Non-nuclear and non-fossil energy resources and their possibilities for future power generation

Nichtnukleare und nichtfossile Energiequellen und ihre Rolle für die zukünftige Energieversorgung

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1. Introduction

The multiple uses of energy in industry and in households result in a rigid correlation between energy consumption and the gross national product. The long-term availability of energy resources is therefore one of the basic preconditions for economic policies aimed at increasing the gross national product or at holding it constant.

The energy resources which we have been using so far originate primarily in solar radiation. The fossil fuels mineral oil, coal and natural gas, which jointly cover more than 90% of the current power consumption throughout the world (8000 million tons coal equivalent per year), were formed by photosynthesis. The formation times of these energy resources were of the order of millions of years, whereas we are consuming them at an incommensurably faster rate. This means that the still available fossil energy resources may become exhausted within a few decades.

Extensive model studies [1] have shown that, owing to the high development level already achieved, nuclear energy is the only source of energy capable of replacing mineral oil and natural gas to a sufficient extent. This means, however, that the utilisation of other primary energy resources, and the development of new technological means for this utilisation, can no longer be motivated by an increasing general shortage of energy. This utilisation and this development will only be justified in future if they fulfil one or more of the following preconditions:

- possibility of economic utilisation,
- reduction of the load on the environment,
- increase in regional security of supply.

It is against this background that we shall discuss below the importance of geothermal energy, of tidal, wind, wave and glacier energy and of the heat stored in the oceans as potential energy supply sources for the future. Owing to the paucity of current knowledge in these areas, we are able to present here only very preliminary opinions and estimates. A more firmly based assessment of these energy resources will only be possible after the completion of a study recently commissioned by the Federal Ministry for Research and Technology (BMFT), on which we are engaged at present.

2. Energy flow-chart of the Earth

The energy resources available for human use can be classified as follows:

a) the chemical and nuclear energy stored in the outer part of the lithosphere and in the oceans;
b) the energy flow reaching the Earth from space, chiefly in the form of continuous radiation of the Sun;
c) the kinetic energy of the Earth and Moon;
d) the thermal energy of the interior of the Earth.

These energy sources and the energy flows which they cause on Earth are illustrated schematically in Fig. 1.

The solar power radiated to the Earth amounts to $1{,}78 \times 10^5$ TW and is by far the largest continuous regenerative energy source on Earth. The energy radiated by the Sun to the Earth is about 24 000 times as large as the current worldwide power consumption. About 33% of this energy is reflected back into space directly by the atmosphere, and a further 45% is radiated into space by the Earth surface in the form of heat. The remaining part is consumed mainly in maintaining the water circulation cycle and the atmospheric and oceanic currents. Only about 1‰ of the solar energy radiated to the Earth is converted into chemical energy by photosynthesis. The energy flows caused by the tides and by geothermal energy are smaller than the solar radiation energy by factors of over 10^4 and over 10^3 respectively.

3. Geothermal energy

Geothermal energy, known since antiquity, is at present increasingly the subject of discussions and studies. For example, an international research group under American leadership is trying to promote the development of small geothermal power stations in the rating range from 500 to 3500 kW with the dual aim of

- supplying electric power to remote areas normally cut off from the rest of the world, and
- improving regional security of supply [2].

Japan is also trying to develop its geothermal energy resources, also in order to improve security of supply [3].

Geothermal energy sources are usually found in volcanic areas where the magma comes close to the surface of the Earth. Geological conditions favourable for a geothermal energy source (Fig. 2) are found when the magma inclusion is enclosed in water-impermeable rock surrounded by porous rock, with a further semi-permeable layer on top. In such cases water which had earlier percolated into the porous rock becomes superheated by the heat from the magma. If such a reservoir filled with superheated water and steam finds an outlet to the surface through a natural vent or a man-made borehole, steam under high pressure will escape and can be used as a source of energy.

