering technique. The sputtered coating, which will be introduced beginning in SEGS VI, will not only remain stable at higher temperatures, but will also improve optical characteristics. To produce the coating, Luz has installed a special, custom-designed sputtering machine - one of the largest and most complex sputtering devices ever built.

*Reheat Turbine

The higher outlet temperatures of the heat transfer fluid, made possible by the introduction of LS-3 SCA's will enable the solar thermal cycle to generate steam at much higher pressures (100 bar or 1450 psia, compared with 43 bar or 630 psia for SEGS II - IV). When operated in combination with a reheat turbine, the overall thermal-to-electric conversion efficiency will be improved by 23% compared with previous Luz power plants.

Comparison of Three Generations of Luz Solar Collector Assemblies

	LS-1	LS-2	LS-3
Aperture	2.5m	5 m.	5.77 m
SCA length	50.4 m.	49.3 m.	99 m.
Distance Between pylons	6.3 m.	8 m.	12 m.
Reflecting surface	128 sq.m.	235 sq.m.	546.5 sq.m.
Fluid Temperature	307 c.	350 c.	390 c.

INTERNATIONAL LTD

THE LUZ SYSTEMS - TECHNICAL ADVANCES

	SEGS I	SEGS III-V	FUTURE: SEGS X
COLLECTOR TYPE	LS-1	LS-2	LS-3
THERMAL FLUID OUTLET TEMPERAT.	307° C	350°C	393°C
SIZE OF PLANT IN MW	13.8	30	80
ANNUAL AVERAGE EFFICIENCY OF CONV. FROM SOLAR ENERGY TO ELECTRICITY	11%	11%	14%
PEAK OVERALL EFFICIENCY SOLAR TO ELECTRICITY	20%	20%	25%

LUZ INDUSTRIES ISRAEL

LUZ SOLAR ELECTRIC GENERATING SYSTEMS

	EXISTING SYSTEMS		FUTURE SYSTEMS	
	SEGS I	SEGS III	SEGS VIII	SEGS X
MW CAPACITY	13.8	30	30	80
REFLECTING SURFACE, SQUARE METERS	71,000	204,000	180,000	400,000
TOTAL MW HRS PER YEAR	30,000	85,000	90,000	250,000
PROJECT PRICE ($ MILLION)	62	101	75	180
PRICE PER KW INSTALLED	$4500	$ 3400	$ 2500	$ 2250
PRICE OF ENERGY OUTPUT ¢/KWH	15	15	8	8

The new turbine employs a sophisticated reheat cycle with multiple extractions to achieve very high operating efficiencies. Hot fluid fr[illegible] the solar field is used to generate steam at 100 bar, and superheat it to 700 degrees Farenheit. The steam is then supplied to the high pressure turbine inlet. After passing through the high pressure stage, the steam exits the turbine, is reheated again to 700 degrees by an additional solar fluid hea[illegible] exchanger, and is supplied to the low pressure turbine inlet, where a maximum of steam is extracted before bein[illegible] passed to the condensor. At various stages in the turbine steam ex[illegible]ction points provide energy for [illegible]edwa[illegible]r heating [illegible] increase [illegible] overa[illegible] cycle efficien[illegible]

The hi[illegible] solar [illegible] operat[illegible] temperatures [illegible]bined with the new t[illegible]ine will yield a the[illegible]o-elec[illegible] conversion efficiency of 37.5% at fu[illegible] load compared with 30 [illegible]5% for SEGs III - VI. This high efficiency rate will be achieved using [illegible]lar energy alone. The SE[illegible] VI design, lik[illegible] that of previous [illegible]ants, include[illegible] a gas-fir[illegible] parallel bo[illegible]r, to generate [illegible] at t[illegible]e same pressures, supp[illegible]ting the solar field [illegible]re necessary and providing on-peak capacity duri[illegible] wi[illegible]er [illegible]ning h[illegible]rs.

SUMMARY

Luz expects to achieve several goals with the LS-3 desig[illegible] Fir[illegible] is the pea[illegible] efficiency of the system, solar to electricity, which will be in the range [illegible] 25%. The installation cost is anticipated to be approximately $ 2,350 (depending on site location), and the energy cost less than 8 cents per Kwh. With the achievement [illegible] these goals, Luz technology will be competitive with more conventional ene[illegible] sources, without any subsidiaries, tax credit, etc.

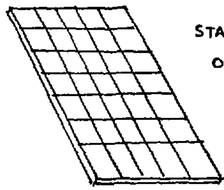
INVITED PRESENTATION

"The Mirror-Assisted
Photovoltaic System at Sede Boqer"

by

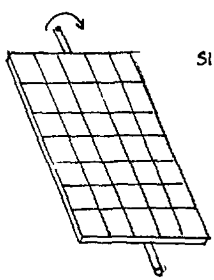
MR. SHAUL ADEL
The Paz Oil Company Ltd

COMPARISON OF COST AND ANUAL POWER OUTPUT OF VARIOUS PV INSTALLATION ALTERNATIVES



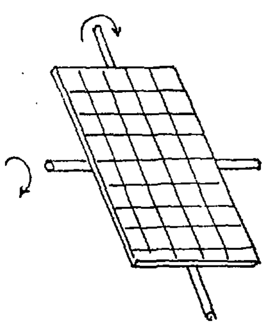
STATIC PV PANELS ON FIXED METAL FRAMES

COST	ANUAL OUTPUT KWH
100%	1,00



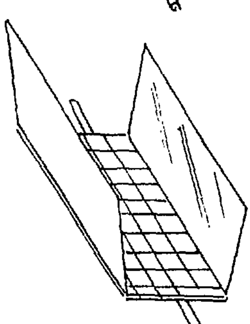
SINGLE AXIS TRACKING P.V PANELS. - ON SOLAR TRACKING HARDWARE

COST	OUTPUT
115 %	1,25



DUAL AXIS TRACKING P.V. PANELS

COST	OUTPUT
1.25%	1,39



SINGLE AXIS TRACKING AND LOW RATIO CONCENTRATING P.V. PANELS

COST	OUTPUT
130%	1,90

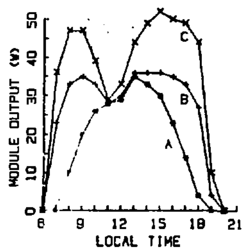


FIGURE 3(a): Hourly measurements of power output, Nov. 4, 1983.

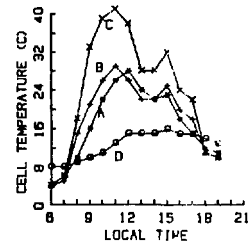


FIGURE 3(b): Hourly measurements of cell temperature, Nov. 4, 1983.

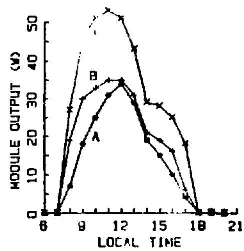


FIGURE 3(c): Hourly measurements of power output, June 8 1984.

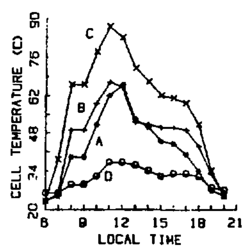


FIGURE 3(d): Hourly measurements of cell temperature, June 8, 1984.

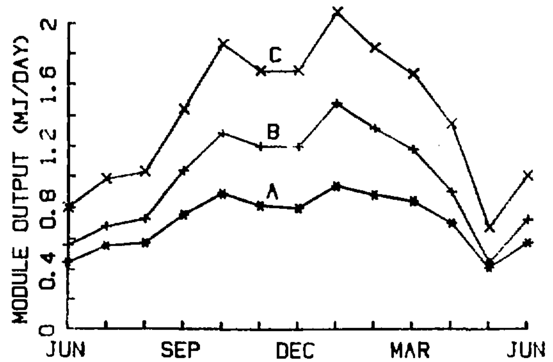
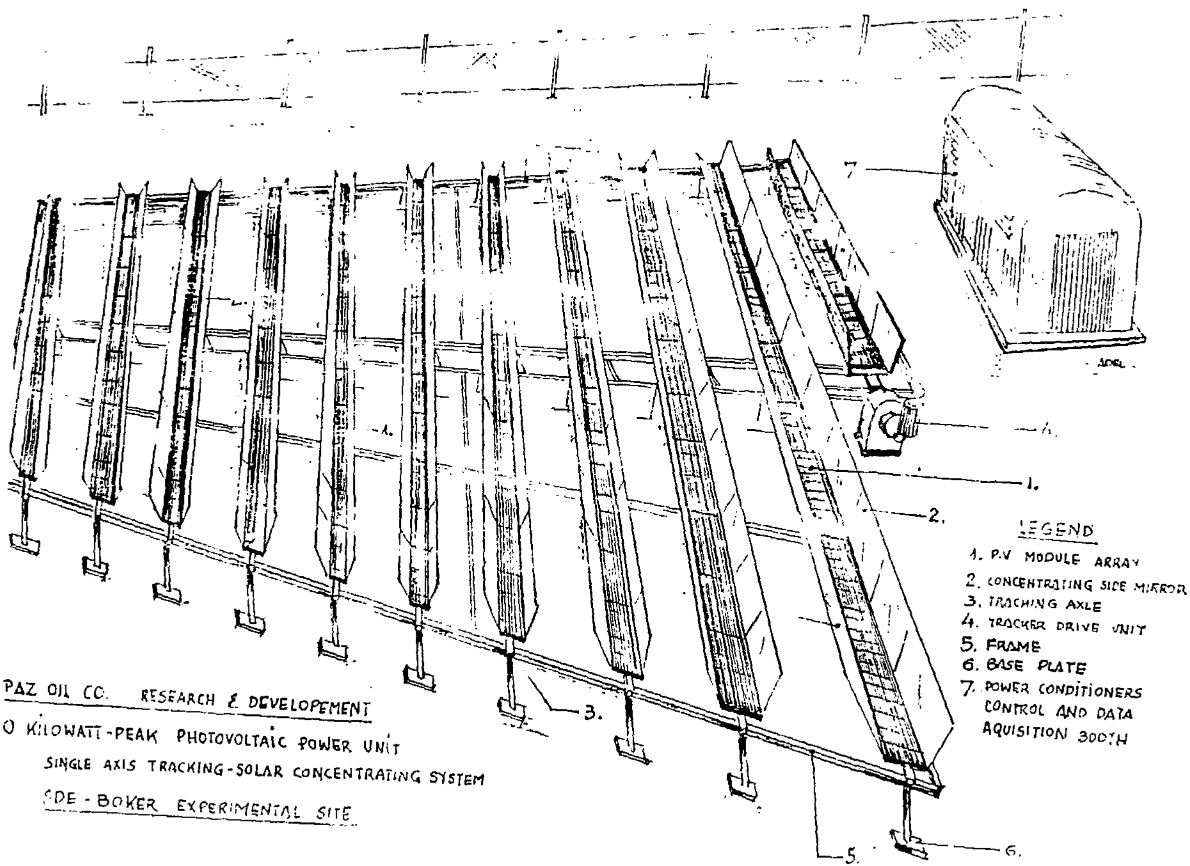


FIGURE 2: Monthly average daily performance; A: stationary flat plate, B: tracking flat plate, C: tracking 2X concentrator.

TABLE 2:
Summary of Performance Results

Configuration	Energy Output (MJ/yr)
A – fixed flat plate	[illegible]
B – tracking flat plate	370
C – 2X concentrator	528

Figures taken from: "Seasonal Performance of Tracking and Reflector Augmented Photovoltaic Modules" by R.W. Stacey and P.G. McCormick, SunWorld 10 (1986) 53

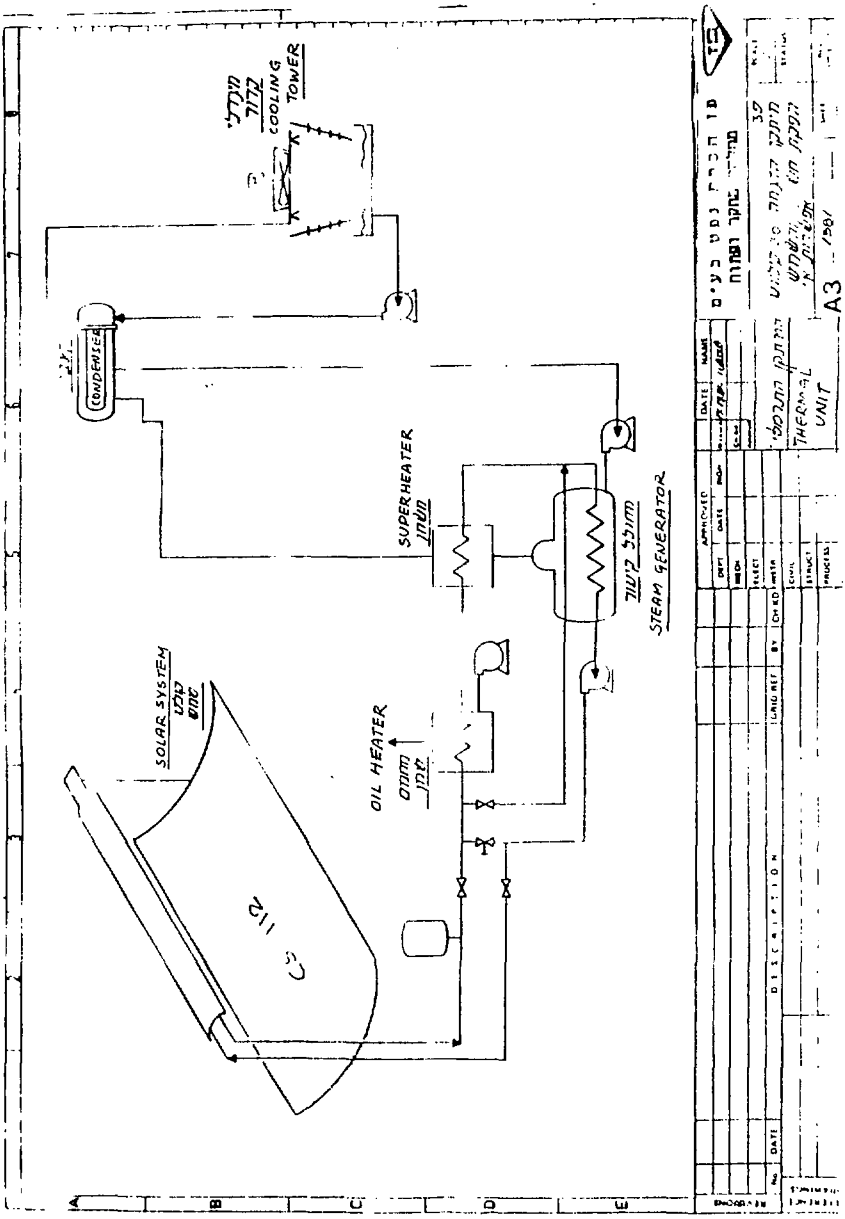


PAZ OIL CO. RESEARCH & DEVELOPEMENT

10 KILOWATT-PEAK PHOTOVOLTAIC POWER UNIT

SINGLE AXIS TRACKING-SOLAR CONCENTRATING SYSTEM

SDE - BOKER EXPERIMENTAL SITE


COOLING TOWER
CONDENSER
SUPERHEATER
STEAM GENERATOR
SOLAR SYSTEM
OIL HEATER
THERMAL UNIT
A3
1981

INVITED PRESENTATION

"Computerized Data Acquisition & Control System:
Design and Selection Procedure"

by

DR. MOSHE HIRSCH
Energy & Control Systems Engineering

PAPER01

Computerized Data Acquisation & Control System - Design and Selection Procedure

by:

Dr. Moshe Hirsch
Energy and Control Systems Engineering - Moshav Zafaria 60932
(Consultant for the Israeli Ministry of Energy and Infrastructure)

The design and selection procedure included the following stages:

1. Basic Configuration

The following basic system configuration was defined:

(1) The system will be able to collect, to store and to do simple and complicated analysis.

(2) The system will be flexible enough to enable connection of the existing solar plants and plants to be installed in the future.

(3) The system will be able to control (in the future) selected equipment.

(4) The system will display data and performance of the plants in text, numbers and color graphics.

(5) The system will put out reports including text numbers, tables and graphics (black & white or in color).

(6) The system will communicate with external users through an external computerized communication network.

A simplified diagram of the overall system frame requirements is given in Figure No. 1.

2. General Requirements:

The requirements relate to the following subjects (see Figure No. 2):

(1) Physical Measured Variables

(2) Accuracy

(3) Designated & Central Data Acquisition

(4) Control

(5) Synoptic Maps; Spreadsheets; Data-Base; Graphics; Texts; Historical Trending, etc.

(6) Flexible Interactive Operation & Screen Editing.

(7) Report Generation

(8) Communication

(9) Reliability

(10) Cost effective system and sub-system selection.

Part of the above-mentioned requirements are described in detail below:

3. Measured Physical Variables

Physical variables were defined for measurement in order to analize the performance of the following aspects of the solar plants:

(a) Solar Photovoltaic Plants

DC power, DC currents, DC voltages, AC power, AC currents, AC voltages, power factor, collectors temperature, collector angular position, plane of array radiation.

(b) Thermal Solar Power Plants

Pressures, flow, temperatures, radiation, collectors angular position, AC power, AC currents, AC voltages, power factor.

(c) Meteorological Station

Wind speed, wind direction, radiation, temperature.

Figure No. 3 describes schematically the relevant measured variable.

4. Accuracy

The basic requirements for accuracy were defined as:

(1) Sensing devices and transducers (0.5% accuracy).

(2) Data aquisition units and computer (12 bit resolution).

According to the solar and energy produced distribution the total accuracy for the whole range of operation is up to +- 3%.

Figure No. 4 describes this requirement schematically.

5. Designated & Central Data Aquisition

The requirement is described in Figure No. 5.

6. Synoptic Maps, Spreadsheets, Flexible Interactive Operation etc.

These requirements are described schematically in Figure No. 6.

Software packages such as FIX and NOVEL were selected in accordance with this requirement.

7. Reliability

According to this requirement a system which is based on the combination of multi-card PLC and IBM-PC/AT microcomputer was selected.

The multi-card based system is described schematically in Figure No. 7.

8. Overall System Configuration

Based on cost-effective system and sub-systems analysis, the final system configuration described in Figure No. 8 was selected and installed.

Figure 1: Basic General System Diagram

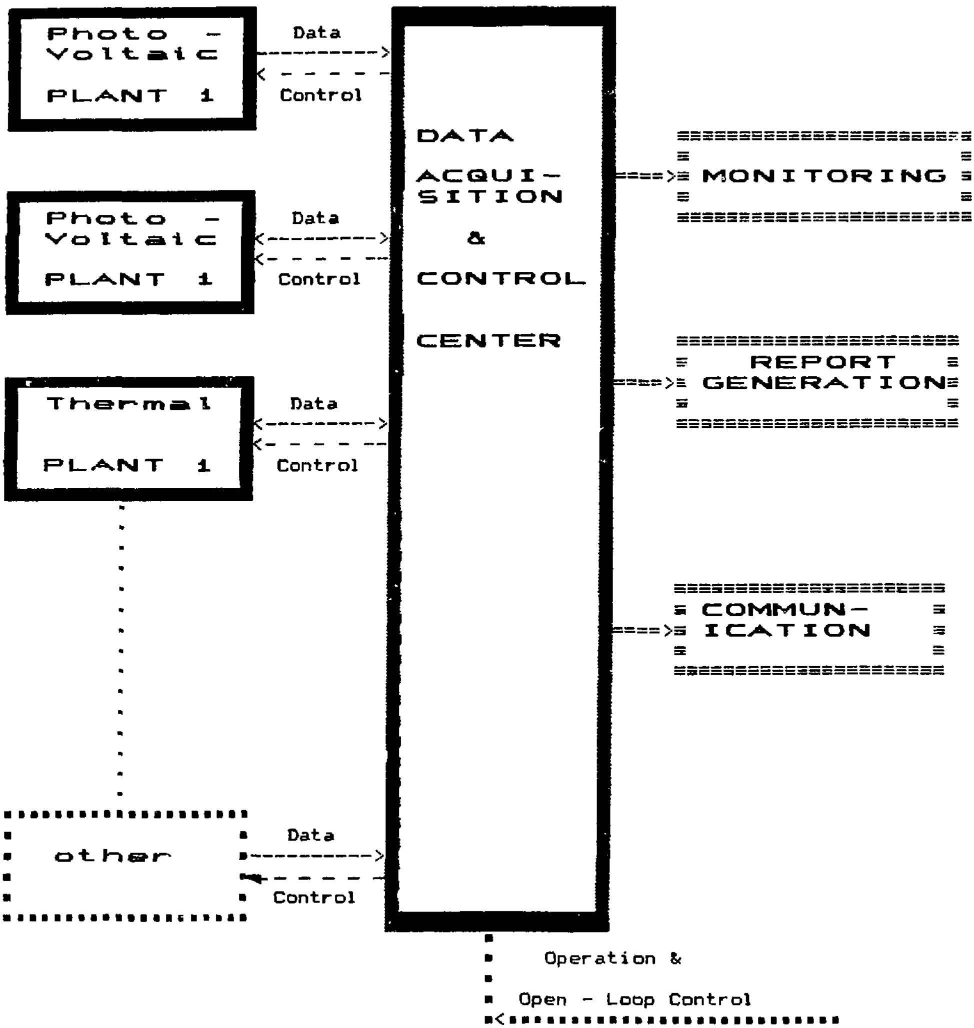


Figure 2:

*	GENERAL REQUIREMENTS
1	* PHYSICAL MEASSURED VARIABLES *
2	* ACCURACY *
3	* DESIGNATED & CENTRAL DATA AQUISITION *
4	* CONTROL *
5	* SYNOPTIC MAPS * SPREAD SHEETS * DATA BASE * * GRAPHICS * TEXTS * HISTORICAL TRENDING *
6	* FLEXIBLE INTERACTIVE OPERATION & SCREENS EDITING *
7	* REPORTS GENERATION *
8	* COMMUNICATION *
9	* RELIABILITY *
10	* COST EFFECTIVE SYSTEM & SUB-SYSTEMS SELECTION *

