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Discussion

Solar Energy Research and Development Achievements in Israel and Their Practical Significance

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This paper reviews the pioneering efforts done in Israel over the last 50 years to explore different directions of developing the solar energy resource as an alternative energy supply. An early start included the improvement of solar collectors for heating water for domestic uses. This was followed by low-temperature Organic Rankine Cycle turbines to supply electricity for remote locations, and then the development and commercialization of the SEGS Solar Thermal power plants. Current research directions are described, including high temperature Solar Tower power systems, production of "solar fuels" at high temperature to enable storage and transportation of solar energy, photovoltaic materials and photovoltaic systems development, solar absorption cooling, and the bold idea of large "Energy Towers" to produce electric energy from cooling of hot dry desert air. The paper concludes that additional efforts in Israel and abroad to continue developing and deploying of solar energy systems, having benevolent influence on the environment, should continue. [DOI: 10.1115/1.1758246]

1 First Steps

Research in Solar Energy started in Israel at the beginning of the 1950's. It was led by the National Physics Laboratory in Jerusalem, founded by the first Israeli Prime Minister David Ben Gurion, with the aim of solving basic issues that are of a significant national importance. Two of the main issues addressed then, solar energy and desalination are as relevant today as they were when first dealt with by this laboratory.

Dr. Harry Tabor established the Solar Energy laboratory within the National Physics Laboratory. In 1955 Dr. Tabor published [1,2] an interesting insight into selective absorption of solar energy. The foundation for this idea was the realization that ‘‘the spectrum of solar radiation and the spectrum of heat radiation for bodies heated to a few hundred degrees centigrade do not overlap by any appreciable amount’’. This basic idea led to the development of practical spectrally selective surfaces, highly absorbent in the solar spectrum, but highly reflective in the infrared, resulting in a surface where total absorptance for solar radiation is high while total emittance is low. Such surfaces have been developed [2] which combine absorptivities of over 90% for solar radiation with emissivities of about 10% of that of a black body for heat radiation. Dr Tabor and his colleagues came up with two types of practical selective surfaces: Black Nickel and Black Chrome. Use of these surfaces in solar collectors reduced heat loss due to radiation by as much as an order of magnitude. Similar selective surfaces are commonly used today in commercial collectors.

2 Solar Water Heaters

2.1 Flat Plate Domestic Systems. The concept of selective surfaces was very quickly accepted, and the development of selective surfaces caused a great improvement in solar thermal energy absorption devices, using relatively simple solution e.g., plate collectors, thus starting the application of solar energy for household uses. The Black Chrome selective surface is probably the most widely used commercial coating incorporated in thermal collectors today. The first Israeli prototype collector based on this approach was demonstrated by Prof. Tabor at the first World Symposium on Solar Energy, which took place in Arizona in 1955.

Today, rooftop, flat-panel solar collectors are supplying domestic hot water to about 80% of the households in Israel, more than a million systems, in a country of 6.5 million inhabitants. The typical single-dwelling domestic unit consists of a 2 m^2 Flat Panel solar collector and a 150 liter insulated storage tank (Fig. 1). The flat panel collects solar radiation and heats the water in the collector. The water then flows to a storage tank in a thermally driven siphon loop. The fine weather conditions in Israel during most of the year, and the high insolation, provide a steady supply of heat during most of the time, including during the winter. As a result, the backup electrical heater installed in the water storage tank is used only infrequently. Such a system may save its owner some 1,800 to 2,000 kWh per year in electricity.

Larger systems, with pump-driven circulation of heated water, are installed in high-rise buildings, in several rural communities and at a number of industrial plants around the country.

2.2 Vacuum Tubes. Solel Corporation (Bet Shemesh, Israel) has developed several new types of solar collectors during the last few years. One of these is the monotube collector, intended for water heating for domestic use and for low-temperature industrial process heat. Figure 2 shows the monotube collector.

The collectors can be assembled together in parallel to provide large amounts of heat. Those collectors can be utilized at relatively high geographical latitudes, e.g., in Europe or in Japan. The Collectors can be installed on vertical walls as well as on roofs.

3 The Organic Rankine Cycle Turbine

A direct derivative of the early development of relatively low temperature flat plate collectors was the development, at the National Physical Laboratory, during the late fifties, of a matching Organic Rankine Cycle (ORC) turbine. This turbine was capable of operating even at the relatively low temperatures (below 100°C) provided by a solar flat plate collector array.

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Fig. 1 Flat panel solar collectors for domestic use in Israel

This invention was privatized in 1965 and an Israeli company Ormat was founded in Yavneh, Israel to convert the laboratory model into a commercial product. Ormat developed a small turbine-generator assembly to generate electricity. The main distinction of this technology was that it is virtually maintenance-free, making it suitable for remote installations.

A first implementation of the low-temperature ORC was a solar powered Ormat Energy Converter (OEC) for pumping 40 m^3/day of water for about 400 cattle was commissioned in Mali in 1966 in the framework of an international project. The plant is shown in Fig. 3. The solar plant operated reliably, unattended and independent of fuel supply.

