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NEW SOURCES OF ENERGY AND ENERGY DEVELOPMENT

REPORT ON THE UNITED NATIONS CONFERENCE ON NEW SOURCES OF ENERGY

Solar Energy - Wind Power - Geothermal Energy

Rome, 21 to 31 August 1961

UNITED NATIONS

Department of Economic and Social Affairs

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Page 32, right-hand column:

Delete the second paragraph As regards medium-size plants ... possible output. Substitute the following text:

As regards medium-size plants used as isolated units or in combination with conventional power sets for community purposes, experience is small to date. The most outstanding case and lesson appear to be presented by Denmark (W/1), where plants in this category have long been used and run by co-operatives. The number of plants there reached peaks of 120 in 1918 and eighty-seven in 1943, during the fuel import blockades. A few have since been converted to big alternating current generators. The cost of power from the Second World War plants is indicated to be five mills per kilowatt-hour or less and this applies also to a plant built at Askov in 1929 and still running, but present replacement costs would probably treble this figure.

With wind electric plants of medium size, only limited battery storage can be envisaged and combination with some type of stand-by plant may have to be provided. This situation calls for a careful consideration of the nature and types of load demand, distinguishing between uses which are essential and must be continuous, uses essential only at certain times and uses which can coincide with intermittent supply. The economy of wind-generated power, the minimization of battery storage and the best combination with a stand-by plant all depend greatly on this consideration and on thorough planning from the outset. The actual operation of this system to achieve optimum economy and the most effective utilization of the intermittent output may be facilitated by an automatic load distributing device such as that described by Walker (W/18), who arrives at a cost estimate of about 42 to 56 mills per kilowatt-hour for a fully automatic system and much less for semi-automatic operation with semi-skilled maintenance.

The large wind power plants are necessarily limited to use in connexion with electrical networks, fed by thermal or hydro-power plants, and usually have the primary role of reducing fuel consumption or conserving water (by reducing the flow out of or pumping water back into reservoirs). Since there must always be available reliable capacity to meet the base load, the total permissible capacity of wind power plants in the system is limited. Care must also be taken in the coupling of windmills to the network (W/8), for example, to avoid excessive voltage and frequency disturbance and for this purpose it may be better to have several small rather than a few big wind plants.

The output is absorbed by the network as and when produced. It is interesting to note from Juul's analysis (W/20), for example, that after conversion from direct to alternating current the output of the plants at Bogo and Gedser in Denmark (measured in kilowatt-hours per square metre of area swept) has increased considerably largely because extensive alternating current grids are able to take delivery of a far greater part of the possible output.

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FOREWORD

The United Nations Conference on New Sources of Energy was held in Rome, Italy, from 21 to 31 August 1961 in accordance with resolutions of the Economic and Social Council and on the invitation of the Government of Italy. The venue of the Conference was the headquarters building of the Food and Agriculture Organization of the United Nations.

In approving arrangements for the Conference, the Council requested the Secretary-General, in resolution 779 (XXX), to report to the Council at its thirty-third session on the proceedings and results of the Conference. *New Sources of Energy and Energy Development* is presented pursuant to this resolution.

The report is divided into two parts. The first part reviews briefly the Conference background and arrangements (chapter 1) and summarizes the proceedings (chapter 2); it also reviews in chapter 3 the implications of the Conference and emphasizes lines of action indicated at the international and other levels.

The second part marshals further information of a more technical nature. It provides a systematic synthesis of the papers submitted to the Conference and the related discussions. Following a broad survey setting the framework for the new sources, this part deals with geothermal energy, wind power and solar energy, respectively.

Annexes contain the agenda, a list of chairmen and rapporteurs, a table of registered attendance and lists of papers and authors.

The full documentation of the Conference, consisting of 250 individual contributions and twenty rapporteurs' general reports and summations, will be printed in the near future. These papers will be published in separate volumes. The first volume will contain those on new sources of energy and energy development and on combined use of various energy sources and energy storage problems; later volumes will contain the papers on geothermal energy, solar energy and wind power.

EXPLANATORY NOTES

Symbols of United Nations documents are composed of capital letters combined with figures. Mention of such a symbol indicates a reference to a United Nations document.

Throughout this report, references to "tons" indicate metric tons and to "dollars" United States dollars, unless otherwise stated.

The term "billion" signifies a thousand million.

The designations employed and the presentation of the material in this publication do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations concerning the legal status of any country or territory or of its authorities, or concerning the delimitation of its frontiers.

CONTENTS

PART I

Chapter 1

CONFERENCE BACKGROUND AND ARRANGEMENTS

The formal antecedents of the Conference date from 4 May 1956, when the Economic and Social Council recommended "that the United Nations should display the same interest in all new sources" as it had in the conventional sources of energy and in atomic energy (which was the subject of a companion resolution). It requested, in resolution 598 (XXI), that the Secretary-General submit a report on the practical utilization of new sources of energy, including solar, wind and geothermal energy.

Pursuant to this resolution, the Secretary-General presented a study entitled *New Sources of Energy and Economic Development*[1] which was prepared with the assistance of five specialists. In resolution 653 III (XXIV) of 26 July 1957, the Council asked that a progress report be prepared on further developments in these fields "together with recommendations (for)... an international conference on the new sources of energy other than the atom and their economic applications, to be convened as early as feasible thereafter".

Upon consideration of the progress report,[2] the Council requested the Secretary-General, in resolution 710 A (XXVII) of 17 April 1959, to take appropriate measures within the framework of the United Nations for the convening of a conference in 1961 on solar, wind and geothermal energy with particular reference to their application in the less developed countries.

For purposes of preparation of this Conference three meetings of experts on solar, wind and geothermal energy were held during 1960 in Madrid (23 to 28 May), Grenoble (14 to 17 June) and Rome (27 June to 2 July), during which the final agenda was formulated as well as a series of substantive guide-lines for potential contributors of papers. On 3 August 1960, the Council, in resolution 779 (XXX), approved the arrangements proposed for the Conference to be held from 21 to 31 August 1961 and accepted with appreciation an offer of the Government of Italy to provide host facilities.

The conference secretariat was established within the framework of the United Nations with the appointment of Mr. A. G. Katzin as Executive Secretary. In October 1960 an *Information Bulletin*[3] was issued setting forth the relevant background information, the agenda and procedures, and the substantive guide-lines for participants. Invitations for the preparation of background papers and for attendance were extended on the basis of lists drawn up by the preparatory meetings of experts and the nominations by Member Governments and various organizations.[4]

Of the many individual papers contributed, exactly 250 were accepted, covering the entire range of items in the agenda approved by the Council and representing the experience of participants from twenty-nine countries.[5] The registered attendance of 447 persons was representative of a wide range of professional disciplines and organizational backgrounds and was drawn from seventy-four countries and territories.[6] Specialized agencies of the United Nations, such as the Food and Agriculture Organization (FAO), the International Labour Office (ILO), the United Nations Educational, Scientific and Cultural Organization (UNESCO), the World Health Organization (WHO) and the World Meteorological Organization (WMO), were also represented at the Conference, as was the International Atomic Energy Agency (IAEA). In addition, 267 visitors were registered as accompanying the participants and about thirty correspondents were specially accredited.[7]

In view of the primary concern of the Conference with the needs of the less developed areas of the world, it may be noted that nearly one-third of the participants came

[1] United Nations publication, Sales No.: 57.II.B.I.

[2] *Official Records of the Economic and Social Council, Twenty-seventh Session, Annexes*, agenda item 5, document E/3218.

[3] Document E/Conf.35/1, printed in English, French and Spanish.

[4] While some of the invitations were issued on the basis of recommendations by Member Governments, all participants, including contributors of papers (not all of whom could attend), took part in an individual and personal capacity and not as representatives of their countries.

[5] By country of origin, these contributions were distributed as follows: Australia, 5; Belgium, 1; Brazil, 2; Canada, 2; Chile, 1; Denmark, 6; El Salvador, 3; France, 31; Federal Republic of Germany, 6; Greece, 1; Hungary, 1; Iceland, 9; India, 9; Israel, 8; Italy, 24; Japan, 16; Mexico, 1; Netherlands, 4; New Zealand, 29; Portugal, 1; South Africa, 1; Spain, 3; Sweden, 1; Switzerland, 1; Soviet Union, 4; United Arab Republic, 6; United Kingdom, 10; United States, 57; and Uruguay, 2. Of the remaining five papers, three came from co-authors in Australia-United States, Belgium-Greece and India-United States, respectively, and one each from the Food and Agriculture Organization and the World Meteroological Organization. The predominance of Iceland, Italy and New Zealand in the development of geothermal energy, of Denmark in the use of wind power, and of France and the United States in solar energy is reflected in this distribution. Lists of background papers are given in annexes 4 and 5.

[6] The Conference included fifty participants from Africa (including eleven from Algeria), sixty-one from Asia, including the Middle East, and twenty-four from Central and South America. Ten came from Australasia, sixty-seven from North America and 219 from Europe. (*See* annex 3 for distribution by country of origin.)

[7] The activities of the Conference received world coverage in newspaper articles and through other media. More substantial articles, often written by active participants, appeared in a variety of journals. The participants and correspondents were kept fully informed through a journal called "The Daily Energy" and a series of press releases.

from countries usually included in that category. In line with the emphasis on the participation of these less developed countries, and the need for assistance to enable contributors as well as non-contributors to attend the Conference, United Nations technical assistance fellowships were granted upon government request to forty-seven participants from thirty-two countries or territories.

The Conference adhered closely to the original agenda approved by the Council.[8] Following an introductory general session on new sources of energy and energy development, the proceedings continued in two parallel series of technical sessions. One series of nine sessions was devoted basically to the utilization of geothermal energy, wind power and solar energy for power purposes, including a meeting on the combined use of energy sources and energy storage problems. The other series comprised seven sessions on solar energy for purposes other than power. The discussions of these technical sessions were reviewed and summarized in four plenary sessions.[9]

The Conference was opened by Mr. Philippe de Seynes, United Nations Under-Secretary for Economic and Social Affairs, on behalf of the Secretary-General. His Excellency Signor Egidio Ortona, Director-General of the Department of Economic Affairs of the Italian Ministry of Foreign Affairs, represented the host Government and presided over the opening session. The general session and the closing session were presided over, respectively, by Sir Vincent de Ferranti, Chairman of the International Executive Council of the World Power Conference, and Mr. David Owen, Executive Chairman of the United Nations Technical Assistance Board.

[8] *See* annex 1 for the agenda of the Conference.

[9] Simultaneous interpretation service was provided at all sessions from and into English, French, Russian and the host language, Italian, and various visual aid facilities were provided at technical sessions. However, no verbatim or formal summary records were taken beyond tape recordings.

Twenty-one presiding officers and seventeen rapporteurs were appointed[10] and rendered very valuable service to the Conference. In order to provide the maximum amount of time for discussion by participants within the three-hour limit of each session, individual papers were distributed in advance and were not formally presented by their authors. The rapporteurs introduced the subjects by briefly presenting the contents of the papers and suggesting topics for discussion. Summations of proceedings were submitted by the rapporteurs at the plenary sessions with emphasis on practical applications for the benefit of the less developed countries. Finally, chairmen of the various meetings outlined the main findings and conclusions of the Conference in the closing session.

The Government of Italy arranged special events for the participants during the Conference. Among them was an audience with His Holiness Pope John XXIII at Castelgondolfo on 28 August, during which he spoke on new sources of energy in relation to economic development and social welfare.

A field visit was arranged at the invitation of the Larderello Company to their geothermal installations at Larderello in Tuscany. More than 200 participants took advantage of this opportunity to see these modern plants, which have a net capacity of about 300,000 kilowatts based entirely on natural steam. A novel type of solar power unit, having a capacity of five horsepower, was exhibited just outside Rome by the National Physical Laboratory of Israel. It was the object of another field visit in which over 300 participants took part and it attracted wide attention as a significant advance towards providing less developed areas with effective solar power on a small scale. In addition, a limited number of working models and panels to illustrate use of the new sources were exhibited on the Conference premises.

[10] *See* annex 2.

Chapter 2

GENERAL REVIEW OF PROCEEDINGS

The proceedings reflect the purpose of the Conference: exchange of ideas and experiences in the applications of solar, wind and geothermal energy; consideration of how techniques can be brought into wider use, particularly for the benefit of less developed areas; provision of up-to-date information on progress achieved and on the potentialities' of as well as the limitations in utilizing these three sources of energy, especially in those areas lacking conventional energy sources or facing high energy costs.[1]

USE OF NEW ENERGY SOURCES IN DIFFERENT ENERGY SITUATIONS

The basic assumptions and the framework for the discussions were brought out in the opening session and in the first general session which set the keynote in terms of the scope and treatment of the subject matter. It was noted that the availability of energy in many different forms is a pre-condition for economic development and that in meeting energy needs the different sources of energy had to be carefully distinguished in terms of their special characteristics in relation to each other and to the socio-economic structure in which they are to be developed and used. Thus, in considering the non-conventional sources of energy and their possibilities for development, the alternative energy sources and the state of economic development had to be considered in the context of each region and country or group of countries.

Among the relevant background facts, it was pointed out that the present rate of world energy consumption is about 4 billion tons coal-equivalent per year for commercial energy alone. This does not count agricultural waste, wood and other "non-commercial" sources (an additional 15 per cent), which represent up to half the energy consumption in the less developed continents. It was anticipated that the total would double and redouble by the end of the century. Taken on a per capita basis, the energy consumption was shown to vary greatly throughout the world and in approximate correlation with average income, which provides another indication of the indispensable role of energy in economic development. The low average consumption figures for the developing countries, however, conceal further disparities between large urban areas and rural areas, where some 2 billion people—two-thirds of the world's population—are living without electricity supply and often at a mere subsistence level.

Special attention therefore was drawn to different energy situations which, in the under-developed countries, could be divided into three categories with regard to power supply: the exceptional areas where a grid exists to connect power stations in industrial and urban centres with enough interconnected capacity to guarantee continuity of supply within a limited area, often at a level comparable to that of developed countries; the areas where isolated power stations meet, at least in part, the most urgent power requirements; and the areas—which are the most numerous —where electricity is entirely lacking. This division into three categories came to run as a thread through the Conference. It served a useful purpose in the consideration and evaluation of the new sources not only for power production but also to some extent for other energy utilization.

Broadly speaking, it was concluded that for areas in the first category, those with grid systems and developed energy supply, wind power and solar energy may be unimportant unless cost studies can show that they could provide power and other useful energy at competitive rates, while geothermal energy, if available, might be far more economic than any other source.

In areas of the second category—usually characterized by high fuel and generating costs—solar and wind power might well be useful supplementary sources effecting fuel savings, and geothermal energy, if available and exploitable, would provide cheap energy.

For many of the areas in the third category, which are by far the most typical in the under-developed countries and for which large-scale rural and village electrification cannot be foreseen for a long time, wind or solar energy offer the only prospect of a power supply. And they might become important factors in ameliorating depressed living conditions and in spurring economic change by providing energy for telecommunications, conservation of perishable foodstuffs, water pumping and simple processing and manufacturing.

In this connexion, and particularly with regard to the many possible applications of solar energy, it was noted that in terms of certain broad social objectives the new sources were not limited by the consideration of economic viability as applicable to advanced industrial societies. Nor was it considered necessary that energy development follow the same path as it had in industrial countries. The question was rather one of either providing no energy at all or of providing it even in an imperfect and limited form, to create worthwhile work and productive effort, as judged on the basis of social as well as economic considerations.

It was made abundantly clear that the new sources provided no panacea and were characterized by certain limi-

[1] For an account of the more technical aspects of the Conference and greater detail, *see* the substantive digest and synthesis in part II.

tations in their geographical locations. It was suggested that several obstacles, such as customs, traditions and lack of training, could be overcome, at least in part, through the establishment of demonstration centres, the provision of technical assistance and the improvement and diffusion of knowledge about the availability and the possible uses of the three energy sources.

GEOTHERMAL ENERGY

The possibilities and full significance of finding and utilizing natural steam and hot water from underground sources have not been generally appreciated. The Conference sessions on geothermal energy may well mark a turning point in this regard. It was the first occasion—in terms of people and purpose—where there was a concerted effort to bring together the relevant available knowledge on the subject and thereby open new vistas and interests.

Natural steam is now driving electricity generating plants with a capacity of nearly 400,000 kilowatts, about three-fourths of it in Italy and the rest in new plants in New Zealand, the United States, Mexico and elsewhere. Geothermal energy also heats the homes of some 45,000 people in Iceland and finds many other applications, from chicken hatching in Kenya to process heating in a pulp and paper factory and in the production of salt and chemical by-products. Still, to judge from the proceedings, geothermal applications are only in their infancy and may become highly significant, particularly for power generation in the countries already embarked on this field and in many others now becoming aware of the possibilities and techniques.