Figure 3

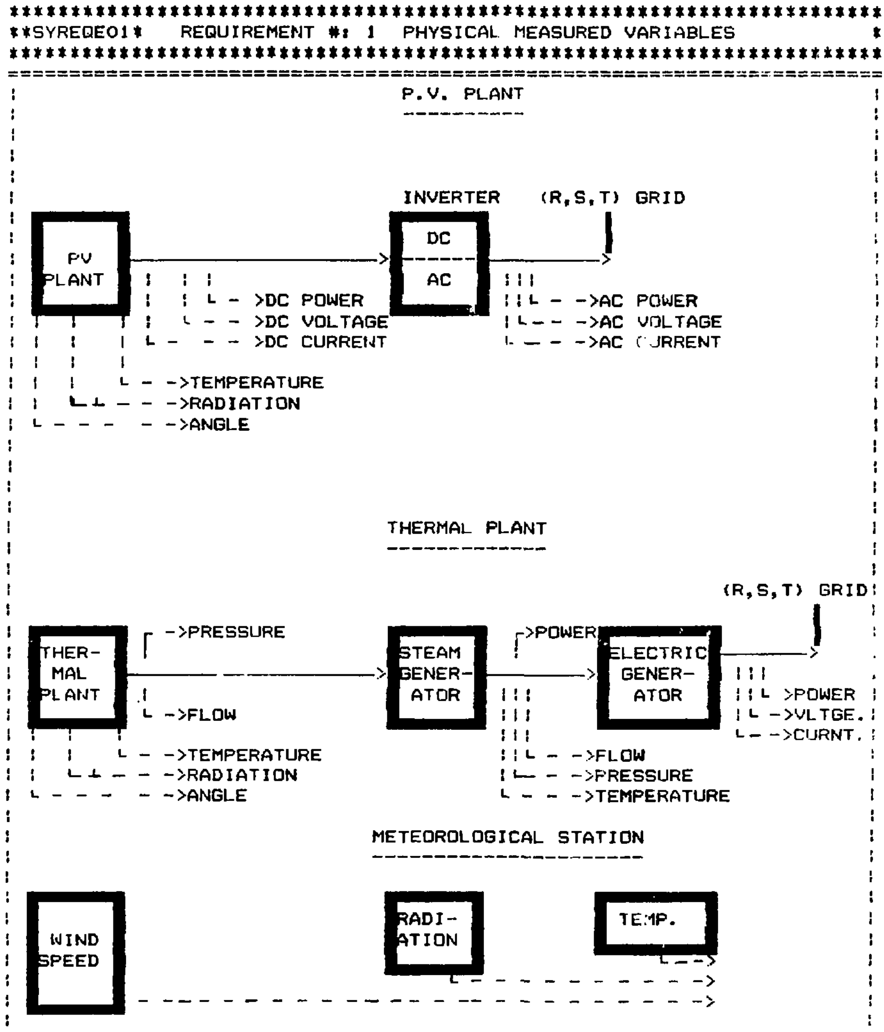
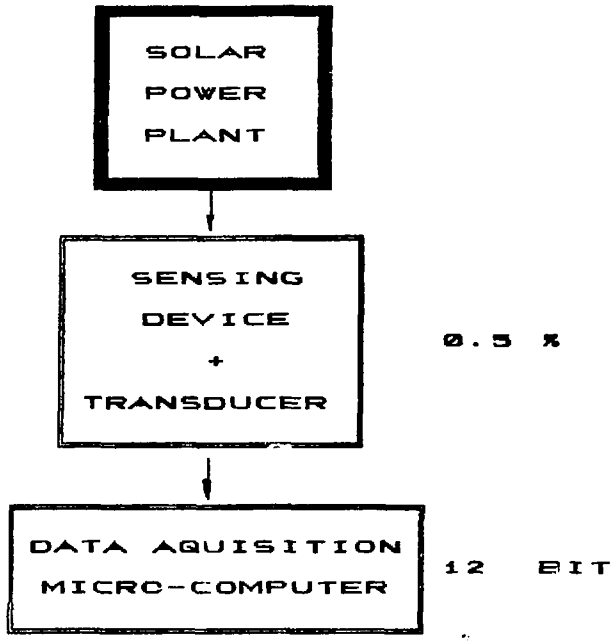

**SYREQE01* REQUIREMENT #: 1 PHYSICAL MEASURED VARIABLES
P.V. PLANT
INVERTER
(R,S,T) GRID
PV PLANT
DC
AC
>DC POWER
>DC VOLTAGE
>DC CURRENT
->AC POWER
->AC VOLTAGE
->TEMPERATURE
->RADIATION
->ANGLE
THERMAL PLANT
(R,S,T) GRID
THER-MAL PLANT
->PRESSURE
->FLOW
STEAM GENER-ATOR
->POWER
ELECTRIC GENER-ATOR
>POWER
->VLTGE.
->CURNT.
->TEMPERATURE
->RADIATION
->ANGLE
->FLOW
->PRESSURE
->TEMPERATURE
METEOROLOGICAL STATION
WIND SPEED
RADI-ATION

Figure 4: **ACCURACY**



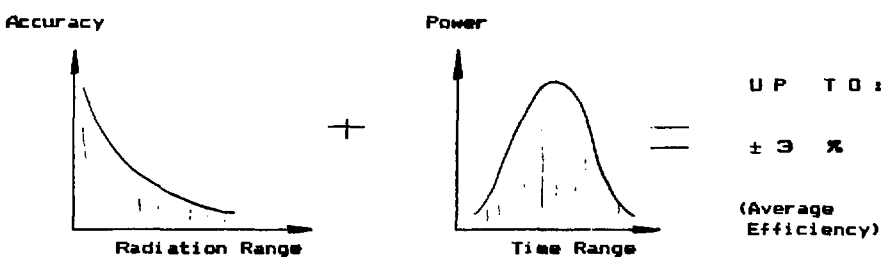


Figure 5:

(3) # DATA ACQUISITION AND PROCESSING FOR DESIGNATED AND CENTRAL SYSTEMS

1. Each plant is connected to a designated data acquisition unit and to a designated microcomputer

2. Each plant's owner wil e allowed to receive data nly from the designated systm which is connected to his p nt

3. A Central Microcompute 1 collect data fr om e designated syst

4. The Ministry of Energy l do analysis on the Cent l Microcomputer.

Figure 6: **SYNOPTIC MAPS ; SPREAD-SHEETS ; DATA-BASE ; GRAPHICS**

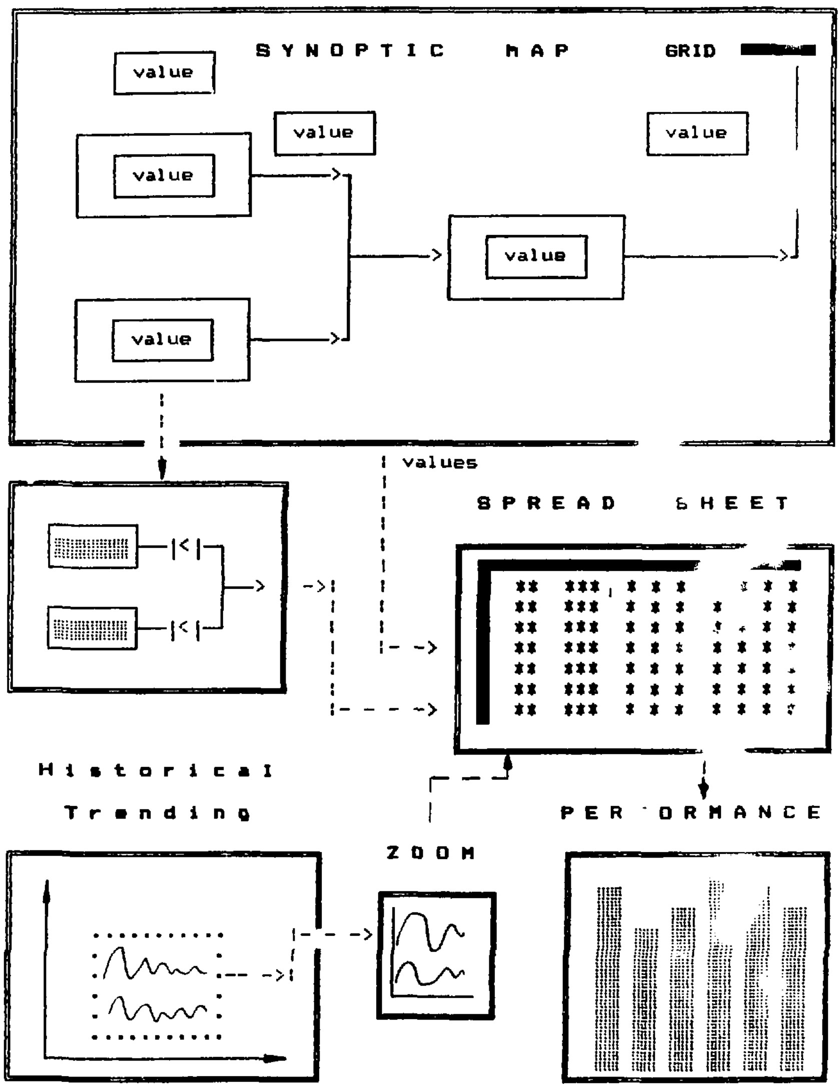
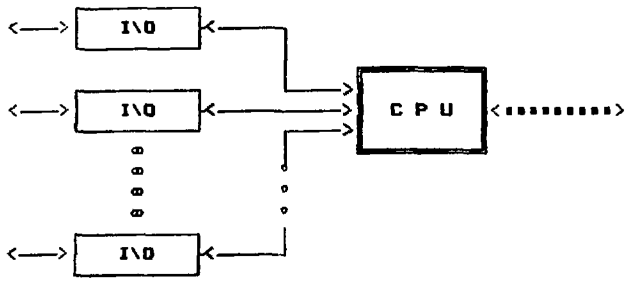
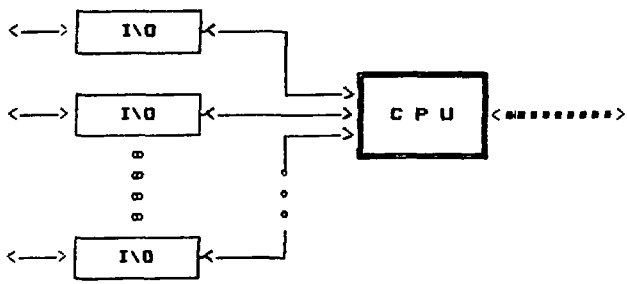


Figure 7: **R E L I A B I L I T Y**

(F i e l d U n i t s)



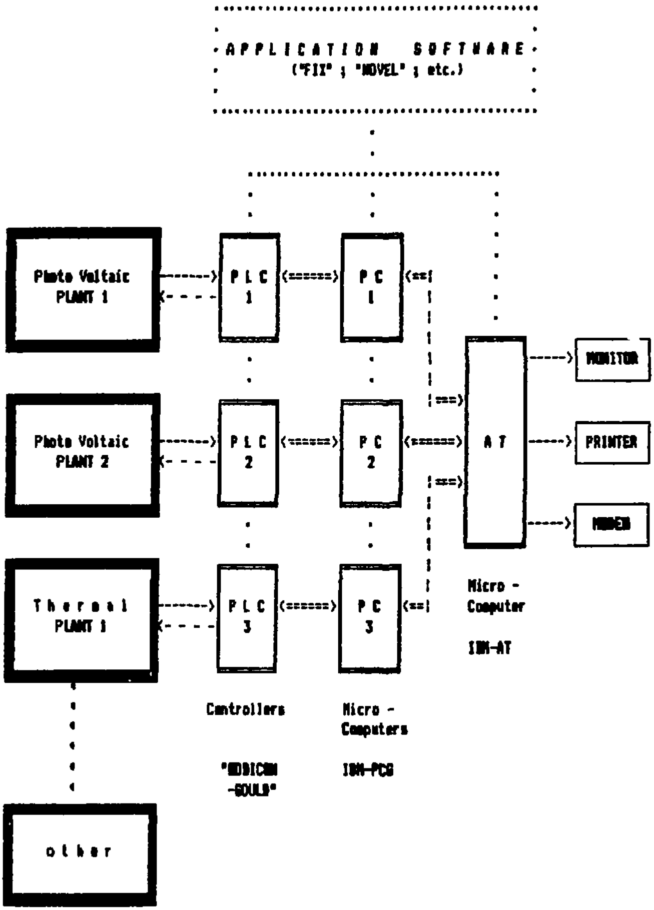


(1) Industrial Standard

(2) Multiple I\O (Input\Output) Cards

(3) Operation Temperature Range: -10 to 60 °C

Figure 8: **DESIGNATED & CENTRAL DATA AQUISITION AND PROCESSING**



KEYNOTE LECTURE

"High Temperature Solar Thermal Power"

by

DR. ARI RABL
Center for Energy and
Environmental Studies,
Princeton University
Princeton NJ USA

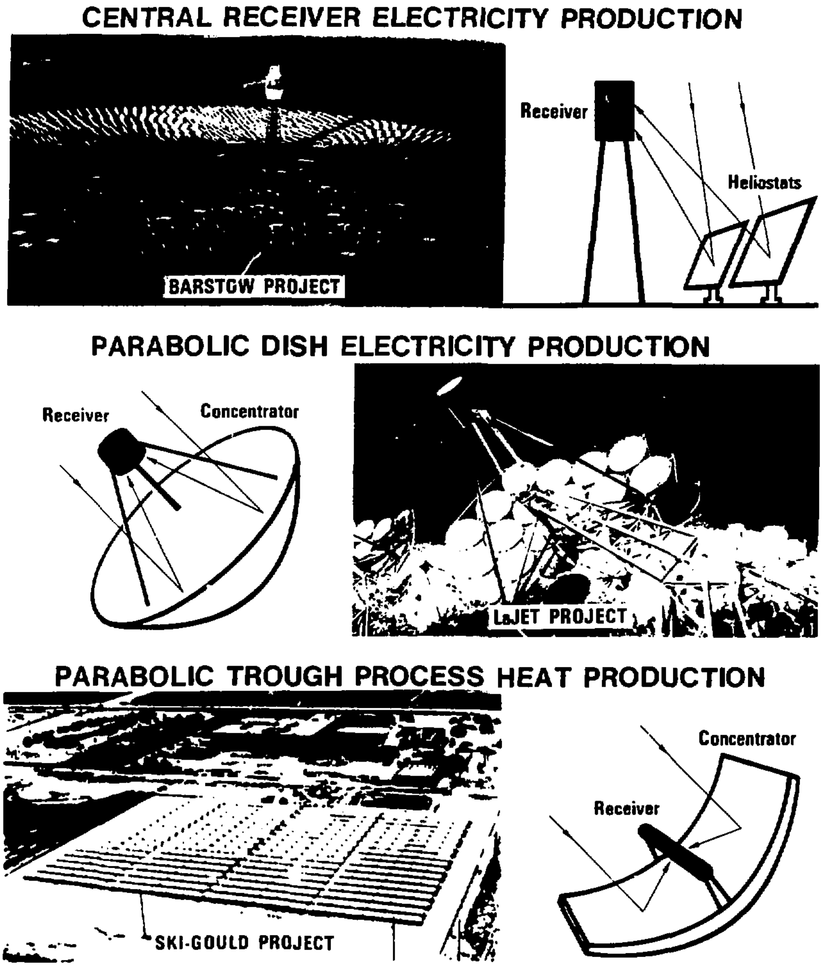
HIGH TEMPERATURE SOLAR THERMAL POWER - A. RABL

SLIDE #1: SUITABILITY OF COLLECTORS FOR ELECTRICITY GENERATION

TRACKING MODE	COLLECTOR TYPE	RANGE	SUITABILITY
non- tracking:	flat plate nonevac. CPC	< 100 degC	No
	evacuated tube + CPC reflector	~ 200 degC	Perhaps
one-axis tracking:	parabolic trough lin. Fresnel lens	~ 350 degC	Yes
two-axis tracking:	parabolic dish Fresnel lens central receiver	~ 1000 degC	Yes
other:	fixed reflector + moving receiver	≥ 250 degC	Perhaps

Figure reproduced from: "Five Year Research and Development Plan 1986-1990"
U.S. Department of Energy, DOE/CE-0160, Sept. 1986.

Figure 2. Solar Thermal Technologies



SLIDE # 2: STORAGE OPTIONS

Storage Types:

* oil
* oil + rocks, glass, etc.
* molten salt
* none (on solar side)
    - backup with hydro (best!) or fuel

Choice guided by ancient principle (attributed to a certain NY banker)

" b u y   c h e a p ,   s e l l   d e a r "

Storage looks promising for T < 500 degC

- a few hours for early evening.

Above 500 degC, storage becomes problematical.

HIGH TEMPERATURE SOLAR THERMAL POWER - A. RABL

SLIDE #3: CONVERSION OF THERMAL ENERGY TO ELECTRICITY

Carnot efficiency = 1 - T(low)/T(high)

at T(low) = 20 degC = 293 K:

T(high) [degC]	90	200	500	1000
Carnot [%]	19	38	62	77

In practice one can achieve approx. 50% of Carnot efficiency.

Conversion types:

Rankine cycle (vapor → turbine → liquid → boiler → vapor)

- employing steam or an organic fluid.

Steam turbines used in conventional power plants
-fuelled by oil, coal, nucl, up to T(high) = ~ 540 degC)

Brayton cycle (gas → turbine → gas → compressor → gas)

Employed in gas turbines and jet engines.
-fuelled by oil, etc.

Stirling cycle (reciprocating, external heat source)

Others , e.g. MHD, ...

HIGH TEMPERATURE SOLAR THERMAL POWER - A. RABL

SLIDE #4: SYSTEM CONSIDERATIONS

Not all combinations of components are practical.

Principal considerations are:

* Cost } of components
* Performance } of components
* Match between components
  - including match to end use.
* Economies of scale
* Efficiencies of scale
* Reliability

HIGH TEMPERATURE SOLAR THERMAL POWER - A. RABL

SLIDE #5: CARNOT RESTRICTIONS ON COLLECTOR PERFORMANCE

Carnot limit implies a need for:

* either high T
* or very cheap collector
  - e.g. solar pond, ocean energy.

Conventional power plants have fuel-to-electricity efficiency = 30-40%

....leading to electricity price $\simeq$ 3 x fuel price.

For example: if collector is just competitive with fuel for heat

- its heat-to-electricity efficiency

must be at least 30%

===> flat plate / evacuated tube + CPC } not suitable

.... unless costs can be reduced.

SLIDE #6: EFFICIENCIES AND ECONOMIES OF SCALE

* turbines (steam and gas)

  best if large , i.e. $\geq$ 1 MW

  (Ac $\geq$ 70 m x 70 m, at 20% efficiency)

  ===> only for large central systems.

* Stirling engine OK for individual collectors

  e.g. dishes ($\simeq$ 800 degC)

  efficiency: 35 to 40% (heat ---> elec.)

  .... not yet commercial

---

* For collectors economies of scale are possible:

  with large units (fewer moving parts)

  ...but more wind + weight stresses

  Optimal length of unit $\simeq$ 5 to 15 m

  (Ac = 50 to 150 sq.m)

  ...increases with production volume.

HIGH TEMPERATURE SOLAR THERMAL POWER - A. RABL

SLIDE # 7: COLLECTOR THERMAL CONSIDERATIONS

*Collectible Heat

- highest for dish

- lower for central receiver
  and for trough } ≃ 2/3 dish, (depending on latitude and spacing)

  (due to cosine factor, shading, blocking)

- But mirrors are simpler for latter, (~flat for central receiver).

* Heat Centralization

......heat losses and cost of piping

- central receiver : best (optical transport)

- trough : moderate (collector ≃ transport)

- dish : highest losses (above ≃ 300 degC)

HIGH TEMPERATURE SOLAR THERMAL POWER - A. RABL

SLIDE # 8: PROMISING OPTIONS

1) Central receiver + steam turbine

+ a few hours of storage

---

2) dish or trough + steam turbine

(La Jet) (Luz) (central)

n o s t o r a g e

e.g. LUZ { solar below ~ 350 degC (evaporation)
+ gas above ~ 350 degC (superheat)

---

3) central receiver + gas turbine

(For N = 20 years and interest rate r = 0.05,
Capital recovery factor A/P = 0.0802)

n o s t o r a g e (1000 degC)

---

4) dish + stirling engine at <u>each focus</u>

n o s t o r a g e

HIGH TEMPERATURE SOLAR THERMAL POWER - A. RABL

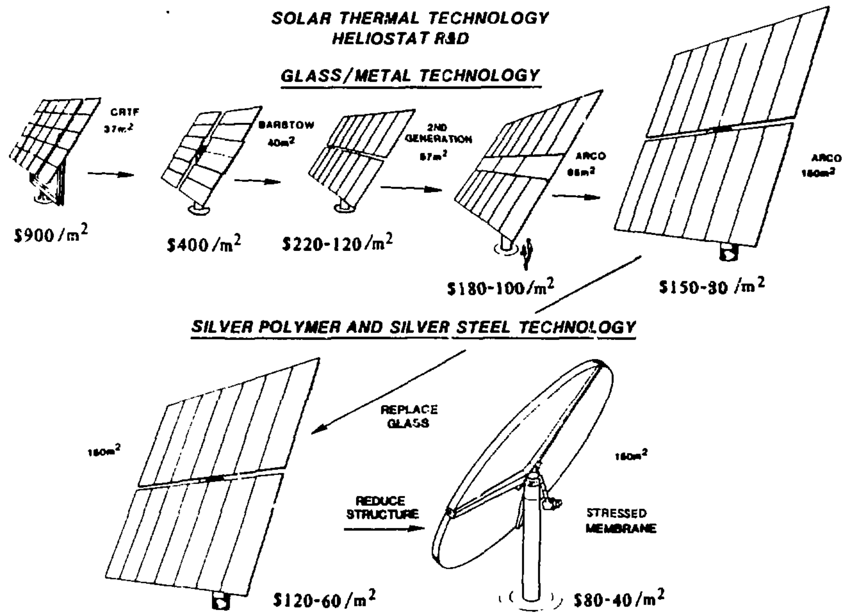
SLIDE # 9: CURRENT RESEARCH EFFORTS (U.S.D.O.E.)

* reflectors
  - Ag with polymer coating
  - stretched steel membrane
* receivers
  - direct absorption (in molten salt or particulates)
  - second stage concentrators
  - ceramic heat exchangers

  (higher T needed to extend range of storage)
* engines
  - Stirling engine
* processes
  - production of hydrogen
  - gasification of biomass (and of toxic wastes)

Figure reproduced from: "Five Year Research and Development Plan 1986-1990"
U.S. Department of Energy, DOE/CE-0160, Sept. 1986.

Concentrators



Concentrators provide avenues for major improvements in the cost of delivered energy for solar thermal systems. Concentrator designs are being developed to achieve these cost/performance improvements through enhanced reflectivity, longer life, and lower initial cost. Substantial increases in heliostat reflective area can result in lower costs without loss in performance or lifetime.

Using the stressed membrane concept, lightweight, low-cost concentrators can be constructed of high-reflectivity silvered polymer films or thin silvered steel. For central receiver system use, large 150m² single module, silvered polymer, vacuum-focused stressed membrane heliostats are being studied because of their potential high performance, lightweight, low cost characteristics.

SLIDE # 10: EXISTING SOLAR-THERMAL POWER PLANTS

(a) CENTRAL RECEIVERS

PLANT	year complete	aperture [sq.m]	peak power [MWe]	cost [$/We,pk]
"Solar 1", Barstow, CA, USA	1982	73,000	10.0	14 [*]
"Themis",Targassone, France	1983	11,000	2.5	12
"CESA 1" Almeria, Spain	1983	12,000	1.0	15
"CRT", Nio, Japan	1981	13,000	1.0	26
'Eurelios" Sicily, Italy	1981	6,000	0.6	12
"CRS-1", Almeria, Spain	1981	4,000	0.5	30

[*] might be reducible to 3 $/We,pk in the future.

(b) PARABOLIC DISHES

PLANT	year complete	aperture [sq.m]	peak power [MWe]	cost [$/We,pk]
"Solarplant-1", Warner Springs CA, USA (La Jet)	1984	30,000	5.0	3.8
"STEP", Shenandoah, GA, USA	1983	4,000	0.4	
"Sulaibiya" Kuwait	1981	1,000	0.1	

HIGH TEMPERATURE SOLAR THERMAL POWER - A. RABL

SLIDE 10 (continued)

(c) TROUGHS

PLANT	year complete	aperture [sq.m]	peak power [MWe]	cost [$/We,pk]
"SEGS 1" Dagget, CA, USA	1984	72,000	14.0	4.2
"SEGS 2"	1985	165,000	30.0	
"SEGS 3"	1986	200,000	30.0	3.3
"SEGS 4,5,6,...20 (?)				
"Vignola, Corsica, France	1981	1,000	0.1	
IEA "DCS", Almeria, Spain	1981	5,000	0.5	
"FPM", Nio, Japan	1981	11,000	1.0	
"Coolidge", AZ, USA	1980	2,000	0.2	26
"Meekatharra, Australia	1982	1,000	0.1	36

SLIDE #11: ECONOMICS

* Analysis per kWe,pk with capacity factor:

$$CF = \frac{kWe,av}{kWe,pk}$$

* Annual output [in kWh]

Q = CF x 8760 hrs/yr x 1 kWe,pk

PLANT TYPE	CF	
parab. trough	0.20	no storage, sunny location.
parab. dish	0.25	

---

annual cost (interest, repayment, O&M)

≃ 1/10 capital cost

" ten percent rule" (e.g. 20 yrs at 8% per yr.)

