http://citeseerx.ist.psu.edu/viewdoc/citations;jsessionid=E07252C7771667B02273AB098E49134A?doi=10.1.1.194.3831

July 2002 ECN-C--02-062

SOLAR THERMAL POWER TECHNOLOGIES

Monograph in the framework of the VLEEM Project

B.J. Groenendaal

Acknowledgement
This study is a result of the VLEEM project (Very Long term Energy-Environment Model), ECN project number 7.7372. This project is co-financed by the European Commission's Fifth Framework Programme: Energy, Environment and Sustainable Development. The project mainly addresses the objectives described in Key Action 5: Cleaner energy systems, including renewables of the Energy sub-programme of the Fifth Framework Programme for Energy, Environment and Sustainable Development. Theo de Lange and Bob van der Zwaan of ECN Policy Studies are gratefully acknowledged for their feedback on this report. I would also like to thank the other VLEEM participants: Bertrand Chateau (Enerdata), Thomas Hamacher (IPP), Hubert Reisinger (Verbundplan), Gerhard Kolb, Ulf Birnbaum, Dag Hamarsen (Julich) and Paul Lako (ECN Policy Studies).

Abstract

Existing long-term energy-environment models provide reliable scenario projections on energy demand and supply and related environmental consequences, under three conditions:

- Unknown technologies cannot play a significant role, neither in energy demand, nor in energy supply, and neither in environmental consequences, under the time horizon envisaged.
- Entirely new and unknown behaviour and preferences of individuals cannot play a significant role, neither in energy demand, nor in energy supply, under the time horizon envisaged.
- There is no major rupture in the socio-economic system development under the time horizon envisaged, such as wars, major energy supply physical shortage, climate disasters, etc.

These conditions usually limit the time horizon in which scenario projections are reliable to a maximum of 25 years, i.e. the time necessary for a scientific breakthrough, or the period of time between two demographic generations. Beyond 25 years starts the 'very long term', in which period most models become increasingly less reliable as the time horizon enlarges. But the new challenges related to climate change, depletable resources of fossil fuels, the management of nuclear waste and the agenda for the development of the technologies necessary to face these challenges require the consideration of these issues up to 50 years or more in advance.

Since the range of possibilities in the very long term is totally open, it is important not to describe this range, but to describe the possibilities that fit within a set of overall constraints imposed on the overall system in the very long term. Instead of exploring and formalising the various causalities on the basis of our knowledge of the past, it is necessary to describe and formalise the association of causalities necessary for bringing the system from the present situation to the targeted future, through a 'back-casting'approach.

The VLEEM project has been organised according to two fields of research: technology and socio-economic development and one horizontal field of research, i.e. modelling. The technology development research programme has focussed on a selected number of new and innovative energy supply and demand technologies for which monographs have been compiled first.

This report discusses the status of different Solar Thermal Power technologies (STP). The statuses of the different technologies are presented from a rather technological point of view. The report serves as monograph document for very long modelling exercise in the VLEEM project, ECN project number 7.7372. This study focuses on global energy supply and demand until 2100. It is difficult to make predictions about the development of these technologies for such a timeframe. Because the VLEEM project focuses on technical options, this monograph pays attention to the expected breakthrough year of 'new'power production facilities, geographical spread, energy payback ratios and land, water and material needs.

CONTENTS

SUMMARY

This monograph, part of the VLEEM study (Very Long Term Energy and Environment Model), gives an introduction into Solar Thermal Power technologies. The monograph focuses on the technical and environmental aspects of the different options. Attention is paid to the potential of these technologies in energy terms for the world as well as for Western Europe. Only limited attention is paid to the cost price of the produced power, since cost predictions for a time scale of 50 years or more are unreliable.

Existing long-term energy-environment models provide reliable scenario projections on energy demand and supply and related environmental consequences up to a maximum of 25-30 years. But the new challenges related to climate change, depletable resources of fossil fuels, the management of nuclear waste and the agenda for the development of the technologies necessary to face these challenges require the consideration of these issues up to 50 years or more in advance.

Solar Thermal Power technologies can be divided into mirror systems and moving air systems. In this monograph, five different technologies are described, among which three mirror systems and two moving air systems. The mirror systems concentrate sunlight on a receiver by means of mirrors. The heat in the receiver is used to produce steam to drive a stem turbine. The three technologies are the Solar Dish, the Parabolic Trough and the Power Tower. The moving air systems heat air at the surface or cool air at high altitude. By changing the temperature of the air, the air starts moving, finding a new equilibrium. By guiding this movement through a tube or tower, the energy content of the moving air can be harvested with wind turbines. The two moving air technologies are the Solar Chimney, an up-draught system, and the SNAP tower, a down-draught system.

Of these five technologies, the Solar Tower and the SNAP tower are selected for a detailed analysis. The Solar Tower and the SNAP plant are selected because they can operate on multi-MW scale, or have the ability to operate almost 24 hours a day without additional storage facilities.

Power Tower

The mirrors focus the solar energy onto a central receiver located on top of a Tower. In order to extend operation time, the schemes often incorporate a thermal storage facility. In a typical installation, solar energy collection occurs at a rate that exceeds the maximum required energy to produce steam for the steam turbine. Consequently, a thermal storage system can be charged while the plant is producing power at full capacity. A power Tower with molten salt storage tanks can be designed for an annual capacity factor of 65%. This means that a Power Tower could potentially operate for 65% without the need for a fossil fuel fired back-up installation. Power Towers are capital intensive compared to conventional power plants. The natural higher investment cost comes from the entire solar part that must be built in addition to the conventional part. The O&M costs are expected to be somewhat higher because beside the costs for the conventional part there are also costs for the solar part of the installation. To reduce costs, Power Tower will likely be hybridised with conventional fossil-fired plants.

An environmental concern of this technology is the relatively large land and water usage. This is an important issue from a practical and environmental viewpoint, since these plants are typically deployed in desert areas that often lack water and have fragile landscapes. Another threat to the environment is an accident with the molten salt storage system. Salt leakage makes the soil unsuitable for agricultural applications and damage the local environment in a permanent way.

SNAP Tower
A SNAP power plant is basically a hollow tower of 1 km height with openings at the bottom. To create a strong sustained wind, water is raised to the top of the tower where it is sprayed over the entire area of the flue opening. The sprayed water evaporates, making the hot dry air at the top cooler and heavier than the surrounding air. The heavier air sinks down the tower and comes out through the opening at the bottom. On its way out, it passes through a battery of shrouded wind turbines, which drive electric generators. The surface acts as a heat collector, filled with heat by the sun during the day. During the night, the surface is still hot and can still heat the air. This means that a SNAP Tower can operate 24 hours a day. However, the energy output changes somewhat during the day and to a greater extend over the seasons, depending on specific conditions at each site.

Beside power production, a SNAP plant can also produce desalinated water from seawater, if desalination units are placed after the turbines. This is an attractive option because the plant does not depend on local water anymore. Seawater is transported to the SNAP plant where it is first used to cool the hot dry air at the top of the shaft. After passing the shrouded wind turbines the wet air is led through desalinating equipment producing fresh water. Together with fresh water, concentrated brine is produced. This concentrated brine could be transported back to the sea.

Due to the proportion of a SNAP power plant with a desalination unit, questions have been raised about the land needed to erect such a system. When a SNAP tower is erected, agricultural use of the direct surrounding land is not possible anymore due to the saline winds coming out of the shrouded wind turbines.

The main disadvantage of this technology is that it only exists on paper. No demonstration plant has ever been built: it is therefore difficult to estimate the actual power and water production and the costs.

Solar resource
Estimates of the total global solar energy resource that might be utilised by solar thermal electric plants are subject to much uncertainty. This is caused by many factors: lack of measured data on direct solar radiation, suitability of local grids, economic factors and the fact that the technology is still developing. The World Energy Council once predicted that by 2020 the global energy production from all types of solar energy (solar thermal electric, photovoltaics and solar thermal heating) would increase to between 109 and 355 Mtoe per year. It was estimated that 30 to 35% of this would come from solar thermal power plants, resulting in a predicted electricity production from these plants of between 140 and 410 TWh per year. A number of constraints, in particular the current high capital costs (relative to conventional fossil fuel plants), are likely to lead to a slow implementation in the short- to medium-term.

Environment
The main environmental impact of solar thermal power systems is that they reduce emissions of greenhouse and acid gases by displacing conventional fossil fuel generation. Proportionally, small-scale schemes do not have smaller impacts than large-scale systems. Stand-alone schemes, such as the Dish System, do have a smaller environmental impact than the other systems. The only significant negative impacts are concerned with:
- emissions during materials' processing, component manufacture and construction,
- thermal pollution of water bodies,
- accidental discharges of pollutants,
- land use of large-scale schemes.

These impacts can be minimised or avoided by use of various methods or approaches.

Solar thermal power is a relatively new technology that has shown significant improvements since its inception about 20 years ago. Of the three mirror types, Parabolic Trough systems are at the commercial stage, whereas Power Tower and Dish systems are still at the demonstration stage, although there are plans for commercial schemes in the near future. The moving air systems are less developed. A Solar Chimney test facility has been built in Spain and a SNAP tower only exists on paper. The deployment of solar thermal power systems, predominantly mirror systems, is expected to increase significantly in the medium to long term up to 2020. Most of this deployment is expected to take place in the US and non-IEA member countries.

Strengths of concentrating solar technologies are:
- Production of clean renewable energy, with no atmospheric emissions, in particular no CO_2.
- The hybridisation option allows Power Tower dispatchability.
- The systems have the opportunity to produce electricity 24 hours per day.

Weaknesses of concentrating solar technologies are:
- The inherent capital intensive nature of these technologies.
- The current high kWh cost.
- The large land requirements for Power Towers and SNAP plants.
- The large water requirements for SNAP plants.
- Both systems are material intensive: SNAP towers need a lot of concrete to built the shaft and Power Towers need a lot of siliciumoxyde to produce mirrors.
- Limited number of near-term opportunities associated with any emerging technology.

1. INTRODUCTION

In general there are three rather well known applications of solar energy use; direct use (lighting and drying), direct conversion into electricity (photovoltaic) and direct conversion into heat (hot water production). A fourth set of technologies is the Solar Thermal Power (STP) system, which converts solar energy use into electrical power. This document gives an overview of five different Solar Thermal Power technologies. Special attention is paid to the environmental burdens of Solar Thermal Power systems.

In Chapter 2 the technical background of the Solar Thermal Power principle is provided. The five different technologies are described in Chapter 3, among which three mirror systems and two moving air systems. Of these five technologies the solar tower and the SNAP plant are selected for a detailed analysis. The Solar Tower and the SNAP plant are selected because they can operate on multi-MW scale, or have the possibility to operate almost 24 hours a day without additional storage facilities. Chapter 4 analyses the mirror based concentrating 'Solar Tower' technology. Chapter 5 analyses the moving air 'SNAP' technology. In Chapter 6 an overview of the available solar resource is given. The combination of solar insolation and the technologies described in Chapter 4 and 5 makes it possible to estimate the potential supply of power by solar thermal technologies in the near future. The environmental impacts of Solar Thermal Power technologies are described in Chapter 7. The final Chapter 8 consists of the conclusions.

1.1 Background of this monograph and the VLEEM study

Existing long term energy-environment models, provide reliable scenario projections on energy demand and supply and related environmental consequences to a maximum of 25-30 years. But the new challenges related to the climate change, the depletable resources of fossil fuels or the management of the nuclear wastes, and the agenda for the development of the technologies necessary to face these challenges, require to consider these issues 50 years or more ahead.

Objectives of VLEEM and this monograph
In order to overcome the limits of the existing long-term energy-environment models, and to benefit at the same time of past experiences with these models, VLEEM is supposed to develop a genuine 'very long term energy-environment model'. This model is based on existing long term energy models, but enhanced with two innovative major functionalities:
- To describe the futures that fit with a set of overall constraints imposed to the overall system on the very long term, like the stabilisation of the concentration of the atmosphere in greenhouse gases, or the stabilisation of the overall inventory of plutonium and minor actinides, or the end of the depletion of hydrocarbons for energy purposes, etc.
- To describe and formalise the association of causalities necessary to bring the system from the present situation to the targeted future, through a -back-casting- approach in which the concepts to describe energy end-uses and resources have to be redefined.

More generally, the very long-term energy-environment model intents to serve the objectives of the RTD activity as specified in the key action of the Energy sub-programme. It will formalise the process of emergence and dissemination of clean and renewable energy technologies subject to research and development action in the work programme, in relation to the very long-term evolution of the socio-economic context in the European Union. Moreover, the whole philosophy of the modelling approach will be based on the 'back-casting' concept, which seems particularly appropriate to define RTD strategies in view of long-term sustainability objectives.

Methodology VLEEM and this monograph
The work programme necessary to conceptualise and develop such a 'very long term energy-environment model' will be carried out in four phases around which the four main activities packages will be organised:

- system analysis, conceptualisation and general specification of the model,
- formalisation of a first skeleton of the model,
- programming analysis of the main energy demand and supply new technologies considered,
- case study: stabilising CO_2 concentration of the atmosphere and world plutonium and minor actinides inventory at sustainable levels.

The project will be implemented by a consortium of five partners with extensive experience both in scientific and technological R&D and in long term socio-economic and energy forecasting and modelling.

2. WHAT IS SOLAR THERMAL POWER?

Solar Thermal Power systems convert short wave direct sunlight radiation into long wave heat radiation or make use of the heat radiation coming from the earth's surface. The heat is used to produce a gas flow, which is fed to a turbine. The turbines that produce the power in a Solar Thermal Power plant are of the same kind as used in fossil fired power plants, hydro plants or windmills. The gas flow produced by a specific technology, like steam, hot dry air or cooled wet air, determines which kind of turbine is used. Because Solar Thermal Power uses direct sunlight, the number of hours with a clear sky determines the suitability of an area for Solar Thermal Power applications. Therefore the moment of power production coincides theoretically with the hours of sunshine. However, with some adaptations, like energy storage, it is possible to manipulate the hours of power production. The application of the produced heat distinguishes a concentrating solar thermal power system from a solar thermal hot water system for residential buildings. A solar thermal system for a residential building uses the produced heat for low to medium temperature warm water or air for space and water heating. A Solar Thermal Power plant transforms the heat into power (DOE I, 1997).

Solar Thermal Power technologies can roughly be divided into two main categories, concentrating - mirror technologies and temperature - density technologies. The concentrating - mirror technologies make use of mirrors that focus the sunlight to a central receiver. In the receiver the focussed sunlight heats a Heat Transfer Fluid (HTF). The HTF creates, after passing a heat exchanger, high-pressure steam that is fed to a steam turbine to produce power. The temperature - density technologies make use of air movements, which are created by natural air temperature differences or artificial air temperature and density differences. These air movements produce power when a turbine is placed in such a stream. Depending on the density of the air a wind turbine or a turbine which is more similar to a hydro turbine, is used (DOE I, 1997).

2.1 Mirror Systems

Large-scale Solar Thermal Power technologies achieve high temperatures by using mirrors to concentrate sunlight from a large area to a small receiver area. In the receiver, a Heat Transfer Fluid is heated. The HTF can be used directly in a small turbine to produce power or indirectly, to produce power when the heat is fed to a heat exchanger. The heat exchanger can transfer the heat in the HTF to high-pressure steam, which is fed to a steam turbine. A mirror system consists at least of four basic elements; mirrors, a collector, a Heat Transfer Fluid and a turbine. In case of indirect power production a heat exchanger is added to the system (DOE I, 1997).

2.2 Moving Air Systems

Up-draught

Hot air has a lower density than cold air and it therefore ascends. The opposite is true for cold air. Solar Thermal Power applications that make use of this physical phenomenon, guide the moving air through a hollow tower. The hollow tower guides and accelerates the moving air. The energy that is captured in the moving air is harvested with wind turbines or with turbines that are more familiar with hydro turbines (Zaslavsky D., 1997). To create an ascending airflow, a large area is over-roofed with glass or plastic frames. The short wave radiation from the sun goes through the frames and reaches the surface where it is transformed into long wave heat radiation that cannot pass the frames. By building the field of frames with a little incline the hot air is forced to move in the direction of the tower. A high tower creates a strong draught that speeds up the hot air. By placing a wind turbine at the beginning of the tower the energy captured in the moving air can be harvested (SBP, 1999).