The total potential of geothermal energy on Earth, down to a depth of 10 km, is estimated at 111 000 TWh [4]. At a conversion factor of 0,25 this energy store would be sufficient to generate 28 000 TWh of electric power. Assuming an exploitation time of 50 years, this would require an average installed electric power plant capacity of 64 GW. According to American proponents of geothermal power, however, the known geothermal energy resources can be substantially increased by systematic exploration. In the Federal Republic of Germany the BMFT has commissioned the Federal Geological Research Establishment in Hannover to prepare studies for the utilisation of geothermal energy in West Germany.

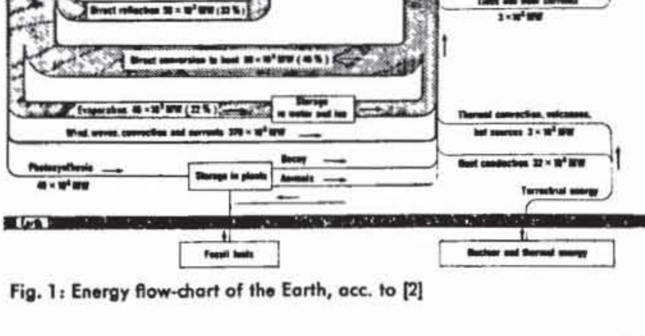

Fig. 1: Energy flow-chart of the Earth, acc. to [2]

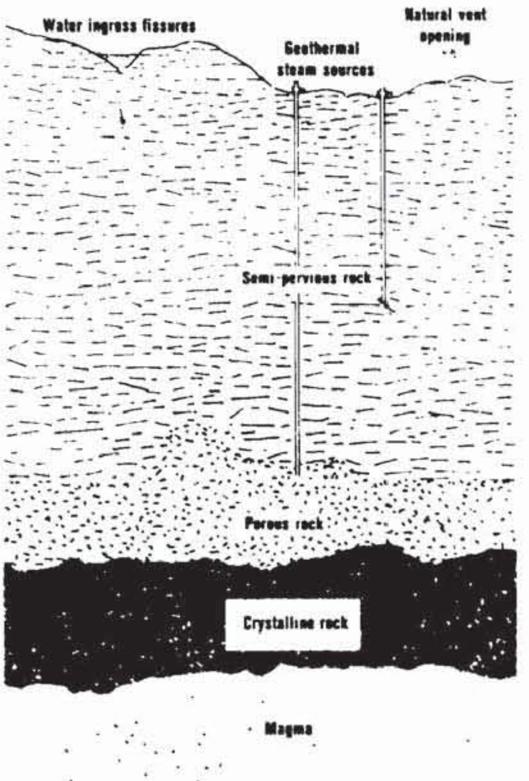

Fig. 2: Geological setting of a geothermal energy source, acc. to [5]