Example: La Jet at 3800 $/kWe peak, CF = 0.25

Q = 2190 kWh /yr

ann. cost = 380 $/yr

$$\Longrightarrow \text{electricity cost} = \frac{380\ \$/yr}{2190\ kWh/yr} = 0.17\ \$/kWh$$

HIGH TEMPERATURE SOLAR THERMAL POWER - A. RABL

SLIDE #12: THE VALUE OF SOLAR ELECTRICITY

* Value = cost of cheapest alternative.

off-peak (~ 10 pm to ~ 7 am in USA)

with coal or nuclear

≃ 0.04 $/kWh (~ $0.020-$0.025 for coal + $0.015-$0.020 for capital)

on-peak (hot summer afternoons in USA)

with gas turbine

≃ 0.08 $/kWh

---

* current solar technologies:

≃ 0.12 $/kWh

* projections for the year 2000 (by USDOE)

≃ 0.05 $/kWh

SLIDE #13: THE LEARNING CURVE

* Empirical industrial observation:
  - there is a reduction of unit cost by factor of ~ 0.7 to ~ 0.9 for each doubling of cumulative total production.

Example: 3.5 \$/W at 50 MW cumul.

- with reduction factor = 0.8

reaches 1.5 \$/W after X doublings,

where 0.8 = (1.5)/(3.5) = 0.43

$$\text{Thus} \quad X = \frac{\ln 0.43}{\ln 0.8} \cong 4$$

===> cumulative production: 2 x 50MW = 800 MW

If factor = 0.9, need 12.8 GW of cumulative production.

---

* Learning curve for Luz?

SEGS I : 4.2 \$/W for 14 MW

- Factor of 0.9 leads to expected costs:

Cumul. Prod. [MW]	14	28	56	112	224	448	896
Expected cost [\$/W]	4.20	3.78	3.40	3.06	2.76	2.48	2.23

... SEGS III at 3.3 \$/W for 74 MW (cumul)

fits nicely within this range!

Extracts from the Discussion Following Prof. Rabl's Presentation

Gordon: Why do you address the economics of solar-produced power from the simple over-simplistic viewpoint of fuel saving?

Rabl : It is clearly not the whole story, as you correctly observe. Capacity credit is, however, as extremely complex issue and it does not clarify the economics. It is nevertheless meaningful to compute the cost of producing solar electricity as a separate issue from how much a utility is prepared to pay for the product. As we have seen, today's solar-produced electricity appeares to cost about twice as much as when it is produced by conventional means. This is an encouraging development.

Nir : I have two comments: First, the use of a learning curve for predictive purposes is fraught with uncertainties owing to the possibility that some new discovery way dramatically alter the cost trend. One has only to look at the effect environmental considerations have recently had in the energy sector.

Secondly, I am disturbed that analyses such as yours always seem to compare the projected cost of some alternative energy source with the present (rather than the projected) cost of conventional-produced energy.
I am aware that electricity production seems to be a rather mature technology, but it should not be ruled out that advances in the technology of storage may radically lower the cost of conventional electricity.

Weiner: One developing technology that appears promising is that of the gas turbine.

Rabl : I agree, although I do not know of any plans to combine solar and gas turbine technologies.

Charats: Luz is looking into that possibility.

Roy : To what extent does the cost of achieving optical precision influence the relative economics of the various kinds of concentrators?

Rabl : Judging by Luz's commercial success, the optical precision of today's parabolic troughs would appear to be adequate in the 300 oC range of temperatures. For the 500 oC range, the present generation of parabolic dishes also have adequate optical accuracy. For higher temperatures it appears that a second-stage concentrator will be necessary to compensate for aberations in the primary reflector. Whether this added complexity will be economically justified-only time can tell.

As to the question of an economically optimal temperature for solar-thermal power production: today the answer seems to reside with Luz. Tomorrow, it might lie with central receivers - but if they are not built, that too will be part of the answer.

KEYNOTE LECTURE

"Low Temperature (T< 100^{0}C) Solar Thermal Electricity"

by

PROF. MANUEL COLLARES PEREIRA

LNETI Lisbon Portugal

LOW TEMPERATURE (T< 100^{o}C) SOLAR THERMAL ELECTRICITY

Key-note lecture presented at the

2nd Sede Boqer Workshop on Solar Electricity Production

by

Manuel Collares Pereira

I - INTRODUCTION

The objective of this talk is to review existing solar energy technologies for the production of low temperature heat (T<100^{o}C) in terms of their potential to generate electricity.

These technologies will be compared on equal grounds, namely in terms of annual costs expressed in dollars/Kwhr, assuming 20 years of operation. In order to do this comparison we first estimate how much energy they can produce on an yearly basis and then we make educated gueses to their present costs (as possible costs, assuming acceptable projections from today's costs in the case these technologies are not usually used for the production of electricity).

Rather than comparing these costs with conventional energy costs we decided to compare them with present day stationary photovoltaic (PV) costs in order to put in perspective the interest of pursuing the efforts in low temperature heat for electricity. The results obtained show PV as already having a lower cost than other technologies presented , and since the costs for the thermal technologies are much closer to their limiting values, this likely means that in the future, low solar temperature heat will be more used directly as such, i.e. rather than for the production electricity.

The talk is organized as follows: II) a brief review of how to convert low temperature heat to electricity, the Rankine Cycle ; III) a brief description of how to calculate yearly average system performance; IV) a brief description of the considered technologies, namely ponds (salt gradient and others), solar collectors (ex: CPC non-evacuated plus storage) and photovoltaic V) a calculation of yearly system performance in each case; VI) an estimate of each system's cost and a comparison of all system in terms of $/KW hr produced; VII) a discussion of the results.

II - CONVERSION OF LOW TEMPERATURE HEAT INTO ELECTRICITY ON RANKINE CYCLE

The appropriate thermodynamic cycle for conversion of low temperature heat is a Rankine cycle <1>.

It is assumed in the following calculations that the ΔT between the hot and cold sources is 55°C, with typical yearly averages values of 85°C at the boiler, and 30 °C at the condenser. Carnot efficiency in this case is around 15%, and a <u>pratical limit</u> for the Rankine cycle efficiency is roughly half <u>of that, i. e.</u> η_R= .08. This can in principle be obtained assuming: expander eff.= .8, pump eff.= .5, Mech eff.= .75, regeneration eff. = .8, high side pressure loss =.05, low side pressure loss = .08.

In the litterature and for the temperatures conditions stated above the tipically reported η_R is .05. Recently η_R .06 was reported <2> which is a good (high) value.

III - SOLAR SYSTEMS YEARLY AVERAGE ENERGY PERRFORMANCE

The instantaneous efficiency of solar collectors can be described in terms of the Hottel, Whillier, Bliss equation, namely

$$\eta = F_R \eta_o - F_R U_L (T_{in} - T_{amb})/I$$

where the T_{in} is inlet temperature to the collector, T_{amb} is the ambient temperature, I is the instantaneous radiation on the collector plane, η_o is the optical efficiency, U_L is the collector heat losses factor and F_R is a factor which takes care of the fact that the collector's performance is being described in terms of T_{in} and not in terms of receiver temperature.

The average energy delivered by a collector operating in a system at a constant inlet temperature can be calculated by (as written Q_{year} must be multiplied by 365 for the total yearly energy).

$$Q_{year}(T_{in}) = F_R \ \eta_o \ H_{coll} \ \phi(X_{in})$$

Where H_{coll} is the average radiation available to the collector entrance aperture, η_o is the average optical efficiency (including incidence angle modifier), and is the utilizability, a function with a value <1 accounting for the fact that radiation below a certain threshold X_{in} is not usable because does not overcome the collector's heat losses.

$$X_{in} = U_L(T_{in} - T_{amb})/ \eta_o$$

In all that follows the radiation data used is from Bet Dagan, Israel, $\simeq$ 32 °.

IV - LOW TEMPERATURE SOLAR HEAT TECHNOLOGIES

There are two general types of technologies, those where collector and storage are combined, the solar ponds, and those where the collectors are separated from storage and which we will refered as collectors plus storage.

1. Solar Ponds

Of all solar ponds, salt gradient solar ponds <3> are the prime candidates for collecting and storing solar energy at temperatures suitable for the conversion to electricity via the Rankine cycle described in II, since they can be constructed and operated at costs which are among the lowest possible for solar collectors. The Rankine cycle uses the hot water of the lower convective zone as the hot source and the surface water as the cold source.

Other ponds have been proposed like shallow ponds or ponds covered by opaque insulating materials, but their thermal performance is not as good as the one of salt gradient ponds. In the analysis below we will consider the salt gradient pond in great detail and the shallow pond as an alternative example.

2. Solar Collectors (CPC) + Storage

The other main type of system to be considered is one in which solar energy is collected in solar (active) collectors by heating a fluid which will be separately stored, until used as the hot source in a Rankine cycle.

Because the collectors must heat a fluid at least to 85 °C with reasonable efficiency and cost, we choose to use in this study non-evacuated CPC 1.2X collectors <4>, which are able to perform with efficiencies above .5 up to temperatures around 100° C and can be produced at the cost of a good single glazed flat plate collector, selectively coated .

3. Photovoltaic System

For comparison we consider a PV system of the flat plate monocristaline type, mounted at tilt-latitude, connected to an inverter and then to the grid. However, and as in the other cases, we will not consider the transformer as part of the system.

V - YEARLY SYSTEM PERFORMANCE

1. Salt Gradient Solar Pond

Following Kooi <5> we can now estimate the best possible performance of a salt gradient solar pond ($1\ Km^2$) for the conditions stated above. We will assume that the ΔT of 55^oC is going to be maintained all year around (this really means for instance, that in Winter time, the temperature of the lower convective zone can drop to 70^oC, and ambient surface water temperature will be around 15^oC). The Rankine cycle will **only** operate, whenever this ΔT is achieved, which allows us to think in terms of a radiation threshold and use the utilizability concept. However night time losses must be explicity deduced from the value of Q_{year} found in the manner described above.

At normal incidence and for pure water <15> we may have $F_R\eta_o = .35$ (note that this is a high value since typically in clear and clean ponds $.25 < F_R\eta_o < .30$). $F_R U_L$ can be assumed to be at best $.64\ w/^oC$ (we are thinking of a pond with a gradient zone of 1m + upper convective zone of 0.5 m; this is again an optimistic estimate since typically $1 < F_r U_L < 2\ W/^oC$).

Radiation does not come at normal incidence but there is an effective angle θ_{eff} (energy weighted) along which, we can assume, comes all incident radiation on the water's surface: $\theta_{eff} = 52^o$ for the case of Bet Dagan. There is reduction of ~ 5% resulting from it. Also the path lenght in the water for the refracted radiation is accordingly increased, resulting in further absorption - ~4% effect.

We then have

$$F_R\bar{\eta}_o = F_R\eta_o * .95 * .96$$

From the radiation data we have

$$\phi(X_{in} = 92W) = .65$$

and

$$\bar{H}_{coll} = 19.2\ MJ/m^2$$

and therefore

$$\bar{Q}_{year} = 3.9\ MJ/m^2$$

from which night time losses still be deducted, i. e. Q_{loss} = 1.5MJ/m².

Assuming that $_R$ =.08 we get an upper limit for the amount of electricity produced of

$$\overline{Q}_{elect} = .08 * 2.4MJ/m^2 = .19MJ/m^2$$

However, the available Rankine cycles have, as stated, lower efficiencies and therefore a more realistic value for Q_{elect} is

$$\overline{Q}_{elect} = .05 * 2.4MJ/m^2 = .12MJ/m^2$$

This net figure is consistent with measurements presented in the last year (1st) symposium by M. B. Doron on the 200000 m² pond at Bet Aravat <2>.

However, to operate the cycle it is necessary to consume a fraction of the electricity produced. We will assume that it is necessary to spend 30% <3> of the electricity produced to power the cycle. This seems to be optimistic assumption since the reported consumption at Bet Arovat was much closer to 50% <2>. We have then

$$\overline{Q}\ elec_{max,net} = .13MJ/m^2$$

$$\overline{Q}\ elec_{present,net} = .08\ MJ/m^2$$

2. <u>Shallow Pond</u>

Based on measurements done at Lawrence Livermore - USA, we have

$$F_R \eta_o = .74 \qquad F_R U_L = 7.4\ W/m^2\ {}^oC$$

with $\phi(X)$ = .08 we have $\overline{Q}_{year}$ = .67Mj/m² and

$$\overline{Q}\ elect_{max,net} = .035MJ/m^2$$

3. <u>1.2X CPC, non-evacuated</u>

In this case the collector's parameters used correspond to a simple cover collector manufactured in Portugal <7> and are

$$F_R \eta_o = .74 \; ; \; F_R U_L = 2.84 \; W/m^2 \; ^oC$$

Assuming that the collectors are operated at tilt = latitude.

We have

$$F_R \bar{\eta}_o \; \bar{H}_{coll} = 12.8 \; MJ/m^2$$

$$\phi(X) = .58$$

$$\bar{Q}_{year} = 7.4 \; MJ/m^2$$

From where we will have

$$\bar{Q}elect_{max.} = .08 * 7.4 = .6 MJ/m^2$$

and

$$\bar{Q} \; elect_{present} = .05 * 7.4 = .4 MJ/m^2$$

In this case operational experience with collector fields of the kind considered here, plus the power consumption for the operation of the cycle proper, leads us to estimate a parasitic power consumption of 20 %, from where we get

$$\bar{Q}elect_{max,net} = .5 \; MJ/m^2$$

$$\bar{Q} \; elect_{present, \; net} = 3 \; MJ/m^2$$

in the two cases above.

4. Photovoltaic System

We assume an efficiency for the PV system of .1. $\bar{H}_{coll}$ at tilt = latitude and zero azimuth is 20 MJ/m^2, resulting in $\bar{Q}_{year} = 2 MJ/m^2$ <8>.

We can collect all the results above in table 1 where we have the amount net electrical energy produced per day on the average by each system per m^2, both in the "maximum" and what we denominated "present" situation.

Table 1

[in MJ/(m2 day)]	Salt gradient Solar Pond	Shallow Pond	CPP + storage	PV
"maximum"	.13	.035	.5	---
"present"	.08	---	.3	2

VII - ESTIMATE OF SYSTEM COSTS

In what follows, we will assume that all land is free, and that salt transport are free (assumptions which favor the low temperature collectors, specially the solar ponds).

We will first estimate system's capital costs and then compare systems, calculating annual costs with the 10% rule, i.e., the total annual costs for interest, repayment of loan as well as Operation of Maintenance are 10% of the initial investment <9>, assuming that the systems function reliably for at least 20 years.

Common to the low temperature systems is the cost of the Rankine generator + associated equipment. For the sake of the comparison we will take a 1 Km2 with which it is proposed to associate a 5MW Rankine <3> with a present total cost of $1500/KWp (lowest estimates are of $1000/KWp but we will retain the higher one).

1. Salt Gradient Solar Pond

From a thorough review of pond related papers (for instance <10, 11> from my own experience in the subject (for instance <12>) and from extensive published material on the construction of water basin my lowest estimates of pond costs in US$ per m^2 are as follows (table 2):

Table 2

	lined pond	unlined pond
	13	9
water + chemicals (20 yr)	6	6
Fence	2	2
Excavation	.7	.7
total	21.7	17.7

These figures should be compared with the typical minimal costs considered all over the world <10, 12> of $50-70/m2 which, however, include the cost of salt and salt transport and a leak proof construction given potential polution problems in areas where contamination of the water table, say, from salt could not be tolerated.

From table 2 retaining the lowest number and adding the Rankine cycle cost we obtain $ 24.8 / m2.

2. CPC 1.2X + Storage

We assume that for a 5MW system we would be able to have a $130/m2 installed system ($120/m2 for collector frame connecting gripes and control <7> and $10/m2 for storage). To this figure we must add $37.5/m2 for the Rankine cycle as before (this number was obtained taking into account that the CPC system produces ~5X more energy on a per a square meter basis as the solar pond). Therefore, the total capital cost is $167.5/m2.

3. Photovoltaics

We assume <8> a $5/Wp for the panels and $5/Wp for frame, invester, wiring, power tracking, etc., for a total cost of $5.5/Wp which in our case and given that peak power per m2 is 100W means a total cost of $550/m2.

Applying the 10% refered above, using table 1 and the costs described in this section we list in table 3 the annual costs in $/Kw hr of electricity produced in each case in both "max." and "present" situations.

Table 3

C_{annual} ($/KWhr)	Salt Gradient Pond	Shallow Pond	CPC 1.2X	PV
"max."	.19	---	.33	
"present"	.30	---	.55	.27

VII - DISCUSSION RESULTS

Table 3 shows that of the thermal options retained it is clear that salt gradient solar ponds are the best. However, PV is already cheaper and its cost is likely to go much further down than the limiting lowest possible cost for ponds (.22$/KW hr) estimated here. This seems to point towards the fact that, at least in the medium term, electricity from low temperature heat sources is not of interest.

A word should be said about ponds and the fact that they can store energy from one day to the next and indeed even for several days, thereby having a potential usage as "stand alone" devices, which was not considered here. They will not, however, deliver more energy in that mode (on the contrary there will be more losses and possibly less gains from an increase of the threshold). The problem with salt ponds is that at these costs/KW hr they are really site limited to those places where there is free flat land, free salt, water, and to low latitudes ($|\lambda| < 35$?! because of the angle the sun makes with the water surface during each day and in the course of the year), conditions only fulfilled by less than a handful of spots on earth.

Photovoltaics clearly does not have these limitations and can be installed on existing structures, rough terrain, etc. Also, while comparing ponds and PV in grid connected situations (as done above) it can be argued that ponds can produce all of their daily electricity a few hours later in the day or night, therefore having a higher value because of their natural adaptation to a "late" peak demand. However, including a couple of hours of battery storage in the analysis above for the PV system would not significantly increase the costs and would have the same effect. Besides, in sunny locations, there seems to be a match between peak demand and peak power availability from the sun, thereby reducing the importance of the argument above.

Therefore it seems that low temperature heat with ponds or collectors will have a much more widespread use directly for heating applications like domestic and industrial process water heating agricultural applications (greenhouse heating, water or solar drying, for instance) and, even, in the case of ponds, applications like the direct industrial extraction of chemicals from mineral ore <13, 14>.

Note Added in Proof

At the Symposium, Paz Company claimed that their own selling costs for a tracking PV system installed, grid connected (transformer excluded) are 5.5 \$/Wp ! Q_{year} in their case should be higher than the one of the stationary PV system considered here, reducing the figure in table 4 for PV costs by a factor between 1 and 2.

AKNOWLEDGEMENTS

I wish to thank Dr. John Hull for providing much of the information used to find out about pond costs, and Dr. Ari Rabl, Prof. Jeff Goordon and Prof. Yair Zarmi for the discussions concerning the assumptions and results pressented in this lecture.

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Extracts from the Discussion Following the Presentation of Prof. Collares Pereira

Faiman: Does not the unique storage capability of a solar pond place it in a special category viv a vis alternative technologies ? You have not emphasized this point.

Gordon: To be more specific, perhaps, in your economic comparison of the various technologies you appear to ignore the greatly increased capacity credit for pond-generated electricity compared with the photovoltaic variety.

Collares Pereira: It is important not to get the storage advantage out of proportion when one is considering power generation. From the utility view-point 24 hours of storage is the same as no storage. Utilities require a few hours of storage in order to shift the output peak of the solar system. In my calculations I have assumed that all of the power produced by both kinds of system in a day is consumed the same day. In principle I could have included a modicum of battery storage in the photovoltaic economics but this would not radically alter the picture. In a stand-alone system this would clearly not be true for in such cases several days worth of expensive storage are necessary for pv systems and here the advantages of a pond are apparent.

Weiner: It is certainly true that a solar pond power plant has extra capacity credit, but are the kWh in your table net or gross? Conventional power plants usually consume about 5% of the power produced. I would like to know what the corresponding parasitic requirements are for solar pond power plants.

Doron: In theory we believe this figure to be about 25-30% (It is considerably higher at Bet Ha'aravah because not all of the planned heat exchangers were installed). In electrical figures one should expect about 20-22 kWh/sq.m/year from solar ponds.

Collares Pereira: For my calculations I used Ormat's published figure of 30% for parasitic losses. Thus my discussion represents net power output.

Roy: Because all of the competing technologies appear to present the same order-of-magnitude economics in your table, I would be interested to hear some more details regarding how you performed the calculations. I am particularly interested to learn how your pond experience compares to the published results of Ormat.

Collares Pereira: First, the fact that "all" competing technologies turn out have the same order-of-magnitude economics is not the whole story. I have deliberately removed from consideration all solar technologies (shallow solar ponds, flat plates, etc) which would have orders of magnitude worse economics.

Secondly, regarding the prices for the various kinds of technology, I reviewed the literature and adopted values typical of those one finds used by the experts. I have made no attempt to pass judgment on the degree to which these prices may be realistic or otherwise.

Thirdly, regarding the physics of each kind of system, I have correctly taken into account the proper average radiation at the surfaces of all collector types - including the relevant thresholds. Regarding the pond calculations, I was delighted to discover, upon my arrival in Israel, that the estimates I calculated for the Bet Ha'aravah pond while in Portugal are extremely similar to the figures presented here at last year's workshop by Mr. Doron - in Hebrew and consequently unknown to me at the time I did my calculations! [I thank Prof. Zarmi for subsequently translating those results into English for me.]

As for my own pond experience, the results are not really comparable. Mine is a low temperature pond (for thermal energy production) and located in an agricultural area. These factors enhance algae growth and result in a transparency of only 0.26 compared to Ormat's 0.38.

Zarmi: How do you define utilizability for a pond?

Collares Pereira: I compute the difference between the incoming radiation and the sum of heat losses and energy drawn. For purposes of simplification I assumed a constant temperature difference all year. This would correspond to something like 85 degC - 35 degC in summer and 70 degC - 20 degC in winter.

Tabor: Notice that for ponds one can ignore threshhold factors. For unlike a flat-plate collector a pond loses heat all the time - day and night. So both solar input and heat losses can be replaced by integrated constant values.

KEYNOTE LECTURE

"Photovoltaic Systems: The Matching of System Components"

by

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PHOTOVOLTAIC SYSTEMS

The Matching of System Components

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INTRODUCTION

The efficiency of conversion of solar energy to useful electric energy by solar cells is relatively low. An effort should therefore be made to match the many systems' components in order to utilize the costly solar cells and the available solar energy. Each component of the system possesses a conversion efficiency; the over-all efficiency of the system is the product of all the individual efficiencies of the single components. The final system efficiency, therefore, may be only a few percent. By increasing the efficiency of each component and matching the components, the system efficiency can be improved. The word "matching" in this context means also adapting , fitting , or optimizing; and the word "component" means here not only actual components or hardware components, but also parameters or characteristics.

The talk will give an overview of photovoltaic systems (PV), will list the different system components and the matching of some components, and, finally, will describe three MW grid-connected Photovoltaic Systems.

PHOTOVOLTAIC POWER GENERATION

The photovoltaic power system can be divided into three categories·

1. Specialized application - discrete power;
2. Village electrification; and
3. Central power stations - a) peak power demand;

   b) bulk power generation.