Unfortunately, the use of flat panel solar collectors coupled with an ORC turbine did not take off commercially. The low fossil fuel cost has prevented the commercial viability of solar electricity generation. This is an effect that is repeated during the last several decades, and prevented the growth of other solar technologies as well.

Fig. 2 The Solel monotube collector

Fig. 3 Solar water pumping plant in Mali with flat collectors and an Ormat ORC turbine

Ormat has used the ORC technology to develop large megawatt sized derivatives of the small ORC turbines. These generators constitute now a major business worldwide, exploiting low-temperature geothermal heat, or industrial waste heat to produce electricity. These turbines are being manufactured since the mid sixties, and are used all over the world to generate electricity in remote places, using fuels available on location. Thousands of such small units are now operating in many countries worldwide, supplying reliable electricity for various needs such as communication, cathodic protection of gas and oil pipelines, operation of remote valve systems and remote sensing.

4 Solar Ponds

The cost of the heat collecting elements (either flat plates, or parabolic troughs or dish mirrors or heliostats) and their influence upon the cost of electricity produced in a solar power plant is a real hindrance in the introduction of solar energy into wider use. A relatively simple and inexpensive solution was thought to be the Solar Pond.

4.1 The Salt-Gradient Solar Pond. Dr. Rudolf Bloch of the Dead Sea Works first proposed the use of a salt-gradient solar pond as a large solar collector in 1948. The idea was to create a pond of saline water, of few meters in depth, which is artificially maintained so that the degree of its salinity and consequently its density is higher at the bottom of the pond than at the surface. The salinity gradient in the pond can be created by dissolving large amounts of salt near the bottom, and keeping the surface of the pond supplied with very low saline water, thus maintaining the necessary salinity gradient to prevent convection. Consequently, there is a much reduced or even no mixing between the layers. Absorption of solar radiation by the floor of the pond heats the lower layers of water that are prevented from rising by their high density relative to the upper layers. The layered saline pond has a relatively low heat loss at the surface, enabling the accumulation of heat. The temperature of the water at the bottom of the pond continues to rise and may attain temperatures close to 90°C.

Two experimental Solar Ponds were built under the supervision of Dr. H. Tabor in 1958. The first pilot scale ponds were built in 1979 at Ein Boqeq near the Dead Sea [3]. The area of the pond was 7500 m^2. The nominal installed power of the plant was 150 kW as peak power for short periods. However, the pond could support only 35 kW on a continuous basis during the summer and 15 kW on a continuous basis in the winter. The overall efficiency of the pond was only 1%, providing a tight margin for its commercial viability.

The development of pond technology continued and a larger demonstration pond was built at Beit Ha'aravah near the northern shores of the Dead Sea. The demonstration plant is shown in Fig. 4. The area of the pond was 250,000 m^2. This assures a large amount of stored heat energy. Ormat Corporation, the Israeli company who pioneered in building the ORC turbines, developed the large solar ponds and the matching turbines. A 5 MW ORC turbine was built for the Beit Ha'aravah pond, with support provided by the Israeli Ministry of Energy.

The Beit Ha'aravah pond could provide approximately 800 kW on a continuous basis. This is due to the relatively low thermodynamic efficiency of such a low-temperature power-producing system. However, the unique feature of the built in heat-storage capability of the solar ponds, can provide for a greater power output for a few hours each day, similar to a pumped storage system, providing peak power. Peak power is required typically during the mornings and evening daily peak load periods.

It takes several weeks until the pond temperature achieves a steady state, after which, one can operate the pond in either a steady state mode or a peaking mode. The ORC turbine at the Beit

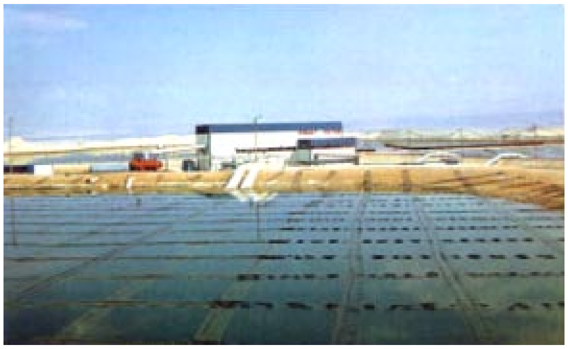

Fig. 4 The 5 MW Solar Pond Power Plant demonstration at Bet Ha'arava near the Dead Sea

Fig. 5 Luz parabolic trough solar power plants, Mojave desert, U.S.A

Haaravah pond was designed to perform this function. The inherent heat storage of the pond enables fuel-free and pollution-free operation of the plant even at night and during cloudy days. The experimental 5 MW Solar Pond Power Plant (SPPP) was operated by Ormat for seven years from 1983 to 1990.

A 3,240 m^2 salt-gradient solar pond was built in El Paso, Texas (USA) in consultation with Ormat on the grounds of a food cannery. The pond produces heat for the canning operation. The pond has been producing heat since the summer of 1986. The system operates at about 86°C and delivers about 300 kW of thermal energy. In 1986, the operators added a Rankine Cycle heat engine to the system. It generates electricity, producing up to 70 kW. In 1987, a 24 stage, low temperature desalting unit was added. It began producing about 16,000 liters of desalinated water per day. In 1992, the facility was shut down due to a failure of its original pond liner. The pond was reconstructed with a new liner system and operations resumed in the spring of 1995.