One of the most serious limitations to its growing use lies in the fact that little is known of the physical availability of geothermal energy, except where hot springs and other readily apparent surface evidence exists, such as in and around the entire Pacific basin, the Atlantic ridge, the Rift Valley in East Africa and some other areas, usually of a volcanic nature. It was noted, however, that the presence of steam is not necessarily limited to volcanic regions or to areas with surface manifestations. Italy provides a clear illustration of this. It was pointed out that there might be unsuspected geothermal possibilities in many countries which have not so far been studied and which might be assisted to determine whether development was worth while. In fact, great optimism on finding geothermal resources was expressed.

Geothermal energy is found and developed through techniques in many ways similar to, though in some important respects different from, those used in the petroleum industry. These include prospecting on the basis of geological, geophysical and other surveys and the drilling of wells. The applicable prospecting techniques are now well developed but the quantitative knowledge and results in the case of geothermal energy resources are still modest largely because field survey work and drilling, which alone can give final proof, have been undertaken on a very meagre scale. Thus, only some 400,000 metres of wells (one-half of which are in Italy) have been drilled in the search for geothermal energy, as compared with millions of metres drilled for oil every year. The techniques for selecting fields for intensive surveying are not, however, widely known. Accordingly, it was suggested that technical assistance through the United Nations might play a particularly important role in this respect. By aiding in the planning and execution of sound prospecting programming, more effort might be encouraged in areas indicated by general geological knowledge and power needs to have the greatest possibilities.

Once steam wells have been developed there admittedly remains some uncertainty as to their length of productive life. This gives rise to a need for understanding the origin of the geothermal steam. In the discussions on this matter the idea was favoured that much of the steam came from rain water percolating slowly down to the hot rocks and thus replenishing the geothermal sources and giving them a character more similar to hydro-power than to petroleum and other wasting assets. The subject is in need of further research and, along with such research, it was urged that there be a dramatic increase in drilling programmes to enlarge our knowledge and use of this natural resource.

Techniques of utilizing geothermal steam are well developed on the basis of the experience with the many types of power plant now in operation. For new regions one of the most interesting types is the simple monobloc unit. This plant combines a turbine and generator with a capacity of up to 3,500 kilowatts in one easily transportable piece that operates directly on the steam as it comes out of the well and discharges it to the air. Other types in operation are larger and incorporate different steam cycles to get more power out of the steam or to recover chemical by-products. With the exception of Iceland, electric power production is currently and prospectively the most important form in which geothermal energy is utilized. The Icelandic experience suggests that, in some areas, conditions may favour the use of geothermal steam for hot water supply, space heating in homes and industries and various processing applications requiring heat in the 100-300° C. range.

Geothermal power generation, it was concluded, has many attractive features, among them avoidance of boilers and fuel (including imported fuel), continuity of supply, simplicity of plant and low operating costs. Where available, the effective energy can also be extremely cheap, in existing cases giving power in the cost range of from 0.2 to one US cent per kilowatt-hour and thus comparing favourably with any conventional plants. Under favourable conditions, geothermal power can thus compete with energy from any other source and should be attractive to both industrial and developing countries.

The initial costs—for the power plant and especially for the exploration and drilling—are such, however, that in the opinion of the Conference experts, the installation must have a minimum size of about 1,000 kilowatts to be economic. A capacity of this size or larger may be easily absorbed in areas having a grid system or markets developed around isolated plants but would be less easy to introduce in more remote areas at present without electricity. For good economy it is further necessary to utilize the capacity at a high load-factor in order to draw full advantage from the relatively high initial investment and low running costs. Before investments are made in detailed prospection and, of course, before capital is committed to drilling and plant construction in subsequent stages, the possibility of absorbing minimum power has to be given early consideration along with preliminary surveys of surface manifestations and other indications of geothermal resources.

With the existing advanced techniques and the promise of often low power costs, the prospects of increased utilization now depend mostly on an intensification of exploration for geothermal resources. It is quite possible that many countries may, without their knowing it, be sitting on top of significant geothermal resources capable of supplying large quantities of heat and power.

There is no doubt that the work of the Conference will lead to new thinking about the role of geothermal energy in many countries where the necessary potentialities may be present. The achievements and experiences already gained—from California in the west to Kamchatka and Japan in the east and from Iceland in the north to New Zealand in the south—indicate that geothermal resources are a ubiquitous and promising source of energy.

Wind power

The sessions on wind power utilization indicated that there was a revival of interest in this source of energy and in new techniques for harnessing it to productive purposes. Developments were reported from fifteen countries ranging from the consideration of small machines for water pumping and electricity generation, to larger machines (10-15 kilowatts) for remote communities and still larger machines (100 up to some 900 kilowatts at present) for connexion to main power networks. Several participants from less developed countries stressed the value of wind power for up-country areas and in this and other connexions called for assistance with wind surveys, training of technicians, arranging of contacts and experimental installations.

The proceedings were mainly concerned with the most modern and perhaps sophisticated developments and ideas in this field. However, it was recognized that there was still considerable scope for the simple traditional windmills, chiefly for water pumping in under-developed areas lacking rural electrification, as in India where a project is currently under way to install some 200 windmills of domestic design. It was pointed out that in rural areas devoid of electric power, small windmills may well be highly economic and, in any case, their direct and indirect benefits were aspects which often far outweigh the purely economic factor.

Consideration was also given to electric windmills for water pumping and other purposes. With respect to water pumping, for example, it was noted that water wells are usually located in depressions in the topography and hence in places with rather weak wind; but by placing the wind power plants on high windy spots to draw on a much more powerful and steady wind, and by leading electric wires down to motor-driven pumps, the problem could be easily solved and several wells served.

The above example provided one illustration of many of the importance attached to site selection and wind measurements. Attention was called to the usefulness of long-period records collected at meteorological stations. The wind measurements at such stations have not been based on wind power requirements and therefore usually have to be supplemented with wind surveys aimed at practical applications and with special measurements for testing purposes. In this connexion, the need was stressed for more stations, more useful data, standardization of measuring instruments and methods and further research and guidance on criteria for the selection of good wind power sites. An encouraging beginning had, however, been made with wind surveys and other preliminary steps towards a modern, rational utilization of wind power in several countries whose experience was fully reported in the Conference.

As regards the design and operating behaviour of wind power plants, the general feeling was that enough was now known to permit manufacturing and installation in considerable numbers and that design no longer posed fundamental problems or held out prospects of a major technical "breakthrough". The technical advances presented in the Conferences were numerous—such as the use of plastics reinforced with fibre glass to make propellers, streamlining according to advanced aerodynamic theory and many other design innovations in the different parts making up a complete plant—but they were mostly in the nature of refinements for incorporation into future plants to increase efficiency and lower costs.

The technical possibilities of wind power production thus were shown to be well established. They should, however, be distinguished from the economic possibilities. From the economic point of view, the experts insisted, a further distinction should be made between large wind power plants and small machines of less than about five kilowatts which can be used on individual farms and in other small applications. The larger machines would have to be used in areas with a transmission grid system, that is, in industrialized areas, where their justification would have to be made entirely on competitive grounds, such as by saving of fuels. Several machines in this category (about 100 kilowatts) were mentioned, mainly of an experimental nature but approaching a cost goal of $140 per kilowatt and applicable in areas of relatively high fuel costs. Further trials were needed, however, to establish convincingly, or to disprove, the economic viability, under highly competitive energy conditions, of really large wind plants, such as the one currently being tested in France.

Medium-size windmills—in the ten- to fifty-kilowatt range and usually envisaged for operation at the village level in conjunction with diesel or other stand-by units to overcome the intermittence of wind supply—might well be economic as fuel savers and competitive, particularly since, in contrast to diesel units, they do not require constant supervision and maintenance.

Most of the interest, however, centred on small machines for which many possible applications in the less developed areas were mentioned. It was indicated that the cost of power from small machines would obviously be higher than that from larger machines, but in the energy situations under consideration the relative height of power cost was of less importance. In many circumstances, even intermittent supply or only limited battery storage capacity could be tolerated. It was emphasized that the first few kilowatts introduced were the most important, not only in terms of their economic contribution but also in lightening the load of manual labour and improving the conditions of life of the rural population. Small wind powered plants most appropriate for use in villages had much to gain from further research so that the cost of power from them could be lowered through standardization and large-scale series production. This required that the two participants in such developments—the manufacturer and the potential user—be brought together. In this connexion, with a view to greatly increased power utilization, it was suggested that the United Nations act as a "catalyst". It was proposed that, as one approach, the United Nations, in conjunction with interested countries, establish demonstration and experimental centres for both wind and solar energy in different parts of the world.

SOLAR ENERGY

The solar energy sessions took up a major part of the Conference. In their variety they reflected the widespread efforts in this field as well as the numerous possible applications, several of which were considered to be of great importance for the less developed areas. The challenging possibilities and the limitations were fully discussed on the basis of 118 papers by authors from twenty-two countries. The Conference thus became a milestone in the long arduous efforts to attain a practical means of utilizing solar energy in other ways than the long-known traditional techniques of large-scale evaporation and drying in fishing, agriculture and the production of salt from sea-water. Solar technicians have met in many specialized scientific meetings over the years, but these sessions afforded an opportunity to review progress in a different context.[2] The specialists were this time confronted with spokesmen from all over the world representing the potential users. They were thus impressed with the need for the early application of solar energy to meet specific requirements, such as the production of power on a small scale, the manufacture of ice for food preservation, the distillation of water for drinking and the production of other items and services most applicable to the needs of the less developed countries.

In the industrialised countries, solar energy is likely to find application for such purposes as solar furnaces for research, solar power in space vehicles and water heating. But solar energy is likely to find its most important utilization in the less developed countries, according to the consensus of views expressed. Two main reasons were advanced: first, in the foreseeable future solar energy may be regarded mainly as a supplementary rather than as a competitive source of energy particularly suitable in areas lacking conventional energy, and second, the availability of solar energy is most favourable in the belt, between latitudes 40° North and 40° South, in which most of the under-developed countries are located.

The assessment of the availability of solar energy depends on a system of station networks, measuring instruments and the like. The discussions clarified the need for filling the major gaps in the world network of measuring stations which are currently very sparse in the less developed countries as a whole and especially in the arid and semi-arid areas, and the need for special attention to micro-climatic conditions and measurements in conjunction with experimental centres, possibly with village leaders trained to supervise measuring activities with simpler instruments. The conclusions pointed to a two-pronged approach, with the meteorologists taking into account the practical guide-lines from the data users and advising on measuring and interpretation at the application level.

Harnessing the low-intensity energy of the solar radiation calls for more efficient devices and a lowering of the costs of collectors. Since the energy-flux is low, a large collection area is required and the reflecting or flat-plate collector accounts for the bulk of the cost of the useful energy; hence, an increased conversion efficiency reduces the area needed to obtain a given quantity of useful energy. The focus of research is therefore on the problems of raising efficiency and improving the collectors and the several devices which are designed to utilize the solar heat or light. In the discussions, it was pointed out that improved efficiency is in part dependent on the materials utilized and their properties as absorbing surfaces, transparent covers or reflecting surfaces; these are making rapid progress with the advance in materials technology. The efficiency of photovoltaic cells which convert sunlight directly to electricity, for example, has been increased a hundredfold during the past decade. Similarly, significant advances were reported for so-called selective surfaces, which are now more efficient in absorbing heat and holding down heat losses so that costs are cut through a reduction in the collector area. The introduction of new materials, such as specially adapted transparent plastics and aluminized plastic reflecting surfaces, has also contributed towards a reduction in the cost per area unit.

A special session was devoted to advances in new materials and adaptations of classical materials which hold the key to increased utilization of solar energy. Progress is being made mainly as a by-product of the vast research efforts being devoted to space vehicles and other applications but greatly benefiting the prospects of solar energy utilization. Participants expressed great optimism on cost reduction, at the same time pointing to the need for further research on the adaptation of local materials available in the less developed areas where solar energy application holds the greatest potentialities.

Most solar applications are now at the experimental or "pilot-plant" stage. In a few cases they have reached a commercial scale (as indicated below) but further efforts are necessary to bring them into widespread practical use under realistic operating conditions. These efforts call for international co-operation to bridge the present gap between high hopes and actual realization. It is to be noted that research and development programmes in this field are supported by public and private sources in many places and, in most aspects, are on a small scale, with most laboratories working independently and relying on personal contacts and current literature for an exchange of information. For the most part, moreover, research on solar applications is being carried out in countries which have relatively little need for it. The development efforts

[2] The last somewhat comparable gathering was in 1955 at the world symposium arranged by the Association for Applied Solar Energy in Phoenix, Arizona.

thus need to be co-ordinated and strengthened and, for most applications, subjected to practical field testing in areas where conventional fuels are unavailable or expensive and the need for solar energy is greatest. Since solar applications are characterized by relatively high initial investment and low operating costs, they appear to hold the greatest promise in the form of relatively small units which can take advantage of the ubiquitous distribution of the energy and minimize transmission distribution costs.

The needs and possibilities for utilizing solar energy processes obviously have to be assessed in the context of the particular energy situations that prevail in the various regions of the world. This summary of proceedings can deal only in rather general terms with specific applications, their status, current developments and trends, and can emphasize only those applications and aspects indicated by the participants to be of particular importance and promise to the less developed countries. It may be pertinent therefore to elaborate on those uses of solar energy which hold the greatest promise for the under-developed countries, as, for example, for power production and for heating, cooling and distillation.

Power from solar energy

The possibilities of power generation with solar energy was one of the more important points brought out at the Conference, especially in recognition of the potential key role that small power units could play in telecommunications, lighting, pumping and many other purposes for the less developed areas lacking conventional power. Two approaches to solar power generation were discussed, one based on heat engines of more or less conventional types operated on energy from solar collectors, and the other based on direct conversion to electricity through different devices.

Although the production of mechanical and electric power through solar heat engines has long been a goal and many models have been built over the years, little use has been made of solar energy for such power generation. Some novel ideas presented in Rome, notably by Israeli scientists, showed promise of resolving this problem in some measure. The Israeli scientists have developed a small solar-powered electric generating plant in the two- to ten-kilowatt range which incorporates a new turbine operating on organic vapour at unusually high efficiency, a novel type of balloon-like plastic mirror collector and a heat storage system allowing night operation at reduced load. Estimated to cost about $1,000 per kilowatt and to produce power at a cost of $0.05 or less per kilowatt-hour in sunny climates, this type of plant promises to be truly competitive in many locations. A working prototype exhibited at the Conference aroused much interest.

Discussions on other promising techniques revealed some details of a novel type of heating system based on a "solar pond" as a collector of solar energy. Though in an early stage of development, this might, if successful, bring solar power to the megawatt scale at a cost comparable with that of large conventional plants. Another type of heating system considered in the turbine and piston category was one which envisaged a novel use of solar energy in the so-called Stirling (or closed-cycle regenerative gas) engine. Adaptations of solar engines which are being developed at great expense for use in outer space may become practical possibilities but, as yet, there is too little knowledge on which to base projections.

Converting solar energy directly to electricity by means of thermoelectric or photovoltaic devices is another approach receiving perhaps the greatest development efforts under the impetus of space research. While the advantages of direct conversion, which avoids the traditional steam cycle and any moving parts, are its simplicity, silence and dependability of operation, the great limitation is the cost. The devices are expensive so that, except for very small loads such as those used in radio and other communications systems, the application will be very limited unless scientific and technological progress cuts the costs. There is reason to be optimistic: costs have been cut by about two-thirds in the past three years alone.

Possibly the most promising progress has been made in the development of thermoelectric generator systems. These are based on a temperature gradient creating an electric current between two joints of semi-conductor materials in a generator or between a heated cathode and a cool anode in a thermionic converter. Since the heat may be drawn from a focusing solar collector or any other high-temperature heat source, a great deal of work is also devoted to these systems by those interested in the more efficient use of fuels. Small solar-powered generators may thus soon appear on the market for such purposes as water pumping in remote regions, and they should certainly be tried out in experimental centres. Moreover, in these small applications, the solar concentrating collector may also be used at other times of the day for such purposes as solar cooking and the regeneration of the cooling systems of small solar refrigerators.

Considerable progress has been made with respect to the photovoltaic devices which convert sunlight or high-energy photons directly to electricity. More popularly known as solar cells or batteries, their sales on the United States market alone exceed $10 million a year. Silicon cell devices, for example, have found a large application in communications systems, in radios, in remote lighthouses and in a variety of other uses where only a few watts are needed. This range includes use in space satellites as well as in simple radio loudspeaker systems in remote villages. For photovoltaic devices to find extensive use in applications requiring kilowatts rather than watts, however, such as in heavy pumping and in homes and small industries, there will have to be a very substantial reduction from the present cost of $100,000 or more per kilowatt. Several proposals and experiments considered in the Conference for improving efficiency, for use of new materials and entirely new manufacturing techniques may, in fact, bring about such a development or at least go a long way towards bringing down the cost by the further 99 per cent or so necessary to make the power competitive in any application.

Reviewing the progress already obtained, it was generally felt that solar power produced through various devices is emerging from the developmental state and, apart from specialized applications, it can already be put effectively to various small-scale uses in the less developed areas so as to improve living conditions, overcome isolation and help raise health and educational levels. With adequate support and field trials there is reason to expect an expansion of applications even if large-scale power production probably still lies outside the economic range for a long time to come.