Another subdivision of these categories may include:

A. Stand-alone systems;

B. Stand-alone systems with grid or diesel generator backup; and

C. Grid interactive systems.

Photovoltaic power systems are most commonly used to-day for specialized applications in which their relatively high cost can be justified. These applications are remote, stand-alone power systems serving discrete energy demands:

- Remote microwave repeaters;
- Water pumping and irrigation;
- Consumer products;
- Navigation aids;
- Telemetry stations;
- Road & track signaling;
- Lighting;
- Water electrolysis;
- Seawater desalination;
- Water disinfection; and
- Residential homes.

In these applications, PV power systems can be the least expensive due to long-distance grid lines or on-site power supply, such as storage batteries or fuel-burning engine generators. This remote, discrete power market is limited in size. A potential larger market, but still economically justified, is supplying power to small isolated villages in developing countries. PV power systems can be attractive in such places due to low maintenance and no need of fuel. The potential market for village power systems is considerably larger than that for remote discrete power systems.

The next step of PV power applications is by central power stations. These applications may be divided into near and far terms. The near term application is using PV power for peak load demand and the far term application is using PV power for producing bulk energy,serving a s supplementary power. This is the largest potential market for solar cells.

The utility's approach to PV power generation is:

. Utilities generally decide on the installation of a new generating plant on the basis of life-cycle cost of 20-30 years; to-day's modules are predicted to last only 10 years.

. Changes in full price could affect the outlook for PV systems either favorably or unfavorably.

. For PV systems to be able to make a significant contribution of energy, the cost of electricity from such systems must be competitive to other new generation options.

. PV power systems are currently much more expensive than other comparable utility options. Current prices for PV modules are in the range of $5. to $7/W; module efficiency 8 - 10%.

. Module efficency for utility power generation should exceed 15%, the levelized cost to be about 15¢/kWh, and a module cost of about $\$100/m^2$ (in sunny locations).

SYSTEM COMPONENTS

A PV system may include actual and other types of component factors:

Climatic conditions;

. Solar cell spectral response;

. Solar cell efficiency, cost and climate relations;

. Energy collection mechanisms;

. Land;

. PV array deployment;

- Power conditioning;
- Storage batteries;
- Transformers; and
- Loads.

If η_i denotes the efficiency of a individual component, the over-all system efficiency is $\eta_{Total} = \prod \eta_i$.

Climatic Conditions

The climatic conditions prevailing at the site of a PV installation is the most important criterion in a PV system design. The climatic conditions include:

a) Annual solar insolation distribution;

b) Ratio of direct/global insolation;

c) Ratio of diffuse/global insolation;

d) Temperature; and

e) Wind.

The amount of direct and diffuse insolation at the site of the PV installation dictates whether to design a flat-plate or a concentrating system. A high ratio of direct/global may favor a concentrator system whereas a high ratio of diffuse/global will favor a flat-plate system. Higher temperatures affect adversely the PV power output, and the wind speed decreases the cell temperature. An example of mapping the solar radiation in the U.S. is shown in Fig. 1.

Solar Cell Spectral Response

The portion of the energy from the total available solar energy that is converted to electricity by the solar cell as a function of the wave-length defines the solar cell spectral response. Fig. 2 shows the spectral response for different solar cells.

Solar Cell Efficiency, Cost, and Climate Relations

For a PV system to be economically justified, the cell efficiency, cost, and PV system location are interrelated. Fig. 3 shows the effect of the required module (or system)efficiency on the model cost for Albuquerque, Miami, and Boston. In order to achieve the target of 15¢/kWh and for the cost of $\$100./m^2$ for the modules, the module efficiency should be 15%, but the installation at Miami should have a model efficiency raised to about 21%, and when the insolation is even lower as in Boston, the required module efficiency should be even higher - about 26%.

Energy Collection Mechanisms

There are two basic photovoltaic array systems: flat-plate and concentrator systems. The flat-plate system may operate either in a stationary or tracking mode. A concentrator system operates in a tracking mode. A tracking system may be either one-axis or two axes.

Stationary mode The PV array is installed with the desired tilt and azimuth angles. These angles may be optimal according to the policy of desired collected energy. The possible optimal angles are:

- Yearly optimal angles;
- Seasonal optimal angles (e.g. summer, winter) fixed or adjustable; and
- Hour of the day optimal angles (e.g., forenoon, afternoon, either for summer or winter).

The yearly optimal angles result in maximum collected annual energy. The summer,or winter, on any desired seasonal angle results in maximum collected energy for that season. In both of these cases, the PV array is facing south (in the Northern Hemisphere) for the optimal azimuth angle. The optimal tilt angle depends on the season. For the hour of the day installation angles of the array, the optimal tilt and azimuth angles are derived from maximum collected energy for the desired number of hours during the day.

Tracking mode Tracking systems may be divided either into two-axes or one-axis. In two-axes systems, the PV array tracks the sun during the day by varying both the tilt and azimuth angles that are always optimal. In the one-axis sytem, several possibilities exist; e.g., (a) horizontal axis fixed in the N-S direction with the PV array rotating 90^{0} in the E-W direction;

(b) tilt angle preset (e.g. latitude) and tracking in the azimuthal (vertical axis) E-W direction.

Land

The topography of the land and the available land area may have an effect on the decision about the tracking mode. Two-axes tracking requires more land area per kilowatt in order to avoid interference and shading. Higher power density (kilowatt/m^2) can be achieved for fixed and single tracking flat-rate collectors.

Inverter

The inverter cost, input voltage (including a voltage window), efficiency and power rating are interrelated. Fig. 4 shows an example of the selling price (Dollars/kW) versus the dc input voltage. The optimum input voltage is 2000 V for the 5 MW inverter.

Load Matching

Two examples of load matching will be mentioned here. One is a storage battery matching in a stand-alone system, and the other is a matching between the daily solar insolation peak and the electric peak deman in a grid-connected system. Fig. 5 shows the load line of a storage battery of 120 V and an appropriate PV array, including the array maximum power line. In order to judge the quality of the battery matching to the PV array, a utilization efficiency factor is defined by the ratio of the battery input power to the maximum array output power for different insolation levels. Fig. 6 shows the battery input power P, the maximum array output power P_{max} and the utilization efficiency η_G, as a function of the percent insolation of one sun. The figure shows that a 20 Volt battery matches well the PV array since the battery line P follows very closely the array P_{max} line; the utilization efficiency η_G is close to 100% for a wide range of insolation levels.

For most utilities and other grid-connected users, the peak demand is in the afternoon, whereas the peak solar insolation occurs at noon. A matching between the electric peak demand and the solar insolation may be accomplished by shifting the azimuth angle of stationary PV arrays west of south in the U.S. A 60^{o} shift in azimuth (35^{o} latitude) west of south has a corresponding time shift of 1 hour and 40 minutes in summer, and a time shift of hour and 20 minutes in winter. This is illustrated in Fig. 7 for three periods during the year. This time shift of the peak power is associated with a small gain in the total energy collected in the summer, but with a higher loss of the total energy in the winter. This energy change is shown in Fig. 8. The tradeoff between the loss in the total energy against the improved match of the insolation peak to the electrical demand peak is taken into consideration in the design of the PV system.

MW GRID CONNECTED SYSTEMS

Three megawatt grid connected systems will be described in the following pages - the LUGO substation at Hesperia, California, the SMUD system of Sacramento Municipal Utility District, and the CARRISA PLAINS PV System. The matching of daily solar insolation peaks (at the afternoon hours) to the electrical peak demands of the utilities are shown in Figs. 9, 10 and 11. The conclusions drawn from the performance of these systems are:

1. The PV system power output matches well with the demand of summer peaking utility;
2. The PV system has proven to be a reliable energy producer over the

period of experience with it;

3. The PV system has low operation and maintenance expenses.

LUGO-1MW

(Substation at Hesperia, California)

Nominal Capacity	1.0 MW DC
Design Type	Two-Axis tracking (Elev. Azi) Plat-Plate 32×32 ft-9KW DC 108 pedestals, 25m space Microcomputer Controlled/ Computed sun position
Operation Data	Feb. 1983
Owner	Arco Solar, Inc.
Utility Interconnection	Southern California Edison Co (SCE), 12 kV
Land Area	8×10^4 m^2
Power Conditioner	1000KVA Line Commutated Inverter or 2×500KVA Self Commutated Inverter ±240V DC/480V, 3~ 60Hz
Transformer	480V/12kV λ/Δ 1MVA

SMUD-100MW

(Sacramento Municipal Utility District, CA)

Nominal Capacity MW DC	1.2 (PVI)
Design Type	One-Axis tracking flat-plate 112 arrays, 8×16 ft (N-S)
Operation Data	July 1984
Owner	Sacramento Monicipal Utility District
Utility Interconnection	Sacramento Monicipal Utility District
Cost	$ 3.2 Million/MW(1982 dollars)
Power Conditioning	1.2 MVA; 12 pulse line-commutated inverter, MPPT, <3% distortion 570-700 operation voltage window
Interconnection	12.5kV distribution network

CARRISA PLAINS– 16.5MW

(SAN LUIS OBISPO COUNTY, CA)

Largest PV central station power plant in the world

Nominal Capacity First Stage	6.44MW DC, 5.79MWAC
Design Type	Two-axis tracking flat-plate with mirror enhancement eigh 1.2×4.8m PV panels + 1.2×4.8m silver glass reflector plates mounted at 60°

total collector surface of each array 10×11 m

reflector increase intensity by 80% results in energy increase 50%. computer controlled

3 subfields

84 trackers/ field

Operation Data	Dec. 1984
Owner	Arco Solar ,Inc
Utility Interconnection	Pacific Gas and Electric Co.
Land Area	64×10^4 m^2
Power Conditioning	±480DC/480V AC, 3~,60Hz 750kW/ Subfield
Transformer	480V/12kV
Step-up Transformer	12kV/115kV to Transmission Network

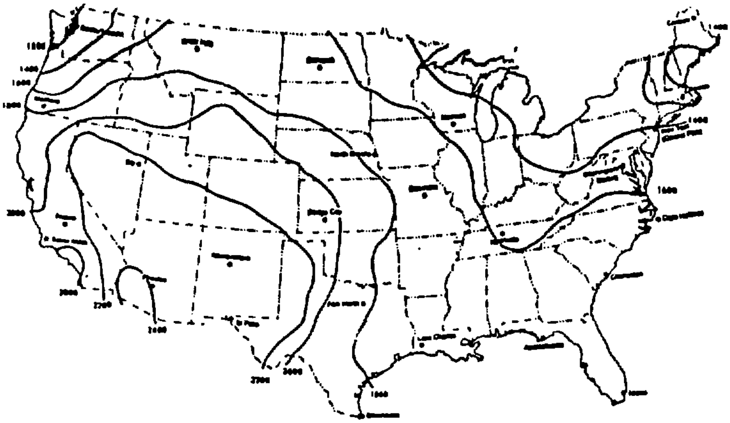

Fig. 1. Average annual solar radiation on a south facing surface at latitude tilt (kWh/m^2-yr)

M. G. Thomas and G.J. Jones, "Grid-Connected PV Systems: How and Where They Fit" 17th Photovoltaic Specialist Conference, pp. 991-996, 1984.

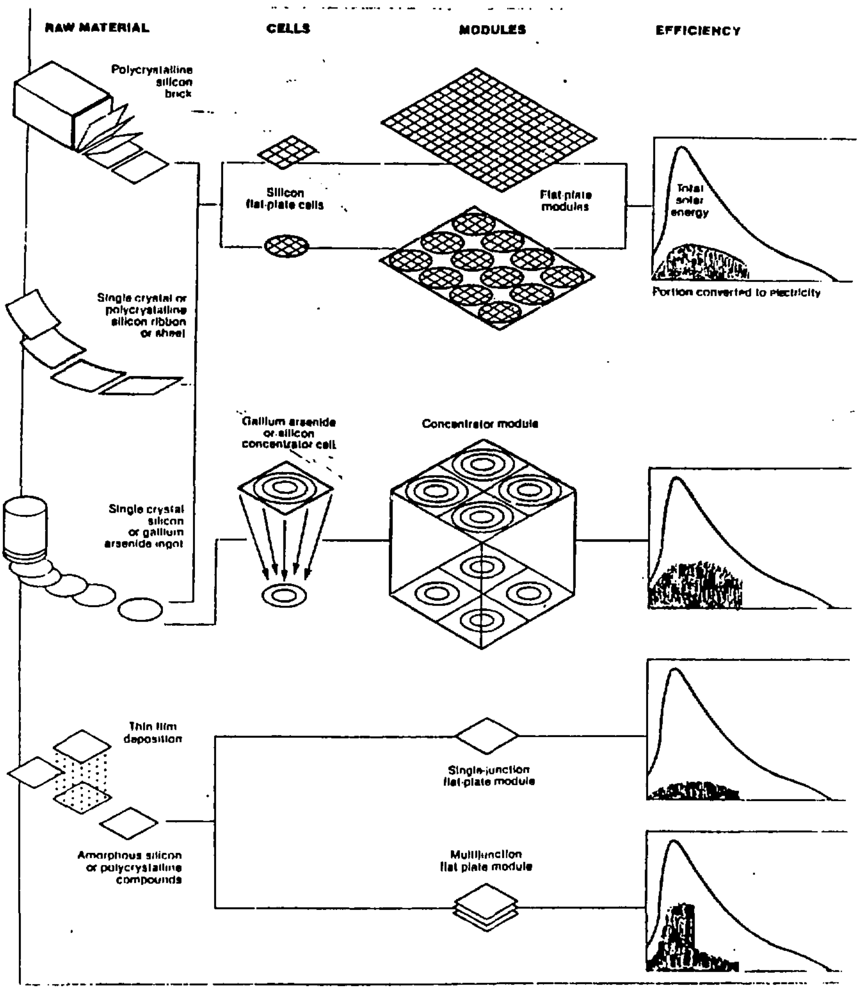

Figure 2. Solar Cell Spectral Response.

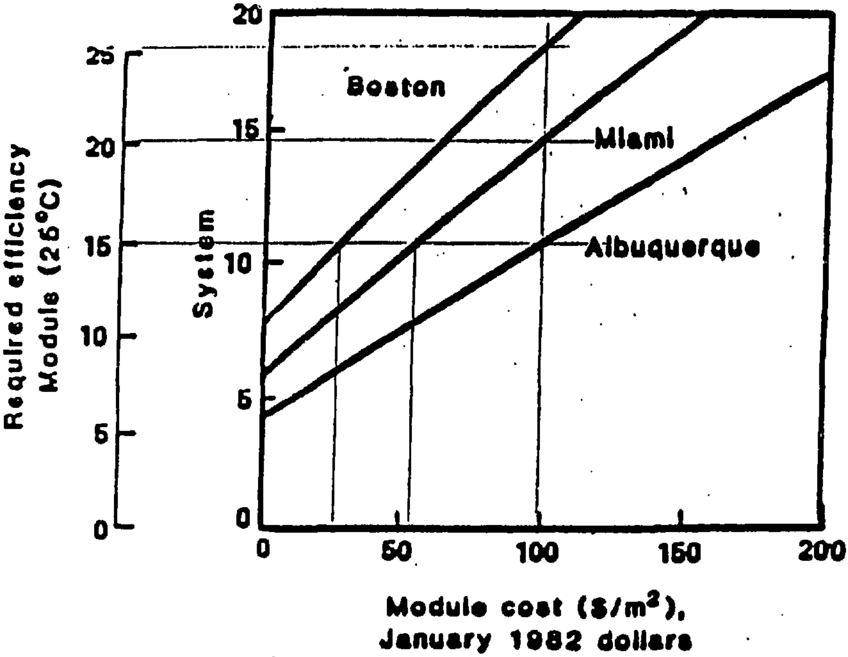

Figure 3. **Required efficiency versus cost for fixed flat-plate systems**

Photovoltiac Power Systems Research Evaluation, EPRI AP-3351, December 1983.

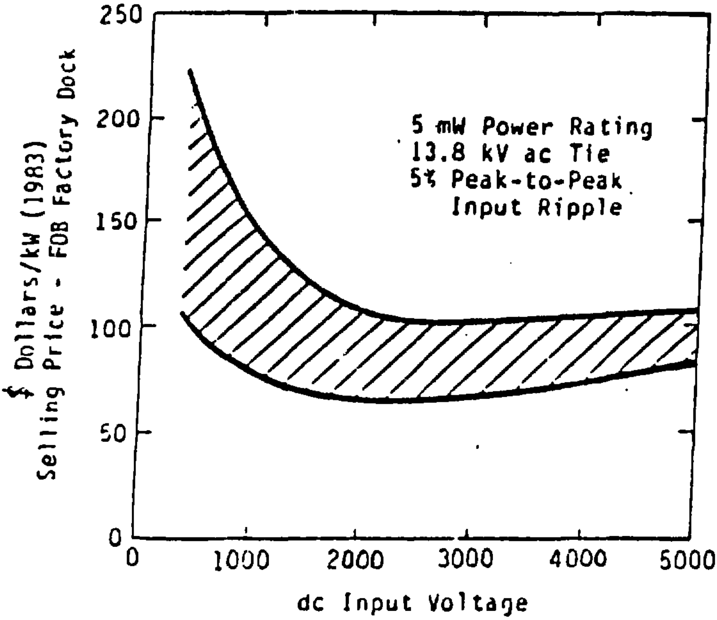

Fig. 4. Range of SMW inverter cost as a function of input DC voltage.

D. Chu and T.S. Key, "Assessment of Power Conditioning for Photovoltaic Central Power Stations", 17th Photovoltaic Specialist Conference, pp. 1246-1251, 1984.

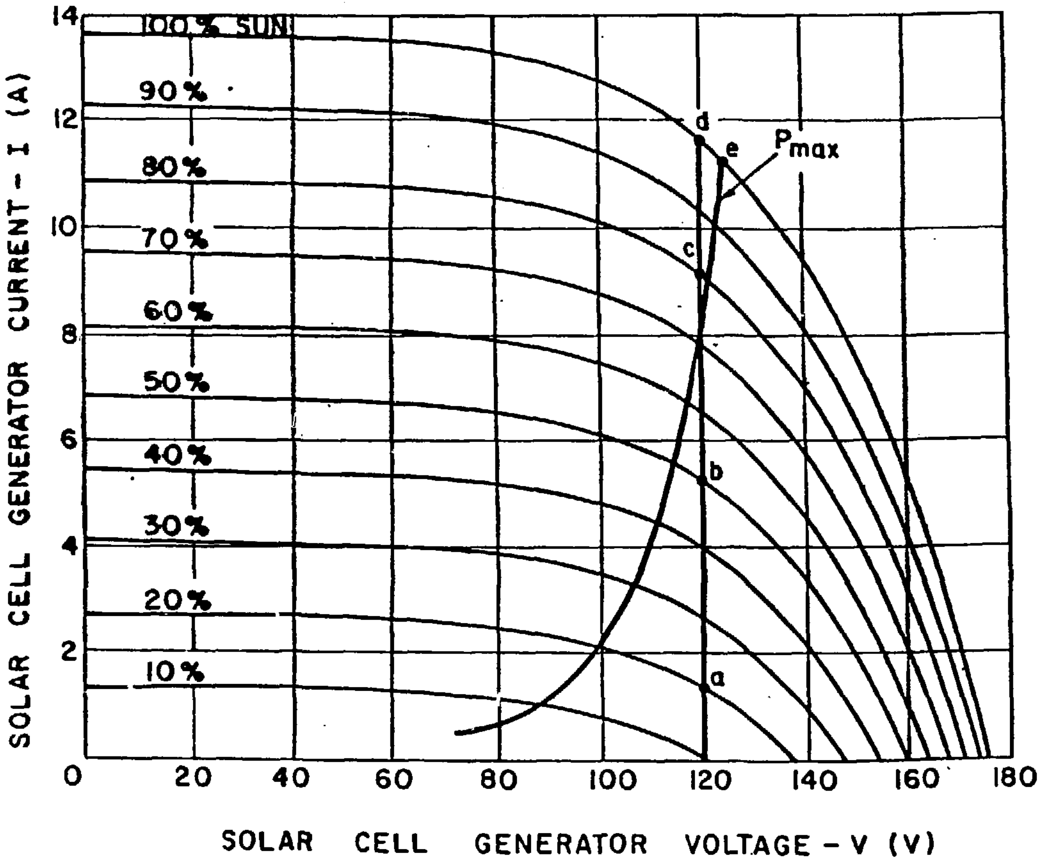

Fig. 5. Storage Battery Load.

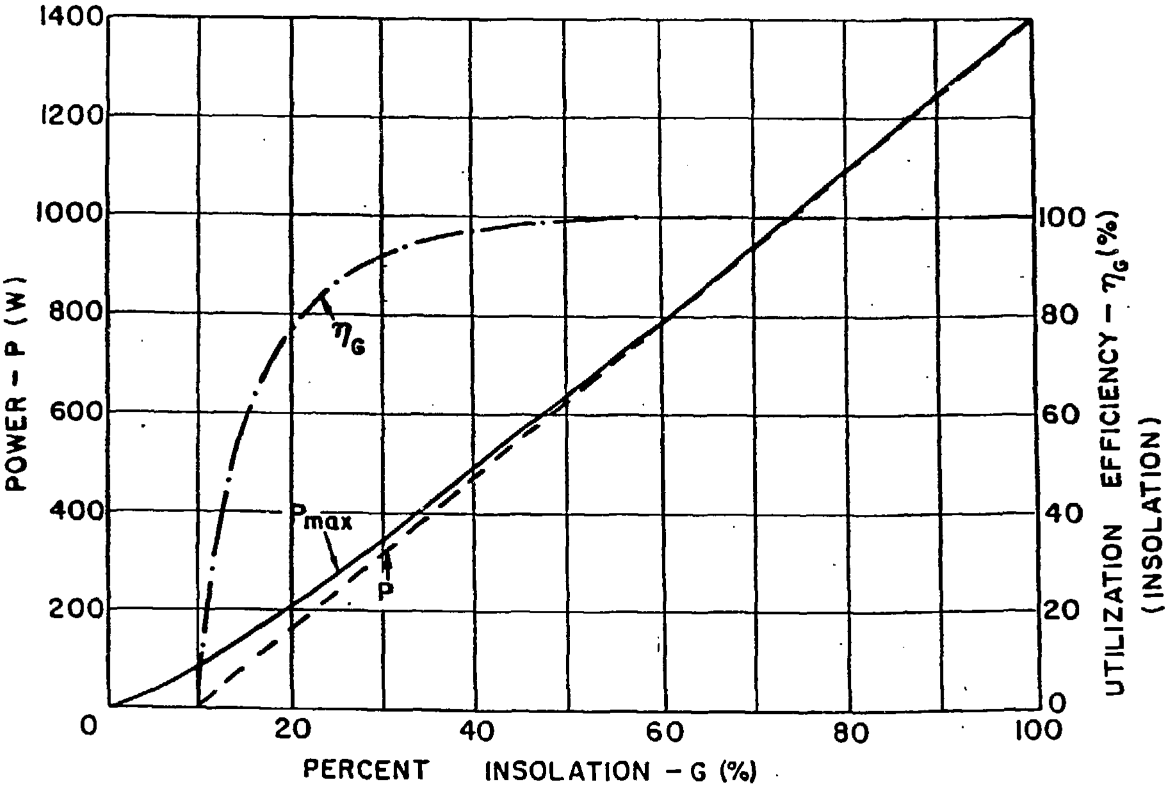

Fig. 6. Storage Battery Utilization Efficiency.