4.2 The Transparent Insulation Solar Pond. Erel company, developed another type of solar pond during the late 80's. This was a shallow water pond, on top of which float thermal diodes composed of an array of translucent honeycombs made of plastic material. The water heated in the pond can reach temperatures of about 85°C. This type of pond is suitable for supplying warm water for household uses and other low temperature applications e.g., laundries, textile factories, canned food factories, greenhouses and the like.

A pilot system was installed in Kibbutz Maoz-Haim in Israel to supply hot water for a housing project with 42 units.

5 Linear Focus Systems

In 1984 The Luz International Corporation, an Israeli company based in Jerusalem, succeeded in commercialising the linear focus parabolic trough solar power plants technology. The parabolic trough concentrators are focusing devices using a single-axis tracking system, usually North-South. The Heat Collecting Element (HCE) is a tube containing a thermal oil heat transfer fluid, located in the focal line of the concentrator. The HCE is made of a stainless steel pipe coated with a selective coating and is enclosed in a vacuum tube. It achieves high enough temperatures in the range of up to 400°C, heating the fluid that flows through the pipe and into a steam generator. There it raises steam to qualities that can be used with steam turbines, to produce electricity.

The company built the first concentrating solar power plant, known as the Solar Electric Generating System, (SEGS), in California's Mojave Desert. The Plants built by Luz included a 14 MW_e pilot plant at the Barstow solar test facility. 6 plants of 30 MW_e each, are located at the Kramer junction site facility, 2 plants of 80 MW_e each are at the Harper Lake site. A combined total capacity of 354 MW_e of Israeli designed solar power plants supply electricity to the Southern California Edison grid. The plants supply enough power to meet the needs of about half a million people. All the commercial plants built by Luz, are fully operational. A view of the Luz solar power plants at the Mohave Desert in California is given in Fig. 5.

The Israeli government has recently decided to build 500 MW_e of parabolic trough solar plants based on the Luz technology. The plants will be located in the Negev desert, at the southern part of Israel. A committee is now evaluating possible sites for the first solar plant of 100 MW_e [4]. Additional projects based on parabolic trough technology following the Luz example are underway or under discussion in India, Mexico, Morocco, Spain and Egypt. The pioneering development by Luz is therefore the most significant solar technology that had the largest impact worldwide during the last two decades.

Luz has sought improvements that will help decrease the cost of electricity produced by the SEGS Thermal Solar Plants. Development work to directly generate steam directly in the Heat Collecting Elements was underway but was not completed, when Luz ceased operation mainly because no additional Solar Power Plants were ordered. The Direct Steam Generation (DSG) idea was later picked up by European investigators and was further developed and demonstrated.

The DSG approach should reduce the installation cost of the power plant by eliminating the steam generator and the high temperature fluid systems that exist in the present generation plants. Another possibility of reducing the investment in the solar field, can also be addressed from another aspect, namely through the reduction of the installation cost of the collector field itself. This may be achieved either through the utilisation of different types of collectors made of different and cheaper materials as well as through savings in the mirrors and mirror-supporting structural elements. Figure 6 shows a new variation of a compact, low-cost parabolic trough collector produced by Solel. This collector produces somewhat lower temperatures than the original Luz collectors. It is suitable for moderate temperature applications such as process heat and absorption air conditioning. It is also possible to

Fig. 6 A Solel compact low-cost trough collector

use it for power generation with Rankine cycle turbines, but due to the lower temperature, the conversion efficiency will be low.

6 Solar Tower

6.1 The Weizmann Solar Tower Facility. The collection of solar radiation with a solar tower can achieve much higher concentration than a parabolic trough, leading to a much higher achievable temperature in the solar receiver. This in turn can produce a higher overall conversion efficiency. The solar tower is therefore a candidate for operating advanced, high efficiency turbines for electricity generation, hydrogen production and other high-performance applications [5,6].

A Solar Tower research facility was built at the Weizmann institute of science, under the guidance of Prof. I. Dostrovsky. In the Solar Tower facility, solar irradiation is diverted by a field of mirrors-heliostats, directing the reflected solar irradiation beams towards a focal point on the central tower. The Solar Tower containing various laboratories to perform the research and the heliostat field are shown in Fig. 7.

6.2 High-Temperature Receiver. To create very high temperatures, two components are needed in addition to the heliostat field. A secondary reflector further concentrates the light collected by the heliostats and reach a high enough concentration level; and a solar receiver converts the radiation to thermal energy. Both components have been developed and demonstrated at the Weizmann Institute with the aim of producing high-temperature compressed air for use in gas turbines for electricity generation.

The secondary reflector can be based on the Compound Parabolic Concentrator (CPC) geometry or other non-imaging optics solutions. Several different types of secondary reflectors have been demonstrated at the Weizmann Solar Tower, from small units intended for several kW to the largest CPC designed for over 1 MW of concentrated radiation.