Use of solar energy for cooling, heating and other purposes

As revealed by the Conference agenda, the possible applications of solar energy for purposes other than power generation are many. With the notable exception of solar water heating, most of them are still in the experimental and development stage and need further verification and advance through research in laboratories, pilot projects and larger-scale field trials in the areas where they are most likely to be used.

Refrigeration and other methods of food preservation by solar energy were revealed by the Conference proceedings as perhaps the most important possible applications outside the solar power field in the less developed areas. The use of solar energy for refrigeration and space cooling has the apparent advantage that the energy supply is generally at its maximum when it is most needed. Food spoilage is highest in hot countries where simple refrigeration could save a good deal of food and make possible a more even distribution of the food supply and a more stable level of prices. One of the most promising solutions would be the introduction of ice making with solar energy through small plants now available in prototype and shown to be capable of producing ice comparable in cost with that delivered from other sources. Because of greater efficiency, better maintenance and easier financing, it was suggested that efforts be concentrated on community or village ice units, as is currently being done in Burma. (A participant from that country noted that the ice maker would be economic even at twice the cost reported by the prototype designer in France.)

Participants were less hopeful about solar refrigerators in family size which are available in prototype operating on an intermittent recharging cycle of about two hours a day. The technical problems for unskilled users and the financial problem for poor families are formidable. Similarly, air conditioning by solar energy would likely prove feasible only for public buildings. But, in any case, space cooling with solar energy is less advanced and must undergo a good deal of research and practical experimentation in conjunction with attention to house design before it can be expected to provide even partial relief from heat and humidity.

Solar drying, the subject of another session, has also been rather neglected despite its large traditional role in drying grains, fruits, vegetables, fish and other products. Large amounts of food and money could be saved by the introduction of modern adaptations to traditional techniques and equipment.

It was felt that the problem was somewhat different with respect to the production of fresh water through solar distillation of sea or brackish water. Family size units for drinking water are well known, within reach and easily made locally at a cost of perhaps ten to thirty dollars per square metre producing about 1,500 to 2,000 litres per year. While they do not seem capable of much improvement in efficiency, they could probably be reduced in cost through the use of new materials, improved designs and mass production. With growing water shortages and recognition of the health factor in drinking water, these small stills are of increasing importance and merit greater attention. Larger solar distillation units (exceeding, say, 50,000 litres a day) for urban areas, industry and irrigation are more questionable since alternative and apparently cheaper methods of production exist. The problem of costs is much more serious and the participants expressed less optimism about the designs presented.

However, on this subject, the session served to synthesize the situation at an opportune stage by bringing together a great deal of recent theoretical work on solar still operation, clarifying needs and introducing some new approaches. In short, despite some discouragement regarding actual operational results, large-scale solar distillation should by no means be ruled out. Several lines of approach still remain to be tried out, such as the so-called Claude process or "solar ponds" which combine water and power production, and other entirely novel ideas which may yet help to make fresh water available in large quantities at acceptable costs.

Solar water heating, as previously noted, is the widest current application yet established on a commercial basis. In Japan, annual sales are as high as 100,000 units, ranging in price from about $6 up to much higher figures for more durable, complex units. In their simplest, cheapest form the solar water heaters should certainly find a place in the less developed areas for bathing, laundry and other purposes, or for larger applications since they can pay for themselves in fuel savings in a few months or years at the most. The heaters may also grow in importance as fuel savers in more advanced countries, as demonstrated by rising trends in the southern United States, Japan and Israel, where competition from solar heaters was reported to have forced a reduction in the price of electricity for heating water. The future for solar heaters thus is bright but it could be improved still further through standardization, simplification and cost reduction.

House heating with solar energy, which is of little importance in warm areas, need not be dealt with at length except to note that it is still in the experimental stage and not yet generally economically feasible. With the scientific knowledge now at hand and with further development the prospects may, however, become brighter, particularly if heating can be successfully combined with air conditioning, and if heat storage can be improved to overcome the lack of coincidence between energy supply and need.

Solar cooker developments appear to have reached a point where practical application may be imminent. Some two dozen variations of workable cookers have been made, eight of which were presented in the Conference. Several of them appear technically capable of supplementing, to a substantial extent, the cooking needs of peoples in sunny climates. Reductions in equipment cost, currently about $15, are a prerequisite to extensive utilization. Credit arrangements for their purchase seem to be needed as well. New designs, materials and fabricating techniques appear desirable both for achieving better performance and for lowering costs of manufacture.

Solar furnaces, which may be likened to large-scale solar cookers (up to 1,000 kilowatts), have unique qualities for high-temperature processing and research. In the view of the specialists, their use will become more widespread so that larger very-high-temperature solar furnaces may compete with conventional furnaces in the processing of high-priced products. However, their use will be limited to special cases in less developed countries where interest is likely instead to be concentrated on lower-temperature systems for such purposes as brick drying and production of ice and power.

Problems of energy storage and combination of sources

There was deep awareness at all sessions of the one big handicap of wind power and solar energy namely, the intermittence of supply. The problem centred on the need to overcome this limitation through energy storage and by other means. For several applications, however, the specific timing of the supply is relatively unimportant, as in water pumping, and the energy can be utilized as it becomes available. In this connexion participants stressed the importance of actually using the energy as it becomes available by adjusting the demand to the supply, and of calculating the effective cost (mostly interest and depreciation on the initial investment) in terms of what is utilized rather than of what is produced.

Research is needed to improve and substantially reduce the cost of storage of heat and power from solar and wind energy and to find new ways of overcoming the intermittence problem. Active research should be directed, for example, towards simpler, cheaper batteries with longer life and towards fulfilling the promise of fuel cells which are regarded as not yet ready for use in under-developed countries. Most of this research might be done in the industrial countries which have better facilities and the personnel to undertake the basic research. Solar and wind energy are likely to play a greater role also in their competitive energy situations as progress is made in this field.

At present, direct storage devices are limited in practice mainly to conventional storage batteries, which are useful for small loads but prohibitively expensive for large electric supplies, and to storage of low-temperature heat. The latter is readily accomplished by simple means in connexion with solar water heating and house heating for short periods, but higher-temperature heat storage required in other applications and heat storage for longer periods, such as from summer to winter, have not received enough attention.

The intermittence problem can be solved also by combining different energy sources. Large-scale intermittent output, for example, can be fed when available into electric grids or it can be used to pump water up to a reservoir for later production of hydro-power in a reverse flow.

More interesting for less developed areas, however, are the proposals considered during the Conference for combining solar and wind energy and energy from other local sources, such as waste materials, into comprehensive schemes at the village level to meet the various energy needs. Wind and sun are random, but vegetable wastes as a form of storage can be used whenever power and other energy supplies from wind and sun are not available. Taking carefully into account the characteristics of these sources and the nature, timing and extent of the energy needs in a typical under-developed village, this idea has been generally accepted as a good one. To test the operation under really practical conditions it was suggested that trial schemes be undertaken in connexion with the proposed pilot projects for selected under-developed areas.

Chapter 3

IMPLICATIONS OF THE CONFERENCE

Solar, wind and geothermal energy—as demonstrated in the Conference on New Sources of Energy with reference to achievements and practical experience already gained—hold out the promise of contributing in a significant way to energy supply and economic growth, especially in the less developed countries.

The Conference was concerned with assessing these possibilities as well as the limitations and the challenges to increased utilization. Although it was limited solely to the exchange of ideas and experience, and did not seek to formulate recommendations or agreements, the Conference served to clarify at least by implication the need for action at various levels by those concerned, including the United Nations and certain specialized agencies, to find solutions to problems such as those discussed below.

The indicated lines of action range from encouragement of research and resource prospection to the establishment of pilot stations and better exchange of information. As pointed out especially in the closing session of the Conference, technical assistance and other means of action at the international level can play an important role in this process.

RESEARCH

Although in different measure, scientific and technological research are essential for increasing the use of all three energy forms. The problem in the geothermal field, however, beside the need for basic research into the origins of the steam, is one of spreading knowledge and of technical training to insure proper choice and use of techniques. Wind power technology is also advanced, but could be better adapted to local conditions for the more extensive use of local materials and skills to lower costs of installation and operation.

As far as solar energy is concerned, however, scientists have a long road ahead with many unsolved problems and challenges. The technological level of most solar applications is at an early stage of development. More basic and applied research are needed for these applications and especially for solving the difficult problem of energy storage. Also needed are the adaptation of devices and field testing under conditions prevailing in the less developed countries. An interesting start has been made in this direction, for example, under an arrangement recently concluded between a Canadian university and the Food and Agriculture Organization; a couple of informal working bulletins prepared by consultants have already been issued.

The Conference discussions indicated that there is much room for greater co-ordination of research activities and more efficient utilization, as well as expansion, of the funds and highly technical manpower already employed in solar research, notably in the industrial countries. The solar energy field is so wide and the scope for scientific research so large that there is need to sort out systematically the promising lines of such research in relation to the needs and possibilities revealed in the Conference. Such an analysis from the scientific research point of view, undertaken for example by the United Nations Educational, Scientific and Cultural Organization (UNESCO), could provide a useful list from which universities and others could choose the most promising research projects on which to concentrate their efforts, and a basis for a more effective co-ordination of effort in the solar field. The listing of indicated solar research priorities, whether by UNESCO or the international Association for Applied Solar Energy (AFASE) or possibly by the two organizations jointly, would be one effective way of following up the Conference documentation and would go beyond the useful directory of world activities and bibliography published by AFASE in 1959.

RESOURCE PROSPECTION AND DATA COLLECTION

The Conference clearly indicated the need for much more information about the availability of solar, wind and, especially, geothermal energy and for complementary data on alternative sources of energy and related economic data and analysis.

As far as physical availability is concerned, general data collection is, or should be, part of the normal work of geological services in the case of geothermal resources and of meteorological services for wind conditions and solar radiation. With the tools now available for geothermal prospecting, interested geological services should have relatively little difficulty in undertaking at least preliminary investigation of the surface phenomena and related geological features which reveal the presence of geothermal fields and on this basis of deciding whether more thorough exploration should be undertaken. If desired, as pointed out in the closing session, teams of United Nations technical assistance experts could be obtained for this purpose drawn from among specialists in the countries having greater experience in the field.

With respect to wind and solar radiation, the gaps in the general data collection are gradually being filled by the expansion of the network of meteorological stations, although perhaps not at the rate and in the areas, such as arid zones and microclimatic spots, which are most appropriate from the point of view of energy utilization.

It may be noted that, besides facilitating the establishment of networks of stations and co-ordinating statistics, the World Meteorological Organization (WMO) is interested in promoting meteorological research and training related to solar radiation and wind observation and in assisting engineers in the use of meteorological data and knowledge. As regards other aspects of a meteorological nature more specifically related to energy resource surveys, it is encouraging that the WHO Commission for Aerology has already responded to the needs expressed at the Rome Conference by adopting a resolution creating a working group on sites for wind power installations. This group is to prepare a technical note on air flow over hills and suggest studies providing guidance on site selection. Another example, now that the Conference has more clearly established the practical needs as regards solar radiation measurements, relates to the indicated intensification of work in this direction by working groups under the WMO Commission for Instruments and Methods of Observation (CIMO), in co-operation, as appropriate, with the Radiation Commission of the International Association of Meteorology and Atmospheric Physics.

The general knowledge of physical availability is, however, only a first step; the selection of areas for intensive surveys must be guided primarily by broad economic considerations. In this respect there is a need for over-all energy surveys which would consider not only the availability of energy in each relevant zone but also the current and foreseeable demand in each sector on the basis of various cost and price estimates and the like. This is an indispensable aspect of investigation and one for which the United Nations has provided various countries with specialists to advise in evaluating the possibilities of developing energy resources. On this basis, a more realistic selection can be made of favourable zones for intensive surveying for geothermal, solar and wind resources.

Standardization

Standardization of measurements, instruments and equipment was recognized by many participants as a means of promoting the wider adoption of new energy-utilizing techniques through its effect in decreasing costs, increasing the exchange of information and facilitating the necessary training and testing of equipment. This applied particularly to various aspects of solar radiation and wind measurements, such as the type of instruments used and the types of data required and their presentation. This field is receiving the general attention of WMO and its various organs, particularly from the meteorological point of view, but it appears in need of a concerted effort which would take more fully into account the data requirements of those concerned with practical energy utilization as expressed in the Conference and elsewhere.

As regards possible standardization of equipment, it was noted that certain devices, such as small windmills and solar water heaters, are already produced in great number and variety. In some of these cases, standardization could bring benefits of economy from mass production, interchangeability of parts and comparability of performance. While such standardization may possibly be difficult to organize and carry out, it was deemed none the less to be highly desirable.[1]

Pilot stations and experimental centres

One of the most significant suggestions to come out of the Conference concerned the establishment of pilot stations and experimental centres in those less developed energy-poor areas favoured with plentiful wind and sunshine. These stations or centres would serve several purposes; they could distribute solar and wind measuring instruments, supervise their use, disseminate information about site selection and equipment and adapt equipment to local needs, and could generally contribute to the clarification and solution of technological problems under actual conditions of operation. Pilot projects would also permit an increased exchange of research workers so that those from developing countries could learn of the latest technical advances and those from industrial countries could become familiar with local conditions and render advisory services.

The pilot stations would be more than technical centres. They would be in a position to demonstrate possibilities of saving and to act as intermediaries for technical and financial aid. They could also innovate actual applications under the conditions prevailing in less developed areas by providing a better understanding of the social and economic problems connected with the introduction and maintenance of these new energy applications—which range from solar cookers and ice-making machines to pumping and other power operations—at the individual household level and the village level. The effective introduction of these new applications would require the assistance of community development services and the experience to deal with problems of psychology, social attitudes and other obstacles, for what is envisaged is not only the odd solar cooker experiment but comprehensive trial schemes such as have been worked out and proposed in fair detail in two Conference papers.[2]

The proposed pilot schemes and centres are regarded as vital at this juncture for a real "breakthrough" in the application stage in the areas under consideration. They represent a practical approach which might be implemented by organizing experimental stations in well selected areas in the different regions of the world. The initiative would have to come from interested governments, which in turn may wish to call on assistance from the United Nations and its specialized agencies under the Expanded Programme of Technical Assistance and the Special Fund for the establishment of such stations, the provision of necessary experts and equipment, and the like.

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[1] It has been suggested that committees of specialized groups, such as the Association for Applied Solar Energy and national wind power organizations, might consider this problem and propose procedures and criteria for governments to consider. This would apply, as well, to the establishment of standards for evaluating the technical performance and efficiency of solar and wind devices.

[2] Notably those by Kapur on "Socio-economic Considerations in the Utilization of Solar Energy in Under-developed Areas" (E/CONF.35/GEN/8) and Golding on "Power from Local Energy Resources" (E/CONF.35/GEN/5).

Conferences and exchange of information

The Conference demonstrated its value as a means of exchanging information and has aroused certain expectations that this work will be followed up by the United Nations, in particular through the dissemination of the technical papers submitted to the conference and by the issuance of periodic progress reports every few years. If such reports justify it, the Economic and Social Council might consider encouraging special meetings at the regional or world level.

Any such plans would obviously take into account conferences organized by other bodies, such as UNESCO in the scientific research field. In this connexion it is worth noting that, for its sixth plenary meeting to be held in Australia in October 1962, the World Power Conference has now included sub-divisions on geothermal, wind and solar energy.

Notwithstanding their great usefulness, conferences are too sporadic to meet the strong demand for continuing means of communication. Only the solar energy field is provided for in this respect, particularly with regard to research, through the activities of the international Association for Applied Solar Energy which has a large membership, a central library and information services and publications.[3] No serious effort appears to have been made in that direction with regard to the other two sources; hence, some Conference participants suggested the setting up of some kind of permanent international wind power group to publish regular newsletters and channel information, while others indicated the need for a journal in the geothermal field.

The hope was expressed that, consistent with its continuing function of dealing with all sources of energy development, the United Nations, and its specialized agencies as appropriate, would play a more active role in the study and application of the new sources of energy. There was thus indicated to be a need to maintain the contacts already well established through the Conference, and to assist—within the staff and financial means available—in the co-ordination of efforts and the systematic exchange of information among the institutions and organzations concerned.

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[3] Notably its quarterly journal of solar energy science and engineering, *Solar Energy*, and its quarterly newsletter, *The Sun at Work*. This association, it should be recorded, gave wholehearted and effective co-operation to the Conference and may be expected to follow up certain aspects of the Conference, at least as far as solar energy is concerned.

PART II

INTRODUCTION

Energy situations in world perspective—Energy and under-developed countries—Salient characteristics of the new sources of energy

Prospects for the practical utilization of new sources of energy other than the atom were reviewed in a comprehensive United Nations report published in 1957.[1] Much progress has since been made in the fields of solar energy, wind power and geothermal energy, as evidenced by the documentation submitted to the Conference and providing the primary material for this part of the present report.[2]

Before taking up the specific economic and technical aspects of each of these new sources of energy—which are "new" not in origin but primarily as regards the methods recently devised for harnessing them—a broad general survey appears appropriate. This is the purpose of the present introduction, which is a condensed version of the report for the general session (GR/1).