Down-draught

In case of descending air the open top is used as a hot air collector. Spraying water at the top of the tower cools the hot dry air at the top of the tower. In contrast with the ascending air tower, the bottom of the descending air tower is made of shrouded wind turbines through which the descending air can escape instead of one turbine (Shilo and Er-el, 1995). The sprayed water evaporates in the hot dry air making the air heavier and colder than the air lower in the tower. The air starts to decline pushing the air through the turbines at the bottom. At the top of the tower a shortage of air parts is created, called underpressure, as a result of the declining air. The atmosphere intends to abolish this irregularity by creating a flow of hot dry air to the tower inlet. The 'new'hot dry air is sucked into the tower and immediately cooled. With this principle it is possible to create a down draught wind, as long as there is hot dry air in the neighbourhood of the tower inlet (Zwin, 1997).

3. WHAT TECHNOLOGIES ARE AVAILABLE

The Solar Thermal Power technologies can roughly be divided into mirror based and moving air based systems. Within the mirror-based systems three main concepts have been developed; dish systems (Figure 3.1), trough systems (Figure 3.2) and tower systems (Figure 3.3). The moving air systems can be divided into ascending - Solar chimney (Figure 3.4) and descending - SNAP tower (Figure 3.5) systems.

3.1 Solar Dish Systems

Dish/engine systems convert the thermal energy from solar radiation to mechanical energy and then to electrical energy in much the same way as conventional power plants convert the chemical energy in fossil fuels through combustion into thermal energy into electricity. In a parabolic dish system, a dual-axis parabolic concentrator tracks the sun, focusing the sun's rays onto a receiver located at the focal point in front of the dish, see Figure 3.1 (De Laquil et al, 1993). A Heat Transfer Fluid gathers the heat as it flows through the receiver. In certain systems a heat engine, such as Stirling[1] or Brayton[2] cycle engine, may be linked to the receiver to generate electricity. Parabolic dishes can reach 1000°C, have high optical efficiency and low start-up losses, which make them the most efficient (29,4% record solar to electricity conversion) of all Solar Thermal Power technologies. In addition, the modular design of dish/engine systems make them a good match for both remote power needs in the kilowatt range as well as hybrid end-of-the-line grid-connected utility applications in the megawatt range (DOE II, 1997).

Figure 3.1 *Principle of a Solar Dish (DOE II, 1997)*

The DOE Solar Total Energy Project (STEP) had a large solar parabolic dish system that operated between 1982 and 1989 in Shenandoah, Georgia. It consisted of 114 dishes, each 7m in diameter. The system furnished high-pressure steam for electricity generation, medium-pressure steam for knitwear pressing, and low-pressure steam to run the air conditioning system for a nearby knitwear factory. In October 1989, Georgia Power shut down the facility due to the failure of its main turbine, and lack of funds for necessary plant repairs (Pharabod, and Philibert, 1991). Several other prototype dish/engine systems, ranging in size from 7 to 25 kW_e have been deployed in various locations in the U.S. and abroad. Dish/engine systems are in the engineering development stage and technical challenges remain concerning the solar components and the commercial availability of an engine which is suitable for direct operation by solar irradiation (Blezinger, 1994).

---

[1] Stirling cycle engines are high-temperature, high-pressure externally heated engines that use hydrogen or helium as a working gas. In a Stirling cycle, the working gas is alternately heated and cooled by constant-temperature and constant-volume process. Stirling engines usually incorporate an efficiency enhancing regenerator that captures heat during constant-volume and exchanges it when the gas is heated at constant-volume.

[2] A Brayton engine is an internal combustion engine, which produces power by the controlled burning of fuel. In a Brayton engine, air is compressed, fuel is added, and the mixture is burned. The resulting hot gas expands rapidly and is used to produce power. In the gas turbine, the burner is continuously and the expanding gas is used to drive a turbine and alternator.

3.2 Parabolic Trough Systems

A parabolic trough system consists of a (large) number of single-axis tracking parabolic trough solar collectors. The solar field is modular in nature and is composed of many parallel rows of solar collectors aligned on a north-south horizontal axis, see Figure 3.2 (CIEMAT, 2000). The reason for a North-South orientation is to create an optimal orientation for solar irradiation capture from sunrise to sunset. Each solar collector has a linear parabolic-shaped reflector that focuses the sun's direct beam radiation on a linear receiver located at the focus of the parabola. The collectors track the sun from east to west during the day to ensure that the sun is continuously focused on the linear receiver. A heat transfer fluid (HTF) is heated as it circulates through the receiver and returns to a series of heat exchangers in the power block where the fluid is used to generate high-pressure superheated steam. The superheated steam is then fed to a conventional reheat steam turbine/generator to produce electricity. After passing the generator, the steam is condensed in a standard condenser and returned to the heat exchangers via condense and feedwater pumps to be transformed back into steam. Condenser cooling is provided by mechanical draft wet cooling towers. After passing through the HTF side of the solar heat exchangers, the cooled HTF is re-circulated through the solar field (DOE III, 1997).

Historically, parabolic trough plants have been designed to use solar energy as the primary energy source to produce electricity. The plants can operate at full rated power using solar energy alone given sufficient solar input. During summer months, the plants operate typically for 10 to 12 hours a day at full-rated electric output. However, all plants have been hybrid solar/fossil plants; this means they have a backup fossil-fired capability that can be used to supplement the solar output during periods of low solar radiation (Holl, 1989).

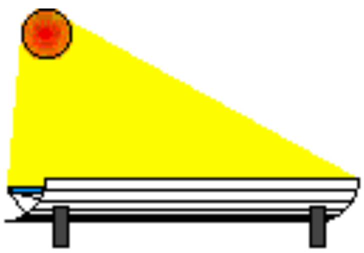


Figure 3.2 *Schematic Solar Trough system (DOE III, 1997)*

Parabolic trough technology is currently the most proven concentrating solar technology. This is primarily due to 9 large commercial-scale concentrating solar power plants, the first of which has been operating in the California Mojave Desert since 1984. These plants, which continue to operate on a daily basis, range in size from 14 to 80 MW and represent a total of 354 MW of installed electric generating capacity. Large fields of parabolic trough collectors supply the thermal energy used to produce steam for a Rankine steam turbine/generator cycle (BMU, 1999).

3.3 Power Towers

Solar Power Towers generate electric power from sunlight by focusing concentrated solar radiation on a tower-mounted heat exchanger (receiver). The system uses hundreds to thousands of sun-tracking mirrors called heliostats to reflect the incident sunlight onto the receiver. These plants are best suited for utility-scale applications in the 30 to 400 MW, range (Kelly and De Laquil, 1989).

In a molten-salt solar Power Tower, liquid salt at 290°C is pumped from a 'cold' storage tank through the receiver where it is heated to 565°C and then on to a 'hot' tank for storage.

When power is needed from the plant, hot salt is pumped to a steam generating system that produces superheated steam for a conventional Rankine cycle turbine/generator system. From the steam generator, the salt is returned to the cold tank where it is stored and eventually reheated in the receiver, see Figure 3.3. Determining the optimum storage size to meet power-dispatch requirements is an important part of the system design process. Storage tanks can be designed with sufficient capacity to power a turbine at full output for up to 13 hours (Fisch, 1993).

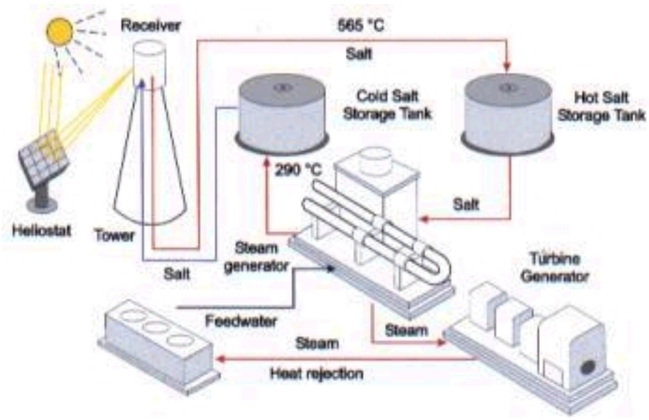


Figure 3.3 *Overview of a Power Tower system (SunLab, 2001)*

The heliostat field that surrounds the tower is laid out to optimise the annual performance of the plant. The field and the receiver are also sized depending on the needs of the utility. In a typical installation, solar energy collection occurs at a rate that exceeds the maximum required for providing steam to the turbine. Consequently, the thermal storage system can be charged at the same time that the plant is producing power at full capacity. The ratio of the thermal power provided by the collector system (the heliostat field and receiver) to the peak thermal power required by the turbine generator is called the solar multiple. With a solar multiple of approximately 2.7, a molten-salt Power Tower, located in the California Mojave desert, can be designed for an annual capacity factor of about 65% (ConSolar, 1999). Consequently, a Power Tower could potentially operate for 65% of the year without the need for a back-up fuel source. Without energy storage Solar Thermal Power technologies are limited to annual capacity factors near 25%. Because of the storage, power output from the turbine generator remains constant through fluctuations in solar intensity and until all of the energy stored in the hot tank is depleted. Energy Storage and dispatchability are very important for the success of solar Power Tower technology, and molten salt is believed to be the key cost effective energy storage. Power Towers must be large to be economical. Power Tower plants are not modular but use a conventional power block and can easily dispatch power when storage is available. Districts with abundant high levels of solar radiation and relatively low land cost are ideal for Power Towers (DOE IV, 1997).

3.4 Solar Chimneys

A Solar Chimney converts solar radiation (direct and diffuse) into electricity by combining three well-known principles in a novel way: the greenhouse effect, the chimney effect and wind turbines. The sun under a large glass roof produces hot air. The air enters a vertical tube, the chimney, placed at the centre of the roof, creates an upward draught there. Inside the tube, Kaplan-type[3], wind turbines are placed with generators that produce electricity, see Figure 3.4.

A 50 kW_{el} prototype was built in Manzanares, Spain and produced electricity for seven years, proving that this kind of concentrating solar power generating works (SBP, 1999). After seven years of testing the test facility was shut down.

The used turbines are basically more closely related to the pressure-staged hydroelectric turbines than to the speed-stepped open-air turbines. Therefore, the turbines used in the Manzanares plant are developed and designed in collaboration with hydroelectric power plant manufacturers, see Box 3.1. There are two places where the turbines can be placed. Either a large number of small turbines with horizontal axes may be arranged around the base of the chimney, or to be more cost-efficient, one large turbine with a vertical axis is placed in the chimney's cross-section (Schlaich and Robinson, 1995).

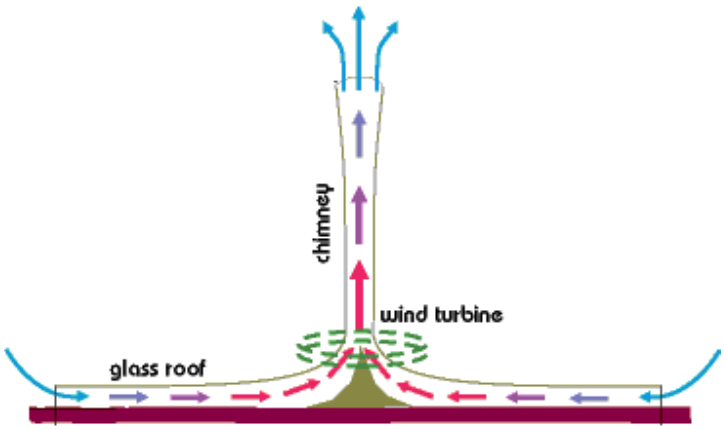


Figure 3.4 *Principle of a Solar Chimney (Schlaich and Robinson, 1995)*

Continuous 24 hours-operation can be guaranteed by placing tight water-filled tubes under the roof. The water heats up during the daytime and emits its heat at night. These tubes are filled only once, no further water is needed. This adaptation reduces the peak power output round noon but makes power production after sunset possible.

Solar chimneys are large-scale power plants with sizes between 50 to 400 MW each to operate them economically. For such plant sizes the glass roof has to be several kilometres in diameter and the tower has to be as high as possible, several hundreds meters up to 1km. As with normal chimneys or flues the taller the chimney the greater the draught obtained. The greater the wind speed the more energy does the wind contain that can be harvested. Therefore, a commercial solar chimney has to be high to achieve a large annual output (SBP, 1999).

For a chimney various types of construction and materials have been compared. A chimney in a desert-country made from reinforced concrete tubes promise the longest life span at least costs. Technologically speaking a chimney is nothing but a cylindrical natural draught cooling tower. For a 200 MW plant a suitable height would be 1 km with a tower diameter of 170 m. In this case the wall thickness decreases from 99 cm to 25 cm, and stiffening spoked wheels are placed on the inside. Such a plant will produce about 1.500 GWh/year at 2.300 kWh/m^2 radiation.

[3] The Kaplan is of the propeller type, similar to an aeroplane propeller. The Kaplan's blades are adjustable for pitch and will handle a great variation of flow very efficiently. Unlike all other propeller turbines, the Kaplan turbine runner's blades were movable. The guide vanes could also be turned and were automatically adjusted to any angle suitable to that of the blades by a combiner, so the turbine was efficient at different work loads.

Box 3.1 *Characteristics of the Solar Chimney Pilot Plant in Manzanares*

GENERAL ARRANGEMENT		
Chimney height	200	m
Collector diameter	240	m
Turbine	50	kW_{el}
Chimney diameter	10	m
Collector height	2	m
Collector area	45.000	m^2
Chimney weight	125	t
Collector weight	5,5	kg/m^2 (without glass)
Roof segment size	9 × 9	m

A solar chimney is a concentrating solar power system, which compensates its low efficiency by a cheap collector technique. A kind of greenhouse structure covers thousands of square meters in order to warm up the air for the chimney effect. The chimney effect is roughly proportional to the height of the chimney. The dimensions of a cost-effective power station are really impressive: the chimney of a 100 MW_e plant would be a tower of 115 m in diameter and 950 m in height, the collector area would cover 9 km^2 (Eisenbeiß, 1996).

3.5 SNAP Technology

Researchers from Technion, Israel have developed the SNAP[4] technology. This technology uses hot dry air and water to produce electricity. When a passing cloud sheds rain onto dry hot air, a strong downward draft called 'wind shear' is generated. The SNAP technology aims at harvesting this natural phenomenon to create a strong artificial wet wind that will drive wind turbines. A SNAP power plant is based on a hollow tower with an opening at the bottom, see Figure 3.5. Water is raised to the top of the tower where it is sprayed over the entire area of the flue opening. The sprayed water evaporates, making the dry air at the top of the flue cooler and heavier than the surrounding air. As example, if air is cooled by 12C° it becomes approximately 4% heavier than its previous state (Zwin, 1997). The heavier air sinks down the tower and comes out through the opening at the bottom. The descending air can reach a speed of 80 kilometres per hour. On its way out, it passes through a battery of shrouded wind turbines, which drive power generators. An Energy Tower needs no artificial collectors in order to capture the solar radiation. The surrounding earth surface fulfils the function of collector. This means that a commercial Energy Tower will operate 24 hours a day. The estimated land area needed for a commercial SNAP plant, is of the same order of magnitude as a conventional fossil power plant if mining activities are included. On the other hand A SNAP plant requires less land by an order of magnitude, than all other concentrating solar technologies (Zaslavsky, 1999). The positive score of a SNAP plant is caused by its nature of being just a huge tower with no additional land consuming installations. However, the first SNAP towers will require considerably more land than conventional fossil power plants. Still strong solar irradiation is needed to provide for the hot dry air.

[4] SNeh Aero-electric Power, Sneh is the Hebrew word for 'Burning Bush'= - "..the bush burned and was not consumed" (Exodus, Chapter 3). The burning bush is seen as an eternal source of energy and therefore compared with the SNAP tower.