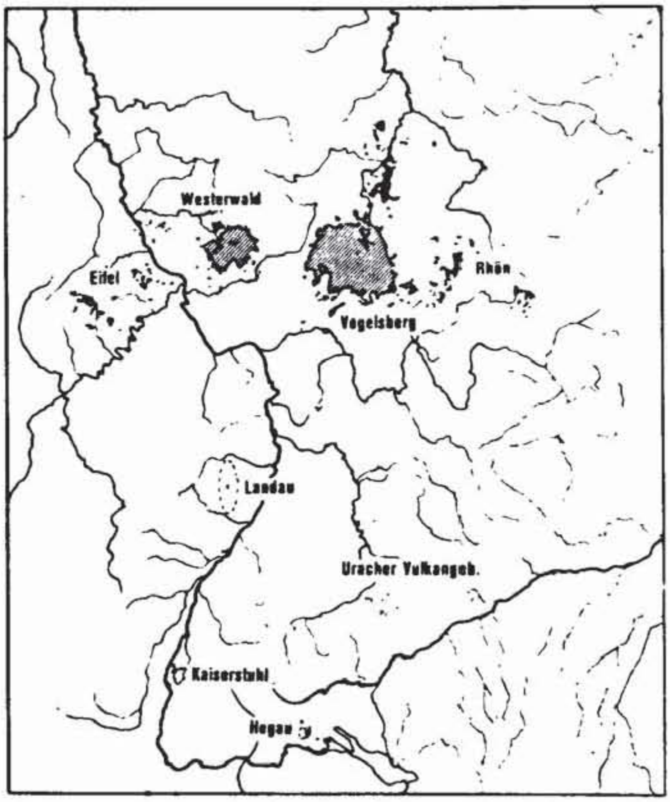

Fig. 3: Presumed reservoirs of geothermal energy in the Federal Republic of Germany, acc. to [7]

Possible exploitation regions are shown in Fig. 3 [5]. A summary of the existing geothermal electric power generating capacities throughout the world is shown in Table 1 [6].

The sources available for geothermal power plants can be classified in three groups:

- dry steam sources,
- wet steam sources,
- hot water sources.

Table 1: Installed capacity and electric power generated by geothermal power stations in 1970

Country	Installed capacity 1970 MW	Generated electric power 10^3 MWh
Iceland	2,6	12
Italy	402	2725
Japan	31	243
Mexico	4	
New Zealand	192	1185
USA	84	525
Total	715,6	4690

Table 2: Data of the geothermal power station in Larderello, Italy

Power units	3 x 14,5	MW
	2 x 11	MW
Total installed capacity	65,5	MW
Steam flow rate	580	t/h
Steam condition	207	°C
	5	ata

The steam flowing out of a dry steam source can be used directly for driving turbines. Typical data for such a power plant are summarised in Table 2 [7]. These data relate to an existing plant in Larderello in Tuscany, Italy. This is the location where the first geothermal power plant in the world was commissioned in 1904. Owing to the steam condition of only 207 °C and 5 ata, which is quite poor by modern power plant standards, the overall efficiency factor of the plant is only 15 %.

In wet steam sources the water is contained in the underground reservoir in liquid form, under pressure, at temperatures of the order of 180 to 370 °C. As the water flows out upwards it is converted into a water-and-steam mixture with some 10 to 20 % of steam by weight. The steam is used to drive a turbine. Various uses have been suggested for the hot water, e.g., heating and air-conditioning or generation of drinking water. Owing to the transportation problems involved, these utilisation possibilities can only be of very limited regional importance.

The hot water sources offer the technically least favourable possibilities of utilisation of geothermal energy. The water flows out under atmospheric pressure and at a temperature of between 50 and 80 °C. This water cannot be used directly to drive a turbine, although various indirect utilisation methods are possible in principle. For example, the working medium could be a liquid with a low boiling point, such as freon or isobutane, heated by the hot water in a heat exchanger. Solutions of this kind, however, are hardly relevant from the practical point of view because of the low efficiency factor and of the high costs involved.

A suggested novel method for the exploitation of geothermal energy is based on using hot rock, at a temperature of about 300 °C, for heating water. With this method it is proposed to drive two parallel boreholes, close to each other, into an appropriate layer of hot porous rock. Water under pressure could then be pumped down one borehole and would return to the surface through the second borehole in the form of steam. If this method proves to be practicable it would make it possible to exploit geothermal sites which have no natural reservoirs of water.