ENERGY SITUATIONS IN WORLD PERSPECTIVE

Several papers (GEN/8, 10, 15) analyse in some detail recent and prospective world energy consumption, which has been growing at an accelerating rate and is currently at a rate of somewhat more than 4 billion tons coal-equivalent per year for so-called conventional commercial energy sources alone. To this consumption of commercial energy should be added, as pointed out by Netschert and Löf (GEN/10), some 15 per cent for "non-commercial" sources (agricultural waste, wood), which still account for one-third to one-half of the total energy consumption in Latin America, Africa and Asia. Long-term projections for the future are necessarily uncertain, estimates of the world total ranging from about 15 to 20 billion tons coal-equivalent by the year 2000. Whatever the estimates, however, they leave no doubt that energy consumption will grow much more rapidly than world population, which is expected approximately to double over the same period.

This acceleration is intimately associated with expected economic development and rising income. Per capita national income and energy consumption are closely correlated, as is demonstrated by Hartley (GEN/4) with figures from forty-nine countries. The relationship, however, is not simple. There are deviations (Mueller, GEN/7) due to such factors as differences in energy resource endowment, climate (affecting heating requirements), industrial structure and transportation systems, as well as statistical complications. Similar reservations attach to electricity, which may also, and perhaps better, be taken as an index of level of living.

Changes in income and energy consumption interact. Neither of these elements can be clearly isolated as the cause of the other. But it can be definitely concluded that availability of energy, especially of electric power, is absolutely indispensable for any substantial economic development. This is widely recognized, and is reflected in various economic development plans.

The income-energy relationship shows up clearly in the geographical distribution of energy consumption. Kapur (GEN/8) thus finds that in 1960, advanced industrialized countries accounted for 30 per cent of the total population but for 84 per cent of the total energy consumption; the corresponding percentages were 50 and 15 for countries near or approaching self-sustained growth, while more backward countries in Africa, Asia and Latin America accounted for 20 per cent of the population and only one per cent of the energy consumption. His projections for the years 1975 and 2000 indicate a slight relative shift of both population and energy use to the second and third groups, and especially to the second group as regards energy consumption in the long run. This shift is supported by average growth rates in individual regions (GEN/10).

Energy requirements are met from several sources (analysed in GEN/10), principally coal and oil. The composition is greatly influenced by the energy resource endowment, which is very unevenly distributed as between countries, in itself a fact of primary significance in evaluating the future role of the new sources of energy. It also reflects differences in end uses of energy, some of which (such as automotive transportation) are tied to particular energy sources and are not easily subject to substitution.

The relative importance of the specific sources of energy has shifted rapidly. At first farm waste and wood were the predominant fuels, then in swift succession came coal, petroleum and natural gas. The pattern is still in rapid flux, and may well absorb the new sources. But it must not be forgotten that the production and utilization of the conventional forms of energy are also undergoing unceasing improvement, as shown by Thacker's suggestive analysis (GEN/15). Some improvements are: reduction of dam evaporation; introduction of reversible pump-turbines, back-pressure turbines and fuel cells; direct conversion; heat pumps; transmission at higher voltages; better load distribution; better coal utilization; use of diesel engines in transport, and a more rational industrial location policy.

The functional pattern of use is also significant in plan-

[1] United Nations, *New Sources of Energy and Economic Development* (Sales No.: 57.II.B.1).

[2] The documentation, as listed in annexes 4 and 5, consisted of twenty rapporteurs' general reports and 250 individual papers. They are referred to in the text by their abbreviated document symbols: reports, GR/1 to 20; individual papers for the general session and for session II.D, GEN/1 to 15; geothermal, G/1 to 77; wind, W/1 to 40, and solar, S/1 to 119.

ning energy development. Such use may be divided into two basic categories, heat and power. On a global basis, it may be estimated (GEN/10) that use of primary energy for heat accounts for some 62 per cent (33 per cent in industry and 29 per cent in households) and for power 38 per cent (industry 16 per cent, households 2 per cent, transportation 19 per cent and agriculture one per cent). The functional pattern varies greatly between countries and between areas in particular countries, but "in view of the well-known increase of productivity and income through electrification, it can confidently be assumed that in the under-developed regions of the world, at least the place of electricity in the total energy picture will be larger in the future" (GEN/10).

By virtue of their very nature of being "new", it may be noted in conclusion, the new sources contribute only an insignificant share to total world energy consumption today. Their promise depends largely on recent or prospective technological breakthroughs. Even so, the future contribution of the new sources of energy in global terms may never increase beyond a small share. But this should not be taken as a reason for underrating the importance of the new sources in meeting local energy needs throughout the world, especially in under-developed regions.

Energy and under-developed countries

There is no generally valid criterion for determining the pattern of planning energy supply to under-developed countries. Their energy requirements, as well as the optimum way of covering them, must be investigated in each case (GEN/7).

Some features, however, are common to all of the less developed countries and may be briefly considered; first, those related to electrification, and then the situations that arise at the local level with reference to other applications of energy. These situations disappear from view in the global surveys occasionally presented. Yet, after all, they are the fundamental situations that must be modified and improved if the levels of living are to be enhanced and a strong stimulus given to development. These are the situations to which small-scale applications and unconventional methods might make a great contribution.

In considering the electric power situation in the under-developed countries, it should always be remembered, first of all, that none of these countries now has a nation-wide grid, or is likely to have one for a long time. Such grids as do exist are usually confined to relatively limited areas—industrial enclaves and peripheral zones of development around the largest cities and ports. Though the systems are often short of installed capacity, and power break-downs are frequent, they do have enough interconnected capacity to guarantee a continuous supply of current to these zones which are often comparable to the industrialized countries. The load factor is relatively high, and the rates charged for power are reasonable. In cases of this kind, only comparative cost studies can justify the use of the new sources of energy.

More typical are the areas with isolated power plants, usually with a capacity ranging from several hundred to several thousand kilowatts, based on diesel engines, small hydro-power turbines, or, more recently, gas turbines. Such plants, whose interconnexion usually cannot be envisaged for a long period, are often established with the introduction of modern mining or manufacturing enterprises, and today on government initiative as well in some areas, before long-distance power transmission becomes justifiable. Owing to the small scale of the generating plant, high fuel cost, low load factor, or a combination of these causes, electricity costs are high in these areas, ranging between 30 and 80 mills per kilowatt-hour, and not infrequently much higher.[3] In these areas there may be large scope for cost reduction, either by the introduction of continuous alternative sources, such as geothermal power (where reasonable baseload can be provided), or by fuel saving devices based on solar or wind energy even on an intermittent basis, or by a combination of local sources.

The areas in a third category, however, are most typical of the conditions that prevail in under-developed countries. This is the category of "remote" areas, where there is no generation of electricity at all. Most of the population of such countries live in such areas. They may be remote in the geographic sense, as in the interior of large countries, and confronted with practically insuperable obstacles to electrification by conventional means, at least for a very long time. Or they may be remote, as is often the case, only in the economic sense, primarily owing to lack of transport facilities. Better prospects of electrification may be offered in the latter case, provided that the introduction of modern transportation or the development of trade and industry would create an adequate power demand to justify transmission lines or central stations.[4] However, these areas are so numerous that most of them will have to wait a long time for this to happen if for no other reason than that large-scale rural and village electrification would be far beyond the financial and technical resources of most under-developed countries.

The situation may be illustrated by some figures from India which might be taken as a typical example of an agricultural and mineral economy. Even with accelerated industrialization and urbanization, as pointed out by Kapur (GEN/8), India would by 1981 still have 75 per cent of the entire population, that is 480 million people, living in small agricultural communities. Great strides have been made. Except for two, all the towns with a population of over 20,000 have now been "electrified", and under the third five-year plan, ending in 1966, all towns with over 5,000 people (there were 4,542 such towns according to the 1951 census) will have some electric supply facilities. Progress has also been made in bringing electricity to the villages (less than 5,000 people), which account for the bulk of the population, the number with such facilities having risen from about 2,800 in 1951 to 15,400 in 1961; a further increase to about 29,500 is expected by 1966. But such an increase would still leave

[3] One US dollar equals 1,000 mills. Generating costs in industrial countries are usually in the range of from 4 to 10 mills per kilowatt-hour.

[4] A sub-category of remote areas might include those which are now relatively unpopulated but which could be developed in the event of some attractive economic proposition, such as a mineral discovery. In such cases, the initial development plan would include provision of power facilities, so that the problem would be reduced to choosing the least costly system.

some 527,000 villages or agricultural communities without electricity, even five years from now (GEN/8).

In view of the conditions prevailing in the under-developed areas, there can be no doubt that an improvement in living conditions would result from placing electricity or any other form of energy at the peasant's disposal, though it would be difficult to determine the precise economic values that would thereby be created. Today, that peasant generally burns dung or similar fuels for cooking meals, and relies primarily on human or animal muscle power to do his tasks.

Indeed, the question is not whether the new sources of energy can compete economically with the conventional sources, but whether they can be usefully and effectively harnessed; or whether, in the alternative, these areas shall have no supplies of energy at all. Kapur (GEN/8) has assessed in detail the extent and nature of the energy required to improve the productivity and per capita income in an Indian rural community of 1,000 population, with special reference to the possibility of using solar energy, including estimates of costs, employment and income effects. His paper contains a frank discussion of the financial and training problems involved. Golding (GEN/5) has also developed a scheme for generating power for a village of twenty to thirty families, using local resources and taking into account the characteristics of solar energy, wind power and other sources, the cost of harnessing each of them, the probable load factors, and the time distribution of such load factors. While schemes of this nature are still in the theoretical stage, they do provide guidance for realistic energy situations and a framework for the introduction of the new sources on a comprehensive experimental basis.

Salient characteristics of the new sources of energy

To understand better the salient characteristics of the new sources, it is useful first to recall briefly the essential nature of geothermal energy, wind power and solar energy, and to review in outline the methods employed to harness each of them. These aspects will be amplified in subsequent sections of the present report, after the principal features that characterize the three new sources of energy have been surveyed, both those features which are common to them and to other sources of energy as well, and those that serve to distinguish them among themselves and from the others.

For geothermal energy in the form of heat in natural steam or hot water to be useful, "a rather fortuitous combination of large masses of fractured or porous hot rock at a depth not exceeding a very few thousand feet, a natural supply of water to this heat source, and a layer of impervious rock between the hot zone and the surface are generally required. If wells are drilled into this hot material, steam at a pressure of several hundred pounds per square inch may be tapped from it, just as natural gas is produced. With a number of wells and steam collection facilities, a central power plant comprising principally a steam turbine, condenser, and electric generator can be operated" (GEN/10). The temperature of natural steam ranges from 100 to 300° C at well mouth; such steam or hot water may be used directly, for instance for space heating and in hot water systems, and need not necessarily be used for electricity production. This type of direct utilization, however, is subject to the practical limitations imposed by transmission.

Wind energy is the kinetic energy in a column of moving air, or wind. It is intercepted by a rotor or propeller, which transforms the energy into mechanical power for direct use as such, or, in accordance with the modern trend, for driving an electric generator. The basic elements determining the energy obtainable are the wind speed, the area swept by the rotor, and the conversion efficiency of the plant. Windmills are rated to reach their capacity output at a certain wind speed, and, at that speed, may extract the energy in the wind with an over-all efficiency of some 35 to 40 per cent, as compared with a maximum theoretical efficiency of nearly 60 per cent.

Solar energy arrives in the form of energetic radiation, which is harnessed in basic conversion processes classified into two general groups utilizing the heat or the light, respectively. The thermal processes, in turn, may be classified according to the temperatures obtained. Low temperatures, useful for water and space heating or for sea-water distillation, are the easiest to obtain by means of simple flat-plate collectors composed of plates coated with a black radiation absorbing substance which heats the water or any other medium used for the heat transfer. Higher temperatures require lenses or reflecting mirrors, which capture only the direct solar radiation, and which must be oriented frequently to keep them facing the sun. The heat can be put to many uses, including the driving of engines, and may even be converted directly into electricity in thermoelectric generators without passing through the stage of mechanical energy. Solar radiation arriving in the form of light may also be converted directly to electricity by means of photoelectric cells, and is most prominently utilized by nature in the photochemical process known as photosynthesis, the basis of all plant growth. Artificial photochemical processes have also been conceived and are of substantial interest, but they fall outside the scope of this Conference through lack of progress in the search for controllable and practical reactions which would offer the possibility of both energy storage and delivery of useful heat or, even better, an electric current.

The salient characteristics of the new sources of energy are well tabulated by Angelini (GEN/1) and are discussed at some length particularly by Netschert and Löf (GEN/10) and, of course, in their detailed aspects, in the technical papers. They are considered here only to the extent to which they affect the general economic value of the energy sources in question, the technology used for their application and the purposes they serve.

Perhaps the most significant feature relates to reliability and continuity of supply. Geothermal energy offers continuous supply, while solar energy and wind power offer only an intermittent supply and thus raise the problem of storage, or combination with other energy sources, if uninterrupted demand must be met or if demand cannot be adjusted in point of time to supply. Solar energy is available only during daylight hours, which vary with the season, and focusing collectors are particularly subject to the vagaries of atmospheric conditions. Wind power availability is never completely predicable for a specific time, but usually shows little variation in a given place from year to year or even as between shorter comparable periods.

Permanence of the source is another significant feature. At least solar energy and wind power are inexhaustible, that is, they are renewable as in the nature of "income" energy, like hydro-power. Geothermal energy may present characteristics of exhaustibility somewhat comparable to those of the conventional non-renewable sources of energy, but this point is not clear, since the experts now point to replenishment through water percolation as the major source of supply, and, too, there are indications in some cases of an increase rather than a fall in temperature when steam deposits are tapped. These three sources, moreover, have no other uses apart from energy applications, and they may thus serve eventually to conserve the conventional exhaustible resources for other uses.

The magnitude of solar radiation on the earth's surface is enormous and so is the total physical force of the wind. As pointed out by Ailleret (GEN/12), the wind and the sun each represent a power of the order of one kilowatt per square metre, or some 10,000 times the total energy consumption "density" even in the most industrialized countries, and, consequently, from a purely theoretical point of view, they could meet a great expansion of need even at a low conversion efficiency. The quantity of available geothermal energy is less well known; but to judge from indications on the earth's surface, such as hot springs, which are numerous but largely unexplored, the reserves could very well be considerably greater than is usually believed. But we must guard against possible illusions when speaking of the available quantities and emphasize the difference between physical availability and economic availability, which varies constantly with technological progress and is intimately dependent on installation and operating costs as well as on other economic factors peculiar to the country involved.

With respect to geographic distribution and conditions of location, it must be noted that geothermal energy is concentrated in a limited number of areas, not always characterized by energy need and scarcity. Like hydro-power, geothermal energy can only be exploited in places determined strictly by geological and geographic conditions; such energy converted to electricity can of course be transported over considerable distances, while steam or hot water can be piped over only limited distances (some 15 to 45 kilometres, as in Iceland) without serious energy loss. Solar energy utilization, though mainly limited to the belt between latitudes 40° North and 40° South, enjoys great freedom of site choice. Wind power is also widely and readily available, without restriction to any particular climatic belt, but some care is required in the selection of specific sites to obtain optimum results.

The status of the technology available for harnessing the new sources of energy may be regarded as being in a relatively early stage. But fully developed equipment is available at least for geothermal energy; that for wind power utilization exists in considerable variety, while the situation as regards solar applications is less advanced.

As regards size of installation, it may be said that the new sources of energy admit of great flexibility. Solar and wind energy can be utilized in plants of small capacity, down to a fraction of one kilowatt, and hence are particularly suited to meet the limited needs of isolated farms or small communities. There is economy of scale in larger wind power plants only to a certain level (perhaps 1,000 to 2,000 kilowatts), while solar energy capacity normally increases in direct proportion to the size of the collectors and therefore has little economy of scale. The size of geothermal plants depends primarily on local natural steam conditions, but does range from small units without condensers—economically limited to a minimum size of about 1,000 kilowatts—up to very large plants with multiple units of 25-30,000 kilowatts each and with economy in cost and steam consumption per unit of output.

Among the most important economic aspects, finally, it is to be noted that the utilization of each of these three energy sources requires relatively heavy initial capital investment, while the operating costs are minimal. It follows that the cost of useful energy obtained from the new sources, as in the case of hydro-power, is determined predominantly by the fixed costs (interest and amortization) resulting from the capital investment. This fact makes it essential to concentrate efforts on minimizing the initial costs and maximizing the life of the equipment. For the same reason, local labour and local raw materials should be employed to the greatest possible extent, to minimize foreign exchange expenditure.

GEOTHERMAL ENERGY

Current utilization and areas of interest—Prospection of geothermal fields and techniques for evaluating their capacity—Harnessing of geothermal energy—Pipeline costs and limitations—Geothermal electricity production—Space and process heating with geothermal energy—Recovery of chemicals and combined schemes

CURRENT UTILIZATION AND AREAS OF INTEREST

Practical utilization of geothermal energy—for generation of electricity, space and process heating and recovery of chemicals contained in the steam—is already a reality, a very economic one at that.