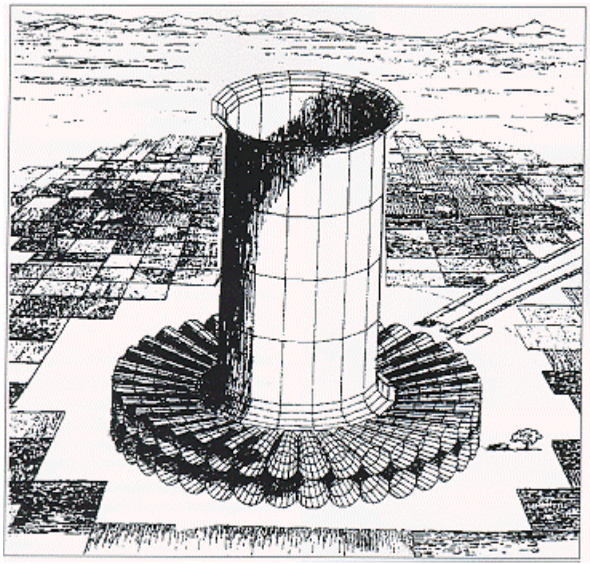


Figure 3.5 *Artist view of a SNAP plant (Technion)*

4. THE SOLAR TOWER

Solar Power Towers generate electric power from sunlight by focusing concentrated solar radiation on a tower-mounted heat exchanger (receiver). The system uses hundreds to thousands of sun-tracking slightly curved mirrors called heliostats to reflect the incident sunlight onto the receiver. These plants are best suited for utility-scale applications in the 30 to 400 MW range. The Power Tower system described in this chapter includes a 'molten salt' storage system.

4.1 System Description

The heliostats focus the solar energy onto a central receiver located on top of a tower, see Figure 4.2. These mirrors cover typically 30-50 m^2 in area, although more modern designs cover 100-150 m^2. They are slightly curved (radii of 50-600 m) and are centrally controlled in order to track the sun in two dimensions. The temperature reached by the fluid in the receiver is tailored for the required purpose (e.g. 500-600ºC for electricity generation using a conventional steam turbine, 1000ºC for other purposes such as the testing of materials). In order to extend operation time, the schemes often incorporate a thermal storage facility (e.g. oil mixed with crushed rock or molten nitrate salts). The systems can be hybridised with a natural gas burner to provide better operating characteristics (Heliotech, 2000). The gas turbine produces power, which is fed to the grid, and steam, which is fed to the steam turbine of the Solar Tower System. Steam from the solar steam generator is blended with fossil steam from the gas turbine from the heat recovery steam generator before entering a steam turbine. With a gas turbine added, the Solar Tower system can still produce power when the sun is not strong enough to run the system solely. This is probably mainly the situation in the morning when the sun might not be strong enough to provide the needed start-up heat. In the evening, when the sun sets, a gas engine can upgrade the sun's last energy to a level, which is usable in the steam turbine.

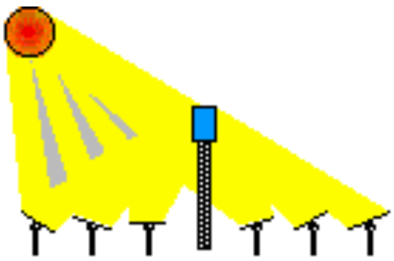


Figure 4.1 *Principle of a Power Tower (SunLab, 2001)*

In a Power Tower system the short wave sunlight is absorbed by a heat transfer fluid (HTF) in the central receiver and then transformed into long wave heat. The heat transfer fluid is pumped to a heat exchanger to produce high-pressure steam to drive a generator, see Figure 4.2. The heliostat field that surrounds the tower is laid out to optimise the annual performance of the plant. The field and the receiver size depend on the needs of the utility. In a typical installation, solar energy collection occurs at a rate that exceeds the maximum required energy to produce steam for the steam turbine. Consequently, a thermal storage system can be charged while the plant is producing power at full capacity (Eisenbeiß, 1996).

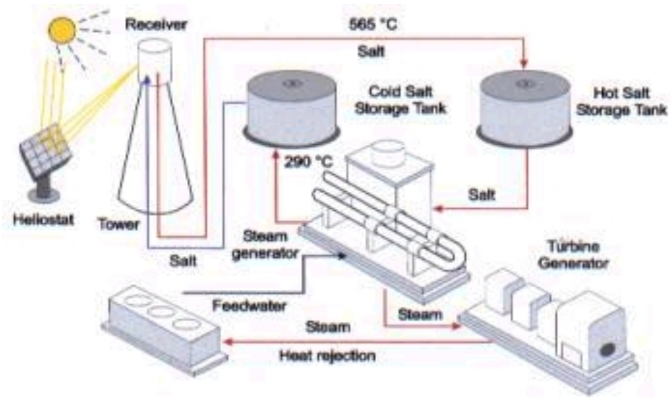


Figure 4.2 *A schematic Power Tower system (SunLab, 2001)*

The heliostat field together with the receiver is called collector system. The ratio of the thermal power provided by the collector system to the peak thermal power that is required by the generator is called the solar multiple. With a solar multiple of approximately 2.7, a Power Tower with molten-salt storage tanks located in the California Mojave desert can be designed for an annual capacity factor of about 65%. This means that a Power Tower could potentially operate for 65% of the year without the need for a fossil fuel fired back-up installation. Without the molten salt storage tanks, concentrating solar technologies are limited to annual capacity factors near 25%. Because of the storage, power output from the generator remains constant through fluctuations in solar intensity until all energy stored in the hot tank is depleted (DOE IV, 1997).

4.2 Storage System

Energy storage and dispatchability are very important for the success of solar Power Tower technology. The Solar One thermal storage system stored heat from solar-produced steam in a tank filled with rocks and sand using oil as the heat transfer fluid. The system extended the plant's power-generation capacity into the night and provided heat for generating low-grade steam for keeping parts of the plant warm during off-hours and for morning start-up. Unfortunately the storage system was complex and thermodynamically inefficient. During the operation of Solar One, research began on a molten salt Power Tower design that cumulated in the Solar Two project. It is believed that molten salt is the key to cost effective energy storage see Table 4.1.

Table 4.1 *Comparison of solar energy storage systems*

	Installed cost of energy storage for a 200 MW plant [$/kWhr]	Lifetime of storage systems [years]	Round-trip storage efficiency [%]	Maximum operating temperature [ºC]
Molten salt power tower	30	30	99	567
Synthetic oil parabolic Trough	200	30	95	390
Battery storage grid connected	500 to 800	5 to 10	76	N/A

In a molten-salt solar Power Tower, liquid salt at 290°C is pumped from a 'cold' storage tank through the receiver where it is heated to 565°C and then on to a 'hot' tank for storage. When power is needed, hot salt is pumped to a steam generator that produces superheated steam for a conventional Rankine[5] cycle turbine/generator. From the steam generator, the salt is returned to the cold tank where it is stored and eventually reheated in the receiver. Determining the

[5] The Rankine cycle is a thermodynamic cycle used to generate electricity in many power stations, and is the practical approach to the Carnot cycle. Superheated steam is generated in a boiler, and then expanded in a steam turbine. The turbine drives a generator, to convert the work into electricity. The remaining steam is then condensed and recycled as feedwater to the boiler.

optimum storage size to meet power-dispatch requirements is an important part of the system design process. Calculations have proven that storage tanks can be designed with sufficient capacity to power a turbine at full output for up to 13 hours (ConSolar, 1999).

The salt storage medium is a mixture of 60% sodium nitrate and 40% potassium nitrate. It melts at 220°C and is maintained in a molten state (290°C) in the ‘cold’ storage tank. Molten salt can be difficult to handle because it has a low viscosity (similar to water) and it adheres metal surfaces extremely well. Consequently, it can be difficult to contain and transport. An important consideration in successfully implementing this technology is the identification of pumps, valves, valve packing, and gasket materials that will work with molten salt. Accordingly, Solar Two is designed with a minimum number of gasket flanges and most instrument transducers, valves, and fittings are welded in place. The energy storage system for Solar Two consists of two 875,000 litre storage tanks. Thermal capacity of the system is 110 MW. A natural convection cooling system is used in the foundation of each tank to minimise overheating and excessive dehydration of the underlying soil. The steam generator system (SGS) and heat exchangers consist of a shell-and-tube superheater, a steam boiler, and a shell-and-tube preheater. Stainless steel cantilever pumps transport salt from the hot-tank through the SGS to the cold tank. Salt in the cold tank is pumped with multi-stage centrifugal pumps up the tower to the receiver (DOE IV 1997).

4.3 History

Since the early 1980s, Power Towers have been fielded in Russia, Italy, Spain, Japan, France, and the United States. In Table 4.2, these experiments are listed along with some of their characteristics. These experimental facilities were built to prove that solar Power Towers could produce electricity. The Power Towers have also been built to get experience with individual system components to find out which parts need improvement (DOE IV, 1997).

California is one of the regions in the world that strongly promote the use of solar and wind energy. As a result of this promotion, a program that should use solar energy to make steam to drive turbines began near Barstow in the late 1970s. This program led to the building of Solar One. This is the most expensive solar power station, which started to produce electricity in 1982. Together with Solar Two, Solar One is the largest experimental Power Tower that has been built. The Solar One is a central receiving station or ‘Power Tower’ with 1818 mirrors of 39.3 m² reflective area each that are laid out in semi-circles around a 78 m high tower. The mirrors focus sunlight on to a boiler at the top of the tower. As the Sun moves, the mirrors turn around, following it. Oil in the central collecting tower heats up and is piped to a power plant. There it heats water to 565ºC, producing steam. The pressure of the steam turns a turbine, which drives a generator to produce 10 MW of electricity. Solar One was very expensive to built, and to replace a conventional power station on MW-basis, a lot more than 1 Solar Power Tower would be needed. Consequently, the produced solar kWh’s will be considerably more expensive than fossil or nuclear kWh’s (Grasse, 1992).

Several small pilot systems were constructed in Europe and the USA with outputs of 0.5 to 10 MW (Holl, 1989). These schemes used water as the Heat Transfer Fluid, with the resulting steam passing directly to the turbine. This proved to be unreliable (thermal transients initiated generator shutdowns) and inefficient. Other pilot schemes utilised molten sodium salts, with the thermal storage facility separated from the receiver and the turbine (to reduce thermal transients). In these schemes, the collector area was in the range of 4000-12000 m^2 per MW_e rating and the tower heights were 50-100 m. From these early efforts, a second generation of Power Towers has been developed which uses air (e.g. the PHOEBUS plant at Alméria, Spain) or molten salt (e.g. the Solar Two plant in the US) as the heat transfer medium. Considerable progress has been made since the first schemes in the early 1980s so that many of the main aspects of this technology are now in the demonstration stage. Further research is required for advanced receivers based on absorption by thin films of salts (Léon et al, 1994) or air (Haeger et al, 1994) as well as new types of heliostats (Jiménez, 1995).

Table 4.2 *Experimental Power Towers*

Project	Country	Power output [MW_e]	Heat Transfer Fluid	Storage medium	Operation began
SSPS	Spain	0.5	Liquid Sodium	Sodium	1981
EURELIOS	Italy	1.0	Steam	Nitrate Salt/Water	1981
SUNSHINE	Japan	1.0	Steam	Nitrate Salt/Water	1981
Solar One	USA	10.0	Steam	Oil/Rock	1982
CESA-1	Spain	1.0	Steam	Nitrate Salt	1983
MSEE/Cat B	USA	1.0	Molten Nitrate	Nitrate Salt	1984
TBEMIS	France	2.5	Hi-Tec Salt	Hi-Tec Salt	1984
SPP-5	Russia	5.0	Steam	Water/ Steam	1986
TSA	Spain	1.0	Air	Ceramic	1993
Solar Two	USA	10.0	Molten Nitrate	Nitrate Salt	1996
Solar Spire	Israel	0.25	Air	-	2000

To encourage the development of molten-salt Power Towers the Solar One plant was redesigned with a molten-salt heat-transfer system. After the rebuilding of Solar One the installation was entitled Solar Two. The objective of Solar Two was to mitigate the perceived technological and financial risks associated with the first commercial plants and to prove the molten-salt thermal storage technology. In Solar One, water was converted to steam in the receiver and used directly to power a conventional Rankine-cycle steam turbine. Solar Two has a capacity of 10 MWe with enough thermal storage to continue to operate the turbine at full capacity for three hours after the sun has set (DOE IV, 1997).

4.4 Further Development

The largest Power Towers ever built are 10 MW plants. After the success of the Solar Two project, the next plants could be scaled-up to between 30 and 100 MW in size for utility grid connected applications. Power Towers must be large to be economical. Power Tower plants are not modular but they do use a conventional power block and can easily dispatch power when storage is available. Districts with abundant high levels of insolation and relatively low land costs are ideal for Power Towers.

Power Towers are capital intensive compared with conventional power plants but cost little to operate (SUNLAB, 2001). The natural higher investment cost compared with a conventional power plant comes from the entire solar part that must be built in addition to the conventional part which is required anyway (Schmitz-Goeb and Keintzel, 1996). The operating and maintenance costs are expected to be somewhat higher than a conventional fossil power plant. The reason is that besides the O&M costs for the conventional part there are also O&M costs for the solar part of the installation. To reduce the financial risk associated with the deployment of a new power plant technology and to lower the cost of delivering solar power, initial commercial-scale (>30 MW_e) Power Towers will likely be hybridised with conventional fossil-fired plants. Many hybridisation options are likely possible; natural gas combined-cycle, coal-fired or oil-fired Rankine plants. In a hybrid pant, the solar energy can be used to reduce fossil fuel usage and/or boost the power output to the steam turbine. Table 4.3 gives an overview of a possible development of Power Towers (Eisenbeiß, 1996).

Table 4.3 *Development of performance and cost indicators of a Power Tower (DOE IV, 1997)*

Indicator name	Units	Solar Two prototype 1997	Small hybrid booster 2000	Large hybrid booster 2005	Solar only 2010	Advanced solar only 2020	Advanced solar only 2030
Plant size	[MW]	10	30	100	200	200	200
Receiver thermal rating	[MW_{th}]	43	145	470	1400	1400	1400
Heliostat size	[m²]	40	95	150	150	150	150
Solar field area	[m²]	81000	275000	883000	2477000	2477000	2477000
Thermal storage	[hours]	3	7	6	13	13	13
	[MWh_{th}]	114	550	1600	6760	6760	6760
Construction period	[Years]	2	2	2	2	2	2
Performance							
Capacity factor	[%]	20	43	44	65	77	77
Solar fraction	[%	1.00	0.22	0.22	1.0	1.0	1.0
Direct normal insolation	[kWh/m²/yr]	2700	2700	2700	2700	2700	2700
Annual solar to elec. Eff.	[%]	8.5	15.0	16.2	17.0	20.0	20.0
Annual energy production	[GWh/yr]	17.5	113.0	385.4	1138.8	1349.0	1349.0
Capital cost							
Structures & improvements	[$/kW[4]]	[1]	116	60	50	50	50
Heliostat system	[$/kW[4]]	[1]	1666	870	930	865	865
Tower/receiver system	[$/kW[4]]	370	600	260	250	250	250
Thermal storage system	[$/kW[4]]	276	420	240	300	300	300
Steam gen. System	[$/kW[4]]	[1]	177	110	85	85	85
EPGS/balance of plant	[$/kW[4]]		417	270	400	400	400
Master control system	[$/kW[4]]	[1]	33	10	15	15	15
Directs sub total (A)	[A*0.1]		3429	1820	2030	1965	1965
Indirect engineering/other	[$/kW[4]]		343	182	203	197	197
Sub total (B)	[B*0.15]		3772	2002	2233	2162	2162
Project/process contingency	[$/kW[4]]		566	300	335	325	325
Total plant cost [2]	[$/kW[4]]		4338	2302	2568	2487	2487
Land (at $4942/ha)			27	27	37	37	37
Total capital requirements	[$/kW[4]]		4365	2329	2605	2523	2523
	[$/kW$_{peak}$ [3]]		2425	1294	965	934	934
	[$/m²]		476	264	210	204	204
Operation & maintenance cost							
Fixed labour & materials	[$/kW-yr]						
Total O&M costs		300	67	23	30	25	25

Notes: totals may be slightly off due to rounding.