Table 3: Power generation costs of geothermal power plants

Power station	Installed capacity MW	Power generation costs in mils/kWh acc. to 8
Namafjall Iceland	2,5	2,5
The Geysers California	81	4,81
Wairakei New Zealand	192	5,14
Larderello Italy	390	2,38

Table 4: Power output potential and possible yearly power generation rates of tidal power stations

Location or region	Mean power output potential GW	Possible yearly power generation rate TWh
North America Bay of Fundy (9 locations)	29	225
South America Argentina San José	5,8	51,5
Europe Britain Severn estuary	1,68	14,7
France (9 locations)	11,1	97,8
USSR (4 locations)	16	140,4
Total	63,6	559,4

Table 3 [8] shows that the costs of electric power generated from geothermal energy are quite low. The power generation costs in conventional power plants range from 1,8 to 3,5 pfennigs per kWh. Such direct comparisons, however, may be misleading for various reasons. Firstly, the power generation costs drop with increasing power unit size; this factor is in favour of fossil-fuel-fired and of nuclear power plants. Secondly, these latter power plants can be sited at convenient locations, whereas the location of a geothermal power plant is dictated by the location of the energy source; this will usually result in higher power transmission costs. Thirdly, geothermal power plants present certain environmental problems, discussed below, the elimination of which may be quite expensive in relation to the amount of electric power generated by such plants.

In considering the environmental consequences of exploitation of geothermal energy the following points should be borne in mind:

- The low efficiency factor results in a high rate of dumping waste heat into the environment.
- The steam flowing out of geothermal sources contains chemical and solid state impurities which cause not only corrosion problems but also environmental problems.
- The steam condensate contains various proportions of sulfur, ammonia and boron; this condensate cannot be released into surface waters without cleaning because these substances are poisonous for fish and/or plants.
- The hydrogen sulfide contained in the steam creates an obnoxious smell in the environment.
- Long-term withdrawal of water from underground reservoirs may result in subsidences.

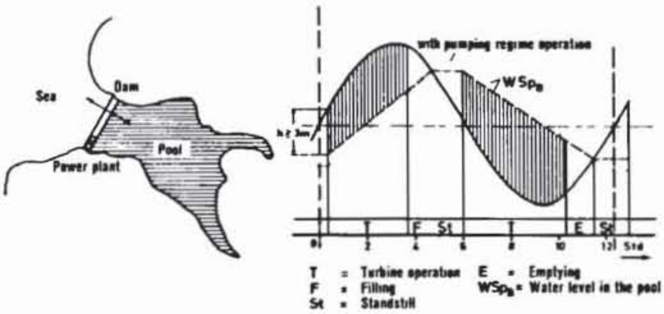

Fig. 4: Operating scheme of a tidal power station

The solution of these environmental problems requires installation of appropriate cleaning facilities. It may be necessary to pump the liquid wastes back into the underground reservoir. If this back-pumping proves to be practicable it might also solve the subsidence problem mentioned above.

4. Tidal energy

Tidal energy, like solar energy, is a permanent source of energy.

Utilisation of tidal energy is based on closing off natural coastline bays with dams, thus creating pools the water level in which differs from that on the seaward side of the dam. This water level difference can be used to drive water turbines as the tide flows in and also as it flows out. The energy that can theoretically be gained by this method is estimated to range from 2,6 to 3,0 TW. This rate of energy dissipation corresponds to about 40 % of the current worldwide rate of power consumption. The possibilities of practical exploitation of tidal energy, however, depend on a large and constant tidal range. The condition of constancy cannot be satisfied owing to the perturbing influence of the sun. The magnitude of the tidal range, on the other hand, depends on local geographical conditions, in particular, on the area and the depth of the basin considered and on the width of the inlet opening. Under favourable conditions which, however, are found only at a few locations on Earth, the spring tide range may exceed 15 m, whereas in the open sea the tidal range is usually less than 1 metre.

Table 4 [9, 10] lists the most favourable locations for the exploitation of tidal energy, their power generation potential and the possible yearly power generation. The total power generation potential at these locations, amounting to about 64 GW assuming full utilisation, is only about 0,75 % of the current worldwide rate of power consumption.

Although large tidal power plant projects have been discussed on and off for some 50 years, the first tidal power plant was only commissioned in 1966 in the Rance estuary in France. The tidal range at this location varies between 3,3 and 13,5 m, average 8,4 m. The plant has an installed capacity of 240 MW, scheduled for extension to 320 MW.