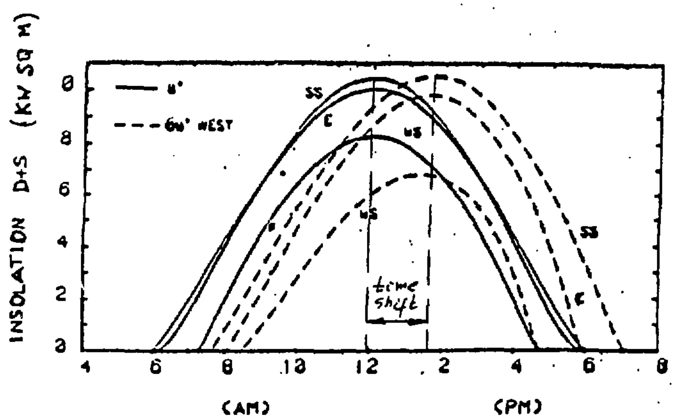

Fig. 7. Solar insolation, both direct and scattered $(D + S)$, plotted as a function of time during the day, for the three periods during the year, summer solstice (SS), winter solstice (WS) and equinox (E, the same for spring and autumn) and for two azimuth angles, 0° and 60° west.

V.Korsum and A.J. Stranix, "Improving the Match Between the Daily Solar Insolation Peak and Electrical Peak Demand", Solar Energy, Vol. 33, No. 2, pp. 171-174, 1984.

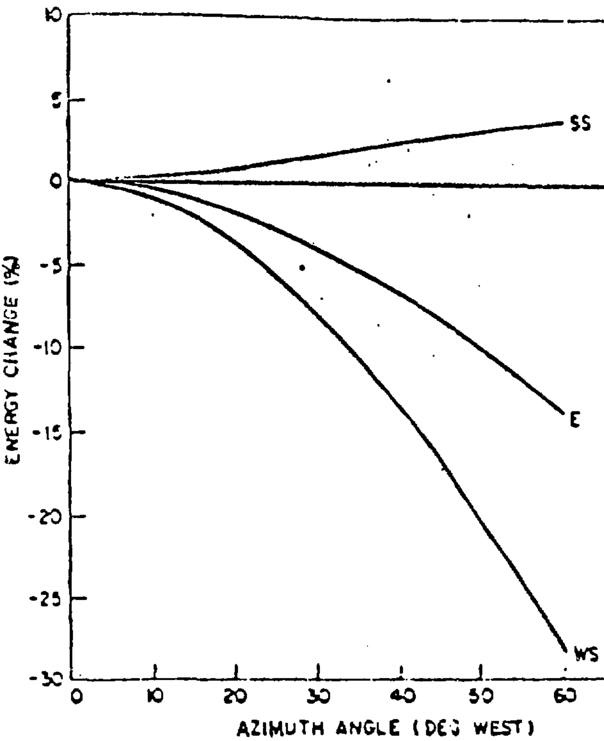

Fig. 8. The percentage change of the cumulative energy compared to the total cumulative energy available at 0° azimuth angle plotted as a function of azimuth angle for the three periods during the year.

V. Korsum and A.J. Stranix, "Improving the Match Between the Daily Solar Insolation Peak and Electrical Peak Demand", Solar Energy, Vol. 33, No. 2, pp. 171-174, 1984.

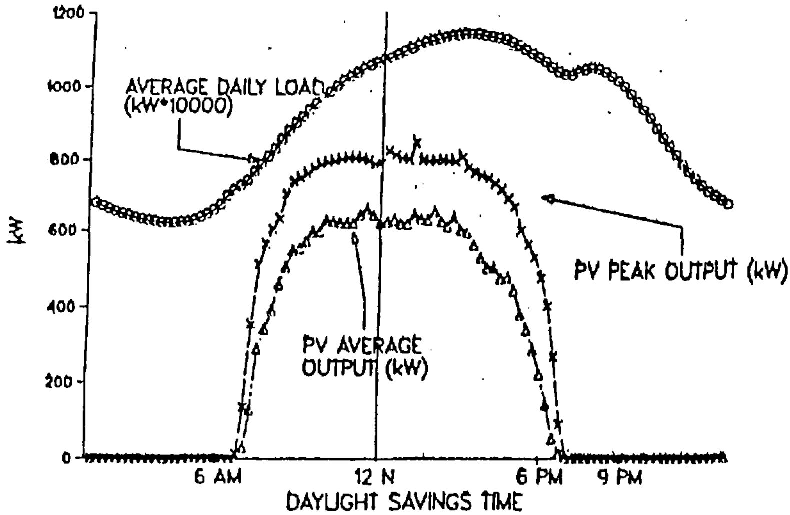

Figure 9. **September 1984 Edison System Average Daily Load (kW x 10^4) and PV Plant Output (kW)**

N.W. Patapoff, Jr., "Two Years of Interconnection Experience with the 1 MW at LUGO, 18th Photovoltaic Specialist Conference, pp. 860-870, 1985.

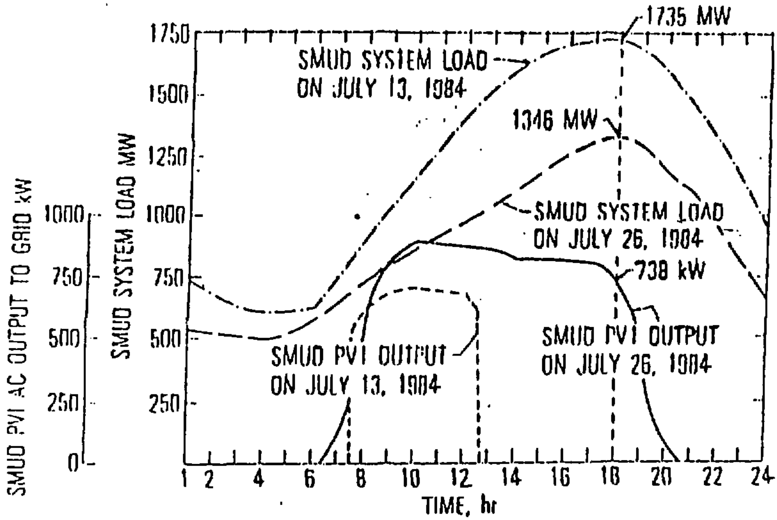

Fig.10: Plot of SMUDPV1 Plant Output and SMUD System Load on July 13, 1984 and July 26, 1984

Special Evening Session on Photovoltaics, New York, IEEE Winter Meeting, Feb. 5, 1985.

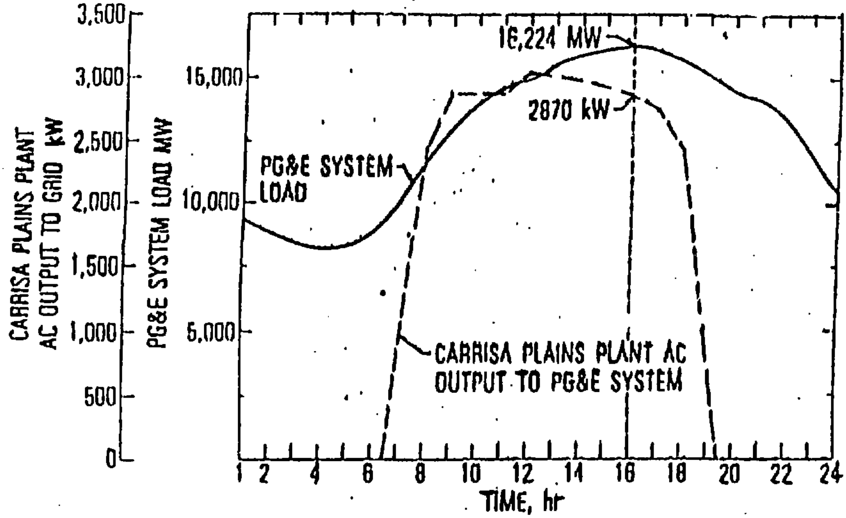

Fig. 11. Plot of Carrisa Plain Plant Output and PG& E System Load on July 13, 1984

Special Evening Session on Photovoltaics,
New York IEEE Winter Meeting, Feb. 5, 1985.

Extracts from the discussion following Prof. Appelbaum's presentation

Roy: I believe that the rating of solar power plants by "peak watts" is misleading. In our poster we show that the delivered power from the largest PV power stations that have been analysed, in no cases fulfil expectations based on the peak power ratings. We have developed what we believe to be a more useful rating index.

Reddy: A peak-watt rating is not necessarily misleading. In the case of photovoltaic panels it provides a number that can be used for what ever calculation purposes one needs. For example, in the poster of Dr. Gordon and myself we present a relatively simple method for computing capacity credit given a few simple parameters - including the peak-watt rating of the PV panels.

Collares Pereira: Misleading or not, a cost per peak-watt rating for a power plant is confusing. Tracking systems are more expensive than stationary ones but they provide more energy. A better comparison would be on a cost per kWh of delivered energy basis.

Faiman: But then we are back to the problem of the value of the energy delivered: i.e. the time of day factor. I was intrigued by the azimuth effect you talked about. All of the power producing systems I know about are designed to be symmetric about a N-S line, e.g. fixed south-facing, tracking about a N-S horizontal

axis, polar axis, etc. From the viewpoint of maximum capacity credit it may turn out that a "not-quite" N-S symmetry would provide the optimal tracking system in certain locations.

EXTENDED ABSTRACTS FROM POSTER SESSION.

SOLAR RADIATION DISTRIBUTION SENSOR

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ABSTRACT

A solar radiation distribution sensor containing a plurality of individual, directional solar radiation detectors (in our case, 24 solar cells), positioned evenly on a semispherical body-member,was designed to intercept directional solar radiation emanating from the sky. In addition, the sensor would supply the common radiation data of the conventional instruments, as well as solar radiation data on various tilts and azimuthal surface angles. The performance of the sensor was tested and compared with the measurements of the standard instruments, and a good agreement was obtained. The sensor may be used by meteorological and research institutions and also in solar energy engineering applications.

INTRODUCTION

A detailed knowledge of solar irradiance on a non-horizontal surface is required in a large variety of solar system applications. Direct measurements of solar irradiance on non-horizontal surfaces are, so far, very sparse, and there are stations that are not equipped with all the different types of instruments needed to meausre global, diffuse,and direct radiation. Although radiation data on various tilt and azimuthal surfaces could be accomplished using the existing instruments, such a station would be very expensive to set up.

This paper describes a solar radiation distribution sensor [1] that is not only capable of supplying the common solar radiation data of the conventional instruments, but, in addition, can also supply at the same time the solar radiation data on various tilt and azimuth angles, as well as the solar radiation distribution from the sky and from reflected surfaces. The sensor is a static, multipurpose, solar radiation measuring instrument, and includes a plurality of individual, directional, solar radiation detectors, oriented radially around a semisphere (or sphere) surface, and individually shielded so as to simultaneously intercept only directional solar radiation. A laboratory prototype sensor, Fig. 1, containing 24 solar cells as detectors has been built, and the computation algorithm for determining the various solar radiation quantities has been derived.

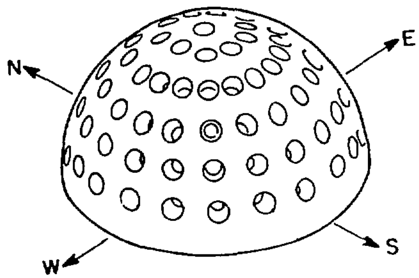

Fig. 1. Semispherical sensor

PERFORMANCE

The performance characteristics of the sensor were tested for a period of a few months, which included days of clear and partly cloudy skies, the location being in the Tel-Aviv area with a latitude of 32^0 06'N, and a longitude of 34^0 48'E. For calibration, comparison of results, and performance analysis of the sensor, three conventional solarimeters were used: EPPLY normal incident pyrheliometer model NIP mounted on a solar tracker model ST3; KIPP & ZONEN solarimeter type CM-5 for global radiation measurements; and KIPP & ZONEN solarimeter type CM-8 equipped with an adjustable shading-ring for diffuse measurements.

The sensor is capable of supplying the following radiation data:

1. Solar beam radiation G_b and its direction $(\alpha,\gamma)_b$ (α - altitude; γ - azimuth);
2. Maximum radiation G_m and its direction $(\alpha,\gamma)_m$ emanating from the sky;
3. Global radiation G_h on a horizontal surface;
4. Diffuse radiation G_{dh} on a horizontal surface;
5. Global radiation $G(\beta_s, \gamma_s)$ *on any desired tilted* - β_s *and azimuthal* - γ_s surface;
6. Diffuse radiation $G_d(\beta_s,\gamma_s)$ on any desired tilted - β_s and azimuthal - γ_s surface;
7. Directional distribution of radiation from the sky and from the reflected surfaces $G_i(\alpha, \gamma)_i$ in the direction of the detectors; and
8. Cloud index, CL = G_{dh}/G_h, which is the ratio of diffuse to global radiation on a horizontal surface; and the sky cloud coverage percentage.

The following two figures describe part of the sensor's performance. The measured global irradiances on different surfaces on the clear day of March 6, 1985, at 10:45 solar time, when the sun was at the altitude of 48^o and azimuth of 153^o, are shown in Figs. 2 and 3; Fig. 3 also includes the ratio of the global irradiances on a tilted surface to a horizontal surface, $G_{tilt}/G_{horizontal}$.

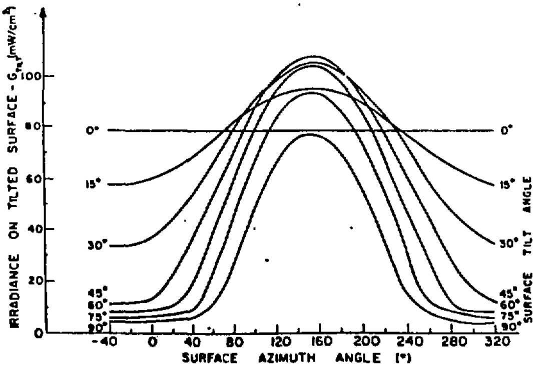

Fig. 2. Global irradiance on tilted surfaces as a function of the surface azimuth angle.

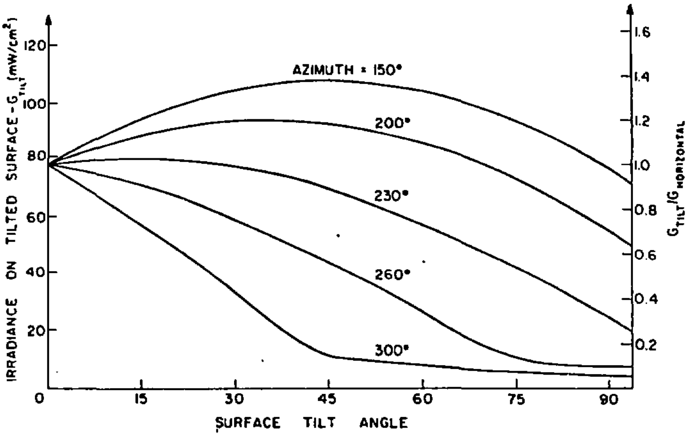

Fig. 3. Global irradiance on tilted surface as a function of the surface tilt angle.

REFERENCES

1. J. Appelbaum and R. Weiss, "Solar Radiation Sensor and System Including Same for Measuring Solar Radiation Distribution", United States Patent, No. 4,491,727, Jan. 1, 1985.

On the Spectral Response of GaAs Photovoltaic Devices

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The importance of obtaining the spectral response is related to both theoretical and practical purposes. The spectral response can provide information regarding the short circuit current, and the quantum efficiency of the photovoltaic device as well as information regarding its other electronic parameters. In this work the usefulness of the spectral response distribution as a diagnostic tool is demonstrated. Specifically the spectral response can serve for identifying sources of either deficiencies or merits of the device structure and its material quality. Once those are identified the information obtained can be used for enhancing the device performance in certain desired wavelength regions. Those improvements can then be achieved, for example, by changing the device structure or material parameters, by readjusting certain fabrication procedures, to yield the desired electrooptical performance.

The parameter selected in this work to demonstrate the above diagnostic usefulness of the spectral response in assessing the influence of structural changes is the junction depth (x_j) of a $N^+/P^-/P^+$ GaAs photovoltaic device. The details of this device are given elsewhere.[1] The junction depth of this type of device is known to be an important structural parameter, since it significantly affects all the aspects of device performance. In this case the aim is to experimentally demonstrate the improvements (or the degradation) in the spectral response distribution characteristics as the junction depth is decreased (or respectively increased). Specifically the intention is to determine which parts of the device's spectral response are dominantly influenced as a function of x_j. This can serve not only tutorial purposes, but also to identify trends resulting from changes of x_j in a series of given experiments.

Seven GaAs photovoltaic devices were fabricated under the same conditions and procedures. This was done in order to keep all the structural parameters the same. The only parameter that was deliberately made different in each device was the junction depth, which ranged from 0.075μm to 1.45μm. This was done by varying the thickness of the different top N^+ layers, while keeping the bottom P^- layer at the same thickness within some tolerance. The structural details of the OM-CVD grown devices are given elsewhere[1]. The family of spectral responses is given in Fig. 1. Standard conditions existed during the measurements, i.e. the entire light active surface was illuminated by both the light bias and the various wavelengths. Twenty -one discrete optical filters were used in order to cover the range between 0.4μm to 0.9μm which is adequate for GaAs photovoltaic devices (bandgap 1.43 ev at 300°K). The light bias used was adjusted so that the resulting D.C. short circuit current reached a level which was about the same as the actual short circuit current (I_{sc}) of the device under measurement. The values of I_{sc} were experimentally determined previously using standard test conditions. The irradiation of the device by the various wavelengths was superimposed on the above light bias by a separate irradiation source. The device temperature was kept constant at 28°C, in a regular laboratory environment.

In Fig. 1 one can observe that distinctly different spectral response (SR) curves were obtained for each device. Defining the relative change of the spectral response at each λ as $(SR_i - SR_{i+1})/SR_i$, clearly marked relative changes occurred at almost all λ for most of the devices, as a result of junction depth changes. Specifically, significant improvement occurred throughout the distribution as the junction became shallower. The above SR dependence on x_j demonstrates, for example, that for this device type more short circuit current can be obtained with a proper selection of junction depth, due to a better utilization of the solar radiation in this particular band of wavelengths. The relative changes in the spectral response due to x_j variations are different for short, medium and long wavelengths, and possess different characteristics in the above λ ranges. Significant relative improvements with x_j reduction occurred mainly in the medium λ range while smaller relative changes occurred in the long λ range. In this range some overlap in the various SR exists. The trend in the short λ region in general is of an increase in sensitivity with x_j reduction; however this increase seems to be mixed and less systematic than that of the medium range.

The reasons for the differences in the above cited λ regions are related to three main factors, namely surface recombination velocity, bulk generation/recombination ratios and back surface field. In general these factors exist for all λ, but their relative contributions change with x_j. The overall result is that as x_j becomes smaller, a shift in the contributions of the optically generated minority carriers to the externally collected current takes place. Specifically a relative increase in the contribution of electrons generated at the P^- side over the holes generated in the N^+ side is such that the overall collected current increases with a decrease in x_j. This shift is primarily related to the fact that the penetration depth of the light into the device increases with increasing λ.

Starting with the short λ range, the light penetrates to shallow depths and hence most of the holes in the N^+ side are generated close to the front surface. Therefore many holes are lost due to the high surface recombination velocity there, which is especially high in GaAs. This constitutes a significant part of the losses in this type of device, a fact which explains the low absolute response at the short λ range to all x_j. This loss is decreased as x_j is reduced since fewer holes are generated (and therefore lost) in such a case, due to the reduction in the generation volume of the N^+ side. At the same time, more short λ electrons are now generated at the P^- side due to the increased light penetration there at short wavelength as a result of a reduction in x_j. The mixed trend in the relative change in the SR in the short λ range, as x_j is reduced, is related to sensitivity to the nature of the surface. The surface recombination velocity is affected by many unforeseen factors (such as spurious effects) occurring in the regular surface treatment processes. In addition even slight unintended occasional variations in the GaAs growth termination process (OM-CVD) or surface doping concentration, or surface As/Ga ratio, may affect surface properties, and cause random changes from one device to another in the short λ range.

In the medium λ range, all of the three above mentioned factors interact in such a way that the relative changes in the spectral response at these wavelengths is the highest. In this range the bulk effects which comprise the generation/ recombination ratios at the two sides of the N^+P^- front junction become the most important ones. As x_j is decreased more medium λ electrons are generated deeper in the P^- side (and fewer holes in the N^+ side) because of the enhanced penetration of those wavelengths. This increases the contribution of electrons from the P^- side to the collected current. At the same time the contribution of holes from the N^+ side to the collected current is also increased despite the fact that the generating volume there is decreased as x_j is reduced, resulting in an increase in the $L_p/(x_j - x_n)$ ratio.

As x_j is decreased to values such that $(x_j - x_n)$ approaches L_p fewer electrons are lost due to bulk recombination and hence more of them diffuse to the depletion region boundary (x_n) and are swept to the P^- side, contributing to the collected current. However the relative contribution of the electrons from the P^- side is higher than that of the holes from the N^+ side, since the ratio of minority carrier generation/bulk recombination losses there is higher. This is related to the fact that both the mobility and diffusion lengths of electrons in the P^- side are higher than that of holes in the N^+ side. To be precise, the $L_n/(w_p - x_p)$ ratio in the P^- side is higher tha $L_p/(x_j - x_n)$, w_p *being the metallurgical width of the* P^- *side*. This means that more electrons can diffuse from the P^- side to cross the junction to be collected, than can holes from the N^+ side. At the same time the reduction in the surface losses in the medium λ range, and the simultaneous increase in the influence of the back surface field for this wavelength range bcomes increasingly important. As x_j is reduced, more medium λ electrons (and to a lesser extent short λ electrons) are generated close to the P^-/P^+ back junction. Accordingly more of those electrons are repelled towards the N^+P^- front junction and are collected to produce current. This drastically reduces back surface recombination losses. The combined effects of the relative increase in bulk generation/recombination ratio of the P^- side over that of the N^+ side, and the increasing influence of the back surface field, together with the simultaneous reduction in the front surface recombination losses, are responsible for the large relative change in the various SR distributions at the medium λ range, as x_j is reduced.

In the long λ region the trends regarding the effect of the three above-mentioned factors on the collected current become even stronger. This is manifested by the fact that the various SR curves reach their peak in this wavelength range. However it is noted that the relative change in the various SR in this λ range is somewhat reduced, as compared to the relative changes which exist in the medium λ region. This is because in the long λ range the electrons in the P^- side are generated deep in the P^- side near the P^-/P^+ back junction. Reduction in x_j in such a case, does not cause much change in the number of electrons which are collected, although it causes an increase in their absolute numbers. The result is that as the various SR approach this peak, they possess a somewhat more "crowded" trend compared with the medium range. Finally the fact that in this λ region some of the *distributions* cross each other is *addressed. This is* related *to unintended variations* that exis. in the $L_n/(w_p - x_p)$ ratios from one junction to another. In principle the fact that all the devices are fabricated using the same deposition conditions and procedures should yield the same ratios for all of them. In practice, however, random variations in crystal quality especially near the various P^-/P^+ back junctions exist. In addition, in the above series the values of w_p were not identical but only close within some tolerance. Those factors have maximum effect in the long λ region since the influence of the back surface field in this range is maximised.

It can be concluded that an improvement in photovoltaic device performance should be and, in fact, is pursued, by reducing surface recombination effects, using an appropriate passivation, and by increasing electron lifetime in the P^- side by producing a better material quality there. Enhancement of the internal fields, both near the front and in the back junctions, are also of importance.

1. A. E. Blakeslee, H. Aharoni, M. W. Wanless, A. Kibbler, K. Emery, C. R. Osterwald: "Effect of junction depth on the parameters of GaAs shallow homojunction solar cells." Proc. of the 18th IEEE Photovoltaic Conf. Las Vegas, Nevada, Oct. 21-25, 1985, pp. 146-150.

Acknowledgement

The author would like to thank Mr. C. R. Osterwald for performing the spectral response measurement, at the Solar Energy Research Institute, Golden, Colorado, U.S.A.