Geothermal electricity production, preceded by about a century of recovery of boric acid and other chemicals, dates back to experiments in 1904 and particularly to 1912 when the first turbine, with a capacity of a mere 250 kilowatts, was installed at Larderello in Tuscany, Italy. It has been followed there by gradual, and of late very rapid, expansion of electricity production. With auxiliaries, the total Larderello capacity exceeds 300,000 kilowatts, spread over about a dozen plants ranging in size from 3,500 to 118,000 kilowatts; they produce over 2 billion kilowatt-hours per year, or enough to run the Italian railway system, which, in fact, gets some two-thirds of its power from these sources; the remaining third of the Larderello output is used for industrial and other purposes. The dependability and high output of the source is demonstrated by the fact that the biggest plant with a net capacity of 100,000 kilowatts has been running continuously with a utilization factor of over 98 per cent for more than a decade (G/72).

Other countries have followed the Italian example in recent years and more plants are in various stages of preparation. A geothermal power plant with a capacity of 69,000 kilowatts went into production in March 1960 at Wairakei on New Zealand's North Island, which draws about 10 per cent of its power from this source; the gross capacity is currently being expanded to 192,200 kilowatts, to supply about one-fifth of the power requirements of the North Island by 1963, and plans have been drawn for a further expansion of 90,000 kilowatts in a third stage (G/4). The United States also became a geothermal power producer in June 1960, when a plant of 12,500 kilowatts was completed at The Geysers, California; it is planned to double its capacity by 1963 now that favourable experience has been obtained (G/41), and other projects are being advanced in the western United States. Further installations include a 3,500-kilowatt plant at Pathé, Mexico, where drilling started in 1955 (G/77); a 275-kilowatt station in the Katanga mining region of the Congo, and pilot plants (of thirty kilowatts each installed in 1951 and 1960) at Beppu and Hakona, Japan, where geothermal power is likely to play an increasingly important role in the face of growing demand, coal production problems, lack of oil and high fuel costs (G/57). In neighbouring Kamchatka in the Soviet Union, considerable drilling has also been carried out during the past three years with a view to power production (G/48).

Another example of prospectively competitive geothermal power production with special advantages is provided by Iceland, where a plant of 15,000 kilowatts (net) is in the advanced planning stage for commissioning in 1964. It is to be noted that Iceland is rich in hydro-power resources, but due to physical factors, the smallest practical additional hydro-power plant would add 40 per cent in one lump to capacity while geothermal stations can be built on a smaller scale and in steps as demand grows (G/9).

Iceland, however, is more famous for using geothermal energy for space heating and other heating purposes. At present, 45,000 people, or one-quarter of the population, live in houses kept warm by natural heat piped from geothermal fields; in addition, these sources provide hot water, heating of large greenhouses and swimming pools, and industrial heat. Their use already corresponds to annual savings of 60,000 tons or 350 kilogrammes per capita in fuel oil imports, and these figures are expected more than to double by 1970 (G/37).

Heat applications are also found in other countries, such as in a pulp and paper mill and in hospitals, hotels and schools in New Zealand (G/52), in the production of salt in Japan (G/7) and prospectively in Iceland (G/27), and in scattered use in the United States, the Soviet Union and elsewhere.

Much of the existing practical utilization, then, is to be found in the relatively industrialized countries. This fact should not be taken as proof that utilization will or should be limited to those countries. On the contrary, with adequate understanding, exploration and expenditure of effort, geothermal energy may ultimately find significant application in the less developed countries, many of which are believed to have substantial geothermal resources and some of which have initiated more or less intensive exploration. At the same time, activities in industrial countries may be extended into exploration of further regions, such as those reported in Italy (G/65), New Zealand (G/17) and the United States (G/48).

In view of the limited exploration so far undertaken, the extent and potentialities of geothermal resources in the less developed countries are relatively little known. Interesting explorations, however, were reported to the Conference, for example, for additional areas in Mexico (G/77) and for El Salvador, where it is hoped to prove enough steam to warrant a geothermal plant of from 50,000 to 100,000 kilowatts (G/11). Another case (G/12) is provided by a preliminary investigation in the Rabaul area of New Britain, aimed at establishing a plant with an initial geothermal power capacity in the first eight years of 5,000 kilowatts and ultimately of 20,000 kilowatts; this investigation is being undertaken in the realization that a possible hydroelectric scheme there would be expensive, particularly in the early stages of power demand. Other explorations reportedly have been undertaken, planned or tentatively considered in, for example, Nicaragua, St. Lucia in the West Indies, the Andean region of Argentina, the Tatio (Antofagasta) area of Chile, Kenya, Uganda, Fiji and in Indonesia before the war. Several additional countries are known to have at least the favourable surface indications of hot springs, sometimes in great numbers; in fact, almost every country appears to have some hot springs, very few of which have been investigated from the point of view of, and as a clue to, possibly worthwhile geothermal energy.

In general terms, the areas of apparently greatest interest and likely geothermal resources may be drawn in some broad sweeps. One such sweep stretches from Kamchatka through Japan, the Philippines, Indonesia and New Britain to New Zealand. Another sweep may be drawn as covering the Rocky Mountain and Andes regions, that is, from Alaska, all along the west coast of North America (including, of course, the geysers of Yellowstone Park) into Mexico, El Salvador and right down to Chile. A third big sweep is in the Great Rift of Africa, through Ethiopia, Kenya, Uganda, Tanganyika and eastern Congo. A number of islands should be added, such as Iceland and the Azores in the Atlantic and Hawaii and Fiji in the Pacific, and of course scattered areas such as in Italy, Algeria and others.

From the above it is tempting to draw the conclusion that geothermal energy is to be found in volcanic regions. It is indeed true that volcanic areas are favourable for exploration. But it does not mean, as is often believed, that exploitable geothermal energy is limited to such areas, as is demonstrated by the Larderello region, the classic example of a non-volcanic geothermal area. One may, in fact, distinguish between three types of areas, namely, those of the Wairakei type linked to active volcanoes, those with a magmatic mass reaching the surface and based on extinct volcanoes, such as the Monte Amiata region in Italy, and the non-volcanic regions of the Larderello type (G/67), with plutonic intrusion of relatively hot magma at sufficiently shallow depth.

Another basic question, worth taking up here and discussed at length in the Conference, concerns the origin of the water carrying away the heat, and a related question is whether the heat source is inexhaustible or at least likely to have a long life. There seems to be agreement that the vast bulk, or 90 to 95 per cent, of the steam and hot water is of meteoric origin (G/2), that is, it is based on surface water filtering down and being heated; the remaining portion, indicated by the new tool of isotope research to be about 8 to 10 per cent in the Wairakei case (G/31), would be magmatic, that is, it originates in the interior of the earth. The water replenishment from the surface implies the necessity of adequate infiltration, at least in the long run, to replace the quantities of hot water taken out through wells, and raises the question of the time required for the water to circulate. The age of the water at Larderello is over forty years (G/62), while at Wairakei, single circulation path time is indicated to be less than fifty years (G/31). If the hot stratum is drawn on at a higher rate than the natural circulation, there will obviously be a decrease in the volume of output. In fact, it is difficult to estimate the useful life of a well; at Larderello the average life of a steam well is about twenty years and several wells are still active after more than thirty years (G/62).

In time, the hot stratum may thus lose in volume, although not in the simple fashion of depletion applying to petroleum fields, and it may cool off, especially if withdrawal of hot fluids invites intrusions by cold water (apparently not a problem so far). But it is by no means certain that withdrawal will lead to a temperature drop; on the contrary, tapping of a stratum may draw up heat from deeper, hotter levels. Thus, there is evidence of temperature increase in New Zealand (G/54), and at Larderello the temperature of the steam has risen about 40° C in the past forty to fifty years (G/62).

The water circulation has a bearing not only on the volume but also on the nature of the well product. At Larderello and The Geysers in California the wells produce superheated steam, but at Wairakei and in Iceland a mixture of steam and boiling water is produced; at least for power purposes this creates the problem of prior separation of the steam (about 10 to 20 per cent by weight) from the hot water, which in turn can be flashed to steam in vacuum vessels (G/13). The steam may also carry a relatively high gas content, as is the case at Larderello (about 5 per cent by weight and even much higher in the new wells at Monte Amiata); this has a significant effect on the plant required for utilization, but it is compensated at least to some extent by the possibilities of economic recovery of the gas chemicals.

All these factors and many others dealt with in the technical papers make it hazardous to estimate precisely the power potential even of working fields, and few estimates are to be found.

Although much remains to be learnt even about fields already being utilized, techniques for prospection of new fields and for evaluating their capacity have been highly developed and can readily be adapted in the search for new areas. The same is true as regards techniques and equipment for harnessing and utilizing the product in subsequent stages.

PROSPECTION OF GEOTHERMAL FIELDS AND TECHNIQUES FOR EVALUATING THEIR CAPACITY (GR/3)

Since the geothermal energy resource is hidden underground, certain investigations must be undertaken before decisions on utilization and further expenditure can be made wisely. Doyle and Studt (G/55) note that "investigations must necessarily be commensurate with the scale of the project envisaged; in the simplest case, a single drill hole will meet all requirements and this might be located by inspection alone, but where larger projects are contemplated extensive investigations are required".

They suggest that six phases may be distinguished, namely: (1) regional surveys—topographical, geological, geophysical, etc.—to understand the setting; (2) preliminary reconnaissance, including attention to location of population and industry; (3) a comprehensive survey, if justified, by specialist field parties; (4) the proving phase, including more extensive use of the drill, which alone can provide ultimate proof; (5) the development stage, leading into (6) the production stage, during which measurements and investigations must be continued for proper field management and extension. The first four phases may be characterized as providing, respectively, geological background, qualitative assessment, broad quantitative assessment and confirmation of amendment of previous assessments.

Conditions and characteristics to look for, mainly of a geological nature controlling the geothermal environment, include the following (G/65): existence of thermal anomaly, which is indispensable and which may be indicated, although not necessarily, by such surface manifestations as warm ground, natural emission of free steam or hot water as in hot springs and by certain chemicals normally associated with hydro-thermal activity; a highly impermeable cover near the surface protecting the hot stratum below, also a highly permeable stratum, constituting that hot boiler layer, within economic drilling reach; and a more or less old fractured base below feeding heat to the permeable stratum, which in turn is tapped by sinking a well through the impermeable layer above. Hot springs and geysers, in a sense, are natural wells and in themselves are not too favourable, except as a clue to the source, since they constitute leaks in the system and therefore may cause a lower pressure and temperature than would otherwise be available.

A number of tools are now available for detecting, measuring, sampling and analysing those conditions and characteristics necessary for successful geothermal development. Besides the tools of standard geology, photogeology and topography, they include those of modern geophysics, geochemistry, hydrogeology, hydrodynamics, thermophysics and chemistry, often with special adaptations to geothermal field problems. They are all described in detail, as methods and as case studies, in the technical papers and need not be gone into here, except to repeat the emphasis in the Conference on the successful use of electrical methods of geophysical prospection in finding fields. Properly selected and applied, the tools help to define the energy available and select a rational operation. Care in selection and application cannot be stressed enough, since misleading information may otherwise result and much capital may be wasted. However, geophysical and other surveys, correctly used, will easily pay their way even if they eliminate only a small proportion of unproductive drilling.

The tools must be used by properly trained people. The number, composition and organization of those people will of course vary from case to case, depending on such factors as the scale of investigations, availability of pre-existing organizations and on whether a government or company builds up its own organization or engages consultants and contracting firms for a large part of the various phases. An example of quite an extensive organization is provided by New Zealand (G/55), where the Department of Scientific and Industrial Research (DSIR) provides services in such fields as geology, geophysics, chemistry, physics and metallurgy under a scientific co-ordinator; the Ministry of Works carries out drilling and construction and is responsible for the over-all investigation and development of geothermal areas in which the Government is directly interested (G/40); and the Electricity Department runs the completed plants and electric installations. At Larderello, the corresponding functions are the responsibility of the various sections in the integrated and autonomous Larderello Company, which has some 2,000 employees in all.

Again to take the example of the DSIR, it has been carrying a complement of from ten to twenty-five professional staff and assistants for geothermal activities over the past ten years, at an average over-all cost of about £2,000 per man-year. The 1960 costs of DSIR investigations amounted to £44,000, or somewhat less than the cost of one 900-metre investigation bore, while its total expenditure so far in the region is of the order of £350,000 or just below one million dollars (G/55). But it is to be noted that these figures do not include drilling, engineering and other costs which are carried by the Ministry of Works and are of a much higher order, and that the different organizations in New Zealand are able to fall back on each other for various services. Another cost example is provided by Mexico, where about $640,000 has been spent on geothermal investigations, including the drilling of sixteen wells (G/77).

Harnessing of geothermal energy (GR/4)

The prospection stage will have prepared the way for the harnessing stage, which is concerned with the bringing of steam or hot water to the surface in production wells. This stage involves a number of steps, notably the planning of drilling operations, the drilling itself, well completion and maintenance of the wells. Many factors and problems enter into these steps, all of which have a significant bearing on well production costs and ultimately on the cost of the useful energy itself.

The number of wells needed for a particular power output cannot be specified in advance. Wells vary in output characteristics, such as with regard to steam quantity, temperature, pressure and long-term behaviour. Some will be failures. All told, perhaps about a thousand geothermal wells have been drilled in the world for various purposes, including a large number of investigation holes in Japan. In the Larderello region, for example, some 380 wells have been drilled of which 160 are currently in production feeding the power plants (G/65), while at The Geysers in California four wells out of twelve drilled in recent years are feeding the 12,500-kilowatt plant (G/51). In Iceland, where may wells have been drilled for heating purposes, it is expected that seven to eight will be needed for the planned 15,000-kilowatt plant, and at Wairakei, about 100 wells totalling over 50,000 metres in depth have been installed (G/49).

The siting of wells is of course determined predominantly by physical factors, although there may be some leeway to take accessibility and other factors of convenience into account. The wells must be spaced so as not to interfere unduly with each other.

The drilling equipment and methods are basically similar to those used in oil drilling, except that some adaptations are needed to allow for the high temperatures involved and certain other problems such as explosion or blow-out risks connected with trapped live steam. As described in great detail in the technical papers, special solutions have been successfully devised through adaptation of drilling fluids, blow-out preventers and other means.

Temperatures as high as 300° C. are encountered[5] raising some special problems in the completion of wells and requiring particular attention to be paid to such aspects as casing, cementing, well perforation and well head equipment for separation of water and steam and removal of impurities. Various silencers have also been devised (G/18) to reduce or eliminate the intolerable noise that may be created by steam roaring out of open wells and that may otherwise cause permanent damage to the hearing of people having to work close to its source.

Once a well has been completed, various measurements have to be made initially and continuously afterwards. During its lifetime, it must undergo periodic checking and sometimes repairs; for example, to prevent casing failures from getting out of hand and causing it to blow up. Chemical deposition can also be a problem, as in the case of calcites in Iceland (G/9), and may require periodic redrilling and cleaning to keep wells from plugging up and losing in capacity.

Drilling and well costs vary widely. In part, they are a function of depth, which in turn depends on the thickness of the impermeable layer. The depth ranges from 300 to 1,600 metres at Larderello (G/71), from 450 to 900 metres at Wairakei (G/40), from 300 to 2,200 metres in Iceland (G/36), from 200 to 800 metres in Kamchatka (G/48), from 160 to 300 metres at The Geysers (G/51), below 600 metres in Mexico (G/77) and down to 900 metres in Japan (G/57).

The actual costs of wells are calculated in some of the technical papers, with considerable details as to components, depth, well diameter and the like. Without repeating the various qualifications made by the authors, it may be noted that the total well costs are estimated at \$41 to \$56 per metre in Iceland (G/36), \$73 to \$133 per metre at Larderello (G/71), about \$130 to \$200 per metre at The Geysers (G/51) and about \$160 per metre at Wairakei (G/40). The low cost in Iceland is in part due to the nature of the drilling and to the need for only comparatively short lengths of casing even in deep wells. Taking depth into account, the total investment in a well ranges from about \$20,000 to \$140,000. To this has to be added piping to the power plant and of course the plant itself.

The depreciation of the well investment, one of the major components in the power cost, depends on the useful life of the well, which is the most uncertain element in the whole picture. As noted previously, the average life of a well at Larderello is about twenty years (G/62); elsewhere, experience is too short to establish any figure. In the circumstances, it may be advisable to consider a rather short amortization period, such as five years on the very cautious side, unless characteristics are such as to warrant a longer period, such as ten years (G/62). In the Icelandic planning, for example, a period of five years is used in the cost estimates (G/9), while "at Wairakei the amortization period for all the assets is twenty years and in arriving at this figure the life of wells was assumed to be ten years" (GR/4).

The organization for drilling and maintaining wells and for auxiliary activities will of course vary in scope and composition. At Wairakei, for example, the New Zealand Ministry of Works maintains a complement of eighty-four staff and 234 workmen, covering a wide range of specialists and items of work (detailed in G/40); in the first ten years, some \$6.5 million was spent on production wells there.