The mode of operation of a tidal power plant is illustrated in Fig. 4 [11]. The hatched areas show the difference in water levels inside and outside the dam. It is typical of a tidal power plant that power generation is interrupted twice daily despite pumping regime operation. Moreover, the average duration of tides is not 12 hours but 12 hours and 25 minutes. As a result, the period during which power generation is interrupted is shifted by 50 minutes per day and therefore coincides at times with peak load periods. This is a serious drawback of tidal power plants.

Considered overall, the potential of exploitable tidal energy is too small to be of significance for the worldwide power needs. This applies particularly to West Germany because of the small tidal ranges along the German coasts.

5. Wind energy

A small part of the energy radiated by the Sun to the Earth is converted into kinetic energy of the atmosphere. The data on the exploitable wind energy potential vary considerably. For the USA the maximum electric power generation by wind power stations is estimated at $1{,}5 \times 10^3$ TWh/a. This is about 7,5 % of the current power consumption rate in the USA.

The technical implementation suggestions range from small facilities down to 100 kW to large wind power plants up to several GW, depending on whether the projects are aimed at local or at general needs. The main problems affecting the economics of wind energy exploitation are posed by:

- the low energy density, and
- the temporal fluctuations of the wind intensity.

The first problem can be partly overcome by an appropriate choice of location of a wind power station, i.e., geographic location, natural high points, man-made towers, etc. The choice of location can also improve to some extent the steadiness of the available wind power, but a large part of the natural wind fluctuations will still have to be accommodated by storage facilities and other design means. The studies carried out so far indicate, however, that utilisation of wind energy is technically feasible [12]. Recent developments in the areas of control, rotor design (glass fibre) and tower construction open possibilities of economically competitive power generation. For example, *Golding* estimates that the power generation costs of a British 50 kW wind power plant will amount to only 1,5 pfennigs per kWh [13]. Such data, however, depend decisively on the kind, size and location of the power plant and are not necessarily valid for West German conditions.

Exploitation of wind energy seems to entail no detrimental effects on the environment. The main problem seems to be the integration of the irregular contribution by the wind into the power supply system.

6. Wave energy

Wave energy is another indirect form of solar energy. The combined action of wind and solar radiation on the sea surface causes waves with a period of a few seconds and of varying amplitudes. These amplitudes are generally too small for the direct utilisation of this kinetic energy. For the generation of electric power, therefore, the large-volume low-amplitude wave motion is converted into a high-head small-volume flow which makes it possible to drive a water turbine with reasonably small dimensions. This can be done on the hydraulic ram principle, with a large area piston driving a small area piston, thus amplifying the pressure in the ratio of the two piston areas. The working medium on both sides is water. The periodic wave energy fluctuations on the primary side can be compensated by appropriate buffering capacity on the secondary side, thus making it possible to run a turbine on a quasi-steady regime. According to estimates by *H. Kayser* [14] a wave power generator of 2 m diameter, driven by waves of a mean amplitude of 2,5 m and a period of 7 seconds, can generate about 1 kW of electric power at an assumed overall efficiency factor of 70 % (Fig. 7).