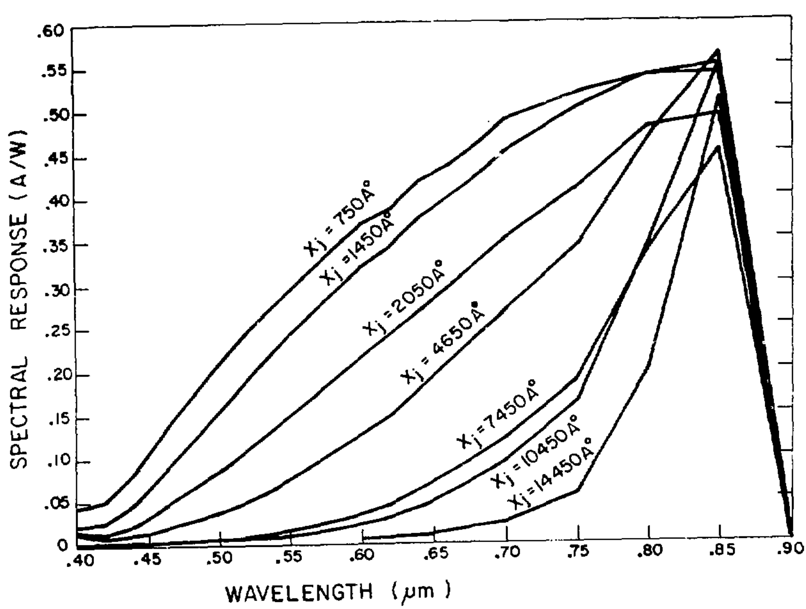
SPECTRAL RESPONSE (A/W)
.60
.55
.50
.45
.40
.35
.30
.25
.20
.15
.10
.05
0
.40
.45
.50
.55
.60
.65
.70
.75
.80
.85
.90
WAVELENGTH (μm)
Xj = 750Å
Xj = 1450Å
Xj = 2050Å
Xj = 4650Å
Xj = 7450Å
Xj = 10450Å
Xj = 14450Å

Fig. 1

EXTRACT FROM

PRACTICAL EXPERIENCE WITH SOLAR PONDS

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Yavne, Israel

Description of the 5MWe SPPP at Beit Ha'Arava

The Beit Ha'Arava plant is located close to the original site of the "Dead Sea Works". It was decided that the pond should be 0.25 sq.km in area with the option of increasing this to 1 sq.km.

Naturally, upscaling a pond by a factor of 40 would introduce problems; the decision was therefore taken to increase the size in two steps, i.e., by a factor of 6.4 to a pond area of 4 ha, and then by a second factor of 5.25 to a pond area of 21 ha, making the total pond area 0.25 sq.km.

As a preliminary exercise, four pilot ponds, each with a 400 sq.m bottom and 2.5 m deep, were built to test methods of sealing for local site conditions and to investigate heat loss from the bottom. It was found that the heat loss to the ground was small due to the low thermal conductivity of the ground (0.5 W/m deg. C) and the slow movement of underground water. Moreover, a new sealing technique, referred to in detail below, was developed during this pilot exercise.

The construction of a 4 ha pond started in September 1981 and was completed the following June when the brine filling process began. This was completed in August 1982. By April 1983, a temperature of 102°C was reached and heat was withdrawn to prevent overheating. The construction of the 21 ha pond was delayed until February 1982 due to unexpected rain in the Dead Sea area during January through March which slowed down construction work. Thus, although the pond was finished by November 1982 and filled by June 1983, the heating process was delayed by much longer than the lost two months due to the annual solar cycle.

The ponds in this installation are six to 34 times the size of the Ein Bokek pond. Thus the extraction of heat by decanting the bottom layer on the pond has had to be re-optimized, involving path flow lengths very much larger than before. But the theory has held up and no serious difficulties have been encountered.

The same methods for suppression of upper-layer mixing due to wind were used here as in the Ein Bokek pond, i.e., floating plastic nets, though the anchoring of these nets has had to be re-optimized, leading to cable lengths of 700 m for the large pond (80 m for the Ein Bokek pond). The upscaling has also required advanced technology for establishing the density gradient, (first in the 4 ha pond and subsequently in the 21 ha pond. Based on the Ein Bokek experience, cooling for the condenser is obtained from a cooling pond in combined use with the surface water of the pond.

As ponds are made larger, the cost per unit area is expected to decrease because a major expenditure is on the civil engineering work, mainly on building the walls. This was confirmed in the larger pond, though an additional factor in reducing costs was the development of a new, low-cost method for lining such ponds. Lining costs dropped from $12/sq. m (1982 exchange rate) for the Ein Bokek pond to $6/sq. m for the new ponds, with a further drop expected in the future.

A 5 MWe power plant has been designed and built by Ormat Turbines Ltd (Figure 8). The construction started in May 1982 and was completed in 1983. After one-half of the evaporator was installed, a rest at half-load began and is proceeding satisfactorily. In particular, parasitic energy losses, including brine and cooling circulation pumps, have been found to be within the predicted range of 20-25%.

The motive fluid used is Freon 114. The single-stage quadruple-flow turbine is directly coupled to a 3,000 rpm 50-cycle 6,600 V synchronous generator (Figure 9). The tube-and-shell heat exchangers (Figure 10) have been optimized using specially developed computer programmes to minimize the temperature differential and pressure drops, keeping parasitic pumping losses (brine and water) below 15%.

Table 1. Principal Design Characteristics of the Beit Ha'Arava Plant

Brine inlet temperature	85°C
Brine flow rate	10 million litres/hour
Cooling water inlet temperature	27°C
Cooling water flow rate	10 million litres/hour
Turbine inlet temperature	75°C
Turbine inlet pressure	118 PSIA
Condenser temperature	34°C
Vaporizer heat load	243 MBTU/hour
Condenser heat load	224 MBTU/hour
Turbine stage efficiency	83%
Turbine mechanical efficiency	92%
Generator efficiency	96%
Gross power plant efficiency	7.12%
Generator output	5,070 kW
Parasitic loads	
Fluid feed pump	350 kW
Hot brine pump	370 kW
Cooling water pump	320 kW
Various	30 kW

After operational tests in 1984, when the Beit Ha'Arava plant was connected to the national grid, the SPPP began its first full year of operations in 1985 as a peaking plant. During that year it accumulated more than 1,000 operating hours. The pond collection efficiency is higher than that of the Ein Bokek pond. From Table 1 and 2 summarize the performance of the two ponds from May 1985 to August 1985, and show that measured efficiencies approach 22% at 87°C.

Table 3. Costs and Other Economic Factors

(Beit Ha'Arava Plant)

Solar pond cost	\$12/sq.m (1983) \$ 8/sq.m (1985) \$ 7/sq.m (1987
Power system cost	1983: \$1,200/kW installed 1987: \$ 900/kW installed 1990 on: \$ 500/kw Installed
Pond water requirements	3 million cubic metres per year per square km, at 6 cent/cu.m for the 1980s; 2.5 million cu.m/year sq.km at 3 cent/cu.m for the 1990s.
Forced Outage Rate (FOR)	Based on cumulative experience in operating experimental SPPP, on comparative figures for conventional power stations (Edison Electric Institute), and on analysis of performance and availability of condensers, heat exchangers, and pumps of IEC power-generating stations along the Mediterranean coast and the Red Sea, as well as Dead Sea Works pumping installations a common figure of FOR = 2% has been chosen for all sizes of SPPP.
Planned Maintenance Days	Based on the above, an average figure of 28 days per year has been chosen.
System Plant Factor	Based on the above, a figure of 82% is used.
Annual Interest Rate	6%
Life	30 years
Capital Recovery Factor	7.26%
Fixed Charge Rate	7.86% (including 0.6% insurance)

Conclusions on SPPP

The Ein Bokek pond has illustrated that a well-built and well-managed solar pond can function successfully for many years (1978 to 1985. The Beit Ha'Arava ponds have illustrated that a SPPP can be built and properly maintained and operated. Economic feasibility depends upon local conditions, in particular the cost of alternative energy supplies in the area, as the cost of electricity produced varies between US $0.16/kWh for a first-generation peaking SPPP to US $0.07 for a third-generation base load plant.

The solar pond power plants can be coupled into a grid system, and their value is enhanced by their utilization as peaking installations. However, solar ponds can also be used as stand-alone plants (of particular interest in areas remote from a grid) primarily because of the built-in storage capability as illustrated in the Ein Bokek installation.

ASCU 87/10

A Method for Monitoring Insolation in Remote Regions

by
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Abstract

A method is proposed for measuring the beam and diffuse components of solar radiation via the use of a set of fixed pyranometers tilted in various orientations. A detailed error analysis was performed for the two cases of 3 and 4 pyranometers and it was shown how orientations may be found such that the resultant errors on the derived beam and diffuse components may be expected to be of comparable magnitude to the errors associated with the pyranometers themselves. Attention was drawn to the fact that certain anisotropic models for the diffuse component may be recast - via the definition of "effective" beam and diffuse components - in such a manner that they take on the mathematical simplicity of an isotropic model.

Anisotropy of the diffuse component

The idea that simultaneous readings of a multipyranometer (MP) system can be used to disentangle the various components of solar radiation on inclined surfaces has already found some interesting applications. In fact, the information obtained from a fixed MP system [1,2] or from a rotating MP system with fewer sensors [3] has been used to deduce the angular distribution of the diffuse component. Since the present circumstances entail long-term monitoring in remote regions it is desirable to restrict one's attention to the simplest of possible configurations: a small number of pyranometers and no moving parts. Moreover, here, the emphasis is not on obtaining angular distribution data but, rather, to derive reliable values for the beam and diffuse components of the solar radiation. Of course, some simplifying assumptions concerning the angular distribution will accordingly have to be made: the most convenient of which being to assume isotropy for the diffuse radiation. However, numerous studies [2-4] have shown that such an assumption is often too crude, leading to considerable errors in the prediction of global irradiance on inclined surfaces. Indeed, Hay and Mckay [4] have recently reviewed various attempts to include anisotropic effects in the calculated irradiances. Out of the large number of proposed prescriptions, the anisotropic models of Hay [4,6] and Perez [5] were found to provide a relatively accurate account of data measured over a wide range of orientations and tilt angles. As is shown in ref. [7], a particularly attractive feature of Hay's anisotropic model is that it can be considered as an effective "isotropic" model. This means that with a proper modification of the terms "beam" and "diffuse" components, a simple formulation in terms of an isotropic model can be used, without the loss of accuracy which is usually associated with this kind of assumption. Moreover, Hay's anisotropic model establishes simple relationships between the conventional values of the beam and diffuse components and their effective values. Consequently, one can easily transform from one set to the other and compare, thereby, the results with direct measurements. These properties make Hay's model particularly convenient for our application.

The new procedure meets obvious difficulties when the sky is partly cloudy. In such circumstances the angular distribution of the radiation can be highly anisotropic, changing rapidly as the cloud patterns move with the winds. One notes, however, that under such conditions the evaluation of irradiance on inclined surfaces encounters the same difficulties, even if the beam and diffuse components are measured by conventional means, since the same assumptions concerning the angular distribution are required.

The Method

The extraction of what may be termed the "effective" (as opposed to the true) beam and diffuse components from pyranometer measurements taken on a set of fixed, tilted surfaces is based on an appropriately defined isotropic model. In this model, the irradiance on each surface is a linear combination of the effective beam and diffuse components with coefficients depending on solar geometry, surface orientation and albedo. These equations may be readily inverted to yield the radiation components from the irradiances measured by each of the pyranometers. To reduce the sensitivity to measurement errors, more than two pyranometers should be used. The problem becomes over-determined, and the method of linear Least Squares can be invoked to obtain the most probable values. The same method also provides estimates of the statistical variance of the derived components as a function of the intrinsic measurement errors associated with the individual pyranometers. The formal derivation is given ref. [7].

The resulting covariance matrix depends on the MP geometry and, for certain solar orientations, may become singular. Therefore, special care must be taken when determining the number and orientations of the pyranometers. Strictly speaking, the concept of an optimum geometry is not well-defined since the error matrix changes rapidly with the sun's position. However, a reasonable approach would be to eliminate the singular and nearly-singular geometries, reducing thereby the associated sensitivity to measurement errors. When applying this kind of strategy, one calculates the variance matrix during the course of a few typical days which represent the solar trajectories in the various seasons. Identifying the singular geometries, it is a simple matter to modify the instrument orientations so as to eliminate these singularities. For a small number of pyranometers the process may be carried out by trial and error; in practice one can find a non-singular configuration after a few tries.

Having thus found the optimum orientations for any given number of pyranometers, the next step is to complement the geometrical considerations by actual measured beam and diffuse data (obtained by conventional methods). These data are used in order to simulate the (half-hourly, say) insolation that would be observed by each of the fixed pyranometers. Assuming a certain measurement error intrinsic to each of the latter instruments one computes the compound error that would be introduced by reconstructing beam and diffuse components from the several pyranometer readings. On the basis of these errors one may judge whether the performance of the system is sufficiently accurate or whether the number of the instruments must be increased.

At this stage one may vary the assumed albedo in order to study the sensitively of the results to this effect. It may then be deemed desirable to modify the previously obtained optimum configuration in order to minimize the over-all sensitively to albedo. In practice it will often be possible to artificially fix the local albedo at the site of the detection instruments in order to minimize the uncertainty in the final measurements. In places where variations in the albedo are expected to be large (e.g. due to snow), one may limit these variations using an artificial horizon. Alternatively, the albedo can be determined from the data themselves.

Detailed numerical studies [7] show that a three pyranometer setup cannot provide sufficient accuracy if the setup has a fixed orientation for the whole year. However, with four fixed pyranometers it is possible to reconstruct beam and diffuse components with a degree of precision comparable to that obtainable from a single instrument. This should overcome the impracticality of using standard tracking instruments in locations where their regular adjustment is not feasible.

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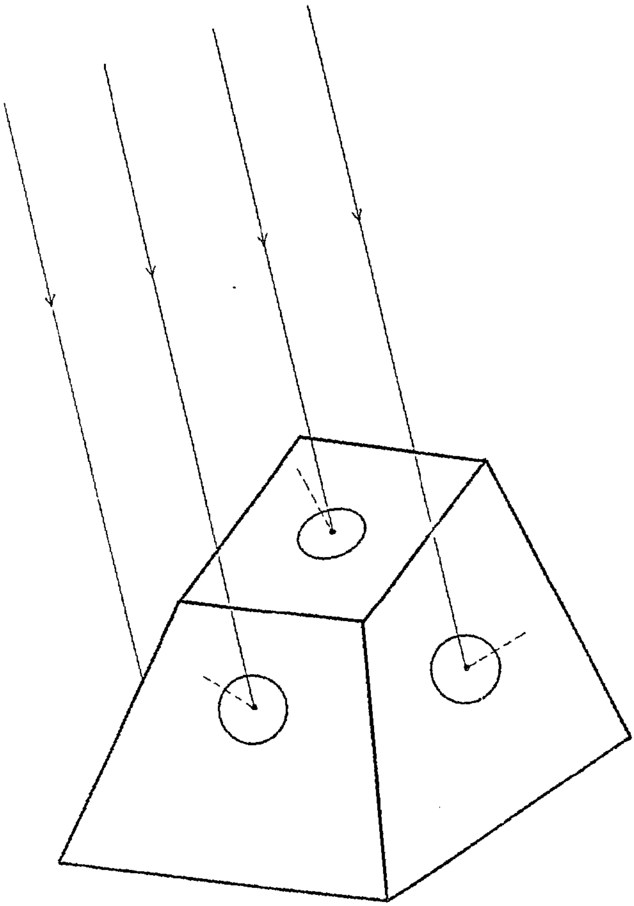

Half hourly averages (in W/sq. m) of insolation observed at Sede Boqer for Jan. 15, 1983 (measured using conventional instrumentation) and expected standard errors for the four-pyranometer configuration (assuming 5% pyranometer error for each instrument)

1	Beam 2	3	Diffuse 4	5
Solar time	Observed value	Expected error	Observed value	Expected error
7:15	3.8	0.8	11.8	0.4
7:45	159.3	8.8	74.3	2.4
8:15	3.9	4.3	92.6	3.0
8:45	292.5	13.6	106.5	3.5
9:15	494.1	19.3	124.2	4.4
9:45	502.2	20.3	173.9	6.1
10:15	459.6	19.9	193.1	6.6
10:45	146.5	17.6	340.0	10.1
11:15	1.3	15.4	318.9	9.9
11:45	31.2	19.5	379.7	12.0
12:15	230.2	22.3	314.7	10.9
12:45	540.0	23.1	197.2	7.8
13:15	661.6	24.7	174.1	7.1
13:45	531.5	22.6	285.1	9.8
14:15	286.1	17.1	252.7	7.9
14:45	621.4	22.3	152.4	5.8
15:15	65.1	9.3	179.5	5.6
15:45	53.9	7.4	134.7	4.3
16:15	80.2	5.8	62.5	2.1
16:45	2.2	1.3	27.1	0.9

Half hourly averages (in W/sq. m) of insolation observed at Sede Boqer for July 15, 1983 (measured using conventional instrumentation) and expected standard errors for the four-pyranometer configuration (assuming 5% pyranometer error for each instrument)

1	Beam 2	3	Diffuse 4	5
Solar time	Observed value	Expected error	Observed value	Expected error
5:15	25.9	1.5	14.5	0.5
5:45	168.2	7.5	48.1	1.6
6:15	234.8	11.8	52.5	3.4
6:45	284.7	13.5	90.9	3.7
7:15	204.2	14.8	176.9	6.5
7:45	245.8	16.0	181.8	6.6
8:15	626.3	23.7	184.2	7.6
8:45	666.3	23.6	192.7	8.3
9:15	728.2	24.7	176.2	8.5
9:45	812.1	26.4	135.3	7.8
10:15	830.6	24.9	136.3	7.8
10:45	842.1	23.8	136.6	8.0
11:15	856.3	23.5	133.6	8.1
11:45	864.2	23.4	133.7	8.2
12:15	857.3	23.4	135.4	8.2
12:45	857.8	23.5	133.2	8.1
13:15	849.0	23.8	135.6	8.1
13:45	832.7	24.9	131.9	7.6
14:15	786.9	25.9	137.5	7.5
14:45	777.2	25.7	126.6	6.8
15:15	753.5	25.2	117.3	6.1
15:45	700.2	23.4	113.1	5.4
16:15	676.4	21.4	93.6	4.6
16:45	643.1	20.0	78.1	3.8
17:15	587.1	18.6	[illegible]	[illegible]
17:45	478.5	16.7	[illegible]	2.0
18:15	307.9	11.4	29.3	1.0
18:45	64.4	2.6	9.9	0.3

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PHOTOELECTROCHEMICAL CELLS: UP TO 200% MORE ENERGY VIA OPTICAL BOOSTING

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ABSTRACT

We propose a method for increasing the yearly electrical energy output of certain kinds of photoelectrochemical cells by close to 200%, per photoelectrode area, without the need for expensive tracking systems or sensitive focussing concentrators. The method is optical boosting with totally stationary, inexpensive, low-concentration, nonimaging collectors. The best suited class of photoelectrochemical cells has a photoelectrode that is optically active on both of its sides, as well as an efficiency and stability that increase with temperature under typical operating conditions.

1. INTRODUCTION

In this presentation we: (1) propose optical boosting for photoelectrochemical cells (PEC's) via stationary, nonimaging concentrators; (2) note the suitability of different kinds of PEC's to low-concentration collectors; and (3) estimate the achievable gains in yearly electrical energy output. The nonimaging concentrators considered here require neither expensive tracking systems nor sensitive focussing optics. Hence their expense should be very small compared to that of the PEC itself.

Why use optical concentration at all for PEC's? On the one hand, PEC's appear to experience serious operational and stability problems at solar flux levels corresponding to concentation ratios of about 3 and higher [1,3,4]. In addition, for many PEC's, cell efficiency decreases with increasing temperature [1,5,6]. Accordingly, concentrators for PEC's have been given limited consideration [4].

On the other hand, there is the economic advantage that concentration saves on expensive absorber per collector aperture area. Furthermore, one can in principle double the electrical output specifically for PEC's whose photoelectrode can readily be coated on both sides for optical activity. Totally stationary nonimaging concentrators also correspond to geometric concentration ratios (ratio of aperture to absorber area) in the range of 1 to 2, which, in terms of stability, is not problematic for most PEC's. Furthermore, the efficiency and stability of certain PEC's increase with increasing cell temperature for temperatures characteristic of actual operating conditions [5,10-17], which implies energetic and chemical stability incentives for low-concentration optical boosters.

2. OPTICAL CONCENTRATION

For stationary, low-concentration solar collectors, "ideal", nonimaging concentrators offer the optically and energetically optimal alternative [7,8]. This class of concentrators achieves maximal concentration for a stationary collector of fixed acceptance angle [7,8]. Furthermore, nonimaging concentrators are relatively "tolerant" to small production and orientation errors since they are not based on focussing optics. Concentrator troughs can be made at very modest expense, and low-cost adhesive reflector films with specular reflectivity of around 87% and higher are now commercially available.

Figs. 1-4 present two-dimensional concentrator cross sections for 4 different receiver geometries that are appropriate for totally stationary PEC's and for year-round energy collection. All PEC's considered here are well sealed, with illuminated faces made of transparent materials such as glass or Plexiglas. The collector aperture should be glazed primarily to minimize reflector degradation and possibly, secondarily, to reduce heat losses to ambient specifically for those PEC's with improved efficiency at higher temperatures. The concentrator module can also be insulated in order to minimize heat losses (when beneficial) at reasonable expense. To maximize optical gains, the photoelectrode can either be deposited on, or placed very close and parallel to, the inner side of the PEC's illuminated surface. The counterelectrode, whose position can vary markedly within the cell [2,5], is placed so as ensure minimal optical losses.

Figs. 1-2 depict the nonimaging concentrators appropriate for monofacial absorbers. In Fig. 1, only surface CD of the PEC is illuminated, and the absorber area is equal to CD. In Fig. 2, the PEC has a triangular cross section. Two photoelectrodes are used, each parallel to, or deposited on, CD and DE. The motivation for a concentrator of this type is that it can minimize reflector area for a given geometric concentration ratio [9]. Figs. 3 and 4 pertain to bifacial absorbers in which the reflector configurations ensure illumination of all PEC faces. The concentratr of Fig. 3 offers a small advantage in optical gains compared to the concentrator of Fig. 4, whereas it requires a deeper concentrator trough and hence is less compact [10].

For maximum economy, one photoelectrode only (of area CD in Fig. 3 or DE in Fig. 4) could be used. For economic, thermal and optical advantages, the PEC should be as thin as possible. For cases where coating both sides of the photoelectrode substrate is feasible, this economical, "one bifacial photoelectrode" configuration would double the active photoelectrode area compared to the concentrators of Figs. 1-2. All the concentrators considered here will also have relatively low heat loss compared to conventional nonconcentrating PEC's [11].

3. ESTIMATION OF YEARLY ENERGY DELIVERY

The following calculation should be viewed as a specific, illustrative example only. The optical elements of our calculation are delineated in Refs. 10 and 18. For specificity, we consider the following system and site details:

1) Site: Bet Dagan, Israel; latitude = 32 deg N.

2) PEC is always operated at its maximum power point, and all electricity produced is utilized.

3) Totally stationary collectors at tilt = latitude and zero azimuth.

4) PEC efficiency (η) temperature coefficient (at maximum power point) constant at $(1/\eta)(d\eta/dT) = 0.01$ (1/K), (a typical value based on experimental findings of [5,12-17]). A positive temperature coefficient is selected in order to illustrate the maximal advantage of low-concentration collectors.