[5] In one special case of drilling into a hot lava lake in Hawaii with a view to possible power utilization and to gaining experience simulating that of an underground atomic explosion, drills withstood temperatures exceeding 1,000° C (G/5).

Pipeline costs and limitations

Once the natural steam or hot water has been brought to the surface, it usually has to be piped over some distance to the point of power generation or heating use.

The geothermal fluids, as pointed out by Bodvarsson (GR/5), are relatively poor carriers of heat. He finds the maximum transportability of natural steam for power generation to be of the order of ten kilometres; converted to electricity, the energy can of course be transmitted over much longer distances and thus overcome the handicap of often awkward location in relation to markets in need of power. High-temperature water, however, can be piped farther, as in Iceland where a fifteen-kilometre pipeline is working and longer ones are designed; in fact, a length of from fifty to 100 kilometres may not be altogether unrealistic for space heating purposes (GR/5). Long main pipelines will add to the cost at the point of delivery and in the Icelandic case actually account for costs amounting to about two and a half times those at the well head (G/37).

Given the power demand, the question may arise whether a large plant should be built or several smaller plants closer to the wells. The answer is governed very largely by local conditions, taking into account pipe length, steam pressure, temperature, rate of flow and pipe diameter on the one hand and plant size economy on the other. At Wairakei, for example, all capacity is concentrated in one location, while the Larderello system is based on decentralized plants. The technical papers give some details on costs of surface pipelines and related auxiliary equipment, amounting to about \$64 per kilowatt installed at The Geysers (G/51) and Wairakei (G/4), to \$35 in Iceland (G/9) and to only \$7 to \$9 in a small plant of the Larderello type (G/62).

Geothermal electricity production (GR/4)

Geothermal energy may be converted to electricity very simply by leading the steam as it comes out of the ground through a turbine, which in turn drives an electric generator, and exhausting it into the air. Such plants, of the non-condensing type operating on direct steam, come in small sizes, ranging in capacity from 500 kilowatts or less up to 6,000 kilowatts (G/64). These small plants, as developed in Italy, are compact and light single-block units, which are easy to transport, install and move from one location to another.

The simple non-condensing plants are the least expensive and the easiest to operate. They are most suitable for less developed areas with an electricity demand of about 1,000 kilowatts or more (to make the steam development economic) and with little need to be concerned about the efficiency of steam utilization, and for testing new fields; in the latter case they utilize steam which otherwise would blow to waste. They are also the only type suitable when the gas content is high (G/62). A plant of this type has been installed in Mexico at the exceptionally low cost of \$53 per kilowatt (G/77), and in several Larderello stations, where the various costs (excluding piping) add up to about \$65 per kilowatt installed for a single-unit station and to about 10 per cent less for a multiple-unit station (G/62). The total power cost (depending on the investment in wells and piping and on the rates of depreciation, interest and utilization assumed) may be estimated to lie in the range of 4 to 8 mills per kilowatt-hour under Larderello conditions.

The non-condensing plant, however, does have a relatively high rate of steam consumption, of about twenty kilogrammes of steam per kilowatt-hour at Larderello with a steam pressure of about five atmospheres and temperature of 200° C. But the rate can be cut in half or the power output from a given steam quantity approximately doubled by means of condensers and other auxiliary equipment, which make it possible to set up a greater pressure and temperature differential between the turbine inlet and outlet.

Since steam utilization efficiency and higher output are significant considerations in competitive power situations, all the new major plants for long-term use at Larderello and elsewhere are in fact so-called condensing plants. Such plants may operate on steam directly from the wells, on secondary steam obtained through heat exchangers (permitting use of dirtier steam and recovery of chemicals) or on steam flashed from hot water under low pressure. The condensing plants require a number of auxiliary units, fully desribed in the technical papers, such as pumps for water circulation and gas removal, and cooling water as well as the condensers proper. It may be noted in passing that provision of cooling water can be a problem and may have to be economized by means of cooling towers, which are a characteristic feature of the Larderello landscape. The gas extracted from the condensers may permit chemicals to be recovered, as at Larderello, or recovery may be made from heat exchangers and steam washing devices prior to the steam entering the turbine inlet; in the latter systems, however, pressure and power output are reduced. In certain cases, some of the auxiliaries may also be necessary to prevent pollution of air and water by impurities in the natural steam or to reduce corrosion problems in the plant itself.

All the auxiliary equipment required in condensing plants will obviously complicate the operation and add significantly to the investment costs of the power house, but, per kilowatt, these cost increases may be more than offset by a lowering of the relative investment in wells and pipes, except in plants with chemical recovery facilities where the revenue from chemicals would have to justify the higher investment per kilowatt. Plants of the condensing type will be economic only in relatively large stations comprising several small units or larger units; turbogenerators currently in use range in capacity up to 30,000 kilowatts and may be accompanied by smaller units which serve the auxiliary equipment or act as standby units; at Wairakei, for example, the firm capacity will be 151,000 kilowatts, with one 11,000-kilowatt set and one 30,000-kilowatt set normally available as spare units (G/4).

The costs of condensing plants, and consequently the costs of power, vary with a number of factors too detailed to go into here beyond some summary figures taken from the technical papers. At The Geysers, for example, the power plant investment is estimated at \$1,900,000 or \$152 per kilowatt, but it would have been about 26 per cent higher with a new generator; the plant has been running at 83 per cent utilization factor since September 1960, and, based on natural steam purchased from another company at 2.5 mills per kilowatt-hour net delivered, it produces power at a cost per kilowatt-hour comparable to that of the most recent conventional thermal plants (G/8). One notable feature of this installation is its high degree of automation. The plant is in fact manned only for eight hours a day and runs the remaining sixteen hours unattended, relying on numerous safety tripping devices and remote control; so far, only two turbine trips and one trouble alarm have occurred (G/8).

The cost estimates for the proposed power plant in Iceland (G/9) indicate an all-inlusive investment cost of \$364 per kilowatt net installed (the complete power station alone accounting for 50 per cent), or a figure comparable with that for hydro-power plants of less than 40,000 kilowatts in that country; the all-inclusive cost per net kilowatt hour is estimated at 7.9 mills, based on maximum output 7,500 hours per year, an average life of only five years for wells and an interest rate of 7 per cent.

The total capital cost of the Wairakei installation is estimated (G/4) at £15,809,000 (about \$44 million) or £82.25 (about \$230) per kilowatt installed, of which the heat supply (prospecting, drilling, etc.) accounts for about 42 per cent and the powerhouse and plant for 46 per cent; if extended in the third stage to 282,000 kilowatts, it is hoped the cost per kilowatt will fall below £78. The calculated all-inclusive cost of power production is estimated at less than 0.4 penny (about 4.6 mills) per kilowatt-hour, based on an output of 1.22 billion kilowatt-hours per year (that is, an over-all load factor of 72.5 per cent) and an interest rate of 5 per cent; with the third stage, the cost per kilowatt-hours would be reduced by about 12 per cent.

The Larderello investment and production costs are more difficult to estimate, in particular because of the spread over many plants of different ages and of the combined production of power and chemicals. An interesting comparison as regards certain cost factors is, however, made by Chierici (G/62) between a conventional thermal power plant having two units of 150,000 kilowatts each and a geothermal power plant with two 15,000-kilowatt units of the direct steam-condensation type, as follows (in Italian lire, one US dollar being equivalent to about 620 lire).

	300,000-kW conventional plant	30,000-kW geothermal plant
Plant investment per kW net installed	70-75,000	80-90,000
Operating expenses per kWh of net output	0.35-0.40	0.70-0.80
Fuel cost per kWh of net output	3.10-3.30	—
Cost of steam per kWh of net output	—	0.50-0.55

These calculations are based in both cases on a working period of 8,000 hours per year. The operating expenses are higher in the geothermal station largely on account of smaller plant scale. The geothermal steam cost is apparently calculated on the annual renewal investment (annual drilling costs, etc.) to maintain the steam output, and even with a very pessimistic estimate the steam cost comes to less than one mill per kilowatt-hour (as compared with five mills for fuel costs in the Italian case). The total power cost depends also on the annual charge (interest and depreciation) resulting from the investment in plant; if the annual charge is taken at 10 per cent for the conventional plant and at 15 per cent for the geothermal plant (to provide for possibly greater corrosion problems and risk of heat supply), the total cost would come to about seven mills per kilowatt-hour in the big conventional plant and to less than five mills in the much smaller geothermal plant. In fact, the actual costs in the biggest Larderello plant, operated as a base load plant, are reputedly somewhere between two and three mills pre kilowatt-hour, or lower than for practically any power plant of any kind or size except perhaps for favourable hydro-power plants in Norway; this range is also about one-half of the most optimistic, and as yet unfulfilled, estimates for nuclear power on a large scale.

In conclusion it may be noted that, from a practical point of view, as far as geothermal electricity production is concerned, the most significant bench-mark is the cost per kilowatt-hour. Based on actual experience and on the conditions set out in the individual papers, this cost is indicated to range from about two to eight mills per kilowatt-hour. These estimates are generally based on a high utilization factor which may not always be possible to achieve in less developed countries unless geothermal plants are used for base load. To the production costs must be added transmission costs—which can be high indeed in cases where location is unfavourable in relation to the market and loads are low—and of course the usual local distribution costs. Even so, however, geothermal energy points to exceedingly low power costs in the few cases of actual exploitation and very possibly in a great many more cases still to be uncovered through prospection and the other stages outlined above.

Space and process heating with geothermal energy (GR/5)

Provided the market is located within a reasonable distance, geothermal energy lends itself particularly well to space and process heating requiring relatively low temperature (up to about 200° C). Reference has already been made to current utilization, particularly in Iceland, where such heating is of the greatest economic importance.

The domestic and district heating systems are developed to a high degree in Iceland (G/37, G/45). The Reykjavik system, for example, provides heat at a lower cost for the consumer and yet is one of the most profitable businesses in the city. The temperature in the main supply line is about 94° C, and drops only 1° C for every five kilometres. Geothermal heating has the advantages of being comfortable and clean (at least when possible corrosion and incrustation problems have been solved) as well as free from ashes or smoke, while at the same time it poses less of a fire hazard.

The production costs in Iceland are on about the same level as, or below, the average well head cost per unit of heat produced by natural gas in the United States. Computed in dollars per gigacalorie (one billion calories), the total cost (excluding profit and taxes) of heat supplied at the point of delivery is made up as follows: production, $0.60; transport in main supply pipeline, $1.45; water storage, $0.16; distribution in the city, $1.35, and booster plant operation, $0.50, giving a total of $4.06 per gigacalorie; this compares with a heating cost of about $7 per gigacalorie based on oil (G/37).

The present use of geothermal energy for process heating is small; but several proposed uses have been studied, notably in Iceland, that may encourage and attract industries there and elsewhere, at least to the extent that advantageous heating costs are not outweighed by transport costs for raw materials and by other cost increases. One such scheme (G/59) concerns the production of heavy water, which it has been found possible to produce in Iceland at a cost considerably lower than would be the case in comparable fuel-operated plants in western Europe. Implementation has been held up, however, owing to uncertainty about the future market for heavy water. Another case is provided by production of salt from sea-water in Japan (G/7), where salt is obtained mostly in open evaporation systems heated by geothermal energy; this production, however, is being abandoned because the costs are higher than those for imported salt and also because it interferes with tourist resorts centred on thermal springs, a common obstacle to utilization of geothermal energy in Japan. A salt production scheme in Iceland (G/27), assisted by United Nations technical assistance, has similarly been found to be marginal if production is limited only to 60,000 tons a year. This project has not yet been adequately studied for the combined production of salt and other chemicals, which may well put it on a very economic footing. Another obvious use would be the production of fresh water, by simple distillation, which could be especially interesting in arid regions lacking potable water but having geothermal energy. Among other applications considered may be mentioned drying and processing of such materials as diatomite, alumina, grass and peat (G/59) and use in absorption refrigeration and air-conditioning (G/52).

Recovery of chemicals and combined schemes (GR/5)

So far, little experience has been gained in combined schemes. The combination of power generation and space heating is an obvious possibility but it has not yet been tried out on any significant scale. The only important combined scheme currently in operation is that of Larderello which involves power generation and recovery of chemicals from the geothermal steam (G/39, G/63).

Geothermal fluids always contain chemicals picked up during their passage through various physical and chemical environments. The composition and proportion of those chemicals vary from field to field. In some cases, they may be rather harmless or low in concentration or both, as at Wairakei, where it has been found that the recovery of lithium and other chemicals would be technically feasible but would require a cost higher than the value of the chemical products (G/56). In other cases the concentration may also be low but may contain harmful substances, requiring elimination or separation of the nuisance chemicals in addition to the normal precaution of selecting metal alloys that will withstand corrosion. At Larderello, for example, it is necessary to clean out sulphur since otherwise 500 to 800 kilogrammes of sulphuric acid would be added to air pollution every hour (G/63).

The nuisance chemicals may play a "passive" economic role, so that final recuperation only reduces the energy cost increase; only in special cases, according to Garbato (G/63), will the chemicals contribute "active" value and be of interest in themselves.

Larderello is the only installation where the geothermal steam contains chemicals in the "active" as well as the "passive" value category. In fact, it will be recalled that Larderello started with recovery of chemicals and only much later did power generation enter the picture and become the main industry. Preoccupation with higher power output has had a profound influence on the design of new plants and reconversion of older plants. But the chemicals still make a not insignificant contribution to total revenue and are taken into careful account in the design of the various types of condensing plants discussed in an earlier section. The main chemical by-products include boric acid, borax, ammonium bicarbonate, boron carbide, sulphur and elementary boron. In another special case, carbon dioxide is now also produced in a geothermal area in Kenya.

WIND POWER

Some basic concepts and factors—Wind availability and site selection—Design and testing of wind power plants—Wind power applications and their improvement

In the industrialized countries, such as the United States, whose rural areas now enjoy the benefits of highly developed transmission networks, wind power plants by the thousand once helped to pave the way for electrification and a different way of life. Interest in those countries then turned to large wind power plants in big systems, under the impact of the early post-war fuel shortages and successful war-time experiments with the so-called Smith-Putnam wind turbine of 1,000-1,250 kilowatts installed at Grandpa's Knob in Vermont in the United States. With an easing of the fuel situation, interest may have been waning, but notable progress has been made in the past few years. Work undertaken, and in progress, has certainly contributed to a better understanding of the entire wind power field, from measurement of wind behaviour and adaptation of extremely simple windmills to the fine points of advanced aerodynamics. These achievements have been made largely without the benefit of large-scale support of the type given, for example, to atomic energy or of the fillip received by solar energy utilization when it was discovered to have applications in space programmes.

The energy situation is quite different in the less developed areas, as pointed out in an earlier section. There may well be considerable scope in those areas for wind plants of all kinds, for small plants of both the traditional mechanical and the electrical types on individual farms, for medium-size plants (ten to fifty kilowatts) in villages and even for larger installations in grid areas. Wind power, as noted by Thacker (GEN/15), "is a source of power well suited for programmes of rural community development in under-developed countries in Asia, Africa and elsewhere and calls for systematic and organized work on a large scale in these areas". This belief is supported by action, for example, in India, where 200 windmills of domestic design are to be installed shortly at selected sites on an experimental basis.

India is one among several countries which have set up a wind power committee or similar organization on government or private initiative. They exist in both industrial and less developed countries and are devoted to different aspects ranging from those of broad scope to wind surveys in the early stages.

Development of wind power plants is centred in Europe, where several national organizations are active and have installed relatively large wind plants (forty kilowatts and over). Among the plants in current operation, the largest one known, reaching a maximum capacity of about 900 kilowatts, has been installed recently in France (GEN/12), while a 200-kilowatt unit has been operating in Denmark since 1957 (W/20). Plants of 100 kilowatts have been installed in recent years in Germany (W/34) and in the Isle of Man in the United Kingdom and also in Algeria (W/8), the latter one having been transferred from the United Kingdom. Hungary has started on a 200-kilowatt unit (W/36), while in the Soviet Union efforts seem to be concentrated on medium-size units, notably at the experimental station at Istra near Moscow, as well as on water pumping and on grouping of generators to overcome problems of intermittent supply. In the Netherlands, long famous for wind power utilization, a traditional Dutch windmill has been converted to produce some forty kilowatts of electricity. Several of these countries also have modern wind power plants of medium size; most of the same countries, as well as Australia, Canada, Japan, South Africa and the Unites States, have small electric windmills in commercial production or in actual operation. Many small units have of course been imported into other areas, from Alaska to the Antarctic.

The wind power organizations in the less developed countries have mainly been preoccupied with wind power surveys, some of them reported at the Conference, to establish the possibilities for effective utilization. In addition to those of India (W/19), mention may be made of organizations and surveys in Argentina (W/10), Burma, Haiti, Israel (W/33), Pakistan, Spain (W/16), Somalia, Trinidad, the United Arab Republic (W/4) and Uruguay. In several of these cases the efforts have been supported by technical assistance from the United Nations and its specialized agencies, and they have in all cases been directed at modern utilization, largely for production of electric power as well as for pumping, based on scientific methods. They are thus distinguished from the use of traditional windmills—often of primitive contruction—which still, however, serve a highly useful purpose.