An innovative high-pressure volumetric solar receiver was developed by the Weizmann Institute and Rotem Industries for heating air to temperatures above 1,000°C. The receiver maintains the high pressure with a cone shaped quartz window. The window can sustain high pressure by utilizing the high compressive strength of quartz, and the design keeps the material under local compression at all operating conditions. The concentrated solar radiation crossing the window is incident on a bed of ceramic fins; compressed air passes over these fins and is heated to high temperature. This receiver has been demonstrated at 1,200°C [7] and in principle can reach even higher temperatures. Since the power to volume ratio of this receiver is very high, this results in a relatively small receiver for a given power rating. The small size is helping reduce the solar power plant hardware cost, even using the high temperature sophisticated ceramic interior of the receiver.

Fig. 7 The solar tower and heliostat field at the Weizmann Institute of Science

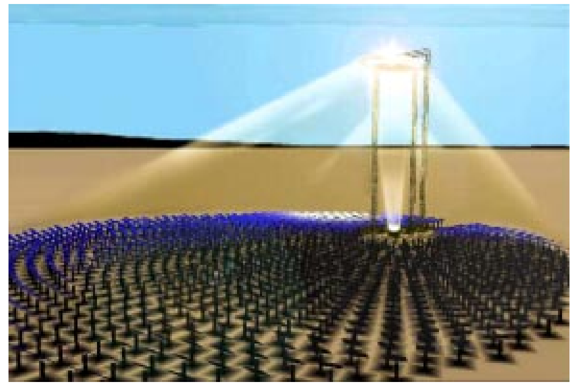

Fig. 8 The Beam-Down "Nur al Salaam" solar plant designed for installation in Egypt

6.3 Beam-Down System. The development team at the Weizmann Institute proposed and also built a prototype of a Beam-Down Solar Tower power plant. In this system, sunlight from the field of heliostats is reflected towards a secondary reflector installed on the tower that reflects the solar irradiation towards the ground level. Near the ground level, the light is further concentrated in the CPC devices and passes into an array of high temperature air receivers. By positioning multiple concentrators and receivers at the focal zone, a wide range of power levels can be achieved. This modularity may also decrease costs, since unique, custom receivers are not needed for specific power levels or designs. Pressurized air from the compressor of a gas turbine flows through the receivers and is heated to high temperature. An artist's view of such a Beam-Down solar plant is shown in Fig. 8. A prototype of the Tower Reflector concept, shown in Fig. 9, was built and tested at the Weizmann Institute.

The high-temperature gas emerging from the receiver enters into a conventional high efficiency gas turbine. With the compressor outlet temperatures of the order of 300–400°C, the air is heated in the receiver to temperatures in the range of 800–1,400°C, depending on the type of turbine. In cases when the air at the outlet of the receiver does not achieve high enough temperatures a result of cloudy skies, the air is diverted to a combustor, where natural gas is added and ignited to further heat up the mixture of air and fuel. The hot combustion products then flow through the Gas turbine for power production. Following the expansion in the gas turbine, the gas can be diverted into a boiler to

Fig. 9 The Tower Reflector mirror prototype installed on the Solar Tower at the Weizmann Institute

create steam to operate an additional steam turbine, producing a Combined Cycle. The wide range of possible temperatures as determined by the system design, makes this approach ideal for integration with the gas turbines or combined cycle gas turbines now in use.

A detailed analysis was performed on the expected performance and cost of such solar plants [8]. The solar power plant installed cost is estimated to be reduced from the initial value of about 5,000 \$/kW for the first 30 MW_e plant to be built under present conditions, to about 1,900 \$/kW when 10,000 MW_e of installed capacity will be built.

The high concentration Solar Tower Power Plant was considered by the Egyptian authorities as a potentially promising technology enabling them to meet the goals of developing cost-effective solar power plants in Egypt. During 1999, representatives of Boeing, Egypt's Ministry of Electricity and Energy, the Weizmann Institute and Ormat have reached a Tri-Lateral agreement to jointly develop and validate the technology by building of a 10 MW demonstration solar power plant in Egypt (Fig. 8). This plant, named "Nur Al Salaam" (Light of Peace), was to become the prototype for the commercialization of this technology [9]. These plans are now on hold awaiting a better political climate.

6.4 Gasification and Fuel Production. The Solar Tower can also be used to produce "Solar Fuels" that could be delivered through piping to a remote fuel consumer [10]. In cooperation with the DLR laboratory in Germany, a solar chemical heat pipe that operates by reforming of methane was built at Weizmann Institute.

Solar steam reforming ($CH_4+H_2O \leftrightarrow 3H_2+CO$), solar CO_2 reforming ($CH_4+CO_2 \leftrightarrow 2H_2+2CO$), and controlled methanation (the reverse reactions) were achieved. The main issues were to adapt and develop a suitable catalyst as well as the appropriate computer models to predict the outcome of the reactions. This project succeeded in developing and demonstrating a complete solar chemical heat pipe with both energy storage and energy extraction components. Such a heat pipe will enable the storage and transmission of energy from sunny regions to distant energy consumers.