1. Costs of these items at Solar Two are not characteristic of a commercial plant and have, therefore, not been listed.
2. Total plant costs for Solar Two are the actuals incurred to convert the plant from Solar one to Solar Two. The indirect factors do not apply to Solar Two.
3. To convert to peak values, the effect of thermal storage must be removed. A first order estimate can be obtained by dividing installed costs by the solar multiple (i.e. SM = {peak collected solar thermal power}/{power block thermal power}). For example, as discussed in the text, in 2010 the peak receiver absorbed power is 1400 MW_t. If this is attached to a 220 MW_e turbine (gross) with a gross efficiency of 42%, thermal demand of the turbine is 520 MW_t. Thus, SM is 2.7 and peak installed cost is 2605/2.7 = $965/$kW_{peak}$. Solar multiples for years 1997, 2000, and 2005 are 1.2, 1.8, and 1.8, respectively.
4. $/kWnameplate.

All annual energy estimates presented in Table 4.3 are based on simulations with the SOLERGY computer code. The inputs to the SOLERGY computer code are based on measured data taken from the 10 MW_e Solar One and the small (~1 MW_e) molten-salt receiver system test, conducted in the late 1980's. The SOLERGY code itself has been validated with a full year of operation at Solar One. However, no overall annual energy data is available from an operating molten-salt Power Tower. Capital and operation and maintenance (O&M) cost estimates for 2000 and beyond are consistent with estimates contained in the U.S. Utility Study and the International Energy Agency studies. These studies have been used as a basis to estimate costs for hybrid options and plants with different capacity factors. In addition, O&M costs for power-tower plants with sizes ≤100 MW_e have been compared with actual incurred at the operating 10 to 80 MW, solar-trough plants in California with similar sizes to insure consistency. Because of the many similarities between trough and tower technology, a first-order assumption that O&M costs at trough and tower plants are similar has been made (IEA, 1998).

The SOLERGY computer code roughly increases the thermal capacity of a Power Tower every new generation (2000, 2005 and 2010) with a factor 3.3. When the thermal capacity reaches 1400 MW_{th} in 2010 it is assumed that the size of a Power Tower is large enough to be commercial. Besides the size of the thermal capacity, the SOLERGY simulations are based on assumptions regarding; mirror reflectance, receiver efficiency, start-up times, parasitic power, plant availability, improved heliostats, improved molten-salt steam generator design, etc. With these data assumptions construction, operation and maintenance costs are calculated. These costs are an indication of the compatibility of Power Tower technology with other power producing technologies. However, one has to keep in mind that besides the costs for Power Tower technology, the costs of the other technologies will decline as well. Another important factor is the price of fossil energy, if these prices stay at the same level as they are in 2002 or even decline, renewables like Power Towers will not be able to compete with fossils. The SOLERGY simulations do not provide information about the potential of Power Tower technology in the world, they produce a figure (costs) which might be used to estimate the economical potential. The economical potential is less than the theoretical or technical potential, which will be treated in Chapter 6.

The simulations with the SOLERGY computer code, shown in Table 4.3, reveal that by 2020 the Solar Power Tower will be mature (DOE IV, 1997). No significant improvements in molten nitrate salt power tower technology are assumed beyond 2020. In order for significant improvements to continue, a radical change in power tower technology must take place. This is only possible if all stages described in Table 4.3 are cone trough without delay. However, the small hybrid booster has not been built in 2000, resulting in a two-year delay. At the moment there are no plans for building the small hybrid booster. It is therefore most likely that the Solar Power Tower technology development must face a five-year delay.

New peaking and intermediate power sources are needed today in many areas of the developing world. India, Egypt, and South Africa are locations that appear to be ideally suited for Power Tower development from a technical and solar irradiation point of view. However, from an economical point of view developing countries are unlikely to invest a lot of their scarce capital resources in electricity generating technologies. As the technology matures, plants with up to a 400 MW rating appear feasible. As non-polluting energy sources become more favoured, molten-salt Power Towers will have a high value because the thermal energy storage allows the plant to be dispatchable. By varying the size of the solar field, solar receiver, and size of the thermal storage, plants can be designed with annual capacity factors ranging between 20 and 65%. Economic studies have shown that adding more storage up to a limit of about 13 hours (~65% capacity factor) reduces Levelled Energy Costs (LEC). Combining high capacity factors and the fact that energy storage will allow power to be brought onto the grid in a controlled, total market penetration should be much higher than an intermittent solar technology without storage (Pharabod F., 1991).

4.5 Environmental Constraints

The land and water requirement values, provided in Table 4.4, apply to the solar portion of the power plant. Land use in 1997 is taken from Solar Two design documents. Land use for the years 2000 and beyond is based on systems studies. The proper way to express land use for systems with storage is ha/MWhr/yr. Expressing land use in units of ha/MW is meaningless to a concentrating solar plant with energy storage because the effect of plant capacity factor is lost.

Water requirement measured at the SEGS VI and VII trough plants are the basis for the estimated figures in Table 4.4. It is assumed that cooling will take place with wet cooling towers. Water usage at Solar Two should be somewhat higher than at SEGS VI and VII due to a lower efficiency of the Solar Two power block (33% gross). However, starting in the year 2000, water usage in a commercial Power Tower plant, with a high efficiency power block (42% gross), should be about 20% less than SEGS VI and VII. However, it is likely that water availability will be a problem in the desert area's which are suitable for Solar Power Towers. If adequate water is not available at the power plant site, a dry condenser-cooling system could possibly be used. Dry cooling can reduce water needs by as much as 90%. However, if dry cooling is employed, cost and performance penalties are expected to raise levelled-energy costs by at least 10% (IEA, 1998).

Table 4.4 *Resource requirements (DOE IV, 1997)*

Indicator name	Units	Base year 1997	2000	2005	2010	2020	2030
Land	[ha/MWh/yr]	2.7×10^{-3}	1.5×10^{-3}	1.4×10^{-3}	1.3×10^{-3}	1.1×10^{-3}	1.1×10^{-3}
Water	[m^3/MWh]	3.2	2.4	2.4	2.4	2.4	2.4

One possible concern with the technology is the relatively high land and water usage. This may become an important issue from a practical and environmental viewpoint since these plants are typically deployed within desert areas that often lack water and have fragile landscapes. However, water usage at Power Towers is comparable to other Rankine cycle power technologies of similar size and annual performance. Land usage, is in the same order of magnitude as coal (including mining) or hydro-electric (including water storage) power plants (DOE IV, 1997). Also, the area needed for building materials is in the same order of magnitude for Power Towers, coal fired power plants and hydro-electric power plants. All these power plants need concrete for the tower itself, cooling towers, coal storage facilities or the dam. A Power Tower also needs silicium (Si) to produce the mirrors and, if a molten salt storage system completes the Power Tower, sodium/potassium nitrate (Na/K NO_3) salts. This makes a Power Tower the most materially intensive power plant.

No hazardous gaseous or liquid emissions are released during operation of the solar Power Tower plant. If a salt spill occurs, the salt will freeze before significant contamination of the soil occurs. Salt is picked up with a shovel and can be recycled if necessary. If the Power Tower is hybridised with a conventional fossil plant, emissions will be released from the non-solar portion of the plant.

4.6 Characteristic Figures

To get an impression of Solar Tower Power plants some figures of Solar Two (USA), which has been shut down, and the CESA-1 tower (Spain) are presented.

Solar Two

The Solar Two power plant is the retrofitted Solar One plant from 1982. The plant at Barslow, California was enlarged regarding the number of heliostats. The rock-oil thermal storage system was replaced by a molten salt storage system (CIEMAT, 2000).

Solar Collectors:
- 1,818 Solar One heliostats (39 m^2 each).
- 108 new large-area heliostats (95 m^2 each).

Solar Receiver:
- 5.1 m diameter by 6.2 m high.
- Thirty-two 25 mm diameter tubes in each of 24 panels.
- 43 MW thermal rating with 800-sun peak-flux capability.

Thermal Storage System:
- Two 12 m diameter by 8 m high storage tanks.
- 1400 tonnes of molten sodium/potassium nitrate salt (Na/K NO3).

Steam Generator System:
- Separate preheater, evaporator, and superheater vessels.
- 35.5 MW thermal rating at 100 bar and 538ºC.

Electric Power Generation System:
- Rankine-cycle non-reheat turbine from Solar One.
- 10 MW net electric power rating.

Project Cost - $58 million:
- Industry and Utility Cost Share - $32 million.
- DOE Cost Share - $26 million.

CESA-1 tower

The CESA-1 tower (Central Electro Solar de Almería) is sited at the Plataforma Solar de Almería test location in Andalusia Spain. The test facility has very favourable conditions for concentrating solar thermal applications; an average of less than six days rain per year more than 300 hours of sunshine per year with >300 W/m^2. The daily period between 09:00 hours and 15:30 hours typically sees up to 1000 Watt irradiance effect per m^2 ground surface (Jiménez, 1995). Some characteristic figures of the CESA-1 tower can be found in text box 4.1.

Box 4.1 *Characteristics of the CESA-1 tower in Spain*

82 meter high concrete tower
300 heliostats with a combined area of 11880 m^2
each heliostat is 39.6 m^2
ground area of 70000 m^2
factor 5.89

4.7 Opportunities and Threats

There have been many problems with clouds over the years. When a cloud passes by it reduces the radiation energy, the pumps reduce the HTF-flow to maintain a constant receiver output temperature. When the cloud disappears the input power goes up sharply to 0.4 MW/m^2 and no regulating mechanism has yet been able to prevent meltdown of conventional materials in the volumetric receiver sun catcher surface (Heliotech, 2000).

At the geographical latitudes under consideration, a 360º field has a higher heliostat field utilisation factor than a north-facing field. Furthermore, with a 360º field, larger unit capacities to over 100 MW$_e$ can be realised, without later queries concerning references or the operational suitability of the receiver (Schmitz-Goeb, 1996)].

Although the amount of construction materials, concrete and steel for a Power Tower plant is mainly claimed to be of the same order of magnitude as other large power plants (hydro-electric and fossil fired plants). The total material needs for a Power Tower will be less favourable. Besides the tower itself a power Tower also needs mirrors and, for optimal operation, a storage system. If those material needs, silicium for the mirrors and salts or oils for the storage system, are added to the construction materials, the other power plants perform better that a Power Tower.

Like all thermal power plants a Power Tower includes a cooling installation. The first Power Tower plants where designed with wet cooling towers. This was possible while those plants where relatively small, maximum 10 MW. However, those plants where and will be built in water scarce areas like deserts. It is unwanted, from an environmental point of view, to use large amounts of local desert water as a cooling medium. Dry cooling might solve this problem while it reduces the water need with approximately 90%. At the same time the cost and performance penalties are expected to raise levelled-energy costs by at least 10%, see Section 4.5. As long as there are no comparable alternatives regarding its efficiency and costs, large-scale development of Power Towers in deserts is less attractive.

A disadvantage of Power Towers is the high investment cost compared to fossil fired power pants. Although this is a general disadvantage of most renewable power plants, for Power Towers this handicap is stronger than for the other renewable sources. A Power Tower can not be built on a small-scale (maximum 10 MW) for commercial operation, a plant of 100 MW or more is most likely to be commercially competitive. A large plant consists of a large tower, a large storage system and a large number of mirrors, which requires a large investment. It is doubtful whether in a liberalised market, investors are willing to make a reservation for such a project.

Although the concept consists of relatively simple, proven technologies, a number of problems still need to be solved. Technicians working on Power Tower technology are convinced that these problems will be solved the coming 10 years. Despite their prediction, history has learned that such a development needs more time, like the commercialisation of PV systems or the status of nuclear fusion. Therefore this study does not expect commercial power towers before 2025.

A Power Tower is relatively vulnerable to Earthquakes. The heliostats that surround the central receiver are placed on an installation that constantly adapt the angle of the mirrors to the position of the sun so that the solar radiation is concentrated onto the receiver. Each heliostat is placed very accurately on the surface and provides with information of the suns' route through the sky. If an earthquake disturbs the position of the heliostat or the central receiver each heliostat needs to be programmed again. This is a costly and time-consuming activity. Before constructing a Power Tower in a certain area it must be proven geologically stable.

A Power Tower might be an interesting object for terrorist attacks or sabotage actions. These plants are most likely to be built in remote areas, like deserts, where there is no 'social' control like in a city or an industry area. Preferably, the construction of the first large demonstration plant should not take place in politically sensitive regions like the Middle East, or India-Pakistan. More favourable areas are Australia, Southern Europe or the south-western area of the United States.

During the construction of Power Tower, several square kilometres that would be obliterated for construction equipment, mobile offices, houses and buildings will influence the fragile desert ecosystems. The majority of this area will only be occupied temporally. If adequate precaution measures are taken, the desert can probable recover from this disturbance. A part of the occupied area consists of roads that are capable of handling massive pieces of equipment and large earth moving and construction vehicles will influence the fragile desert ecosystems. These roads will be permanent while during operation of the plant, operation and maintenance employees and equipment must be transported to the plant. Besides the occupation of a certain area of the desert, the people who will build the plant will also influence the desert. With adequate information and training the influence of this disturbance will be minor.

Research must be done on the effects of the concentrated solar radiation beams from the heliostats to the central receiver. These beams might cause eye injuries to birds. The knowledge received from the Solar One and Solar Two are indicative. These plants are small compared to the plants that should be built in the future and the intensity of the concentrated solar beams will increase due to better reflectance of the heliostats.

5. THE SNAP PLANT

The SNAP power plant is a machine that produces artificial wind. Cooling hot dry air high in the atmosphere creates the artificial wind. The hot air is brought about through solar irradiation on the earth surface. The SNAP plant is a very large vertical tube where the hot and dry air is cooled at the top. The cool heavy air descends in the tower and reaches high speed at the bottom. Before the air leaves the tower it goes through turbines that run generators for electricity production. This idea is developed in Israel based on a natural phenomenon called ‘wind shear’.

5.1 System Description

When a passing cloud sheds rain onto dry hot air, a strong downward draft (called ‘wind shear’) is generated. The SNAP technology aims at harvesting this natural phenomenon to create a strong sustained wind that will drive wind turbines. A SNAP power plant is basically a hollow tower with openings at the bottom, see Figure 5.1. In those openings wind turbines are placed. To create a strong sustained wind, water is raised to the top of the tower where it is sprayed over the entire area of the flue opening. The sprayed water evaporates, making the hot dry air at the top of the flue cooler and heavier than the surrounding air. The heavier air sinks down the tower and comes out through the opening at the bottom, which can reach a speed of 80 kilometres per hour. On its way out, it passes through a battery of shrouded wind turbines, which drive electric generators (Zaslavsky, 1999). The whole system is constructed with well-known, proven and mature technologies, and materials. An Energy Tower needs no artificial collectors in order to capture the solar radiation. However, the scale of the construction makes the feasibility questionable. The surrounding surface acts as a collector. During the day, the area is heated by the suns’ short wave radiation. This radiation makes the land hot. As a result, the surface warms up the air. The heated air ascends because the density decreases, as a result a local shortage on air originates. This shortage will be refilled by surrounding less hot air. During the night the surface is still hot and therefore produces hot air, which ascends. This means that a SNAP Tower can operate 24 hours a day (Shilo and Er-el, 1995). However, the energy output changes somewhat during the day and to a greater extent over the seasons, depending on specific conditions at each site.

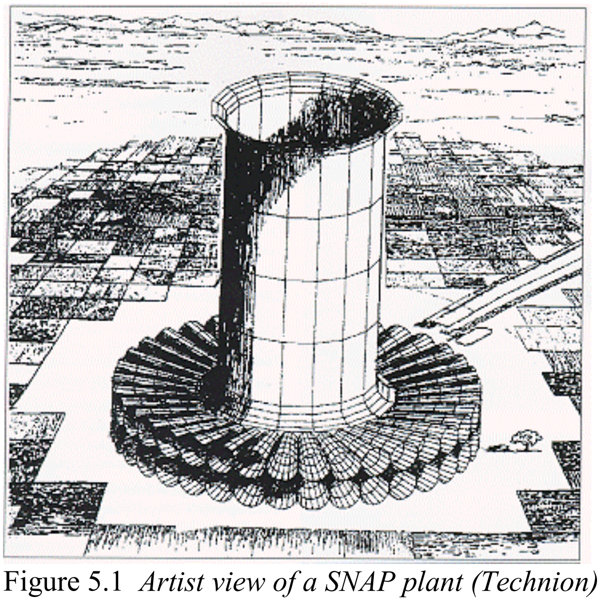


Figure 5.1 *Artist view of a SNAP plant (Technion)*

5.2 Storage System

Due to its nature a SNAP tower can produce power 24 hours a day (Shilo and Er-el, 1995). Therefore, a storage system for a SNAP tower is not necessary. The heat, which is stored in the surface that surrounds the tower, cannot be released in a controlled way. Controlling the release of the earth's heat is possible by covering the surrounding area with a greenhouse. By opening a certain number of windows the release of heat is determined. This comes close to the idea of a Solar Chimney. However, one of the major disadvantages of a Chimney is the large area, which is occupied by such a system. If a storage system is added to a SNAP tower it is not for storing the heat but for storing the produced power. This is possible but would raise the production costs of the electricity. On the other hand the power output of a SNAP tower can be slightly controlled by the amount of water, which is sprayed at the top of the tower, see Figure 5.2 and Figure 5.3.