5) In the case of bifacial photoelectrodes (Figs. 3-4), we neglect losses associated with any small voltage mismatch which results from the fact that both sides of the photoelectrode are not illuminated identically.

6) Flat plate (nonconcentrating) PEC is insulated on back and sides.

7) Nonimaging concentrator PEC (as in Figs. 1-4) with nominal geometric concentration ratio 1.5, insulated on back and sides. In the case of Figs. 3-4, for economy, we consider a PEC with one bifacial photoelectrode only of area CD (Fig. 3) or DE (Fig. 4). If we now define the concentration ratio of this device as aperture area divided by photoelectrode area, then this concentration ratio will be slightly less than 3.

8) Optical efficiencies at normal incidence: 0.7 for flat plate collector and 0.58 for concentrator (reflector reflectivity of 0.87 has been assumed).

9) Heat loss coefficient (for passive cooling) of 12 W/(K-m^2) for flat plate PEC and 5 W/(K-m^2 of aperture) for PEC concentrator (based on experimental observations of [5] and calculational procedures of [11]).

We then find the following values for the ratio of yearly electrical energy delivery, Q, of the PEC concentrator to the flat plate PEC:

Q(PEC concentrator)/Q(flat plate PEC)
= 0.94 per aperture area
= 1.4 per monofacial photoelectrode area for the concentrators of Figs. 1-2
= 2.8 per bifacial photoelectrode area for the concentrators of Figs. 3-4.

Even on a "per aperture area" basis, the flat plate and concentrator configurations yield roughly the same yearly energy delivery. Since the key cost component of the PEC concentrator will be the PEC itself, in particular the semiconductor photoelectrode, it is probably more meaningful to compare the two devices on a "per photoelectrode area" basis, which indicates a roughly 40% advantage to the monofacial concentrators of Figs. 1-2, and a roughly 180% advantage to the bifacial concentrators of Figs. 3-4.

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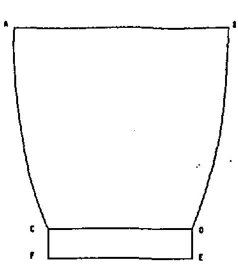

Fig. 1

Figure 1: Two-dimensional cross section of ideal (CPC), stationary, nonimaging concentrator appropriate for one-sided absorber. Aperture AB. Absorber CD (upper, transparent side of PEC). PEC is CDEF. Photoelectrode is on or parallel to CD. Geometric concentration ratio, AB/CD = 1.5.

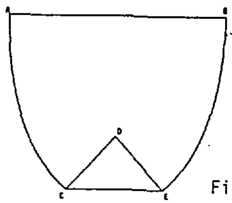

Fig. 2

Figure 2: As in Fig. 1 for wedge-shaped absorber CDE. PEC is triangle CDE, with 2 photoelectrodes on or parallel to CD and DE. Geometric concentration ratio, AB/(CD + DE) = 1.5.

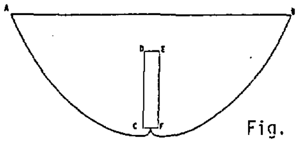

Fig. 3

Figure 3: "Bifacial" PEC absorber CDEF with geometric concentration ratio AB/(CD + DE + EF + FC) = 1.5. CD/DE = 5.

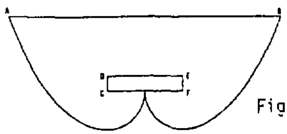

Fig. 4

Figure 4: As in Fig. 3, with CD/DE = 0.2. Geometric concentration ratio = ...

GENERALIZED CAPACITY FACTORS FOR GRID-INTERTIE SOLAR PHOTOVOLTAIC SYSTEMS

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Abstract

We present a simple calculational and graphical procedure for direct determination of the annual capacity factor of no-storage grid-intertie photovoltaic systems. Our results pertain to the principal solar collector types and to a wide range of climates. Our procedure enables a designer to make accurate preliminary assessments concerning suitability of potential sites and solar collector types by simply reading points off the graphs presented herein.

1. Introduction

We consider the problem of the preliminary sizing and energy delivery prediction for central no-storage utility-intertie photovoltaic (PV) systems. The designer typically requires an accurate estimate of the yearly average system output or, equivalently, the "capacity factor", CF, defined as:

$$CF = \frac{\text{24 hr/day average system power output}}{\text{Maximum power rating of system}} \quad . \qquad (1)$$

Accurate calculation of capacity factor is important not only because of the obvious value of the PV system as a fuel saver, but also because of the potential "capacity credit" of the PV system. By "capac credit" we refer to the displacement of conventional generating capacity at fixed reliability level, as a consequence of installation of the PV system [1].

One problem that arises is the ambiguity of the maximum system power rating. Typically, one stipulates the incident solar radiation, solar cell temperature or ambient temperature, and wind speed at "standa conditions", and then measures system output at maximum power point. However, different laboratories employ different "standard condition" Furthermore, the PV arrays may rarely experience conditions close to "standard conditions", particularly since standard conditions often correspond to a solar radiation of 1 KW/m^2 and a solar cell temperature of 28 deg C. We will derive "translation equations" that can convert measurements under any reasonable test conditions into yearly average performance or CF.

A second problem is that CF values are usually obtained via large-scale, time and money intensive computer simulations which require extensive climatic data bases. An accurate but short-hand method for estimating CF is hence a key objective.

2. Procedure

We first derive an expression for a PV's energy output that depends on climatic variables and readily measurable solar cell characteristics only. This expression pertains to the PV array only. We assume that losses due to power conditioning will be accounted for separately based on equipment specifications, and that PV's are operated at maximum power point.

PV efficiency can be expressed in two equivalent forms. One form notes the empirical and verified observation that PV efficiency, η, decreases linearly with cell temperature T_c :

$$\eta = \eta_R [1 - \beta (T_c - T_R)] \qquad (2)$$

where η_R and T_R are the efficiency and PV temperature under reference or test conditions, respectively, and β is the PV temperature coefficient.

The other form simply states that all absorbed solar radiation that is not converted into electricity is dissipated as heat:

$$\eta = \eta_n - [U(v) / I] (T_c - T_a) \qquad (3)$$

where η_n is array optical efficiency: U(v) is the linearized array heat loss coefficient as a function of wind speed v; I is the incident insolation including incidence angle modifier losses: and T_a is ambient temperature. All tests are conducted at normally incident solar radiation. *Eliminating* cell temerature, T_c, *from* eqs (2)-(3), *we obtain:*

$$\eta \cong \eta_R [a1 - a2 \, T_a - a3 \, I] \qquad (4)$$

with $a1 = 1 + \beta T_R$; $a2 = \beta$; and $a3 = \beta (\eta_n - \eta_R)/U(v)$.
The instantaneous PV power output per unit area, P, is then:

$$P = \eta_R [(a1 - a2 T_a) I - a3 \, I \hat{} 2] \; . \qquad (5)$$

We then average eq (5) over all hours of the year and take advantage of a combination of the facts that solar radiation is weakly correlated to both ambient temperature and wind speed, and that the terms in which th cross-correlations occur are small, to obtain for the yearly avera power output, $\langle P \rangle$:

$$\langle P \rangle \cong \eta_R \langle I \rangle [\quad (a1 - a2 \langle T_a \rangle) \; - \; a3 \langle I \hat{} 2 \rangle / \langle I \rangle \;] \qquad (6)$$

where $\langle T_a \rangle$ is the yearly average daytime ambient temperature, $\langle I \rangle$ is the yearly average collectible energy, and a3 is evaluated at the yearly average daytime wind speed. If the PV array is tested at "standard conditions" of solar radiation I^*_{max}, ambient temperature T^*_a and wind speed v^*, the CF relative to those test conditions is:

$$CF = \frac{\langle I \rangle [a1 - a2 \langle T_a \rangle - a3 \;\; X \;]}{I^*_{max} [a1 - a2 \, T^*_a - a3 (v^*) \, I^*_{max}]} \qquad (7)$$

where $X = \langle I \hat{} 2 \rangle / \langle I \rangle$. Thus the problem of predicting CF accurately is reduced to the calculation of two factors: (1) yearly average collectible energy $\langle I \rangle$: and (2) a "correction factor" which depends only on r dily measurable (or manufacturer provided) PV parameters and the radiation statistic X. Note that eq (7) permits evaluation of CF independent of th arbitrary choice of "standard conditions". Exemplary calculations using eq (7) with actual climatic data and PV array parameters show that the contribution of the "X" term can be far from negligible, in extreme cases reaching 20-30% of CF. We therefore treat this contribution in detail below.

3. Generalized Radiation Statistics and Results

Fig. 1 presents $\langle I \rangle$, as a 24-hr/day average, for the principal solar collector types, as a function of yearly average clearness index (ratio of horizontal global to horizontal extraterrestrial radiation), $\langle K \rangle$, and latitude. These figures are based on the empirical correlations of [2], which in turn are based on typical meteorological year data for the 26 U.S. SOLMET stations.

Fig. 2 presents our calculation of $X = \langle I^2\rangle/\langle I\rangle$ for the same cases as Fig. 1, this calculation being based on the observation of [3] that $\langle I^2\rangle$ is simply proportional to the area under the plot of utilizability vs. radiation threshold. The utilizability curves of [2] have been used in these calculations.

Hence by combining measured or manufacturer-supplied PV parameters with points that can be read off the graphs of Figs. 1-2, the designer can calculate accurately the CF for a proposed PV system in a specific location.

4. Partial Validation and Conclusions

We compare our predictions with the experimental results of the 3-year PV monitoring program of PG&E on 26 flat plate and concentrating PV modules [4]. Capacity factors are expressed relative to "standard conditions" of I^*_{max} = 1 KW/m^2 for flat plates and 0.85 KW/m^2 for concentrators; T^*_a = 20 deg C; and v^* = 1.8 m/s. The test site had approximately $\langle T_a \rangle$ = 16.7 deg C and $\langle K \rangle$ = 0.61. A comparison of our predicted values with experimentally measured values is presented in Table 1, which shows satisfactory agreement. The systematic overprediction of 5% in CF for concentrators, while being well within experimental uncertainty, could be due to small tracking errors and/or dust accumulation, or errors in the empirical correlations used in our method.

Two sets of simple but powerful graphs based on yearly average radiation statistics provide accurate and extremely rapid estimates of CF values for the principal PV collector types over a wide range of climates. Our results can handle any arbitrary standard test conditions, and can serve as a valuable tool in the sizing and optimization of utility-intertie PV systems.

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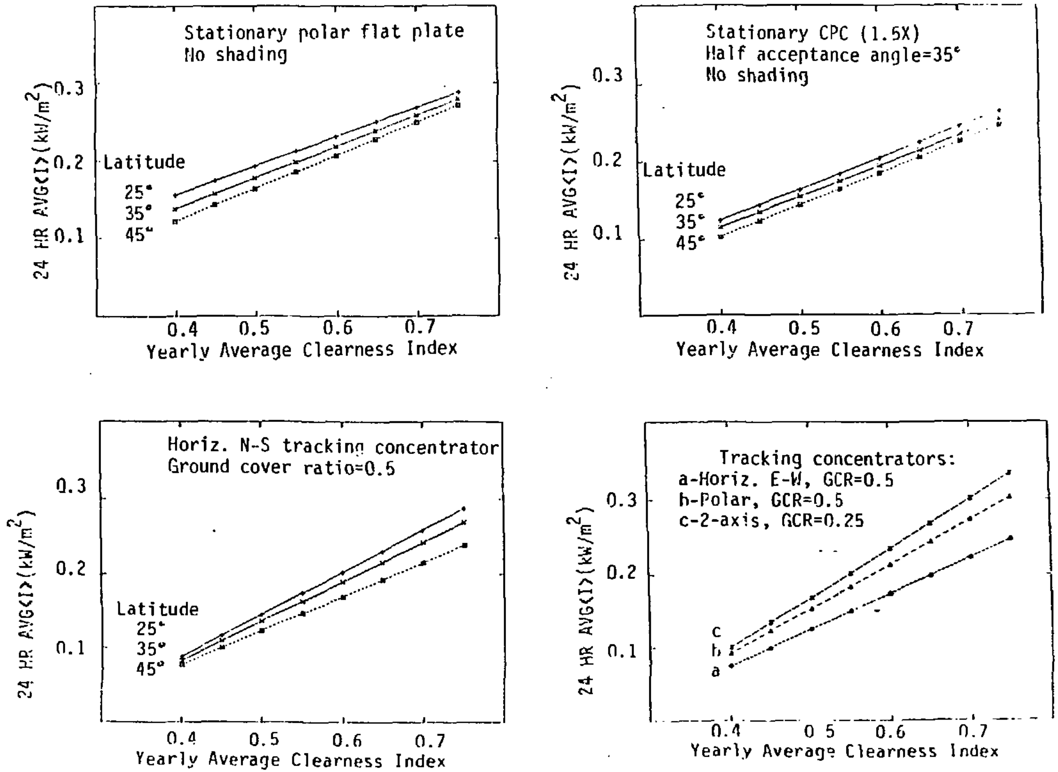
Table 1: Partial Validation of Simple Calculational Procedure

Collector Type	PV Module Manufacturer	Annual Capacity Factor (Experimental)	Annual Capacity Factor (Predicted)
	Solarex	0.235	0.228
Fixed	Mobil Solar	0.236	0.237
Flat	ARCO Solar	0.237	0.233
Plates	Solavolt	0.236	0.237
	Westinghouse	0.236	0.239
	Applied Solar	0.236	0.238
Concen-	Entech (40 X)	0.278	0.291
trators	Intersol (100 X)	0.281	0.292
	Varian (1000 X)	0.279	0.288



Stationary polar flat plate
No shading
Latitude
25°
35°
45°
24 HR AVG<I>(kW/m²)
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Yearly Average Clearness Index
Stationary CPC (1.5X)
Half acceptance angle=35°
No shading
Latitude
25°
35°
45°
Horiz. N-S tracking concentrator
Ground cover ratio=0.5
Latitude
25°
35°
45°
Tracking concentrators:
a-Horiz. E-W, GCR=0.5
b-Polar, GCR=0.5
c-2-axis, GCR=0.25
c
b
a

FIGURE 1

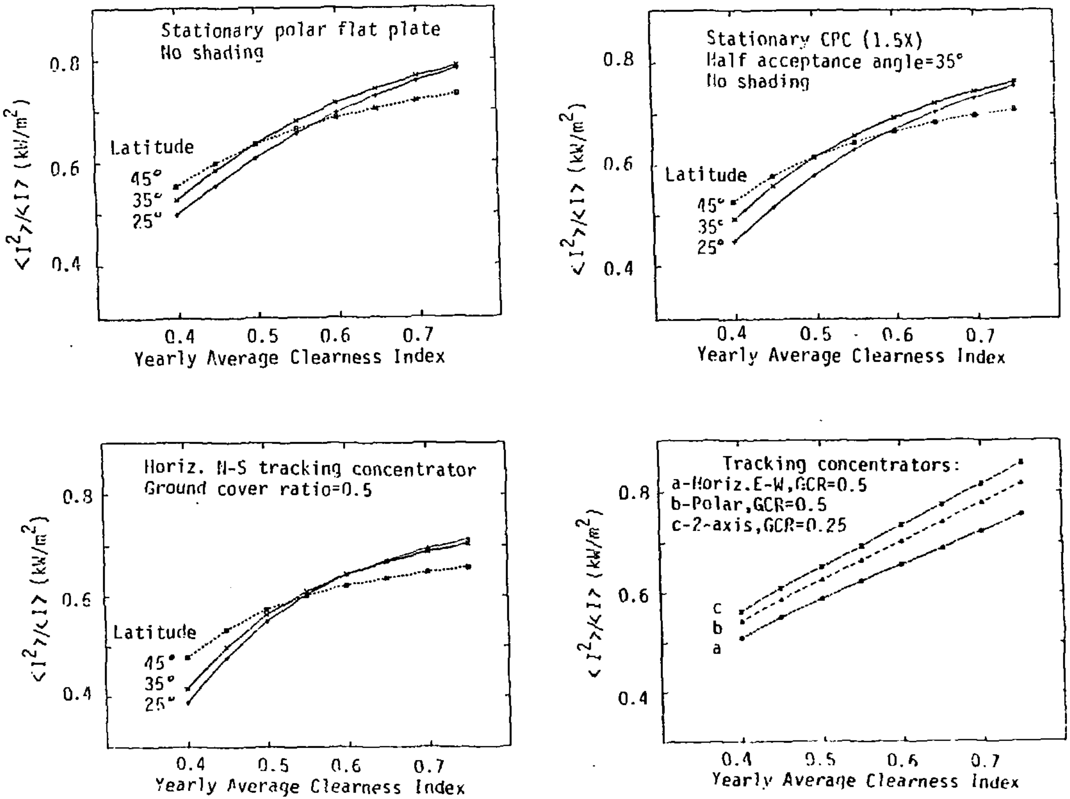

Stationary polar flat plate
No shading
Latitude
45°
35°
25°
0.8
0.6
0.4
<I²>/<I> (kW/m²)
0.4 0.5 0.6 0.7
Yearly Average Clearness Index
Stationary CPC (1.5X)
Half acceptance angle=35°
No shading
Latitude
45°
35°
25°
Horiz. N-S tracking concentrator
Ground cover ratio=0.5
Tracking concentrators:
a-Horiz.E-W,GCR=0.5
b-Polar,GCR=0.5
c-2-axis,GCR=0.25
c
b
a

FIGURE 2

A Manufacturing Process for GaAs/GaAlAs Solar Cells Using Continuous LPE Growth

by

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GaAs solar cells are attractive for use in space applications because of their advantages, when compared with Si, of increased energy conversion efficiency, higher operating temperature, and an increased radiation tolerance. The main limitation to the use of GaAs is the high cost.

The process suggested here will have the advantages of a line manufacturing process, improved productivity, higher crystal growth rates, and improved quality. The manufacturing process is based on a continuous liquid phase epitaxial (LPE) growth, which permits the growth of four separate epitaxial layers. For that purpose, instead of using the conventional horizontal furnace with sliding boats, the new system will use a vertical furnace with a rotary crucible. A diagrammatic representation of the vertical furnace is given in Figure 1. The components of the rotary graphite crucible are shown in Figure 2.

The basic principle of LPE method using the rotary (multihole) graphite crucible is to transfer a sequence of GaAlAs solutions with appropriate doping onto the slice while the temperature is gradually lowered within the range 870 to 820°C.

The advantages of the proposed method over the sliding boat are:

a) The ability to grow up to 25 substrates in one run cycle.

b) Improved quality of the grown layer. This can be obtained by mounting $Ga_{1-x}Al_xAs$ substrates on the four walls of the crucible holes.

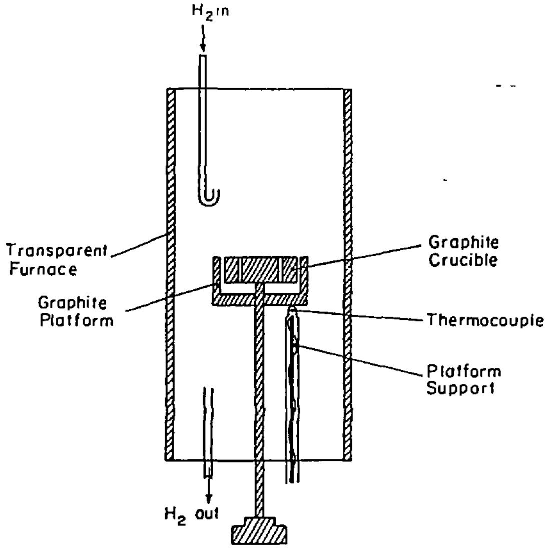

Figure 1. Diagrammatic representation of the vertical furnace

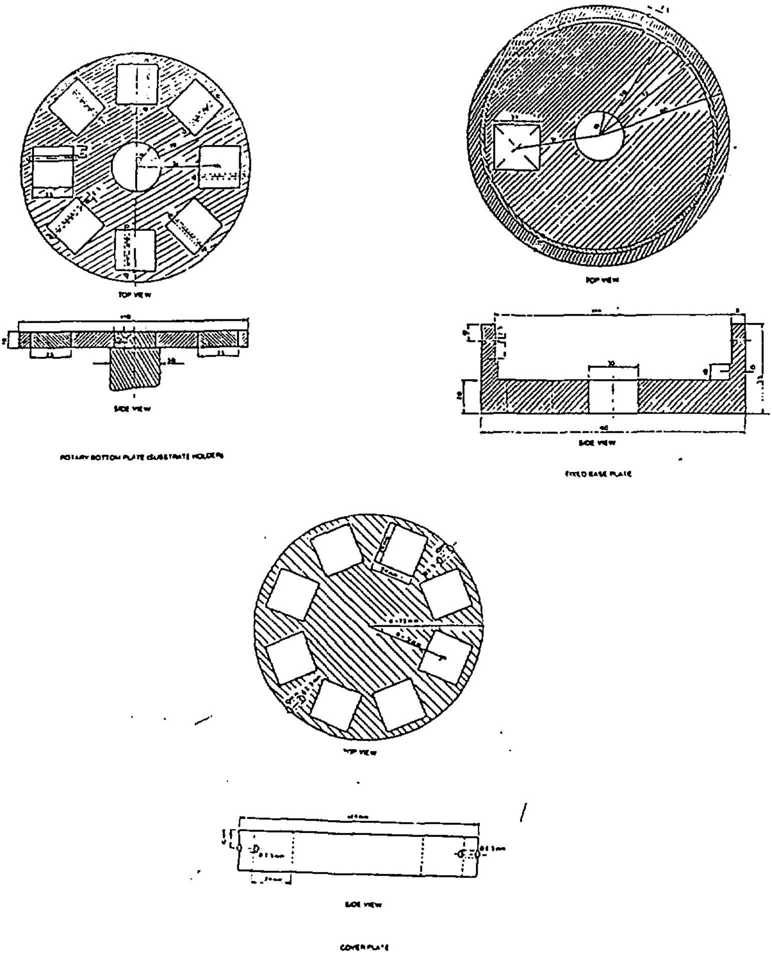

Figure 2. The components of the rotary graphite crucible

SOLAR BEAM RADIATION AVAILABLE FOR CONCENTRATING SOLAR COLLECTORS IN THE BEER SHEVA REGION

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INTRODUCTION

In March 1983 the Solar Energy Laboratory's meteorlogical station at the Ben-Gurion University of the Negev (lat.=31°15'N, long.=34°48'E, elevation≈315 m) began measuring normal incidence solar or beam radiation by means of an Eppley Pyrheliometer connected to an Eppley Electronic Integrator Model 413-6140 (which includes a Digitec 6140 digital recorder). Cumulative radiation values are printed on an hourly basis. At the present, there are insufficient data available to determine monthly daily or hourly average values. Nevertheless, we have accumulated sufficient data to determine average seasonal daily values for normal incidence solar radiation in the Beer Sheva region.

DEFINITION OF SEASONS

(1)Winter: Dec.-Jan.-Feb. (6 months of data)
(2)Spring: Mar.-Apr.-May (8 months of data)
(3)Summer: June-July-Aug. (6 months of data)
(4)Autumn: Sept.-Oct.-Nov.(7 months of data)

TYPES OF CONCENTRATING SOLAR COLLECTORS

The equations cited are those used to convert NIP values to values corresponding to the various concentrating collectors.

NIP: Two axis tracking (seasonal average of measured data).