An attempt was also made to gasify solids containing hydrocarbons using high temperature central receiver at the Weizmann institute. Local Oil Shale was chosen because it is found in Israel, with large known reserves. The major advantage of using concentrated sunlight for high temperature endothermic processes of this type is the rapid heat delivery to the reaction site, resulting in a high reaction rate when a fluidized bed or a falling particle bed is used in a transparent reactor. The experimental results show very high conversion efficiency provided in a short reaction time of about 160 s. The conversion efficiency can reach the range of 84.5–98% at reaction temperatures of 650–943°C, respectively. The experiment proved that sunlight could be used effectively to drive a highly endothermic reaction in solid particles, and that an open cycle gas production using Oil Shale is feasible technologically, albeit its economic advantage is yet to be proven.

7 Dish Concentrators

7.1 The Large Solar Dish (PETAL). The 400 m^2 dish concentrator PETAL (Photon Energy Transformation & Astrophysics Laboratory) is a research facility at the National Solar Research Center of the Ben-Gurion University at Sede Boqer. This dish was designed to reach a concentration of 4,000 suns at its focus and can reach even higher concentrations up to approximately 10,000. The Israeli dish was developed from an earlier prototype designed by Prof. Stephen Kaneff of the Energy Research Center at The Australian National University. The Israeli design has a number of significant changes from the original, aimed at achieving the almost threefold improvement in concentration. These include tighter specifications on mirror accuracy and tighter tolerances attained by adjustments of the mounting panels and frame to achieve better focusing. Prof. D. Faiman of the Sede Boqer solar center heads the Israeli team responsible for construction of the dish. A photograph of the dish is shown in Fig. 10.

Fig. 10 The PETAL solar dish at Sede Boqer Campus

The dish is used, among other research activities, to test the operating parameters and the economic viability of Concentrated Photovoltaics (CPV). The idea behind CPV systems is to offset the high cost of PV material by using small areas of costly PV cells illuminated by cheap mirrors reflecting the light from large collecting areas. There is, however, a penalty to be paid in increased cost and complexity of the tracking and control of the solar dish. Prof. Faiman believes that nevertheless, a CPV system based on a large dish could lead to system costs of around \$1/Wp, and electricity costs below 10 ¢/kWh [11].

7.2 The Mini Solar Dish. Prof. Jeff Gordon of Sede-Boqer has developed a new device, for high-flux and high-temperature applications. The device is based on a small 20-cm diameter mini-dish solar concentrator. An optical fiber at its focus transports the concentrated sunlight to a remote receiver. This mini-dish represents a different approach compared to the conventional approach of bigger solar collectors. The miniaturization enables high-

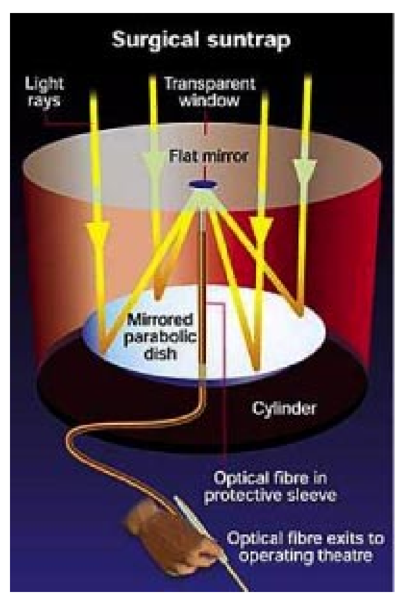

Fig. 11 The mini dish feeding a surgical device

accuracy, low-cost manufacturing of collectors due to their small scale. In addition, it is possible to decouple between collection and delivery points of concentrated sunlight. The receiver can be then conveniently located under controlled conditions.

An interesting and original application for this collector was proposed as a replacement for surgical lasers, leading to ''solar surgery'' [12]. The concept is shown in Fig. 11. Since surgical power requirements are typically only several watts, the solar collection unit can be miniaturized. Solar surgery can serve as a low-cost alternative to laser fiber optic systems. Insolation data indicate that in regions with clear climates, solar surgery would be feasible on at least half the days of the year.

A number of such mini-dishes could be mounted on a single platform to constitute modules. The modules can than be clustered on Heliostats and serve as building blocks for a relatively large solar field. The collected radiation can be channeled to a central location using the optical fibers. Central receivers for electricity producing turbines and receiver-reactors for high-temperature chemical energy storage could be proposed as possible applications for this centralized version of the mini-dish collector.

8 Solar Cooling

The development of advanced solar absorption cooling units and heat pumps utilizing solar energy is a major and important task, to help in reducing the use of fossil energy in hot climates. It is an especially important application due to the good correlation between the demand for cooling and the availability of solar energy.