The wind power survey is a fundamental step and will be considered below in relation to wind availability and site selection, after a brief review of some basic concepts deemed helpful for an understanding of subsequent sections.

Some basic concepts and factors

Simple windmills have of course been used for many centuries, without much concern about the science of wind power and its utilization. Simplicity is still a desirable criterion. Modern techniques, however, provide the tools for designing more effective wind plants and for better utilization, including provision of energy in the form of electricity, as well as a better comprehension of the underlying, complex principles.

One of the basic factors is the very nature of the wind energy itself, which is based on mass (air) in motion. The energy increases with the density and the velocity of the mass. Air has a low density compared with, for example, water, whose energy on this account is about 800 times greater at the same rate of flow. Consequently, compensation has to be sought in a greater velocity or by a larger cross-sectional area of interception (swept area) of the mass flow or both.

The power (*P*) in the wind is proportional to the cube of the wind speed (*V*) and the swept area (*A*); it is expressed with the formula $P = KAV^3$, where (disregarding variation the units used to measure *A* and *V*. The speed is usually measured in miles per hour or metres per second (one mile per hour being equal to 0.447 metres per second).

The significance of wind speed is illustrated by the fact that if the swept area or interception area is 100 square feet and the wind speed ten miles per hour, the power available for extraction is 0.53 kilowatt, while at wind speeds of thirty, fifty and 100 miles per hour, it jumps to 14.3, 66.3 and 530 kilowatts, respectively.

The wind is intercepted by sails or blades on a rotor, which may be either vertical or horizontal. The vertical axis system has the advantages that it can accept wind from any direction and transmit the power directly to the ground, but it is inherently less efficient and is not used in modern machines. The horizontal axis system has to be supported by a tower of a height at least sufficient to clear the rotor blades safely from the ground and it must have some orientation device, such as a fantail, to keep the blades turned against the wind; it must also have, in the case of mechanical power, some kind of gearing and drive shaft to transmit the power to the ground, while electric generators can be mounted on top of the tower and even be directly coupled to the rotor, the energy being taken out through electric wires. A variation of the horizontal type is the so-called Andreau machine, designed in France and currently used in Algeria (W/8); it is based on a hollow tower and hollow blades or propellers, the latter being rotated by the wind, throwing out air to create a depression near the bottom of the tower where air is drawn in, and driving a turbogenerator on the ground.

With a given wind speed, the plant capacity may be raised by increasing the size of the propeller blades. The propeller or rotor diameter currently ranges from thirty to thirty-five metres in the largest machines, requiring a correspondingly high tower and extra investment. Conversely, and this is more important, the capacity of a machine having a given size can be increased by finding a windier site.

The capacity of a wind plant thus is determined not only by its physical size, but also by the wind speed to which it is geared or "rated". Machines are designed to give their full output at a certain chosen or "rated" wind speed; the energy in a wind of greater velocity is wasted. A high rated speed can be chosen (even as high as forty miles per hour) to take advantage of the very strong winds, but such winds occur rarely and machines reaching their capacity at those speeds would be very inefficient or inoperative at much lower speeds. Attention must also be paid, therefore, especially in the case of electric wind plants, to the so-called "cut-in" speed, at which the machine starts to operate and below which it may even, unless properly arranged, drain electricity from a battery or grid in a reverse operation. At the other extreme, there are braking devices and a "cut-out" speed to prevent overrunning and damage to the plant.

Another basic consideration, in addition to the capacity determined by rotor size and rated speed (and the conversion efficiency), is the annual output which can be obtained from that capacity. The number of kilowatt-hours produced per unit of capacity (specific output, which decreases with an increase in rated speed) is also a function of the rated speed of the plant and of the wind régime in the particular locality; the latter is disclosed by local wind power surveys usually resulting in so-called velocity duration curves and power duration curves (W/12). The number of hours in the year with wind of speeds in the operating range of the machine thus determines the maximum output which can be obtained. Again, the importance of selecting especially windy sites is pointed up by the fact that they permit a larger number of operating hours at a given rated speed as well as the choice of a higher rated speed. Both have a significant influence on capital investment and energy cost.

Plant investment varies with capacity and of course with location. The capital cost per kilowatt installed generally declines with an increase in capacity, particularly when a greater capacity is achieved by a higher rated speed, but also as a result of economy of scale in the case of a larger rotor diameter. Broadly speaking, the cost may still, as in the 1957 study mentioned in the introduction to this part of the present report, be estimated at some \$420 to \$560 per kilowatt for small electric plants, including battery, at \$280 to \$420 per kilowatt for medium-size plants with a capacity of from 10 to 100 kilowatts, and at \$140 to \$280 per kilowatt for larger plants.

The cost per kilowatt-hour depends on the number of kilowatt-hours produced per kilowatt, on the rates of interest and amortization applied to the investment and, to a small extent, on annual operating and maintenance costs. For most of the plant, a depreciation period of twenty years may be reasonable, so that with an interest rate of from 5 to 6 per cent, the annual charge (including maintenance) would be about 9 to 15 per cent of the investment, with the higher range applying to small plants with battery. This annual charge is divided by the number of kilowatt-hours to obtain the most significant cost figure. Applying the above figures and a reasonable range of specific output (some 900 to 5,500 kilowatt-hours per kilowatt per year), the cost is in the order of from 10 to 100 mills per kilowatt-hour for small electric plants with battery, between 6 and 60 mills for those of medium size and three mills or more for large plants, provided of course that the output is fully utilized despite the intermittent nature of the supply.

The ability to use the output as and when available, which will be discussed at a later stage, is a major consideration. It may be noted in passing, however, that for large plants in a grid system the primary concern is to obtain the lowest possible cost per kilowatt-hour, which in turn is likely to lead to the choice of a relatively high rated speed at the expense of a reduction in the number of operating hours. For smaller windmills operated in isolation and not in combination with other power plants, however, a relatively low rated speed is likely to be chosen in order to extend the number of hours of operation at full capacity, even at the expense of some increase in the cost per kilowatt-hour. In any case, every effort should of course be made to find the windiest site possible within reasonable and economic distance of technically feasible transmission. The possible distance decreases with the capacity of the plant and, in the case of a direct mechanical drive, as in pumping, the location is completely limited to the point of use.

Besides the multiple uses of its output, the modern electric wind plant does have the advantage that it permits a greater freedom in the choice of specific location, on more windy sites, thereby often more than compensating for conversion losses even in the case of water pumping.

Wind availability and site selection (GR/6)

General wind observations have long been collected by national meteorological stations, airports and other installations, for purposes of their own ranging from weather forecasting to interest in the wind as a meteorological phenomenon. This work is now co-ordinated at the international level by the World Meteorological Organization (WMO), which was represented at the Conference with a survey of existing wind observational information (W/11). Wind measurement in meteorology is further described by Perlat (W/13).

The meteorological data give a good first general indication of windy areas or regions and should certainly be taken into full account. The large body of data clearly reflects the importance of trade winds and the fact that coastal regions and islands generally are much windier than inland regions (W/11). In and around Africa, for example, some of the windiest areas are to be found in north and north-west Africa, in the Canary Islands (W/16), Madagascar and the Red Sea coast (W/4), while central and equatorial Africa may be characterized as less windy. Similarly, the coastal stations generally show the highest wind readings in Australia and in the western hemisphere, where the unobstructed plains east of the Rocky Mountains also are a relatively windy region. Eurasia is strongly under the influence of the seasonal heating and cooling of the huge land mass and, for example, in south Asia, the shifting monsoon. Some of the windiest areas are to be found in north-western Europe, especially in the winter time when the demand for electricity also happens to be at its peak and the river flow feeding hydroelectric stations is often at its lowest point.

The meteorological observations available—usually calculated as the mean monthly or annual wind speed but sometimes also with a frequency distribution of wind speeds—are thus useful for a general assessment, but they are not adequate for those interested in the wind as a source of power. This limitation is recognized by the meteorologists and the WMO, which notes that conclusions as to the practicability of tapping the wind "are left for the engineer or the economist" (W/11).

The inadequacy of the meteorological data for power purposes is due to several factors, among them the very location of meteorological stations interested in representative regional data rather than extremely windy sites. In wind power studies, on the other hand, the primary purposes are to find especially windy sites related to power needs, to obtain data on the probable power output and the wind structure there and sometimes special information related to wind power plant design and performance.

Consequently, special surveys usually have to be undertaken and at least temporary measuring stations set up to establish specific wind power possibilities. Such surveys in less developed countries have already been referred to above and are well illustrated, for one, by Soliman (W/4). They have also been undertaken in several industrialized countries, sometimes on a large scale; Argand (W/35), for example, summarizes pertinent data and results for 181 stations in France, as well as for 140 in Africa and some others, expressed as the mean theoretically recoverable wind energy in kilowatt-hours per square metre per year and obtained directly in that form through an ingenious French measuring device.

The special wind survey, which requires careful planning and proper execution to give reliable information on the wind régime, provides data which may be analysed in such terms as short-term variations (important for the plant designer), diurnal and seasonal variations, frequency and duration of low wind spells and other wind factors affecting the technical and economic possibilities of power production. At least hourly records may be needed for a year or two, and they may then be extrapolated by correlation with longer-term meteorological data, which should be put to full use "because the general features of the wind régime for an area will hold also for particular sites within it" (GR/6). Moreover, and this is highly significant, so-called velocity duration and power duration curves (W/12) constructed from the data have been found in several surveys to be remarkably similar in their distribution in relation to a particular mean annual wind speed, so that the latter figure may often go a long way in the preliminary estimates. The wind data on the site may be obtained through a variety of measuring instruments, ranging from simple cup-counter anemometers to complex registering and integrating devices described in the technical papers; it is sufficient to note here that the choice of instruments has to be properly decided in relation to what is to be measured and that care has to be taken in noting their height above the ground since the wind speed generally increases with altitude.

The geographical placing of the instruments, and of the ultimate power plants, has to take proper account of the local topography so as to draw advantage from the compression and higher speed of winds over certain types of hills and mountains, as discussed for example by Frenkiel (W/33), Lange (W/28) and Petterssen (W/26). Such careful site selection may give a mean wind speed several miles per hour higher than that in near-by locations and this may make it possible to obtain an increase of at least 50 per cent in power output. Site selection thus aims at finding those windy spots, whether on the coast or inland, that are reasonably accessible and near the point of use.

Design and testing of wind power plants (GR/7)

The designing and testing of wind power plants are functions of the engineer. As illustrated by several of the technical papers, he has many choices. They cannot be considered in detail in this report, beyond noting a few variations and stressing the profound importance of the intended use and the influence of the local conditions.

The engineer will be concerned not only about designing a machine actually able to work efficiently under the conditions and for the purposes envisaged; he will also want to give primary emphasis to meeting those purposes in the most economic way, in terms of the lowest possible initial cost compatible with a reasonably long service life, and he will be especially concerned with obtaining a minimum cost per unit of output. That most economic way will take into adequate account the needs for easy replaceability of parts, transportation and installation, for simple and inexpensive operation, minimum maintenance and for withstanding risks of destruction in high winds.

For certain purposes, notably water pumping, improved versions of the simple mechanical windmills may still be the best solution in particular localities. They can often be made wholly or largely from locally available materials and with local labour, incorporating such materials as bamboo and reed mats for rotor sails. The classical Dutch windmills (W/32), for example, were made almost entirely from wood and were either of the horizontal rotor type with a geared vertical shaft or arranged in a sloping position directly connected with a so-called Archimedean water screw for shallow pumping; they still have a future in less developed countries, if adapted to the skills, materials and tools of the local tradesman. Modern technology can make a significant contribution to such adaptations, as pointed out by Stam (W/40). The conventional steel windmill may in fact be too advanced for the villagers (W/23).

An example of adaptation is provided by India (W/23), where a mechanical windmill (costing about 2,500 rupees, with a pump) has been developed; designed for five to eight mph winds, it has twelve blades with a rotor diameter of eighteen feet and is able to lift some ten million gallons per year (depending on depth). The mechanical mills often have such a large number of rotor blades, and may have either a slow-running wheel connected with a piston pump or a high-speed rotor with a propeller pump or centrifugal pump.

The modern trend, however, is towards electric wind power plants. They introduce many more possible design variations and problems. The variations relate to such factors as the choice of current (alternating or direct), slow or fast and constant or variable rotor speed, arrangement and number of rotor blades, type of tower, kind of materials and control mechanisms. Several of the variations are interdependent.

Small electric plants, for example, usually generate direct current, which is an advantage in connexion with storage betteries and creates less of a problem as regards speed regulation. For larger plants in electric grids, on the other hand, alternating current generation is preferred and calls for a number of control mechanisms and matching arrangements, as described for example by Armbrust (W/34), Juul (W/17) and Sterne (W/30).

Modern design draws on advances made in aerodynamics, as illustrated by Hütter (W/31). It is no accident that several recent improvements have been brought about by technicians closely connected with aeronautics, notably in the design of rotor blades. The latter now often look like airplane propellers and are usually two or three in number. The big Hungarian plant (W/36), however, is designed with four blades and incorporates a new type of speed-up gear as a major development; it is designed to start at three metres per second, give 100 kilowatts at eight metres per second and reach its capacity of 200 kilowatts at 10.4 metres per second for an annual yield of 320,000 kilowatt-hours.

Aerodynamics also enters into the placing of the propellers, a frontal position being preferred while a position behind the tower gives auto-orientation (W/39). The propeller blades on some new machines, both in France and Germany (W/27, W/34), are made of plastics reinforced with glass fibre rather than of metal to reduce weight and corrosion and to lengthen life considerably. The rotation of the blades may be controlled, for example, by varying the blade-pitch (W/5) or by brake flaps (W/17).

The tower itself requires careful design considerations in order not to become a wind obstruction or cause vibration, and to facilitate installation and maintenance. Among interesting designs in this respect is one reported by Villinger (W/27), who has developed small wind electric plants of 200 and 500 watts having a telescopic tube tower that can be manipulated from the ground; his plants, however, appear relatively expensive in the prototype stage, the initial cost being estimated at $750 to $1,000 and the output cost at 15 to 27.5 cents per kilowatt-hour (with battery).

The refinements can be carried to extremes, making the plant very costly. It is therefore not surprising to detect a certain new emphasis on robust and relatively simple design with a view to economy, as in the 100-kilowatt plant on the Isle of Man and the 200-kilowatt plant at Gedser in Denmark (W/17). The former, designed to start operation at winds of eighteen miles an hour, costs some $140 per kilowatt while the cost of the latter was DKr 272,000 (about $39,000) plus DKr 48,000 for designing, etc. and DKr 55,000 for measuring equipment, and it could probably be reduced to about $36,000 or $180 per kilowatt if built in large numbers (W/20).

The tests made on this plant (W/15) as well as on others have been extensive. Some of the results are applicable to other machines, while those for example on the Andreau-type machine in Algeria (W/9) are more limited to the type in question. Tests refer to such factors as the power-output/wind-speed relationship and stress levels in the blade system (W/24) as well as to the possibility of cutting costly testing time by short-period testing (W/3).

Wind power applications and their improvement (GR/8)

In considering the utilization of wind power plants, it is useful to distinguish between three categories, namely, household and other individual uses, community use and use in connexion with electrical networks. These three purposes approximately correspond to the use of plants of small, medium and large capacity, respectively.

Household and other individual uses require only small plants—which are readily available commercially in the range of from 0.25 to three kilowatts—but usually also need full battery storage to make the unit self-contained and able to carry on over calm spells. The users of such plants thus take advantage of local energy and free themselves from the cost of transmission or, more commonly, from the lack of a transmission network.

The small electric plants have been sold by the thousands, especially in the industrialized countries. For one such plant of 2.5 kilowatts, the total factory cost is indicated (W/22) to be $1,025 (including $360 for battery and $175 for tower) or about $400 per kilowatt, to which has to be added shipping and installation costs. Records for more than one thousand of these plants show repair costs to average less than $5 per year; hundreds of them are used for cathodic protection of underground steel pipe lines, while the more usual applications of the power output from small plants are, naturally, for lighting and other domestic amenities and for grinding, mixing, refrigeration and other small power uses.

Two interesting case studies may be noted in this connexion. One (W/6) refers to the installation of a 2.5-kilowatt plant at the port of Eilat in Israel prior to the opening up of road and other facilities. The total investment cost in this plant was about $2,500 (including $1,100 cif for the plant proper, $1,100 for the battery and $300 for erection). The cost of power is estimated at 100 mills per kilowatt-hour produced and 150 mills per kilowatt-hour consumed as compared with about 180 mills per kilowatt-hour for comparable diesel-generated power; the author (Frenkiel) draws the conclusion that in any undeveloped area requiring less than 10,000 kilowatt-hours per year and having a mean wind speed of five metres per second or more, there is advantage in installing wind power units.

The other case study (W/25) refers to a rather typical Indian farm using a wind electric plant (rated at six to eight kilowatts but giving two to four kilowatts under the given wind conditions) without battery for water pumping, the cost of which is estimated at less than one-third of that based on a diesel engine there. Another paper from India (W/23) also stresses water pumping—by means of equipment which must be simple and cheap to be suitable—and ranks the demand for electricity as secondary.