HEWSD: Horizontal east-west axis with single daily adjustment so that its surface-normal coincides with the solar beam at noon.

$$\cos(\theta)=\sin2(\delta)+\cos^2(\delta)\cos(\omega)$$

HEWCA: Horizontal east-west axis with continuous adjustment to minimize the angle of incidence.

$$\cos(\theta)=[1-\cos^2(\delta)\sin^2(\omega)]^{0.5}$$

HNSCA: Horizontal north-south axis with continuous adjustment to minimize the angle of incidence.

$$\cos(\theta)=\{[\sin(\phi)\sin(\delta)+\cos(\phi)\cos(\delta)\cos(\omega)]^2+\cos^2(\delta)\sin^2(\omega)\}^{0.5}$$

NSPCA: North-south axis parallel to the earth's axis with continuous adjustment.

$$\cos(\theta)=\cos(\delta)$$

NOTE: All radiation values are in W/m^2.

NOMENCLATURE

θ angle of incidence

δ angle of declination

ϕ site latitude

ω hour angle

AVERAGE WINTER BEAM RADIATION COLLECTED BY TRACKING CONCENTRATOR FOR BEER SHEVA (LAT.=31°15')

HOUR	OMEGA	NIP	HEWSD	HEWCA	HNSCA	NSPCA
6.5	-82.5	26	6.37	9.95	24.12	24.23
7.5	-67.5	238	110.41	121.07	206.78	221.79
8.5	-52.5	440	290.51	296.28	350.53	410.03
9.5	-37.5	547	448.84	450.46	394.01	509.74
10.5	-22.5	577	538.86	539.06	377.18	537.70
11.5	-7.5	549	544.92	544.92	337.00	511.60
12.5	7.5	536	532.02	532.02	329.02	499.49
13.5	22.5	516	481.89	482.07	337.31	480.85
14.5	37.5	441	361.86	363.17	317.65	410.96
15.5	52.5	349	230.43	235.00	278.04	325.23
16.5	67.5	167	77.47	84.95	145.09	155.62
17.5	82.5	15	3.67	5.74	13.92	13.98
DAILY TOTAL		4401	3627.24	3664.70	3110.65	4101.22

WINTER: DEC.-JAN.-FEB (n=15)
δ=23.45*SIN(360*(284+n)/360)
δ(WINTER)= -21.269

AVERAGE SPRING BEAM RADIATION COLLECTED BY TRACKING CONCENTRATOR FOR BEER SHEVA (LAT.=31°15')

HOUR	OMEGA	NIP	HEWSD	HEWCA	HNSCA	NSPCA
6.5	-82.5	152	23.38	31.64	151.59	149.95
7.5	-67.5	334	133.33	137.42	333.48	329.50
8.5	-52.5	434	268.75	270.14	427.55	428.15
9.5	-37.5	500	399.44	399.79	481.96	493.26
10.5	-22.5	551	510.18	510.22	519.56	543.58
11.5	-7.5	551	546.41	546.41	512.43	543.58
12.5	7.5	536	531.54	531.54	498.48	528.78
13.5	22.5	527	487.96	488.00	496.93	519.90
14.5	37.5	486	388.26	388.60	468.47	479.45
15.5	52.5	427	264.41	265.78	420.66	421.25
16.5	67.5	303	120.96	124.67	302.52	298.92
17.5	82.5	133	20.45	27.69	132.64	131.21
DAILY TOTAL		4934	3695.07	3721.91	4746.27	4867.54

SPRING: MAR.-APR.-MAY(n=105)
δ=23.45*SIN(360*(284+n)/360)
δ(SPRING)= 9.415

AVERAGE SUMMER BEAM RADIATION COLLECTED BY TRACKING CONCENTRATOR FOR BEER SHEVA (LAT.=31°15')

HOUR	OMEGA	NIP	HEWSD	HEWCA	HNSCA	NSPCA
6.5	-82.5	250	61.87	96.59	242.02	232.58
7.5	-67.5	463	215.63	236.66	459.14	430.73
8.5	-52.5	615	406.76	414.96	614.88	572.14
9.5	-37.5	710	583.02	585.16	708.29	660.52
10.5	-22.5	766	715.54	715.81	759.27	712.61
11.5	-7.5	781	775.22	775.22	770.31	726.57
12.5	7.5	777	771.25	771.25	766.36	722.85
13.5	22.5	750	700.59	700.86	743.41	697.73
14.5	37.5	723	593.69	595.88	721.26	672.61
15.5	52.5	659	435.86	444.65	658.87	613.07
16.5	67.5	502	233.80	256.60	497.81	467.01
17.5	82.5	271	67.07	104.70	262.35	252.11
DAILY TOTAL		7267	5560.30	5698.35	7203.97	6760.54

SUMMER: JUNE-JULY-AUG.(n=196)
δ=23.45*SIN(360*(284+n)/360)
δ(SUMMER)= 21.517

AVERAGE AUTUMN BEAM RADIATION COLLECTED BY TRACKING CONCENTRATOR FOR BEER SHEVA (LAT.=31°15')

HOUR	OMEGA	NIP	HEWSD	HEWCA	HNSCA	NSPCA
6.5	-82.5	77	11.91	16.22	75.29	75.92
7.5	-67.5	307	122.75	126.65	288.90	302.70
8.5	-52.5	488	302.38	304.01	434.82	481.17
9.5	-37.5	571	456.29	456.70	477.49	563.00
10.5	-22.5	631	584.30	584.36	497.49	622.16
11.5	-7.5	639	633.69	633.69	485.76	630.05
12.5	7.5	639	633.69	633.69	485.76	630.05
13.5	22.5	600	555.60	555.65	473.05	591.60
14.5	37.5	544	434.71	435.10	454.91	536.38
15.5	52.5	438	271.40	272.86	390.27	431.87
16.5	67.5	244	97.56	100.66	229.61	240.58
17.5	82.5	55	8.51	11.59	53.78	54.23
DAILY TOTAL		5233	4112.79	4131.16	4347.15	5159.73

AUTUMN: SEPT.-OCT.-NOV.(n=288)
δ=23.45*SIN(360*(284+n)/360)
δ(AUTUMN)= -9.599

Storage and Transport of Solar Energy by a Chemical Heat Pipe

by
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The concept of the chemical heat pipe was developed in KFA, Julich (1), for transporting nuclear energy for distances of a few hundred kilometers, and using it as process heat in industry. They worked on the well known steam reforming reaction:

$$CH_4 + H_2O = CO + 3H_2 \quad \Delta H = 204 \text{ KJ/mole}$$

The forward reaction is endothermic and is carried out at temperatures of about 850^{o} C in the nuclear site. The product gases are transferred by pipes, at ambient temperatures, to the consumer, where the back exothermic reaction is carried out. The evolved heat is used to produce process steam up to 650^{o} C . The regenerated methane is then transfered back to the nuclear site where the cycle is repeated. This process, nick-named EVA-ADAM, was successfully operated up to a scale of 10 MW, using electric heating and helium as the heat transfer fluid. It was never operated in conjunction with a nuclear reactor.

We have suggested using the same concept in conjunction with concentrated solar energy (2). In this case it can serve both for transport and for storage, as the product gases can be stored in large containers, or in the pipelines and used whenever needed either as process heat or for generating electricity. We have shown that the reaction:

$$CH_4 + CO_2 = 2CO + 2H_2 \quad \Delta H = 250 \text{ KJ/mole}$$

has some advantages over steam reforming as it does not involve the heat of evaporation of water and it can be handled easier.

The major difference between working with a nuclear source or with solar energy is the intermittant nature of the latter, where we have to work under non-stationary conditions with daily start-ups and shut-downs and slow and fast changes in the solar insolation. This mandates a whole new way of operation and the development of a catalytic system that can withstand such variations.

Working with an electrically heated 10 W laboratory scale system (2), we have shown that one can use a nickel catalyst and operate both the reforming and the methanation reactions, in a closed loop, under variable conditions, for a number of cycles. We have later found that a Rh on alumina catalyst is superior to nickel and can withstand more drastic conditions.

We then built a receiver/reactor to be operated in our solar furnace. The results of some preliminary work on methane reforming, under solar conditions, in this reactor, are reported in this presentation.

Experimental

The solar furnace at the WIS is comprised of a 96 m^2 Arco heliostat, operated by a computer, to follow the sun and reflect the solar radiation onto a spherical concentrator which is 7.3 m in diameter and has a rim angle of 65 degrees. The concentrator is made of 590 trapezoidal-shaped concave mirrors, arranged in concentric rings. The mirrors were individually focused, by special clamps, to a distance of 3.5 m from the center of the sphere (3). The solar furnace was charachterized by radiometric and calorimetric measurements (4). It showed a solar concentration ratio of over 9000 and a power input of over 15KW.

The receiver/reactor* comprises an 11 mm i.d. Inconel tube, 25 cm long, filled with a Rh catalyst, and inserted in the center of an alumina cylinder, 15 cm diameter, well insulated with alumina felt. Thermocouples were connected at three points on the outside surface of the reaction tube, and four others were inserted in the alumina cylinder to monitor the incoming solar flux. The reactants were CO_2 and methane, in a ratio of 1.4/1, they were introduced at a rate of 40 to 340 l/h and at pressures of 1 to 7 atmospheres. The measured temperatures on the outside wall of the reactor varied from 720 to 940° C. The product gases were analysed by gas chromatography and the enthalpy changes were calculated from the degree of conversion and the measured flows of gases. Some representative results are given in the Table 1.

These results are preliminary and were aimed to show that one can control the energy input into the receiver and control the temperature of the reaction by changing the flow rate of the reactants. It was shown that even in such a small reactor tube one can easily absorb 430 W, at a flux density of 40 KW/m^2. These values can be increased further by working at higher temperatures and higher reactant flows.

Such experiments will give us the information we need in order to scale up the reactor to a 20 KW unit so that we can make full use of the solar furnace. This will be operated in a closed loop with a methanator of the same size. We are then planning to scale it up to the next stage of 1 MW and to operate it in the solar central receiver now under construction at the W.I.S.

* Acknoledgment

The receiver was built and tested in the solar facility of Prof. E. Fletcher with the help of Dr. R. Diver during M. Levy's stay at the University of Minnesota as a visiting professor. It was then shipped to the WIS and used here with some modifications. We wish to thank them for their help and cooperation.

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Table 1

P at	T C	reactant flow l/h	linear flow m/s	contact time sec.	% conv.	absorbed power W	flux KW/m2
1	770	44	1.3	0.22	85	64	5.8
1	745	60	1.8	0.16	84	88	7.9
1	760	69	2.0	0.14	84	70	9.2
1	710	82	2.2	0.13	67	101	9.2
1	740	133	3.6	0.02	73	174	15.8
1	820	146	5.0	0.06	95	239	21.8
1	805	212	5.9	0.05	70	276	25.1
1	735	284	5.1	0.05	45	284	25.8
1	745	316	7.7	0.04	44	304	27.7
1	780	321	8.7	0.03	54	351	31.9
2.7	875	76	0.70	0.40	96	130	11.9
6.3	895	100	0.34	0.76	94	170	15.4
3.0	860	104	0.78	0.36	94	174	15.8
2.7	765	112	0.79	0.35	73	148	13.4
5.5	810	113	0.42	0.67	74	155	14.1
5.6	770	117	0.34	0.70	66	149	13.5
6.0	720	150	0.42	0.66	47	150	13.7
7.0	890	160	0.51	0.55	87	253	23.0
5.4	935	187	0.79	0.35	93	318	28.9
5.1	780	189	0.67	0.42	55	212	19.2
3.9	830	204	1.06	0.26	80	300	27.3
5.5	755	209	0.68	0.41	47	216	19.7
5.5	750	214	0.68	0.41	42	207	18.8
6.5	920	239	0.79	0.35	87	383	34.8
5.7	800	296	0.97	0.29	48	315	28.6
5.7	725	324	0.94	0.30	31	264	24.0
5.9	865	336	1.17	0.24	63	429	39.0

SUMMARY OF THE PERFORMANCE OF 8 PHOTOVOLTAIC PLANTS IN 1982-1984

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Billions of dollars have been invested in search and development of various methods for producing electrical power from solar energy. Since 1979, several dozen utility-scale solar power-plants have begun operation. Reviewing the operation and performance data of such plants is of great interest. For a number of years we have been searching and analyzing performance data of both small and large field test facilities and comparing plants in terms of efficiency, capacity factor, availability, energy density, and other plant performance indicators. In order to obtain meaningful comparison of performance between facilities which are based on different technologies or located at sites which greatly differ in solar radiation and other meteorological conditions, a number of performance indicators, many of them normalized, had to be developed and tried.

Following is a concise table summarizing the yearly performance of 8 photovoltaic facilities in the U.S.A., arranged according to their particular technology. All are based on silicon solar cell modules (Georgetown and Oklahoma with polycrystalline, all the others single crystal silicon cells).

Four yearly performance indicators are given: 1) Efficiency (the percentage of the solar energy which ends up as net electrical output, transmitted to the customer), 2) the energy density (kWh net electrical output per square meter of collector, per day, yearly averaged), 3) capacity factor (percentage of the real net transmitted energy out of the hypothetical output which is based on the nameplate power-rating and 8760 hours of the year), and

Table 1: SUMMARY OF YEARLY PERFORMANCE

Site	Technology	Power Rating kW	Year	Efficiency %	Energy Density $kWhm^{-2}d^{-1}$	Capacity Factor %	Availability %
1. Beverly	Flat, fixed tilt	100	1984	4.0	0.16	5.4	72
			1983	4.6	0.19	14.4	84
			1982	4.3	0.17	12.9	84
2. El-Paso	"	18	1984	5.3	0.31	19.8	95
			1983	5.4	0.32	20.9	93
			1982	5.2	0.28	18.0	92
3. Georgetown	"	300	1984	5.9	0.21	9.2	81
4. Lovington	"	100	1984	4.5	0.26	17.9	76
			1983	4.8	0.28	21.6	89
			1982	4.9	0.28	19.8	93
5. Oklahoma	"	135	1984	4.8	0.25	9.4	76
			1983	5.3	0.23	9.9	82
6. San Bernardino	"	35	1982	4.5	0.22	9.0	--
7. Dallas	Fresnel, tracking, 1-X	27	1984	7.2	0.37	13.7	89
			1983	7.0	0.29	12.2	86
8. Phoenix	Fresnel, tracking, 2-X	225	1984	4.8	0.31	6.6	53
			1983	5.0	0.27	12.5	--
9. Hesperia	flat, tracking, 2-X	1000	1984	6.1	0.58	23.2	92

4) availability (percentage of plant operating hours out of the solar hours, above a defined radiation threshold).

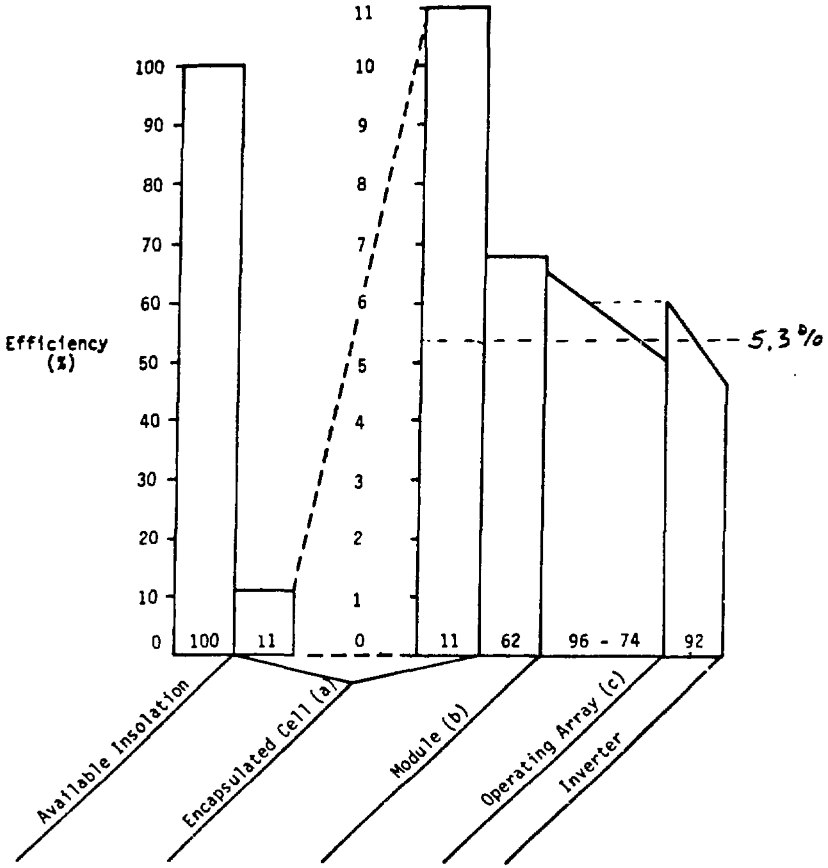
It should be noted that the efficiency and capacity factor are based on net transmitted energy and on the full year performance. As parasitic loads and various energy losses in solar facilities are large and they vary widely between technologies and sites, it has been found mandatory to select the real final net output values as the major basis for performance evaluation. Many reports still quote values based on gross outputs and on operation during selected periods, which result in higher performance numbers. Such information cannot be considered satisfactory for comparison for most purposes between facilities and technologies.

There are other points of interest in this work of assessment with additional, generalized and mostly normalized, performance indicators.

One point, which is quite striking, is the low final yearly efficiencies of all the plants. This is despite the higher efficiency value (e.g.,11%) which is quoted for industrial silicon photovoltaic cells. The reason for this deserves illustration, as shown below. It is clear that it is one thing to achieve a certain gross (DC) efficiency (11%) of a cell in the laboratory (under ideal radiation conditions, etc.), and quite another thing is the final net (AC) transmitted yearly output efficiency of the field (4.5%), after a series of unavoidable energy losses and parasitics.

The generalized indicators, those mentioned and additional ones, are instrumental for assessing various technologies on a comparative basis. It is desired to be able to distinguish between three types of capabilities: the inherent energy-process capability of the technology in question, the degree of the mechanical success of the particular facility in carrying out that capability, and the meteorological properties of the particular site. With the full set of performance indicators and normalized parameters, it is possible to accomplish an analysis that will highlight such a distinction.

Support by the Israel Ministry of Energy and Infrastructure is gratefully acknowledged. A full report is forthcoming ("Summary of Operating Solar Power-Producing Facilities", by A.Roy, A. Halperin and D. Eisenberg).



(a) *Efficiency at nominal operating cell temperature.*

(b) Module efficiency is less than encapsulated cell efficiency due primarily to cell packing factor and cell mismatch losses.

(c) Operating array efficiency is less than module efficiency due primarily to temperature effects, module mismatch, dc wiring losses, and dirt accumulation on the modules.

Approximate Efficiencies for Beverly and Lovington

FLUCTUATIONS IN PERFORMANCE OF PHOTOVOLTAIC SYSTEMS

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The assessment of the performance of a photovoltaic (PV) system is based on the estimated value of the expected (long-term) average energy delivery. The expected value suffers from uncertainties. Some result from inaccuracies in our knowledge of system parameters and others from fluctuations in climatic data (e.g., radiation, ambient temperature and wind speed) and in the load. Such fluctuations manifest themselves in our inability to predict the "exact" expected average performance since our estimates are based always on data collected in the past. Any evaluation of the average performance of a solar device is close to the "exact" average within a certain standard deviation.

Here an estimate of the effect of the random fluctuations in solar radiation on the expected standard deviation of the performance of photovoltaic systems is presented. The deviation affects the economical assessment of the long-term performance of a system. Moreover, the fluctuations in system performance determine the statistical significance of short-duration tests (e.g., the comparison of different PV systems over short periods of, say, a few weeks).

The hourly solar radiation is assumed to be a random variable. This crude assumption can be a rather good approximation for collectors that track the sun (primarily for two-axis trackers which under clear sky conditions see almost constant radiation throughout the best part of the day and to a lesser degree for polar mounted collectors), in regions (northern and tropical) or seasons (automn, winter, spring) which are characterized by significant fluctuations in radiation.

The instantaneous power delivery of a PV system can be written as [1]:

$$q = \eta_R \left\{ A \cdot I - b \cdot I^2 \right\} \qquad (1)$$

where the coefficients A and b depend on the thermal properties of the PV array and on ambient temperature and η_R is a reference efficiency. Since we intend to analyze the effect of fluctuations in solar radiation, I, only, we keep η_R, A and b constant throughout the analysis. For typical system designs A is close to unity, and b/A is of the order of .05-.1. (m^2/kW)

The long-term avarage power delivery of the system is thus,

$$\overline{q} = \eta_R A \left\{ \overline{I} - (b/A) \cdot \overline{I^2} \right\} \qquad (2)$$

In order to calculate the standard deviation around $\overline{q}$ we need to calculate $\overline{q^2}$:

$$\overline{q^2} = \eta_R^2 A^2 \left\{ \overline{I^2} - 2(b/A)\cdot\overline{I^3} + (b/A)\cdot\overline{I^4} \right\} \tag{3}$$

The various moments of I can be expressed [2] in terms of integrals of the utilizability function [3]:

$$\overline{I^2} = 2(\overline{I})^2 \int_0^{X_m} \phi(X)\ dX \tag{4}$$

$$\overline{I^3} = 6(\overline{I})^3 \int_0^{X_m} X\ \phi(X)\ dX \tag{5}$$

$$\overline{I^4} = 12(\overline{I})^4 \int_0^{X_m} X^2 \phi(X)\ dX \tag{6}$$

For $\phi(X)$ we choose an empirical expression which has been shown to describe the utilizability function reasonably well for low and intermediate values of the dimensionless radiation, X [4]:

$$\phi(X) = \left(1 - (X/X_m)\right)^{X_m} \tag{7}$$

$$X = I/\overline{I} \qquad , X_m = I_{max}/\overline{I} \tag{8}$$

(Eq. (7) applies to flat or low concentration ratio collectors. The slight modification for high concentration collectors will not affect the conclusions reached in the following and will be therefore ignored).

Using eqs. (1-8), the standard deviation of the instantaneous power,

$$\sigma_q = \sqrt{\overline{q^2} - (\overline{q})^2} \tag{9}$$

can be expressed as a relative deviation:

$$\sigma_q / \bar{q} = \sqrt{\frac{X_m - 1}{X_m + 1}} \left\{ \frac{1 - 8\frac{b}{A}\frac{I_{max}}{X_m + 2} + 4\left(\frac{b}{A}\right)^2 \frac{I_{max}^2 (5X_m + 6)}{(X_m+1)(X_m+2)(X_m+3)}}{1 - 2\frac{b}{A}\frac{I_{max}}{X_m + 1}} \right\}^{1/2} \quad (10)$$

The value of $\sigma_q / \bar{q}$ ranges between 0.58 (for $X_m = 2$) to 0.75 (for $X_m = 3.5$).

The energy delivered by the system during a period of operation T on the average is:

$$\overline{Q(T)} = \bar{q} \cdot T \quad (11)$$

Using well known methods from the theory of stochastic processes [5], the relative standard deviation of $\overline{Q(T)}$ can be shown to be given by:

$$\sigma_Q / \overline{Q(T)} = (\sigma_q / \bar{q}) \sqrt{\frac{\tau_{corr}}{T}} \quad (12)$$

where τ_{corr} is the average correlation time characteristic of the fluctuations in solar radiation. Its values are not known. If we assume that it is about one hour, than eq. (12) yields a possible relative error of up to 10% for a one week operation period (84 hours of operation) and 1-2% for a whole year's operation period.

It is concluded that estimates of system performance, or comparative system studies, based on a short-duration experiment (say, a week to two weeks) are significant to no better than 10% even before experimental error sources are included. The 10% figure represents a rough estimate of the effect of the instantaneous fluctuations in radiation. The clearer the climate, the smaller is this number expected to be. Longer range weather changes cause an increase in the estimate of fluctuations in system performance. This should be born in mind especially in comparative system studies based on short-duration tests.

A more refined analysis of the statistical nature of system performance requires the determination of the distribution of radiation values, correlation functions and corelation times.

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