Paz Corporation developed an absorption-cooling machine using a proprietary mixture of two immiscible fluids. It has no noxious effects contrary to the water ammonia mixtures or lithium bromide fluids used in other absorption machines. The cooling machine is suitable for use with temperatures of about 85°C that can be provided even by flat plate solar collectors. This technology was further developed by Coolingtech Ltd. Following a search for refrigerants that will comply with the requirements of Kyoto protocol, new mixtures of immiscible fluids were tested and adapted to the cooling process and equipment. An absorption machine of 10 Ton Refrigeration capacity is presented in Fig. 12. This technology has demonstrated a Coefficient of Performance (COP) of 1.0–1.1 in the temperature range suitable for air conditioning (5–10°C). When the heat supply is at higher temperatures around 110–130°C, a COP of around 0.5 has been demonstrated for refrigeration down to −15°C.

Fig. 12 The Coolingtec absorption-cooling machine

9 Photovoltaics (PV)

9.1 PV Research. The approach in Israel towards the Photovoltaic (PV) Research field is based on the premise that Israel cannot compete with the huge investments made by the leading industrialised countries in this R&D area. As a result, PV research activity in Israel is mainly in academic ''niches'' in which the local contribution of effort could impact the PV community.

The potential of CPV is being investigated. The developing of silicon cells having a minimum efficiency of 20% under a concentration of ×300 suns at operating temperatures around 100°C was performed at the Jerusalem College of Technology.

At the Hebrew University in Jerusalem, wave length shifting and wave guiding of light spectra to increase Efficiency of solar cells showed solar to electrical conversion efficiencies of 15% at the edges of the glass that was used as a frequency converter and a wave guide.

The Weizmann Institute achieved considerable progress in research on the issues of photoelectrochemical cells, reaching an efficiency of 10% [13].

9.2 New Materials for Photovoltaics. Research into the prospects of using C_{60} (fullerene)-based solar cells have been performed at the Sede Boqer National Solar Research Center. The doping of solid C_{60} to increase its conductivity is one of the central challenges for high efficiency fullerene-based solar cell production. The research team at Sede Boqer developed a new technique for doping (intercalation) of C_{60} thin films. The technique involves the vacuum deposition of highly crystalline C_{60} thin film onto a metal (Cu or Au, or Ag) sub-layer and subsequent exposure of the samples to a reactive gas atmosphere. Semiconductor behavior with increased conductivity values and decreased conductivity activation energy has been demonstrated for the doped samples. This behavior indicates the possibility of using doped C_{60} fullerenes for PV cells production.

Experiments on the temperature dependence of photovoltaic parameters of solar cells fabricated from conjugated polymers and fullerenes have shown that the conversion efficiency increases with increasing temperature, reaching a maximum in the range 47–60°C [14]. This positive temperature dependence is a remarkable peculiarity for solar cells, which is not observed in most inorganic solar cells. This phenomenon is of major significance, since the cell temperature during normal operation in sunny climates is expected in this range. It is then possible that fullerene-based cells could be more suitable for operation under these conditions than competing inorganic cells.

9.3 PV Applications. Grid electricity is easily available and relatively cheap in Israel in most locations, making the use of PV non-cost effective, except in unique situations. There are currently no government initiatives or subsidies for PV. Therefore there is virtually no PV market in Israel except for special niches.

Some attempts were made to install PV systems in mainstream applications such as domestic use. Resident of Klil village, a small community in the Galilee, chose during the eighties to provide all of their electric requirements with off-grid photovoltaic installations. Each house has a 766 W_p array installed. Following the ageing of the community, the demand for electricity increased, to the extent that the residents were willing to compromise their ideological approach and connect to the electricity grid. There were also some technical problems with some components such as charge controllers, diminishing the full energy potential of the system. Another approach was taken by the Israel Electric Corporation, installing a 5 kW_p grid-connected, net-metering PV system on a house in Mitzpe Adi in the Galilee. Operation has been practically trouble-free for the last six years. Kibbutz Samar in the Arava Valley is planning to install a 200 kW_p, of which the first 4.5 kWp are already installed. However, these isolated projects did not produce a trend for additional installations.

The Israel Electric Corporation built, in a cooperation project within the European Union-4th Framework Program, a reverse-osmosis (R.O.) desalination plant powered by PV and wind generators. The purpose of the project was to investigate the energy balance of a renewable energy hybrid system connected to a R.O. plant and backed up by a battery bank. The PV array capacity is, and the desalination unit can provide 400 L/h. The unit represents a fresh water source for a small and remote community, and the project concentrates on aspects such as meeting the community daily water needs, reliability and economics.

An interesting approach to the practical use of PV was provided by Solor (now Millennium Electric T.O.U.). The company developed a hybrid solar collector supplying both electricity and heat for dwellings. The system built by Solor is composed of an array of PV cells adhered to a flat plate heat collector. Although the performance of the solar cells is somewhat degraded because of their operation at a relatively high temperature, the system supplies both electricity through solar cells and hot water through the flat plate collector for domestic use, with high reliability. The installed cost of this combined system is lower when compared with the installation cost of two separate systems for providing electricity and heat. A typical system will have a daily output of 2–4 kWh and about 8,000 kcal of hot water. This system can provide a family with its daily energy needs.