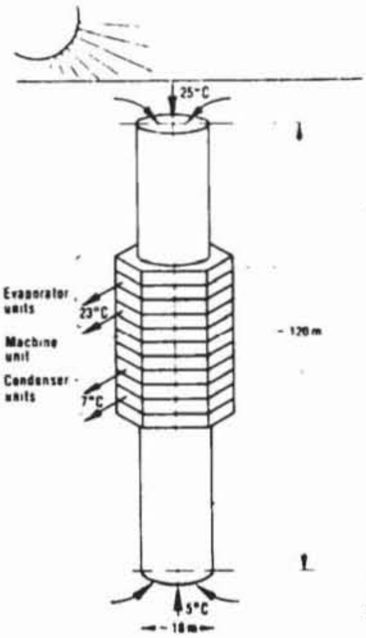

Fig 6 Artist's impression of an oceanic heat power plant

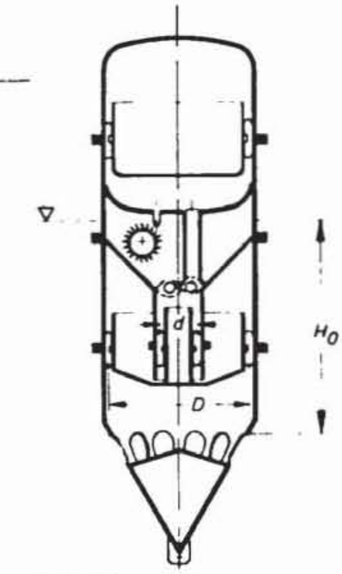

Fig 7 Scheme of a wave power generator

Another possibility of exploitation of wave motion is presented by surf on beaches. In this instance also a hydraulic intensifer is required to boost the low pressure difference. The surf impinges on a flexible membrane and the pressure surge is transmitted to a second medium. A surf generator developed in the USA is said to be capable of generating about 22 MW electric power over a length of beach of 1 mile and a wave height of 1,35 m, increasing to 147 MW for a wave height of 3,3 m.

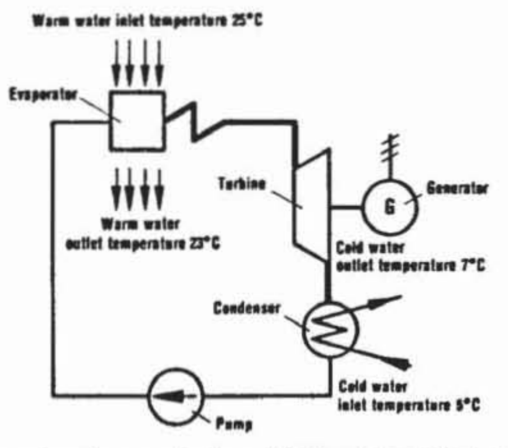

Fig. 5: Ammonia cycle process for the exploitation of oceanic heat, acc. to [15]

7. Ocean heat

The oceans are one of the largest storage reservoirs of solar energy. *Zener* [15] estimates that the energy stored in the tropical oceans alone would be sufficient to supply the world population of 6000 million people anticipated in the year 2000 with power at the same per capita rate as that consumed in the USA in the year 1970. These estimates are based on a cyclic process using as working medium ammonia or some other appropriate liquid with a low boiling point, such as freon or butane (Fig. 5). The cycle would utilise a temperature differential of about 20 K, with the working medium being heated to about 25 °C by the warm surface water.

The partial components of such an oceanic thermal power plant are sufficiently well known. Economic difficulties arise, however, because of the very low Carnot efficiency factor of only 3,3 % [15]. The flow rate of seawater through the evaporators of a 100 MW power plant would have to be of the order of 700 m^3/s [16]. Assuming a judicious choice of location, part of the kinetic energy required to maintain this flow could be supplied directly by oceanic currents, but this would certainly result in problems of anchoring the plant. Whatever the answer, the solution of these problems entails increased power plant costs. Optimistic estimates, based on a buoy-like arrangement of evaporators, turbine and condensers (Fig. 6) and anchoring the system in 60 m depth (pressure equilibration) result in total power costs of about 1 pfennig per kWh [17]. This, however, does not take into account the costs of transmitting this power to the consumers.

The problem of power transmission is the most important obstacle to economic exploitation of oceanic heat on a large scale. Consideration should also be given to the consequences of cooling the superficial and heating the deeper water layers. The cyclic process described above, however, is only one of several possibilities of exploiting oceanic heat. For example, a study should be carried out on whether oceanic heat can be used for desalination in an open seawater cycle.