5.3 History

The idea of an energy tower is based on an article from 1975 by Dr. Philip Carlson, a physician in California. He had observed the downdrafts created during brief rainstorms and had contemplated possible alternative energy production based on the principle. In the 80s, at the Israeli Institute of Technology - Technion, a team of engineers studied the SNAP concept over a period of more than a decade. This succeeded in devising a design proposal in which the cost effectiveness ratio of the project was improved by a factor of seven over the original. The search for this type of energy sources was driven by the lack of abundant fossil energy reserves in Israel. This, combined with the tensed relation with their neighbouring countries, was the main driver behind alternative energy research (Zaslavsky, 1997).

5.4 Further Development

Currently the Technion design team has joined with an outside investor to create Energy Towers, Ltd., a corporation designed to pursue and bring to completion the project with the construction of a first tower in the Arava. End 1996 a Memorandum of Understanding, to promote and support the building of a 1:7 pilot plant, was signed. As a result this 1:7 pilot plant is planned nearby a currently operating saline pond site where the existing salt water pumping system could be used. The baseline schedule shows that the pilot pre-design phase would continue through autumn 1997, overlapping with the first stages of the pilot plant's construction. These dates have been pushed back due to negotiations with government and private investors, as well as the inevitable uncertainties of planning a major project such as this. The baseline schedule calls for the pilot plant to be tested until the first quarter of 1999, with the full-scale commercial unit's construction scheduled for 1999-2002 so that the plant is scheduled to go on the Israeli power grid sometime in 2003 (Zwin, 1997). As mentioned before, this time schedule has been delayed. Until now, no new time schedule has been published. The result of all past studies is that most of the involved persons and institutes are convinced that, all physical principles that are needed for SNAP tower were proven, and that the project can be realised completely with proven technologies.

5.5 Environmental Constraints

Besides power production, a SNAP plant can also produce desalinated water from seawater, if desalination units are placed after the turbines. This is an attractive option because with this extension the plant does not depend on local water anymore. Seawater is transported to the SNAP plant through pipes or channels where it is first used to cool the hot dry air at the top of the shaft. After passing the shrouded wind turbines, the wet air is let through desalinating equipment, producing fresh water. Together with fresh water, concentrated brine is produced which contains the salts. This concentrated brine could be transported back to the sea. First studies show that a 388 MW plant with a yearly output of 3.4×10^9 kWh, can produce 200×10^6 m^3 of water that requires 700×10^6 kWh. The income from power sales reduces, but the income from water sales compensates this loss, because water has a high value in desert areas.

Due to the proportion of a SNAP power plant, questions have been raised about the land needed to erect such a system. A distinction has to be made between the surface area of the tower and the area, which acts as a solar collector. When a SNAP tower is erected, agricultural use of the direct surrounding land is not possible anymore due to the saline winds coming out the shrouded wind turbines. Although no real data is available, Table 5.1 presents an overview of estimates that have been made for different plant layouts (Zaslavsky, 1997).

Table 5.1 *Theoretical characteristics of a SNAP tower*

	Shilo & Er-el, 1995	Zaslavsky, 1997[1]	Zaslavsky, 1997[2]	Zaslavsky, 1999
Tower height [m]	800	1200	1200	1200
Tower diameter [m]	400	400	400	400
Water consumption [ton/kWh]	0.2	0.25	0.17	0.17[3]
Gross power [MW]	450			620
Net output [MW]	187	480	480	388
Annual output [GWh]	1558	4000	4000	3399/3400
Required land [m^2/GWh]	n.a.	2250	562	502[3]
Required land [km^2]	n.a.	9	2.25	1.71
Land diameter [m]	n.a.	1705	870	765
Water output [ton/kWh]	-	0.075	0.075	0.059
Water output [$\times10^6$ m^3]	-	300	300	200

[1] pilot plant
[2] first commercial plant
[3] best guess.

The land diameter is calculated by first calculating the tower surface. Additionally the tower surface and the required land have been added. From this total surface a diameter is calculated which represents the diameter of the total area needed for tower and the surrounding land.
Example for Zaslavsky, 1997[1] from Table 5.1:

$$Towersurface = \pi \times \left(\frac{400}{2}\right)^2$$

Tower surface = $\pi \times$ (tower diameter/2)^2

Tower surface = 125.7×10^3 m

Total area = tower surface + heliostat surface

$$Totalarea = 125.7\times10^3 + 9000\times10^3$$

Total area = 9125.7×10^3 m

Land diameter = square root from total area / π

$$Landdiameter = \sqrt{\frac{9125.7\times10^3}{\pi}}$$

Land diameter = 1705 m

The two most positive cases in the right columns of Table 5.1, the land area needed is of the same order of magnitude as a conventional power plant and an order of magnitude less than all other concentrating solar technologies (Zaslavsky, 1997).

Although the land needed to erect a SNAP tower seems to be relatively small it is not the only aspect of these installations where environmental concerns have been postulated. However, most hazards are speculative and must be considered as part of a 'worst case' or at least a 'worse case' scenario. As long as no SNAP tower is build, these hazards stay speculative. Although, scientific research will give better insight of those risks only a real operating tower will provide reliable information (Zwirn, 1997). Recent concerns are:

- Aesthetic - it is estimated that a 1.2 kilometre tower with a base of 400 meter can be seen from 20-25 kilometres away. In the Arava desert in Israel this would mean that the tower could be seen from the Timna Park, an ecosystem with wild animals and plants and extensive recreational hiking.
- The tense situation in Israel makes it unlikely that a SNAP tower will be build. Such large systems might attract the attention of terrorists.
- Noise - concern exists, that the turbines would produce a continual roaring echo in the desert like that of an aircraft. No realistic estimation of the noise production has been made so far.
- Construction area - during the construction of a SNAP tower several kilometres square that would be obliterated for construction equipment, mobile offices, houses and buildings will influence the fragile desert ecosystems.
- Roads - also the building of a road capable of handling massive pieces of equipment and large earth moving and construction vehicles will influence the fragile desert ecosystems.
- Silicates - during the construction of a SNAP tower silicates might be dispersed into the air and influence the surrounding agricultural lands.
- Ecological footprint - the demands on the local environment from the men and women who will be living in the ecosystem during construction and operation might have a negative influence on the desert ecosystem. The people involved will number around several thousand.
- Saline brine - if a leakage occurs in the systems, that transports the seawater to the tower and the brine back to the sea, the soil or groundwater would be contaminated and the surrounding area would be rendered unusable for years. Not only infertile for agriculture aspects but also for indigenous plant and animal life. Building the plants in an already salinate area reduces this specific risk.
- A SNAP Tower might be vulnerable to Earthquakes. There is no experience with such huge constructions and earthquake durability. To prevent problems one should construct a SNAP Tower in a geologic stable region.
- A SNAP Tower might be an interesting object for terrorist attack or sabotage actions. Although the impact on energy supply by destroying one plant is small the symbolic impact is large. Israel might not be the right country to erect the first SNAP plant at this moment although the idea and most of the research originates in that county. More favourable areas are Australia, Southern Europe or the southwestern art of the United States.
- Meteorological effects - the effects of a 1.2 kilometre high tower cannot be determined adequately yet. But any structure this large will create a microclimate where winds and even humidity or precipitation patterns change. Forecasting climates through mathematical and computer modelling is notoriously difficult, and no one can say with certainty what a SNAP tower will cause within a desert.

- Bird migration - this is probable a site-specific concern. The environmental community is, for example, concerned for bird life in the Arava desert. Each year vast numbers of birds migrate in spring and winter from Europe to Africa. The cold water sprayed over the top of the tower generates a downdraft that could endanger the lives of small birds, sucking them to their deaths at the bottom of the tower. It is difficulty to estimate he number of casualties because there is limited knowledge about the flying height of migrating birds. However by modifying the original design with a narrow chute to a wider duct, the intake air speed reduces from 29 m/s to 10 m/s, this will presumably reduce the risk of birds being sucked in.

5.6 Characteristic Figures

This section focuses in more detail on the net deliverable power of a SNAP tower. The temperature difference, the droplet size and the amount of water sprayed determine the net deliverable power. The temperature difference between the ground surface and the top of the tower is related to the height of the tower and can not be influenced artificially. The droplet size and the amount of sprayed water can be influenced artificially. Those two parameters together with the turbine efficiency determine how much power is produced, and how much power is needed to spray the wanted droplet size and amount of water. Power output minus the input makes the net deliverable power. Another advantage of these parameters is the option to control the net deliverable power by spraying more or less water. This characteristic of the SNAP tower makes it possible to follow power demand curves to a certain extends.

The net deliverable power N of a SNAP plant can be expressed by the following equation:

$$N = A_c \eta_t \left(\frac{2}{3} E_{net} \right)^{3/2} \frac{1}{\sqrt{F\rho}}$$

Where:

Ac	the cross-sectional area of the main shaft.
η_t	the efficiency of the turbine - transmission generator aggregate.
E_{net}	is the net mechanical specific energy in terms of [Pa]. The mechanical specific energy is computed as the difference between the excess static pressure of a cooled air column minus the pumping energy required for spraying a certain amount of water [m^3], air, and addition of recovered energy of the water that has not been evaporated.
ρ	is the average air density.
F	is the energy loss coefficient.

This formula is a result of an analysis showing that the term ⅔E_{net} gives the maximum possible deliverable power, and that exactly ⅓E_{net} is dissipated through energy losses. The rate of airflow Q can be expressed by:

$$Q = A_c \left(\frac{2}{3} E_{net} \right)^{\frac{1}{2}} \frac{1}{\sqrt{F\rho}}$$

Where Q, the airflow, is expressed in [$m^{3/s}$]. Interestingly, the ratio N/Q is:

$$\frac{N}{Q} = \eta_t \left(\frac{2}{3} E_{net} \right)$$

E_{net} increases more or less in proportion with the tower height. In a 1000 meter tower, the net power N for delivery makes about 1% of the heat involved in the water evaporation which is provided by the hot air (Zaslavsky, 1999).

The cooling of the air is gradual as in Figure 5.2. The upper line shows the temperature in the outside air. The other lines on the bottom are the inside air temperatures. In Figure 5.2 one can see the cooling rates with spray droplets 100µ, 300µ and 500µ in diameter. The optimal droplet size must be chosen because the smaller the droplets the better is the cooling. Figure 5.2 Shows that the optimal cooling is achieved with a droplet size of 100µ, a temperature decline of 12ºC. However, the smaller the droplets the higher is the energy spending for pumping. The potential of mechanical work is reflected by the area between the outside temperature line and each inside temperature line. This area expresses how much the inside air column is heavier than the outside air (Zaslavsky, 1999).

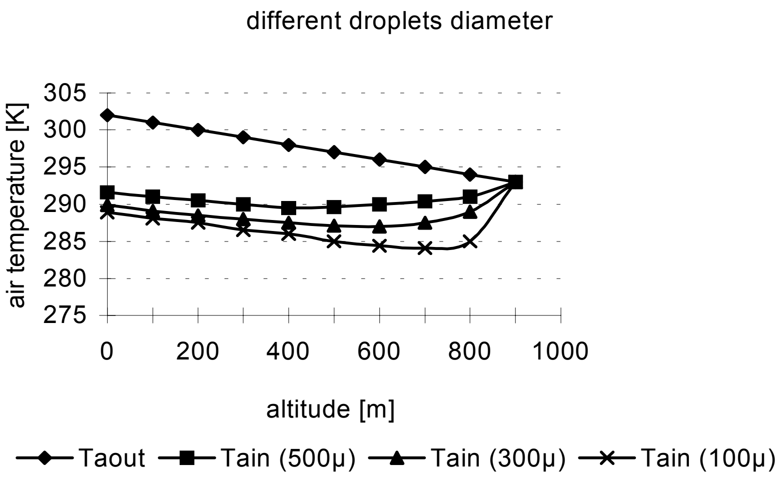


Figure 5.2 *Temperature change with elevation (bottom - inside air, top - outside air (Zaslavsky D., 1999)*

The more water is sprayed the more efficient is cooling. More efficient cooling results in a higher power production. However, the more power is devoted to pumping fewer of the produced power is left for consumer needs. Figure 5.3 shows the optimal rate of spray for net deliverable power of a given tower at given climate conditions. One can also see the gross power in Figure 5.3. The gross power is also important because it can be used when pumping storage is incorporated. In short, it is necessary to optimise by choosing the right size of the droplets and the amount of excess water spray (Zaslavsky, 1999).

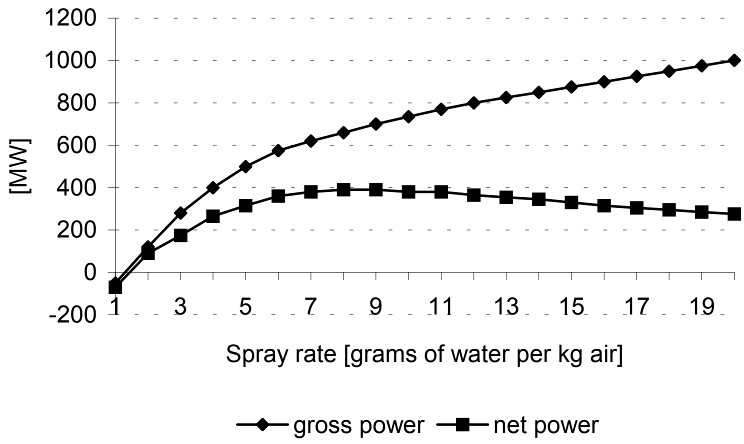


Figure 5.3 *Gross and net power vs. spray rate (Zaslavsky, 1999)*

5.7 Opportunities and threats

The main advantage of a SNAP plant is the production of large amounts of CO_2-free power. During the construction of the plant CO_2 is produced for the production of concrete, steel and other construction materials and the CO_2 emissions involved with the transport of the construction materials. The production of power is CO_2 free while the plant uses air and water as fuel.

The production of fresh water in desert areas with a SNAP tower by desalination of sea water provides such a plant an advantage above fossil fired power plants or Power Towers that need water for cooling. The produced fresh water generates extra income while water is valuable in desert areas.

A SNAP power station can operate 24 hours a day instead of 6-8 hours a day like PV, solar thermal and solar mirror systems without a storage facility (see Power Tower - Chapter 4).

There is no need for back up by fossil fuels or large storage systems because the earth functions as a heat collector. This makes the whole system simpler, therefore reducing the risk of a system failure.

The needed surface in the best-estimated plant layout is of the same order as a coal fired power plant including coal mining. Strong supporters of the SNAP plant do this assertion without giving proper argumentation. The author of this report is of the opinion that a SNAP plant requires, even on the best situation, two or three times as much land as a coal fired power plant. On the other hand, all the different estimated plant layouts of a SNAP plant require an order of magnitude less surface than other large scale solar concentrating technologies, like the solar chimney and the Power Tower. The author doubts if the difference will be that large but think that it is plausible that SNAP requires the least surface. It is difficult to make a comparison with PV-technology while PV does not need to be placed on the surface. Implemented on roofs or facades PV does not occupy additional land. In this situation PV performs better than a SNAP plant. However, comparing the power output per square meter, A SNAP plant performs better than a PV-system.