10 The Energy Tower

The basic idea behind the Energy towers is to produce solar energy without investing at all in expensive large-area collectors. This idea employs the availability of large amounts of hot dry air at mid-latitude regions, about 30°, due to the well-known global meteorological cycle discovered by Hadley in 1735. A tall chimney is constructed, and a wind is created in the chimney by cooling the hot and dry air using a spray of water at the top, similar to the process used in evaporative cooling devices. The cooled air becomes denser and starts descending creating a downdraft. Turbines at the bottom of the chimney extract mechanical energy from the airflow and generate electricity. In arid desert areas the hot dry air is available day and night, the energy tower will therefore produce electricity all the time, as long as the spray of water continues. This process is shown in Fig. 13.

This idea was first proposed by Carlson in 1975, and followed by Prof. Dan Zaslavsky at the Technion—Israel Institute of Technology. According to the calculations made at the Technion, the output of one plant located north of Eilat in the Israeli desert, with 1,200 m height and a diameter of 400 m will be about 3–4 billion kWh per year. The cost of electricity produced will be in the vicinity of 4 ¢/kWh, which is much better than other solar technologies and competitive against conventional fossil fuel plants.

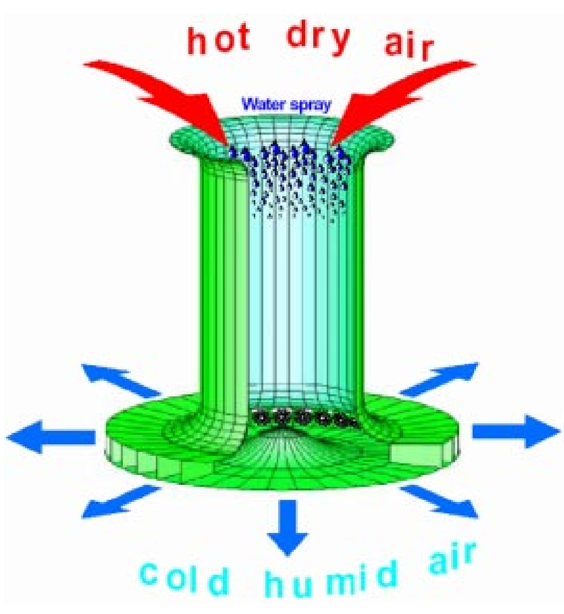

Fig. 13 Hot dry air enters the Energy Tower at the top, increases its density due to water spray, and leaves at the bottom through wind turbines

11 Concluding Remarks

When solar research for providing heat and electricity started in Israel in the fifties, pollution and degradation of the environment were not yet in the public eye. Neither were the energy supply problems as identified now, considered a serious problem. The Israeli early start in solar energy research provided locally a wide spectrum of solar energy technologies that were developed by the Israeli scientific and technological communities. However, only a small part of the developed technologies reached the marketplace and penetrated the barriers on the way to practical implementation.

The most prevailing solar technology in Israel is the flat plate solar collector used for water heating, mainly because of its simplicity in manufacturing, installation, and the very low maintenance requirements. This coupled with a relatively long lifetime of the solar collector and the whole system, created a real winner. The flat plate solar panel technology reached a plateau in its development and performance and in the level of market penetration in Israel. Future expansion of this technology can occur mainly in other regions of high insolation such as the Mediterranean and southern Europe.

In regions of lower insolation values, e.g., Japan, Central Europe and North America, the solar collectors of the monotube type can penetrate the market place when the real cost of using fossil fuel will be fully understood and considered by the societies and decision making bodies in those regions.

The Israeli R&D teams tackled many of the modern technologies aimed at supplying solar energy. In some of the technologies the Israeli teams where able to provide breakthrough achievements. The SEGS power plants are a clear demonstration of this ability. In those plants electricity was provided on schedule and at a known cost. To achieve this, the SEGS plants had to be subsidized to some extent. At the present relatively cheap cost of conventional fossil energy, this subsidy is inevitable as long as the hidden costs (externalities) of using fossil fuels are not included in the electricity price. As the understanding of the real cost of fossil energy will mature, more solar and other alternative energy systems will be able to penetrate the unseen barrier of the present false energy cost valuation of the market place.

The same argument holds for the provision of solar cooling through the use of absorption units as could be adapted using the equipment depicted above.

Based on the experience with residents of Klil village, an interesting observation could be withdrawn for households equipped with stand-alone PV units with no electric grid backup. A significant spare capacity or ability to expand must be included in the design of the PV system, to provide for the natural growth of the household electricity requirements. If this extra capacity is not provided, the residents may revert to installation of small fossil fuel generators or ask to be connected to the electricity grid.

The development of the solar tower concept, and especially its high temperature collector, enables a relatively high efficiency solar generation system. It also provides a tool for gasifying solids while using highly concentrated solar energy. This promising concept did not mature yet to an operating full-size plant. To reach this stage the first pilot plant must be built under favorable financing conditions, as done when constructing other solar demonstration plants.

The approach of the Israeli researchers to identify niche opportunities in Photovoltaic research fits well with the funds available for this purpose. Using the solar dish also provides a possibility to investigate concentrated photovoltaics, a domain in which achievement, as depicted above in the report, were made by Israeli research teams. The exploitation of ''collectorless solar energy'' through Energy Towers is a bold approach to supply renewable electricity on a relatively grand scale. However, because of the large physical dimensions of the chimney necessary to achieve production and the breakeven in the cost of supplying energy using this method, it appears that implementation of this idea will not materialize in the near future.