8. Glacier energy

About 1 % of the total quantity of water on Earth is stored in the form of ice in the polar regions and on high mountains. Disregarding the large polar ice masses, most of the remaining ice is found at considerable altitudes above sea level. This bound water is thus a store of potential energy, also originating in solar energy.

The use of the energy of melt water has been limited so far to locations in moderate climatic zones suitable for the construction of hydroelectric power stations. Concepts have also been put forward, however, envisaging collection of melt water in natural or artificial retention pools on the surface of glaciers. *H. Stauber* [18] has suggested this method for glacier power plants in Greenland. Greenland is suitable for the operation of glacier power plants because of its massive glaciers located at high altitudes (up to 3000 m) above sea level. The melt water forming in the summer months would be collected, by means of an extensive system of canals, in retention pools artificially formed on the surface of the glaciers. From there the water would flow to power stations located on the coast. *Stauber* estimates that by using only the yearly precipitation, i.e., without depleting the glacier reserves, it would be possible to generate in 10 large glacier power stations between 900 and 1800 TWh per year, i.e., about 1,4 to 2,8 % of the current worldwide power consumption. This power would then have to be transported to Europe or to North America over a distance of about 2500 km.

9. Solar energy

The discussion presented below is concerned mainly with new methods for the conversion of solar energy on an industrial scale. For this reason this discussion is not concerned with conventional uses of solar energy, e.g., for heating water or for desalination, or with recent work on photosynthesis.

The biological photosynthesis rate is too low for industrial uses.

The methods for the conversion of solar energy, discussed at present in the literature, include

- photo-electric methods,
- thermal methods.

The most important component of systems for the photo-electric conversion of solar energy is the solar cell the reliability and functional capability of which have been proven over many years in space technology. The efficiency factors already achieved are of the order of 10 %, the theoretical limit is about 25 %.

The fundamental problems involved in industrial utilisation of solar energy can best be illustrated by considering the following hypothetical power plant concept:

A power plant with an electric power rating of 1000 MW is to be built in an equatorial desert zone where the yearly mean solar energy flux density is 320 Wm^{-2} (the yearly mean value for the Earth is 157 Wm^{-2}). Assuming an efficiency factor of the solar cells of 10 %, the collector surface area required is 31,25 km^2. If the power output of 1000 MW is to be supplied continuously, then gigantic power storage facilities are required for smoothing out diurnal variations and bridging over cloudy periods.

This shows that a solar cell power station would require

- a large surface area,
- large capacity power storage facilities.

Quite apart from the technical problems involved, this would entail enormous investment costs; for example, the cost of the solar cells alone is estimated at 13 000 dollars per m^2 [19, 20]. In addition, an equatorial location would entail transport of the generated power over thousands of kilometers to the main consumption centres.

The day/night cycle and the low solar energy flux density on the surface of the Earth lead to the concept of extra-terrestrial exploitation of solar energy by installing a solar energy converter in a geostationary orbit (Fig. 8). The electric power generated in the collectors is converted into microwaves which are beamed to the Earth by directional antennas. Assuming an overall efficiency factor of 2,6 %, a plant with an electric power rating of 5 GW would require a collector surface area of 51 km^2.