Like for the Power Tower in Paragraph 4.7, the investment costs are high compared to fossil fired power stations. It requires also a larger investment than most other renewable energy sources because of its scale. A SNAP plant can only be built in large plants that need a large investment. A significant cost saving is therefore needed before private investors become will supply capital for such systems. No investment means no cost reduction, so a national or an international governmental body should take the lead in developing this technology.

The focus under which most analysis is being conducted is troubling. It seems clear that an independent multi-disciplinary analysis should be added to the reviews that have been done so far. The current technical reviewers have isolated concerns with their own fields while no one has undertaken an analysis of the proposals as a whole. Without this perspective, the danger exists that individuals put their own specialities under the microscope, while the larger project balloons into bankruptcy.

Reviews and analysis are not publicly available, and are subject to bias. The opportunity for publicly distributed, independent analysis should be given priority. It should be possible for skilled professionals to get access to information and publish their findings, while respecting the intellectual property rights of the research that has been done. However, the 60-odd reviews are all confidential, and someone examining the proposal must rely on the scant publicly available data, all produced in-house with the expected biases.

A comprehensive analysis of energy needs does not exist. Rather than merely presuming that demands for energy will follow their current path, the SNAP tower supporters should examine the projections for need under a number of alternative energy patterns that incorporate greater conservation measures. If the profitability and economic viability of a SNAP tower proposal diminishes in such an analysis, this would be a good reason to question whether or not a country should devote its resources to producing greater supplies of energy.

A revised environmental impact statement on proposed construction technology and waste disposal should be made available every time the proposal moves forward, in light of both construction needs and the regional environment. The same applies to the amount of land that is occupied by a SNAP plant.

The People who live in or nearby deserts are the ones that have the most to lose from a regional aesthetic menace. If on-going studies indicate that noise pollution on a large scale can not be prevented by technical means, shielding mechanisms should be investigated. While a kilometre-tall tower cannot be conveniently hidden out of sight, efforts should be made to minimise the visual pollution by keeping it close in colour to the desert tones and ensuring that bright lights at night are not aimed directly at human settlements.

Saline pollution. The possible danger is that salt spray will escape the tower either at the top or through the turbines at the bottom, salinating the area's soils permanently. In addition, the system of pipes and channels that will carry the seawater to, and concentrated brine off the tower pose problems with leakage, which would contaminate the land permanently. Exceptional care must be taken with the construction and maintenance of this pipe and channel system in order to protect agriculture and native ecosystems.

It is not known if a SNAP plant would have meteorological effects in a desert. If a SNAP tower has detrimental local effects like changing the temperature, wind patterns, or humidity, the viability of the local settlements could be threatened. Unfortunately, this cannot be determined wholly from computer models, therefore a 1:7 pilot plant needs to be built. As long as the designers cannot determine the possible detrimental effects from the pilot plant on desert climate, there can be no proceeding to the construction of a commercial unit. On the other hand is it unlikely that such an installation will have an influence on the climate, which goes, beyond its direct surrounding.

A hollow tower that sucks in the surrounding air, what a SNAP plant basically is, might threaten migrating birds. There is still no way of judging whether a SNAP tower will have negligible impact on bird populations, or whether it will literally suck birds out of the sky. More study is essential, some of which can only be conducted after the construction of 1:7 pilot model, but nothing can ever ensure that bird populations are safe. The best way of avoiding possible danger to migrating birds is not building a SNAP plant in a bird migrating route. The Arrava desert in Israel, where the supporters of the SNAP technology would like the first 1:7 plant to be built, is a migrating route for birds from Europe to Africa.

6. THE AVAILABLE SOLAR RESOURCE

Solar thermal power plants depend on direct sunlight, so they must be sited in regions having high direct solar radiation. Suitable sites require at least 2,000 kWh per m^2 of sunlight annually, where sites with more than 2,500 kWh per m^2 per year are considered favourable for deployment. Such sites will be situated in areas where the climate and vegetation do not produce high levels of atmospheric humidity. Typical regions would include the steppes, savannahs, semi-deserts and true deserts, situated within ±40º of latitude, see Figure 6.1 (De Laquil, 1993).

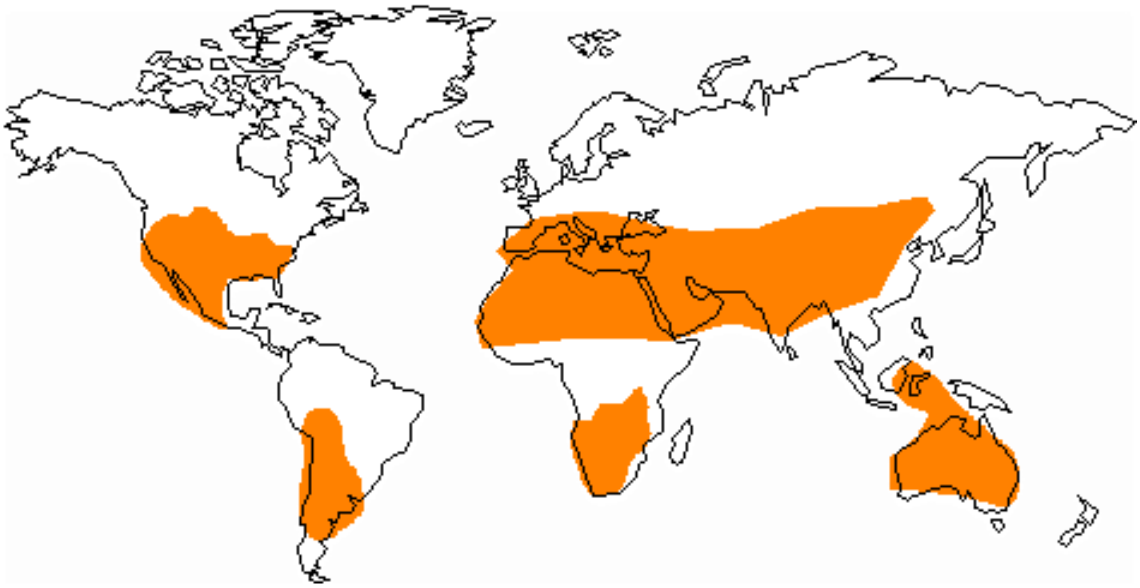


Figure 6.1 *Areas in the world with high insolation (Stine and Geyer, 2001)*

6.1 World potential

Estimates of the total global solar energy resource that might be utilised by solar thermal electric plants are subject to much uncertainty. This is caused by many factors: lack of measured data on direct solar radiation, suitability of local grids, economic factors, and the fact that the technology is still developing (Pharabod and Philibert, 1991). The World Energy Council predicted in the study, 'Renewable Energy Sources: Opportunities and Constraints', that by 2020 the global energy production from all types of solar energy (solar thermal electric, photovoltaics and solar thermal heating) would increase to between 109 and 355 Mtoe per year (in primary energy terms), depending on the scenario assumed. It estimated that 30 to 35% of this would come from solar thermal power plants, giving a predicted electricity production from these plants of between 140 and 410 TWh per year, see Figure 6.1. A number of constraints, in particular the current high capital costs (relative to conventional fossil fuel plants), are likely to lead to a slow implementation in the short- to medium-term, although there is "a clear indication that penetration will increase after 2020" (WEC, 1993).

The WEC scenarios use a number of building blocks such as; population projections, economic prospects, changes in energy efficiency, shifts between the various fuels - fossil and non-fossil, more or less successful technology innovation and diffusion, stronger or weaker efforts to tackle environmental problems, larger or smaller mobilisation of investible funds, more or less effective institutions and policies. With these blocks three alternative cases were explored in detail to 2020 and in outline to 2100. Case A described a High Growth world in which economic growth, energy consumption increases and energy efficiency improvements were strong. Case B was a

Reference, or middle-of-the-road evolution (but not simply Business As Usual), to which a Modification - B1 - was added which reflected stronger growth in energy consumption in developing countries and poorer performance in the improvement of energy efficiency. Finally, Case C was Ecologically Driven, with policy makers and other actors in society succeeding in promoting energy efficiency, technology innovation and transfer, non-fossil fuel development, and the reduction of institutional barriers. Case C had the lowest energy consumption and greenhouse gas emissions trajectories of the three cases. The main features of the scenarios are summarised in Table 6.1. There are two other important features of the WEC's scenario work. It is based firmly on current realities as well as future possibilities. One key current reality is that nearly two billion people out of six billion people do not have access to commercial energy services. Another is that just over 75% of the world's current primary energy supplies comes from the fossil fuels (and only 2% from new renewables other than large hydro). Although some may claim that fossil fuel reserves are restricted, the reality is that geological resources for these fuels and uranium are huge and technological advances are allowing more and more of them to be exploited. The decarbonisation of the fuel mix is likely to be a very protracted process.

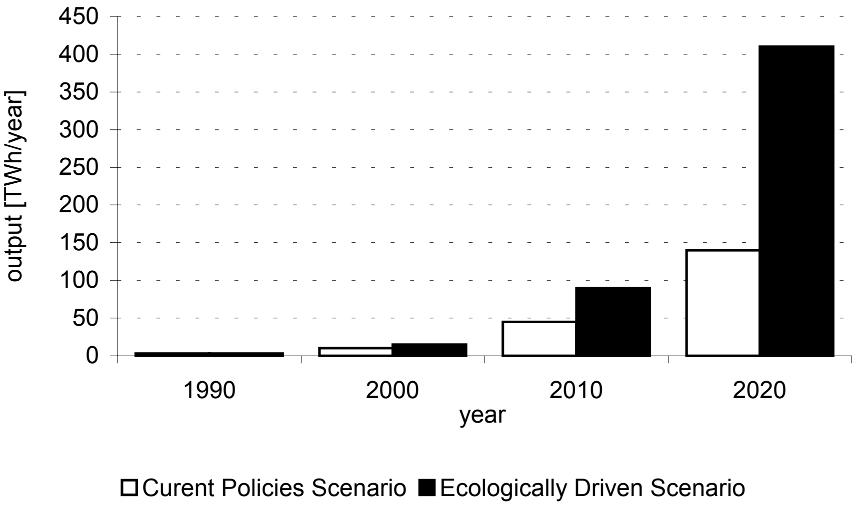


Figure 6.2 *Predicted global deployment of solar thermal power systems (WEC, 1993)*

Table 6.1 *Summary of cases for global energy scenarios*

	Case A current policy scenario	Case C ecologically driven scenario
World Population 2050 (10^9)	10.1	10.1
World economic growth 1990-2050	2.7% p.a.	2.2% p.a.
World energy intensity improvement	Medium	High
1990-2050	-1.0% p.a.	-1.4% p.a.
Primary energy demand (Gtoe) 2050	25	14
Resource availability		
Fossil	High	Low
Non-fossil	High	High
Technology costs		
Fossil	Low	High
Non-fossil	Low	Low
Technology dynamics		
Fossil	High	Medium
Non-fossil	High	Low
CO_2 emission constraint	No	Yes
Carbon emissions (GtC) in 2050	9-15	5
Environmental taxes	No	Yes

6.2 Regional potential

The WEC study also gives a regional breakdown of the predicted growth in generation from solar thermal electric plants, which is shown in Figure 6.2. This is based on predictions of the growth in all solar technologies, solar thermal power and PV-systems, therefore, it does not fully reflect the influence of the need for direct solar radiation on the suitability for solar thermal power plants. Nevertheless, it clearly indicates that much of the growth is likely to be in non-IEA countries, apart from the USA (WEC, 1993).

Besides the WEC Pharabod and Philibert have conducted another survey of suitable areas for Solar Thermal Power in the world (Pharabod and Philibert, 1991). They have identified several regions, including:

- the south-western United States and Mexico,
- the north-eastern part of Brazil,
- the central Andes,
- a vast area embracing North Africa, the Sahel, the Middle East, Afghanistan and Pakistan, Turkey, northern India, the southern part of the former Soviet Union, and western China,
- Southern Africa,
- Australia.

They estimated that in the regions listed above, about 40 GW of natural gas hybrid parabolic trough systems might be installed by 2000. These would produce about 160 TWh, of which half (80 TWh) would be contributed from the solar part of the plants (Pharabod and Philibert, 1991). In reality, installed Trough capacity is about 350 MW with approximately 4000 full solar load production hours, resulting in a yearly output of 1.5 TWh (BMU, 1999).

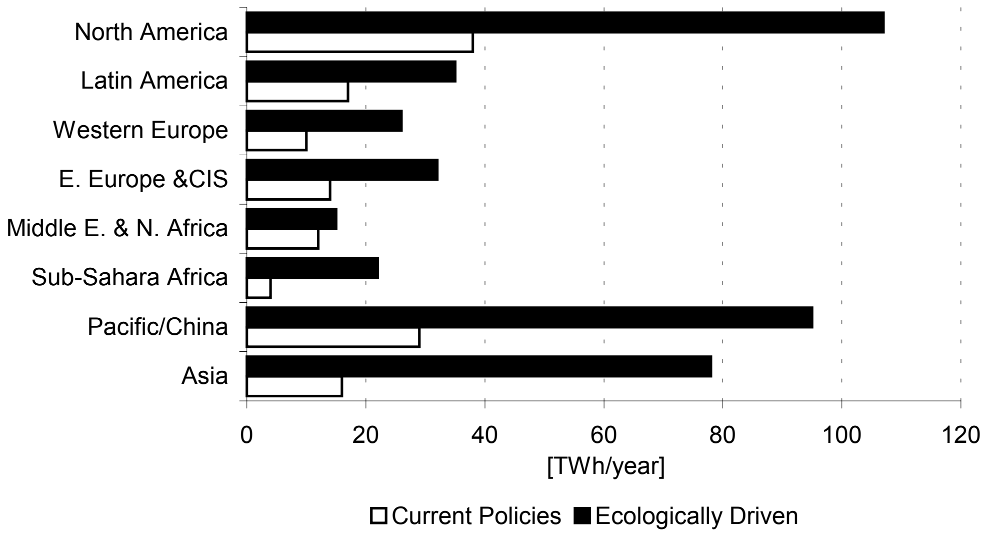


Figure 6.3 *Regional breakdown of solar thermal power contribution in 2020 (WEC, 1993)*

6.3 The Mediterranean area

In addition to the areas mentioned in Section 6.2, considerable attention is focused on Mediterranean regions (Nitsch et al, 1991). Western Europe does not have a large potential for Solar Thermal Power production of its own, but North Africa is nearby. With Solar Thermal Power production the northern African countries can generate income and Western Europe can fulfil its renewable energy objective. The WEC predictions for regions surrounding the Mediterranean (Southwest Europe, Middle East and North Africa) are in the same order of magnitude to those derived by Nitsch, as shown in Table 6.2.

Besides these more political reasons, the Mediterranean region also has special importance for the VLEEM study. The VLEEM study will perform a High Renewable case study for Western Europe. Part of the energy demand in Western Europe will be supplied with solar thermal power plants located in southern Europe or in North Africa.

Table 6.2 *Estimates of the potential contribution from solar thermal power in the Mediterranean area [TWh/year]*

Source	Scenario	2000	2005	2010	2020	2025
WEC [1]	Current policies	1	*2*	6	18	*31*
	Ecologically driven	2	*4*	9	38	*75*
Nitsch [2]	Anticipated Potential	*7*	8	*10*	*27*	51
	Accelerated Introduction	*14*	16	*20*	*52*	93

Notes: cursive figures are estimated figures
1 Southwest Europe, Middle East and North Africa (WEC, 1993).
2 Countries bordering the Mediterranean, plus Portugal and Jordan. Generation estimated from installed capacities using a 25% capacity factor (Nitsch et al, 1991).

From the Figures 6.1 and 6.2 and Table 6.2 it becomes clear that the potential of Solar Thermal Power on a global and Mediterranean scale is large. However, it is difficult to estimate when this potential will be exploited. Technology uncertainties, an insecure investment climate, the development of fossil fuel prices and the growth of power demand cause this.