A crucial technical challenge still facing the spreading of Solar energy results from the intermittent sporadic nature of this resource, the outcome of insolation changes due to night and day, or that of a cloudy weather and high geographical latitudes. To enable circumventing this issue a solution must be found for storage of solar energy. This will enable the installation of solar energy facilities even in regions of high latitudes, the regions where most of the affluent population now lives.

As previously stated, the present ''market place'' cost of conventional fossil energy is relatively low when compared to cost of energy from solar resources, hence the most crucial question of solving the issue of financing of pilot and commercial size Projects was not answered as of now. This ''financing barrier'' must be resolved by any promoter willing to venture into the solar technology. It could be overcome only when governments, local or state, will contribute to the promotion of the solar technologies during the two crucial stages; the first stage of research and development and the second stage of technology demonstration.

In Israel, most of the research and development in solar energy were performed with government or public available funds. The Israeli government promoted mainly the research stage but failed to promote the second demonstration stage. As a result, research and development entities in Israel now possess the required know-how to commence the demonstration stage of the developed solar technology, as was indicated in the article. However, those entities do not have the necessary financial means to turn this know-how into a full size energy project. This is a result of the competing investment opportunities private investors are facing when considering the various possible investment schemes, and the lack of government incentives to promote solar energy technologies.

With the present potential of solar energy to replace a part of the fossil energy used, a more concentrated international as well as local effort must be initialized to enable the deployment of large-scale solar energy projects employing available solar technologies. This will provide the necessary technological feedback to enable a cost improvement scheme in the future and make solar technologies become more competitive in the marketplace.

References

[1] Tabor, H., 1955, ''Selective Radiation I. Wavelength Discrimination: A New Approach to the Harnessing of Solar Energy,'' Bull. Res. Council Israel, **5A**, pp. 119–134.

[2] Tabor, H., 1955, ''Solar Energy Collector Design, With Special Reference to Selective Radiation,'' Bull. Res. Council Israel, **5C**, pp. 5–27.

[3] Tabor, H., and Bronicki, Y. L., 1980, ''The Next Twenty-five Years: Solar Utilization in Israel,'' ASSES-ISSES meeting, Phoenix.

[4] Zohar, A., 2004, ''Siting Considerations for a Solar Power Plant in the Negev,'' *12 Symp. Solar Electricity Production*, Sede Boker (Israel), Feb. 2004.

[5] Kribus, A., Zaibel, R., Carey, D., Segal, A., and Karni, J., 1998, ''A Solar Driven Combined Cycle Power Plant,'' Sol. Energy, **62**, pp. 121–129.

[6] Yogev, A., Kribus, A., Epstein, M., and Kogan, A., 1998, ''Solar 'Tower Reflector' Systems: A New Approach for High-Temperature Solar Plants,'' International Journal of Hydrogen Energy, **23**, pp. 239–245.

[7] Kribus, A., Doron, P., Rubin, R., Reuven, R., Taragan, E., Duchan, S., and Karni, J., 2001, ''Performance of the Directly-Irradiated Annular Pressurized Receiver (DIAPR) Operating at 20 Bar and 1,200°C,'' J. Sol. Energy Eng., **123**, pp. 10–17.

[8] Thomas, F. C., 2000, ''Commercializing Solar Thermal Towers in the Mediterranean: A Guide to Finance Options and Issues,'' Weizmann Institute of Science internal report.

[9] Blackmon, J. B., Sugarmen, C., Erez, A., Yogev, A., and Zannoun S., ''Status of the U.S./Israel Science and Technology Foundation (USISTF) High Concentration Solar Central Receiver Program,'' *ASME Solar Forum*, April 2001, Washington, D.C.

[10] Dostrovky, I., 1991, ''Chemical Fuel From the Sun,'' Sci. Am., December, pp. 50–56.

[11] Faiman, D., Biryukov, S., and Kreske Pearlmutter, K., 2002, ''PETAL: A Research Pathway to Fossil-Competitive Solar Electricity,'' *Proc. 29 IEEE PVSC*, New Orleans, May 2002, pp. 1384–1387.

[12] Feuermann, D., and Gordon, J. M., 1998, ''Solar Surgery: Remote Fiber Optic Irradiation With Highly Concentrated Sunlight in Lieu of Lasers,'' Opt. Eng., **37**, pp. 2760–2767.

[13] Licht, S., Hodes, G., and Tenne, R., 1987, Nature (London), **326**, p. 863.

[14] Katz, E. A., Faiman, D., Tuladhar, S. M., Kroon, J. M., Wienk, M. M., Fromherz, T., Padinger, F., Brabecb, C. J., and Sariciftci, N. S., 2001, ''Temperature Dependence for the Photovoltaic Device Parameters of Polymer-Fullerene Solar Cells Under Operating Conditions,'' J. Appl. Phys., **90**, pp. 5343–5350.