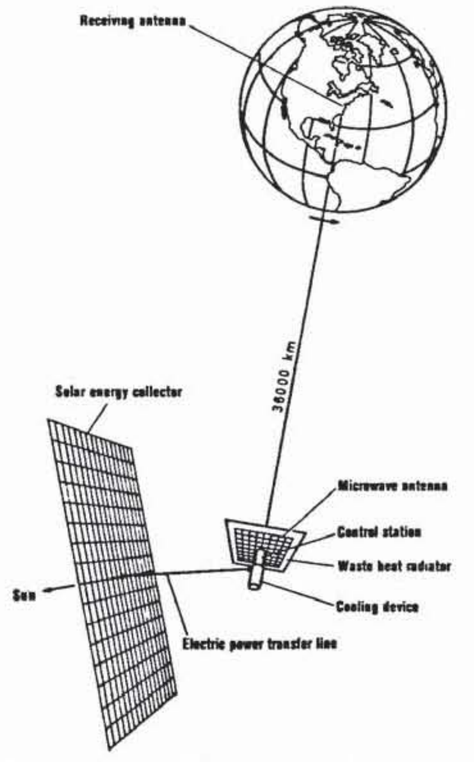

Fig. 8: Principle of extra-terrestrial exploitation of solar energy. 1 Receiving antenna; 2 Solar energy collector; 3 Microwave antenna; 4 Control station; 5 Waste heat radiator; 6 Cooling device; 7 Electric power transfer line

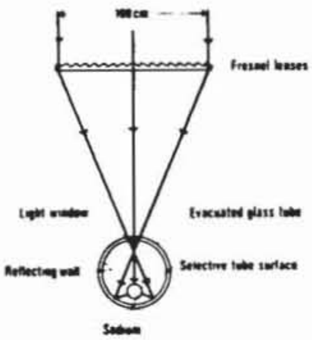

Fig. 9 · Solar energy collector. 1 Fresnel lenses; 2 Light window; 3 Evacuated glass tube, 4 Reflecting wall; 5 Selective tube surface; 6 Sodium

Another concept for the utilisation of solar energy, based on heat, has been put forward by *A. B. Meinel* [21]. For this concept to be practicable economically it is necessary to achieve a high efficiency factor in the conversion of radiation energy into high temperature heat. Meinel therefore proposes a selective surface absorbing short-wave solar radiation and reflecting long-wave radiation. The principle of such a solar energy collection and conversion system is illustrated in Fig. 9. The solar radiation is focussed by Fresnel lenses and passes through a window into an evacuated tube with a reflecting inner surface. Inside this evacuated tube is a second tube with a selective outer surface. The thermal power generated in this tube at a temperature of about 500 °C is removed by a flow of liquid sodium.

It may be stated in summary, that solar energy is a gigantic source of energy. For its practical exploitation on an industrial scale, however, the following problems must still be solved:

- A practical and economic concept must be developed for compensating the seasonal and diurnal variations of the intensity of solar radiation, in order to satisfy power grid requirements.
- The efficiency factor of solar cells must be increased in order to reduce the collecting surface areas.
- The capital costs must be reduced, because they will be decisive for whether a solar power plant is ever built.

10. Prospects

It must be stressed that the assessment of the exploitation possibilities of the energy resources discussed in this paper requires further studies. With this proviso, the situation can be provisionally summarised as follows:

The total potential of known geothermal steam sources is only 64 GW. Geothermal energy could therefore only make a significant contribution to covering the worldwide power needs if we succeed in exploiting dry geothermal reservoirs. The development of the necessary technology, particularly of deep drilling will certainly require considerable efforts.

Exploitation of tidal energy is limited to a few geographically favourable locations. The power generation potential at these locations is only about 64 GW. An important drawback of tidal power is discontinuous power generation.

Large scale exploitation of wind, wave and glacier energy, and of ocean heat, requires solution of a number of technological problems. The economic feasibility of the exploitation of these energy resources cannot be assessed until some at least of these solutions are known.

All the energy resources discussed above, except wind energy, are location-bound. Their exploitation would therefore entail transporting power to consumer areas, often over thousands of kilometres.

The environmental effects of exploitation of these energy resources are to some extent of a qualitatively different nature from those of operation of fossil-fuel-fired and of nuclear power plants. The scanty knowledge in this area often results in these effects being underestimated. In any case, however, it would be deliberately misleading to postulate that any form of power generation is possible without some detrimental effects on the environment.

It may be stated in conclusion that, owing to their small potential or to the as yet insufficiently advanced technological development, none of the energy resources discussed in this paper can make a significant contribution to the solution of middle-term energy supply problems, i.e., to a rapid replacement of mineral oil and natural gas.

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