7. THE ENVIRONMENTAL IMPACTS OF SOLAR THERMAL POWER

The most significant difference in environmental impact of solar thermal electric schemes compared to fossil-fired power stations is that they produce electricity without the atmospheric emissions (CO_2, SO_2, NO_x). However, there are some emissions connected with energy use in the pre-operation life cycle stages such as the manufacturing and construction of systems. These are evaluated in Section 7.1. The net reduction in emissions, which might be achieved through the deployment of solar thermal electric systems is estimated in Section 7.2. The non-energy related impacts and burdens from manufacturing, construction and operation, and decommissioning of systems are discussed in Section 7.3. In Section 7.4 a summary of potential environmental burdens of moving air systems is given. Unfortunately the environmental information about solar chimney's and SNAP plants is less detailed compared to the moving mirror systems. As long as no SNAP tower is constructed, the environmental impact of this technology can only be described on a theoretical basis. The information available for solar chimneys is mainly derived from the test facility in Manzanares in Spain. However, the information available from the other three technologies combined with the theoretical information, makes it possible to get an impression of the possible impacts of these technologies on the environment.

7.1 Life Cycle Emissions

The energy use involved in each of the life cycle stages of a solar thermal power plant has not been studied in detail. However some broad conclusions can be drawn from studies which have been conducted for other renewable energy technologies (EC-6, 1995). If the pattern of energy use in various life cycle stages of solar thermal power plant is assumed to be similar to other renewable energy technologies, it can be assured that the dominant energy use (and concomitant emissions) is associated with the materials'processing and component manufacturing stages.

To a large extent, energy use and emissions in these two stages can be quantified against materials'use. As an initial guide to the life cycle emissions, a preliminary evaluation was carried out for the three moving mirror solar thermal power technologies:

- *Parabolic Dish*. This technology was represented by the scheme deployed at the three stretched-metal-membrane dishes installed at the Plataforma Solar in Alméria, Spain (Blezinger H., 1994). Each is 7.5 m in diameter with a reflecting surface provided by 0.9 mm thick glass mirrors glued to the front side. Each dish concentrates the sun's rays onto a 9 kW Stirling engine, which is designed to operate at insolation levels above 300 Wm^2. This represents the robust, cheap type of technology that can be deployed in remote areas.
- *Solar Trough*. This technology was represented by the SEGS VII commercial plant at Kramer Junction, California (De Laquil et al*,* 1993). This comprises a 30 MWe solar/gas hybrid plant, with 584 solar collector assemblies totalling 194,280 m^2 in area.
- *Power Tower*. This technology was represented by the design of the PHOEBUS plant for operating in Jordan (Grasse, 1992). This comprises a central air/volumetric receiver with a 30 MWe output, powered by 1751 heliostats with a total surface area of 202,200 m^2.

The results have been listed in Table 7.1. It should be emphasised that these are preliminary findings. Clearly the results will vary with location (insolation levels) but they indicate that emissions from solar thermal power technologies, including the emissions during the manufacturing of the needed materials, are about an order of magnitude less than the emissions from conventional fossil fuel technologies. More detailed studies of this technology are required.

Table 7.1 *Emissions due to material's processing and manufacture (IEA, 1998)*[1]

	Emissions [g/kWh]		
	Parabolic Trough	Parabolic Dish	Power Receiver
CO_2	38	27	26
SO_2	0.27	0.13	0.21
NO_x	0.13	0.06	0.08

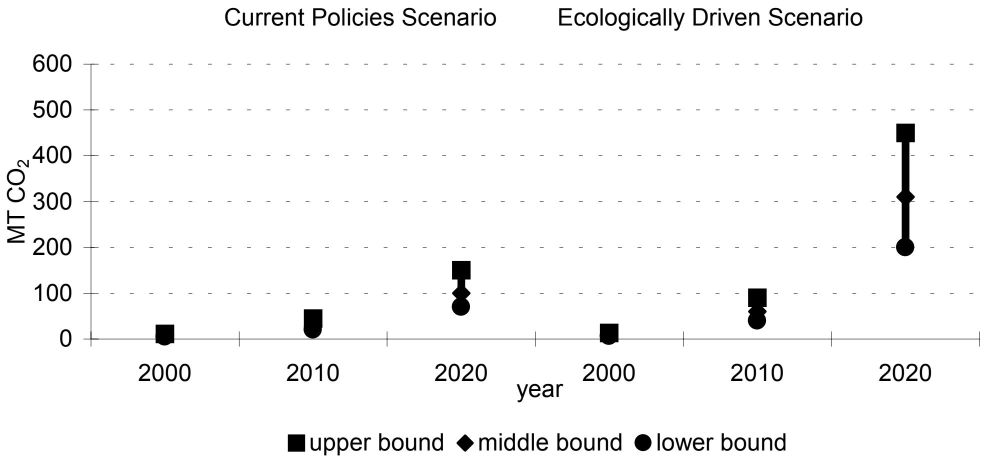
[1] These values are preliminary and have been derived for specific schemes. They will vary according to the individual technology chosen and its location.

7.2 Avoided CO_2 Emissions from Global Deployment

The avoided emissions of CO_2 resulting from the global deployment of solar thermal power plants were evaluated using the emissions data from Table 7.1 and the deployment levels predicted for the 'Current Policies'and 'Ecologically Driven'scenarios for 2000-2020 (WEC, 1993). The Life Cycle Analysis methodology has been chosen to calculate the avoided CO_2 emissions. Detailed studies of the main renewable energy technologies have been carried out using this approach, like the ExternE study (EC-6, 1995) and others. These have shown that for most renewables:

- The energy use and emissions released during the manufacture of the materials are most important.
- Energy use in all of the transportation stages is likely to be negligible; energy use in freight transport is typically only 1 MJ/t/km for rail and in road transport is typically 3 MJ/t/km (Eyre and Michaelis, 1991).
- Energy use in the extraction of the primary materials used in construction or in components is typically an order of magnitude lower than energy use in their primary processing.
- Energy use in the construction, decommission and disposal processes is also likely to be at least an order of magnitude lower than for material manufacturing.
- Typical energy payback time for solar thermal power plants is in the order of several years.

Figure 7.1 shows the possible annual savings of carbon dioxide with solar thermal power plants by 2020. The annual saving is between 70 and 150 Mt for the 'Current Policies' scenario and between 200 and 450 Mt for the 'Ecologically Driven' scenario. More detailed information can be found in the WEC study 'renewable energy sources: opportunities and constraints' (1993).



Key: Lower bound = displaced CCGT generation; middle line = displaced current generating mix; upper bound = displaced coal generation (pulverised fuel + flue gas desulphurisation). Data from WEC.

Figure 7.1 *Reduction in CO_2 emissions from solar thermal power technologies (full fuel cycle)*

7.3 Environmental Burdens of Solar Thermal Power

The limited deployment of solar thermal power plants to date means that there is little actual experience of the environmental impacts that such schemes may cause. The main impacts are related to the large land area required for the technology and the visual change of the landscape. Other impacts, such as burdens on water resources, are associated with the conventional steam generating plant and heat transfer fluids used in some of these systems. The main potential burdens, which have been identified, are:

- impacts from construction activities (emissions, noise, occupational accidents, effects on local ecosystems and habitats, etc.),
- visual impact,
- noise,
- land use and subsequent ecological impacts,
- water resources,
- occupational hazards.

Many of these burdens are local in character and hence are highly affected by the siting of the technology. As discussed previously, the requirements for the technology (high levels of direct solar radiation, low levels of atmospheric humidity and large land area) mean that typical sites will be in areas away from dense population concentrations, thus minimising impacts on landscape experience. With sensitive siting, the impacts of other burdens such as ecological impacts may also be minimised. For convenience the burdens are discussed in detail below in terms of large-scale systems (parabolic trough or Power Tower) and stand-alone parabolic dish systems.

7.3.1 Impacts during building

The impacts associated with the building of stand-alone schemes are minimal, whilst those associated with large-scale schemes are equivalent to those from any civil engineering project of a similar scale. The main impacts are:

- There will be atmospheric emissions from, all materials and equipment used on site, transportation of the workforce to and from the site, and transportation of construction materials by heavy goods vehicles. These emission levels are likely to be low relative to those from other life cycle stages, (EC-6, 1995).

- Transport of workers and materials is generally by road. This additional traffic will also produce noise, increase public road accidents, etc. However, because of the remote location of these schemes, these effects are likely to be small.
- There will also be an increased level of visual intrusion during the temporary construction period, from site activity and vehicle movements of all personnel, plant and equipment.
- Occupational accidents may occur, though these are common to any construction activity.

In most cases, the building period is short - at most a few years. Provided care is taken during the activities, most potential impacts will be minimal, temporary and fully reversible.

7.3.2 Visual intrusion

The visual impact of parabolic trough and Power Tower systems can be significant, because a considerable area is occupied by the mirror systems. There are also associated buildings for the generating plant, cooling towers and, in the case of the Power Tower system, the tower itself. For instance, one design for a 200 MW_e plant has a tower height of 239 m and a collector area of 180 ha covering about 1000 ha of land (Kelly and De Laquil, 1989). In comparison, a large new coal-fired plant (1800 MW) would occupy 67 ha and have a chimney height of 230 m, with cooling towers about 170 m high (EC-3, 1995; EC-4, 1995). However, most fossil fired power plants will be smaller than 1800 MW and therefore the height of the chimneys and cooling tower will also be lower. In addition there would be the visual impact of mining, coal transportation and ash storage. Visual intrusion is obviously affected by the site location. Deployment away from residential areas (as has been the case to date), would reduce the impact. Avoiding siting in areas regarded as particularly scenic can further reduce this. The scope for mitigating visual impact by landscaping is limited, because of the topographical requirements of these technologies.

The visual impact of parabolic dish systems will be smaller than the impact from Power Towers and trough systems. Their relatively small size offers more options both for being incorporated unobtrusively near to residential areas and for mitigation by landscaping.

7.3.3 Noise

The inclusion of steam generating plants, particularly in Power Tower and parabolic trough systems, means that noise will be generated from fans, pumps and turbines. However, noise would only be generated primarily during the day, because at night (when people are most sensitive to noise), the plant will be unable to operate (unless thermal storage is incorporated for the Power Tower or a SNAP plant operates at that specific site). In addition, the remote location, typical of such schemes will mean that noise is unlikely to have a significant impact because of the large distances from residential dwellings.

The Stirling engines of parabolic dish systems are a source of noise whilst operating. However, they are likely to be less noisy than the stand-by diesel generating sets, which they displace and which would be required for generation during the night.

A SNAP tower will probably make a roaring noise 24 hours a day, coming from the wind turbines. But also a SNAP tower will be built in remote areas, typical of such locations will be that noise is unlikely to have a significant impact because of the large distances from residential dwellings, see also Section 5.5 and Section 7.4.

7.3.4 Land use and impacts on ecosystems

To date most sites used- or considered for solar power plants are in arid desert areas, which have typically fragile soil and plant communities. Unless due care and attention are taken during the planning, construction and operation phases, the effects of the scheme on vegetation and soil could enhance the potential for soil erosion and habitat loss. The shade offered by the reflectors from both sun and wind would change the microclimate around the scheme, with possible beneficial effects on vegetation. Providing such schemes are not deployed in ecologically important areas, it is unlikely that any of the above changes would be considered significant.

The concentration of light and heat energy in Power Tower systems could pose a danger to local fauna. Operational experience has shown that whilst flying insects are frequently incinerated, birds avoid the danger areas (possibly by being sensitive to air turbulence).

Parabolic dish systems have a smaller land requirement than Power Towers and trough systems. In addition, their use in small numbers would have negligible impact on ecosystems.

Renewable technologies do require more land than conventional fossil fuel stations even when the life cycle land requirements for fossil fuels are taken into account (e.g. land used for mining of coal and waste disposal of ash). The approximate life cycle land requirements for renewables and coal-fired generation is shown in Figure 7.2, which shows the range of electricity produced annually per unit area of land. This is based on a generating station fuelled by open cast coal with non-useful waste being deposited to landfill. There are two ranges of values for wind; the lower is based on the area of land within the perimeter of the wind farm, the higher is based on the actual area occupied by the foundations of the wind turbines. Whilst coal clearly requires less land per unit of electricity produced, its advantage over some renewables is less than an order of magnitude. Since land use requirements will vary from scheme to scheme, these values should be taken as indicative. Many uses of PV do not require any land for their application (e.g. on the roofs and facades of buildings).

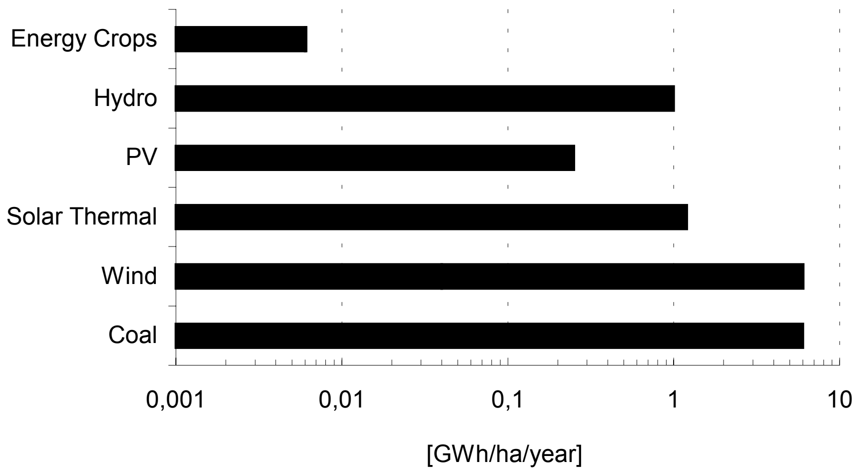
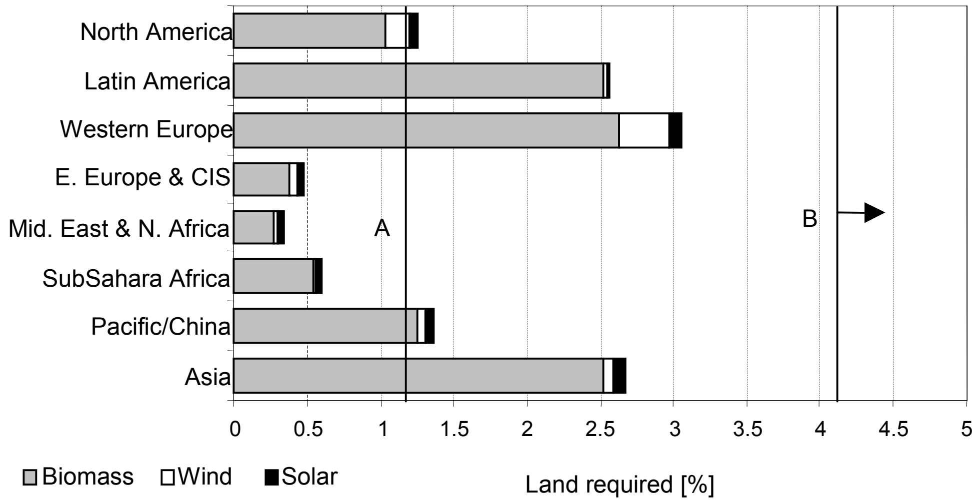


Figure 7.2 *Life cycles land requirements for electricity generation (WEC, 1993)*

Figure 7.3 shows a regional breakdown of the percentage of total land area in the EU that would be occupied by new renewables in 2020 under the ‘Ecologically Driven’ scenario (WEC, 1993). The amount of land required is similar to that currently occupied by roads in the EU (line A in Figure 7.3). Objections to road construction are rarely based on the fact that roads occupy too much land, but that the land prescribed for road building has some special feature (e.g. scientific interest, landscape value). Figure 7.3 also show that renewable energy land use is less than that of a single crop in the UK (line B). Again, there are no objections to growing crops based on their land requirements, but farming does encounter objections when it employs poor environmental practice (e.g. heavy uses of agrochemicals, eradication of meadows, woods and hedges). Therefore, in the light of this kind of experience, the future land requirements for intensive deployment of renewables is unlikely to be a significant obstacle to their public acceptability, providing they are not deployed in sensitive locations and environmental best practice is adopted.



Key: Line A is the current percentage of land in the EU covered by roads. Line B is the current percentage of land in the UK used for one minor crop (e.g. sugar beet, peas, etc.).

Figure 7.3 *Percentage of total EU land required for new renewables in 2020, ecologically driven scenario (WEC, 1993)*

The percentage of land required, presented in Figure 7.3, overestimates the amount of land required for renewables. However this does not apply for all the renewable technologies. Especially the overestimation of PV and wind can be significant. In Figure 7.3 the fact that some PV would have zero land usage, when mounted on roofs or as cladding to buildings, is ignored. For wind, the percentage of land required, includes the entire area within the wind farm. The actual area is much less and the intervening land could be used for other purposes such as agriculture, as is commonly practised. Finally, it should be emphasised that for most renewables, the effects of land use are easily reversible. Hence, in this respect, the promotion of renewables is in keeping with the concept of sustainable development.

7.3.5 Water resources

Parabolic trough and Power Tower systems using conventional steam plants to generate electricity will have a requirement for cooling water. This could place a significant strain on water resources in arid areas. The PHOEBUS consortium has designed a water storage scheme for use in a Power Tower plant that aims to cope with the water constraints in arid regions, by using the cold air at night to cool the water that is heated during the day (Haeger et al*,* 1994; Schmitz-Goeb and Keintzel, 1996).

There may be some pollution of water resources. During normal operation, concentrations of some compounds in the water will increase, largely as a result of evaporation of the water. Discharged water may also contain biocides. There will be some ‘thermal’ pollution, although the significance of thermal and any chemical pollution will depend on the characteristics of the local receiving body of water. Pollution of water resources may also occur due to accidents or unsound operating practices (e.g. uncontrolled flushing of the heat transfer and heat storage systems or plant washing), which can lead to the discharge of pollutants including hydrocarbons, oils, corrosion inhibitors, bactericides and glycols. Such incidents can be minimised by good operating practice.

Stand-alone parabolic dish systems require no water, other than for periodic cleaning of reflective surfaces.

A SNAP tower needs water for cooling the hot dry air. To prevent overexploiting the natural water recourses of deserts, the Israeli concept will use seawater. A disadvantage of seawater is its salt content. A leakage in the seawater transportation canals or pipes will contaminate the desert with salt. The impact of a leakage will increase if a SNAP tower is combined with a desalination plant. After passing membranes the seawater is separated into fresh water, and brine with a high salt concentration (Zaslavsky, 1999). The risk of salt contamination can be minimised by a good design and maintenance of the water canals or pipes and with good operation practice, see also Section 5.7.

7.3.6 Occupational hazards

Power Tower systems have the potential to concentrate light to intensities, which could cause eyesight injuries or even blindness if it is reflected into the eyes of operators. Under normal operating conditions, this should not pose any problem, because the operators would not be in the danger area. Failure of the tracking systems could result in straying beams that could pose a danger to workers near the receiving spot on the Power Tower (in other areas the concentration would not be sufficient to cause injury). However, there has never been such an incident at any of the operating plants.

The accidental release of heat transfer fluids (water and oil) from parabolic trough and Power Tower systems could form a health hazard. The hazard could be substantial in those Power Tower systems that use liquid sodium or molten salts as the heat transfer medium. Until today one accident has occurred in one system using liquid sodium but no injuries were sustained (IEA, 1998). This was caused by human error (i.e. neglect of agreed procedures and maintenance) and not by the technology involved.

Occupational accidents may also occur at manufacturing, construction and transportation phases. There might also be accidents caused by general industrial work associated with the system.

7.4 Potential Environmental Burdens of moving air systems

As mentioned before in Section 3.4 and 5.5 the main environmental burdens of moving air systems are difficult to determine since only a solar chimney has been built as a test facility, and no SNAP plant has been built so far. However, due to the fact that those systems are constructions that create and guide wind by natural principles, none or only a few environmental hazardous substances are used. The main burden comes therefore from the direct impact on the immediate environment of the plant that is occupied by these systems and in case of the SNAP plant the water use. Both systems are supposed to be built in desert areas, which are fragile ecosystems. Although the test facility in Manzanares in Spain did not result in irreversible environmental impacts, the larger the plants become the more cautious one should be with the surrounding environment.

The SNAP plant needs water to create the downdraft wind. Most studies suppose that no local desert water will be used, but seawater, which is pumped through pipes or channels to the plant. By solving the depletion of the desert water sources, a new threat arises with the import of seawater. The salts in the seawater might disperse the area when the water is sprayed at the top of the shaft, polluting the surrounding area. After fresh water production from the seawater the concentrated brine is transported back to the sea. A leakage in the seawater, brine channels or pipes will contaminate the soil with salts. Land contaminated with salt is unsuitable for agricultural purposes and is catastrophic for the local ecosystems.

7.5 Summary of Potential Environmental Burdens

The discussion presented in this chapter has been summarised in Annex A Table A.1. The main environmental impact of solar thermal electric systems is that they reduce emissions of greenhouse and acid gases by displacing conventional fossil fuel generation. Small-scale or standalone schemes (e.g. parabolic dishes) have negligible impacts. The only significant negative impacts are concerned with:

- emissions during materials' processing, component manufacture and construction,
- thermal pollution of water bodies,
- accidental discharges of pollutants,
- land use of large-scale schemes.

These impacts can be minimised or avoided by use of various methods or approaches, as indicated in Annex A in Table A.2.

8. CONCLUSIONS

Solar thermal power is a relatively new technology that has shown significant improvement since its inception about 20 years ago. Of the three mirror types, parabolic trough systems are at the commercial stage, whereas Power Tower and parabolic dish systems are still at the demonstration stage, although there are plans for commercial schemes in the near future. The moving air systems are less developed. A solar chimney test facility has been built in Spain, but a SNAP tower only exists on paper. The deployment of solar thermal power systems, predominately mirror systems, is expected to increase significantly in the medium to long term, 2020. Most of this deployment is expected to be in the US and non-IEA member countries.

Strengths of concentrating solar technologies are:

- Production of clean energy, no atmospheric emissions in particular, no CO_2.
- The produced energy is renewable, the sun as energy source is unlimited and can not be depleted.
- The hybridisation options that allow dispatchability.
- The storage options for mirror systems that allow 24-hour production and dispatchability.
- The moving air systems have the opportunity of 24 hour production from itself.
- The variety of markets that the technology can service.

Weaknesses of concentrating solar technologies are:

- The inherent capital intensive nature of these technologies.
- The current high kWh cost.
- The large land requirements for Power Towers and SNAP plants.
- The large water requirements for SNAP plants.
- The early mass-production hurdles.
- The visual impact of 1km high SNAP towers and the tens of square kilometres of mirrors focusing the sunlight to the Power Tower top.
- The limited reliability data for SNAP plants because all data comes from theoretical exercises.
- Limited number of industry partners, especially for the SNAP technology.
- Both systems are materially intensive, SNAP towers need a lot of concrete to build the shaft and Power Towers need is lot of siliciumoxyde to produce mirrors.
- Limited number of near-term opportunities associated with any emerging technology.
- Accidental discharges of pollutants. This can be avoided by good working practice.

Most of these burdens (e.g. noise, visual intrusion etc.) are likely to prove insignificant (provided areas of scenic beauty are avoided), because such schemes are likely to be situated in areas of low population density. Therefor, all the impacts of suitably located solar thermal power schemes are expected to be small and (most importantly) reversible. Hence, there is no potential conflict with sustainable development.

REFERENCES

Blezinger H. (1994): *Continuous Operation of a Dish/Striling Field on the Plataforma Solar de Almería.* Presented at the UN-ECE Workshop on Renewable Sources of Energy, May 1994.

BMU (1999): Bundesministerium Für Umwelt, Naturschutz und Reaktorsicherheit. *Erneuerbare Energien und Nachhaltig Entwicklung*. Referat Öffentlichkeitsarbeit, Postfach 120629, 53408 Bonn, July 1999.

CIEMAT (2000): http://www.ciemat.es/eng/instalacion/psa-diss.html#TOP, updated October 2000.

ConSolar (1999): http://magnet.consortia.org.il/ConSolar/consolar.html, latest update 1999.

DOE I (1997): US Department of Energy - Concentrating Solar Power programme, *Overview of Solar Thermal Technologies*, www.eren.doe.gov/csp/resources.html.

DOE II (1997): US Department of Energy - Concentrating Solar Power programme, *Solar Dish Engine*, www.eren.doe.gov/csp/resources.html.

DOE III (1997): US Department of Energy - Concentrating Solar Power programme, *Solar Parabolic Through*, www.eren.doe.gov/csp/resources.html.

DOE IV (1997): US Department of Energy - Concentrating Solar Power programme, *Solar Power Tower*, www.eren.doe.gov/csp/resources.html.

EC-3 (1995): European Commission DGXII Science, Research and Development, *JOULE Externalities of Energy*, ExternE Project, Volume 3 Coal and Lignite.

EC-4 (1995): European Conmmission, DGXII Science, Research and Development*, JOULE Externalities of Energy*, ExternE Project volume 4 Oli and Gas.

EC-6 (1995): European Commission, DGXII, Science, Research and Development, *JOULE Externalities of Energy*, ExternE Project, Volume 6, Wind and Hydro.

Eisenbeiß G. (1996): *Solar Thermal Power Stations - solar thermal power is the bigger brother of photovoltaics*, EUROSUN '96.

Eyre N.J. and L.A. Michaelis (1991): *The Impact of UK Electricity, Gas and Oil use on Global Warming*. AEA Environment and Energy Report AEA-EE-0211, September 1991.

Fisch M.N. (1993): *Solar Thermal Energy in Ulmann's encyclopedia of Industrial Chemistr, 5th edition*. VCH Verlaggsgesellschaft mb, Weinheim.

Grasse W. (1992): *Solar Power and Chemical Energy Systems: Report on Activities and Results 1989-1991*. Deutsche Forschungsanstalt fur Luft- und Raumfahrt Report, Almería, May 1992.

Haeger M., Meinecke W. and Cordes S. (1994): *PHOEBUS Technology Progamme Solar Air Receiver: Operational Experience and test Evaluation of the 2.5 MW Volumetric Air Test Facility at the Plataforma Solar de Almería*. Presented at the 7th symposium on Solar Thermal concentrating technologies, Moscow, 26-30 September 1994.

Heliotech (2000): http://www.heliotech.dk/industrial/stpp-info/stpp-info-index.htm.

Holl R.J.(1989): *Status of Solar-Thermal Electric Technology*. Electricity Power Research Institute, report EPRI GS-6573, December 1989.

IEA (1998): *Benign Energy?, the environmental implications of renewables*. published 10/1998, ISBN 92-64-16183-X.

Jiménez M.D. (1995): *Pataforma Solar de Almería: Annual Technical Report*. PSA-TR03/95-MS, Almería June 1995.

Kelly B.D. and P. De Laquil (1989): *Solar Central Receiver Technology Advancement for Electric Utility Opertions*. Summary Report, Bechtel National Inc., December 1989.

Klaiß H. and F. Staiß (1994): *Systems Comparison and potential of Solar Thermal Installations in the Mediterranean Area.* Cited in Solar Thermal Power and Solar Chemical Energy Systems. The Franklin company Consultants Ltd., Birmingham, September 1994.

Laquil, de, P., D. Kearney, M. Geyer, and R. Diver (1993): *Solar-Thermal Electric Technology*. 'Renewable Energy: Sources for Fuels and Electricity', edited by T. Johansson et al, Island Press, Washington, pp 213-297.

Léon J., et al (1994): *Design and First tests of an Advanced Salt Receiver Based on the Internal Film Concept*. Presented at the 7th symposium on 'solar concentrating technologies', Moscow, 26-30 September 1994.

Nitsch T., et al (1991): *Systems Comparison and potential of Solar Thermal Installations in the Mediterranean Area (Phase I)*. Solar and Hydrogen Energy Research Centre, Badem Wurtemberg (ZSW), Stuttgart, 1991.

Pharabod F. and C. Philibert (1991): *LUZ Solar Power Plants: Success in California and World-wide prospects*. Report produced for the IEA by Deutsche Forschungsanstalt Fur Luft- und Raumfahrt e.V., July, 1991.

SBP (1999): Schlaich, Bergermann and Partners, http://www.sbp.de/en/fla/index.htm.

Schlaich J. and Robinson M. (1995): Solar Chimney, Axel Menges GmbH, ISBN 3930698692, http://www.argonet.co.uk/users/bobsier/sola6.html.

Schmitz-Goeb M. and G. Keintzel (1996): *The Phoebus Solar Power Tower.* EUROSUN '96.

Shilo D. and J. Er-el (1995): *ENERGY 95 - energy in Israel: data, activities, policies and programs, ministry of energy and infrastructure.* Jerusalem, 1995.

Stine W.B. and M. Geyer (2001): Power from the sun - web book, http://www.powerfromthesun.net/book.htm.

SUNLAB (2001): http://www.energylan.sandia.gov/sunlab/documents.htm. Solar Power Towers, update 2001.

Technion : http://www.technion.ac.il/technion/dimotech/sharav.html.

WEC (1993): *Renewable Energy Sources: Opportunities and Constraints 1990-2020*. World Energy Council, London 1993.

Zaslavsky D. (1997): *Solar Energy without a collector for electricity and water in the 21th century*. A key note lecture at the 8th Sede Boqer Symposium on Solar Electricity Generation, Technion - Israel Institute of Technology, 3-5 November Haifa 1997.

Zaslavsky D. (1999): *Energy Towers for Producing Electricity and Desalinated Water*. A presentation prepared for the inter-ministry committee for renewable energy, Technion, Israel Institute of technology R9901, Haifa, 14-1 1999.

Zwin M.J. (1997): *Energy Towers pros and cons of the Arubot Sharav alternative energy proposal*. Arava Institute for Environmental Studies, Kibbutz Ketura, Israel, January 1997.

APPENDIX A

Table A.1 *Summary of potential environmental burdens for solar thermal electric schemes*

BURDEN	RECEPTOR	IMPACT	RANGE[3]	PRIORITY
Resource extraction[1]	various	Emissions/noise/etc.	L/R/G	Low
Resource transportation[1]	Various	Emissions/noise/etc.	L/R/G	Low
Materials processing[1]	Various	Emissions/noise/etc.	L/R/G	Medium
Component manufacture[1]	Various	Emissions/noise/etc.	L/R/G	Medium
Component transportation[1]	Various	Emissions/noise/etc.	L/R/G	Low
Construction[1]				
Construction activity/road traffic	Various	Atmospheric emissions	Local	Low
Road construction		Increased local access	Local	Low
Emissions				
Various	Various	Atmospheric emissions	L/R/G	Medium
Amenity				
Noise (including road traffic)	General public	Noise amenity	Local	Low
Visual intrusion	General public	Visual amenity	Local	Low
Ecology				
Noise/construction activity	Ecosystems	Disturbance	Local	Low
Land use/excavation	Ecosystems	Loss of habitat	Local	Low/medium[2]
Occupational health				
	Workers	Accidents	Local	Low
	Employment	Increased employment benefits	Local	Low
GENERATION				
Emissions				
Operational	Water body	Thermal pollution and concentration of compounds	Local	Low/medium[2]
Accidental releases	Water body/soil	Discharge of pollutants	Local	Low/medium[2]
Amenity				
Noise	Residents/Others		Local	Low
Visual impact	Residents	Visual intrusion	Local	Low
	Travellers/Others	Visual intrusion	Local	Low
Occupational health				
Reflected light	Workers	Eyesight injuries/blindness	Local	Low
Releases of heat transfer medium	Workers	Health impact	Local	Low
Employment	Workers	Increased employment benefits	Local	Low
Ecosystems				
Land use	Ecosystems	Loss of habitat, disturbance	Local	Low/medium[2]
DECOMMISSIONING				
	Various	Emissions/noise/etc.	Local	Low

[1] The impacts from the stages of resource extraction, transportation and component manufacturing are not detailed separately here. The atmospheric emissions from these stages are presented in Section 7.1.
[2] Depending on location and size of scheme.
[3] L = local, R = regional, and G = global.

Summarising the information in Table A.1 it is clear that the main environmental implications for solar thermal power systems are related to thermal or chemical pollution of water bodies and the loss of habitat. The threat of thermal or chemical pollution can be minimised by implementing extensive safety regulations and good operating practice. The loss of valuable habitat can be minimised by not building solar thermal power plants in ecologically sensitive areas and the reestablishment of local flora and fauna after the construction of the plants, and after the decommissioning of the plants.