Nevertheless, small supplies of electric power for various uses will undoubtedly continue to be sought to an increasing extent in less developed areas. One such use is the powering of radios, which it is claimed in one paper (W/38) can be built, together with a wind-driven generator, for as little as $15. In industrialized countries, such as Japan (W/5), the small plants presumably are more limited, for example, to islands, isolated villages and relay stations.

As regards medium-size plants used as isolated units or in combination with conventional power sets for community purposes, experience is small to date. The most outstanding case and lesson appear to be presented by Denmark (measured in kilowatt-hours per square metre of area swept) has increased considerably largely because extensive alternating current grids are able to take delivery of a far greater part of the possible output.

Juul (W/21) argues with conviction that, at least in Denmark, the role of big wind plants is more than that of just saving fuel (and foreign exchange for fuel imports) and claims for them a certain capacity value in view of the usual coincidence of peak demand and wind availability. In fact, he believes that 20 per cent of the Danish electricity consumption ought to be met from wind power.

If capacity and other value can be claimed, a higher cost per kilowatt-hour from wind plants can be allowed than the fuel cost saved in thermal plants. Otherwise, the latter usually sets the upper cost limit. The permissible cost in hydro-power systems is more difficult to pin down, partly because transmission costs also enter the picture more significantly in this case. The possible role of big wind power plants in industrial countries is still under study, however, and the conclusions, notably from the experience with the big French wind plant referred to by Ailleret (GEN/12), are awaited.

SOLAR ENERGY

Solar energy availability and its measurements—New materials in solar energy utilization—Water heating—Space heating—Heat storage—Solar drying—Solar cooking—Solar refrigeration for food preservation—Solar airconditioning—Solar distillation producing fresh water—Solar furnaces for high-temperature processing—Mechanical and electric power from solar heat engines—Direct conversion of solar heat to electricity—Direct conversion of solar light to electricity

The widespread interest in solar energy utilization is clearly reflected in the large number of papers on solar energy submitted to the Conference. They are indicative of relevant activities in Australia, Belgium, Brazil, Canada, Chile, the Federal Republic of Germany, France, India, Israel, Italy, Japan, the Netherlands, New Zealand, Portugal, South Africa, Spain, Sweden, Switzerland, the Union of Soviet Socialist Republics, the United Arab Republic, the United Kingdom and the United States. To this list might be added Burma, China, Greece, Mexico, Senegal and many more, as demonstrated during and after the Conference and by membership in the international Association for Applied Solar Energy.

Solar radiation may be put to many uses through the utilization of various processes and types of equipment. The practical applications may be divided, as was done in the Conference, into the production of mechanical and electric power, which will be dealt with last in this section, and applications for other purposes. The latter include water and space heating, solar drying and cooking, refrigeration, space cooling, water distillation and high-temperature processing (solar furnaces), as well as simple evaporation used on a huge scale for salt production and other industrial operations. First, however, it is necessary to consider the solar energy availability itself and its measurements and also the new materials finding use in various applications.

Solar energy availability and its measurements (GR/11)

An understanding of the nature and extent of the available solar energy is fundamental for the designing of equipment to convert the energy into a useful form and harness it for effective utilization. It is an area in which the meteorologists play a predominant role, as the technical papers on this subject demonstrate, but it is also one in which the solar energy engineer has to make his particular data needs and requirements clear and perhaps even fill the gaps himself.

The electromagnetic radiation emitted by the sun is known to reach the outer atmosphere at a rate of about two calories per square centimetre per minute, the value of the so-called solar constant. The radiation may be divided according to its spectral or wave-length distribution—significant notably for photoelectric devices—into ultraviolet and visible and near infra-red, the latter two accounting for over 90 per cent. The atmosphere distorts the radiation and alters the wave-length distribution. The energy actually reaching the ground varies with latitude, altitude, season, time of day and other factors, such as topography, meteorological elements, atmospheric dust and contamination. The radiation available on the ground is composed of beam or direct radiation, which is the only kind useful in focusing collectors, and of diffuse radiation; the latter can account for up to half the available energy in the humid tropics (S/98) but is less important in clear, dry climates. There is also solar radiation reflected by the earth's surface, and long-wave re-radiation, such as nocturnal radiation (S/34, S/95), which is particularly significant for some cooling purposes. The direct plus the diffuse radiation, or the global radiation, may reach some 750 calories per square centimetre per day in sunny locations; but it varies greatly and in any case is characterized by a low-energy density. Taken at about one calorie per square metre per minute, for example, an area of fifteen square feet is required to receive the heat equivalent of one kilowatt, and in practice a much larger area is necessary after taking account of practical conversion efficiencies and losses.

If the radiation were not distorted after entering the atmosphere, it would be quite easy to calculate the solar energy availability at any particular place and time. Since this is not the case, measuring stations have had to be set up and more will be required. Most of them are part of meteorological networks, whose work, co-ordinated at the international level by the World Meteorological Organization, was given a special impetus during the recent International Geophysical Year. Some 500 pyrheliometric stations thus have records of global radiation and many of them of diffuse and direct radiation as well. Most of them, however, are located in North America, western Europe and Japan, so that the density of stations is very low or practically non-existent in the less developed areas and particularly so in the arid zones where some of the best opportunities for solar energy utilization may exist.

Examples of solar radiation data and analysis are contained in the reports to the Conference on such countries as Australia (S/32), Canada (S/18, S/20), India (S/60, S/105), Japan (S/2) and the United Arab Republic (S/62). In the case of India, for example, it is interesting to note that Bombay receives less than three hours of sunshine per day during the monsoon, but that this season is also the windiest, so that wind and solar energy could supplement each other in many parts of India (S/60).

The purpose of data collection and analysis is to gather information on the different types of radiation, on the spectral distribution, on the total and mean daily, monthly, seasonal and annual values, on the frequency of periods of successive days of low radiation (S/13) and on other factors. The likely periods of low availability, for example, have a significant bearing on the size of the energy storage needed. To some extent, fairly good estimates may be made with the help of various formulae from such simple data as the number of sunshine hours, but the solar engineer will frequently be dissatisfied with crude estimates and data from distant stations. They fail to detect microclimates, and an increase in station density appears essential.

Various instruments and methods are now available for measuring radiation. They are discussed in great detail in the technical papers, by meteorologists and solar engineers reflecting various views, for example, with respect to the kind of measurements desired, the choice and design of instruments, the accuracy required, the standardization of data presentation, the placing of measuring stations and the period of time required to establish records sufficiently reliable for practical purposes. Low instrument cost, robustness and ease of operation by non-specialized personnel are stressed, although these may have to be achieved at the cost of some accuracy.

New materials in solar energy utilization (GR/12)

Increasing attention is being given to the development of new and improved materials particularly suited for use in solar equipment. The technology in this field is advancing rapidly. To a large extent it holds the key to the reduction of existing technical and economic limitations and to the opening of new possibilities for practical solar energy applications.

The performance and costs of materials are especially significant in relation to the solar energy collectors, whether of the flat-plate or focusing type, owing to the relatively large surfaces required and because the collector or heat exchanger usually accounts for the bulk of the investment. Improved performance, for example, reduces the collector area required for a given heat output and may have much the same economic effect as the introduction of cheaper or more durable materials.

Performance is substantially determined by the radiation properties of the materials used: absorptivity, or ability to absorb the incoming energy; emissivity, or heat loss through outgoing energy; transmissivity, or characteristic of letting radiation through, as in the cover of a flat-plate collector or solar still, and reflectivity, of particular importance in focusing collectors which concentrate the radiation on to a smaller surface to reach a higher temperature. Ideally, then, an absorbing surface, for example, should have high absorptivity and low emissivity for radiation losses, while a reflector surface should have high reflectivity throughout the solar spectrum. At the same time, attention must be paid to the physical properties of the materials, such as weight, thickness, pliability, resistance and durability, which determine the design possibilities and, of course, ultimately, the cost of the useful energy.

Materials differ widely with regard to these various properties, as described in detail in the technical papers dealing with plastics (S/33), aluminium alloys (S/86), glass (S/91) and a variety of materials (S/42); efforts are continuously being made to improve the desirable properties and minimize the unfavourable ones, both of which have to be taken into account in seeking an optimum solution in the specific application. In particular, a great variety of plastic films with different characteristics have been developed and hold out promise for several applications, in part because they can reduce the initial investment very considerably. Plastics are most readily thought of in connexion with flat-plate collectors, but metallized plastics are also used for reflectors supported by glassfibre-reinforced plastics at a material cost as low as about one dollar per square foot (S/104); indeed, new plastics and techniques may have brought focusing collectors, at least those of small size, down from what was formerly thought to be a prohibitive cost level for many uses, and have found their way into lenses and prisms, too, as an alternative way of concentrating radiation (S/22). Alongside these developments, improved glass mirrors and anodized aluminium have been put into focusing collectors, while for flat-plate collectors, plates and tubes are now produced in one operation. In addition, experiments have been made with the configuration of receiving surfaces (S/71) in attempts to reach much higher temperatures without the necessity of tracking the sun.[6] Also noteworthy are experiments, demonstrated in Rome, with new shapes of reflectors, such as a cylindrical reflector forming part of an inflated plastic cylinder operating at 150° C, or a crude type of cooker made of simple conical sections covered with inexpensive reflecting material.

Perhaps the most exciting development, however, relates to so-called selective surfaces (S/6, S/43, S/46). By means of various coatings and other surface treatments, it has become possible to increase absorptivity and especially to reduce emissivity considerably (or the reverse for "cold" surfaces), resulting in lower heat losses and consequently in greater collector efficiency or higher working temperatures. This is highly significant in flat-plate collectors which are otherwise characterized by relatively low equilibrium temperature (at which the energy absorbed equals thermal losses and the efficiency becomes zero). Selective surface treatment is in commercial use, for example, in the production of water heaters in Israel (S/46), where the particular coating is estimated at 5 per cent of the total collector cost.

Interest in selective surfaces, as well as in relevant materials generally, has been heightened by the increased space exploration efforts, which are also a major factor behind the development of materials and devices for direct conversion of solar energy into electricity dealt with in a later section.

Water heating (GR/13)

Solar water heaters are used in vast numbers and represent the most widespread direct application of solar

[6] An automatic tracking device is usually an expensive part, but for small focusing collectors tracking can be provided simply in the form of a spring device set each morning. With simple solar cookers the turning is, of course, done by hand.

energy. The countries or areas reported on in the Conference include Algeria (S/72), Australia (S/38), France (S/58), India (S/102), Israel (S/26, S/31), Japan (S/68), South Africa (S/97), the United Arab Republic (S/50) and the Unites States (S/1, S/96), and many others may be added. The greatest number is undoubtedly to be found in Japan, where some 350,000 solar water heaters were in use at the end of 1960 (including 100,000 added in that year) and a figure of one million is hoped for by 1965; they will save over a million tons of high-cost fuel (S/68). There are about 10,000 units in use in Israel (S/26), while in the United States some 25,000 units are employed in Florida alone. A new application has been found in the heating of swimming pools to extend the season from 50 days to about 150 in the north (S/96).

The popularity of solar water heaters, which can suitably be used in areas between latitudes 45° North and South having more than 2,000 hours of sunshine per year (S/58) and which achieve temperatures up to about 70° C, may be traced to the growing demand for hot water, the simplicity and usually the low cost of equipment and an improved competitive position in relation to other sources of heating.

In its simplest form, the water heater consists of a plastic "pillow" containing 200 litres of water and costing as little as $6 in Japan (S/68); it has no separate storage unit and is tapped in the afternoon or evening for bathing and other uses. An insulated box with a transparent cover and regulated by hand operates in the same way, and for a family-size unit costs $20 or less.

Most types, however, have a separate storage unit to provide hot water at any time (S/1). They essentially consist of a blackened metal absorber surface (containing ducts to let water through for heating) in an insulated box with a transparent cover (to reduce heat losses), an insulated storage tank and piping to lead water to the absorber, the tank and the point of use. The hot water is usually led to the tank (at higher elevation, by natural (thermosyphon) circulation so that no mechanism is needed, but a small pump may be added to force the circulation or change its direction. There are many variations in these basic elements, such as in the choice of materials for the absorber and other parts, the arrangement of ducts in the absorber and the orientation and inclination of the unit in relation to the incoming solar energy. Among the innovations may be noted the use of plastic coating to prevent corrosion (S/68), plastic tubes in the water ducts to avoid freezing (S/96), and the introduction of flexible inclination (allowing seasonal change with solar altitude to increase efficiency) and an irreversible thermosyphon (S/58).

Heater units may be divided into sizes for household use and larger ones for public baths, laundries, hotels and so on. In the former, the collector area is usually about two square metres; the number of collector units can of course be increased as is usually done in larger installations. The storage capacity is similarly geared to the quantity needed, and to the length of periods without sunshine.

The capital costs (or selling prices) of solar water heating installations vary greatly and cannot be compared directly without taking into account the many factors involved. With this reservation, however, it may be noted that for "family-size" units, figures of $6 to $120 are indicated in Japan (S/68), about $75 to $105 in India (S/102) and $315 to $400 in France (S/58) while in Israel (S/26) it is believed possible to reduce the price of the collector from $70 to $40 with mass production. Larger installations will of course cost more in total, but less per square metre or similar unit. The useful life also varies, ranging from about two years (for the plastic "pillow") up to fifteen years or more.

For this and other reasons, it is also difficult to compare directly the cost per unit of useful energy output or even to calculate it at all, although a few technical papers do give figures ranging from about four to thirty mills per kilowatt-hour. Rather, there is a tendency to estimate how quickly the initial investment can be recovered in terms of saving of electricity or fuel costs. This period is found under given conditions or assumptions to range from a few months to many years. Generally, a capital cost "recovery" period of three years seems to be aimed for. Solar water heating is thus a most promising application in economic terms, at least when the favourable comparative calculation is based on what can actually be utilized and not just on what can be produced.

Space heating (GR/14)

At first sight, space heating with solar energy may seem incongruous since space heating is usually most needed when there is little or no sunshine. Indeed, a large part of the problem lies in the storage of heat, dealt with in the next section, particularly since no economic device has so far been designed to store summer heat for winter use.

Nevertheless, a keen interest has been taken in solar space heating, particularly in the United States, where it may be the most important potential solar application (S/30) in view of the large share of space heating in total energy consumption. Space heating is of primary concern in temperate, industrialized regions which have adequate solar radiation in winter and where the potential users can afford the relatively heavy investment to save fuels. In those under-developed areas which need domestic heating, systems of this cost and complexity would be very few, at least in the near future, primarily for economic reasons; such areas would be better served in the first instance by closer attention to improved design of the dwellings themselves.

Several experimental solar-heated houses and laboratories have been built recently, many of them described in detail in the technical papers dealing with installations in Japan (S/94, S/112) and the United States (S/3, S/30, S/67, S/93, S/114), as well as with a Swedish station at Capri, Italy (S/49). They provide useful design and operating experience, if not economic encouragement.

There are several similarities between devices used in water and space heating and the two may in fact easily be combined. Basically, the system consists of circulating water or air through a black flat-plate collector in order to remove the heat, which is then carried into the house or into a storage tank containing water, crushed rocks or chemicals capable of absorbing heat and later released for useful purposes. The system may in some cases be operated in reverse in the summertime so that warm air or water is drawn through the collector (S/30, S/94) or other part of the roof (S/3) for moderate cooling through night radiation. The various systems in operation differ in details. For solar space heating systems to be successful in underdeveloped regions, however, it may be prescribed (S/30) that they should: require no auxiliary electricity; permit moderate and simple use of auxiliary fuel; permit moderately wide variations of interior temperature; be low in initial cost. Unfortunately, few or none of these criteria appear to be met in the existing solar houses.

The most significant, and costly, item is the solar energy collector itself. The largest collector on the houses described in the technical papers measures 1,623 square feet or 150 square metres (S/30). The size of the collector (for a particular heating load) depends on many factors, including its efficiency and the extent to which it is desired to rely on solar energy. Collector costs appear to range from one dollar per square foot (S/3) up to much higher figures. Among the important cost and design criteria, it may be noted (S/93) that the solar heating system and the design of the house should be integrated, so that the collector becomes a part of the roof or better still of the south wall (in the northern hemisphere); the latter gives greater efficiency in the wintertime and loses heat to the house rather than to an attic. The design decisions may be facilitated by the rapid simulation of different solar and efficiency conditions in an electronic-mechanical analogue (S/19).

The economics of solar space heating is largely determined, apart from its own merits, by the alternative cost of fuel or electric heating. The latter may deliberately be incorporated as auxiliary units, to reduce collector and storage costs. Among the cases reported, aside from a laboratory heated entirely by solar energy (S/93), the houses have obtained from 25 (S/114) to 95 (S/3) per cent of their heat requirements from solar collectors and have saved fuels accordingly; but in some cases, this saving has been partly offset by increased use of electricity in the system. Moreover, the fuel or electricity savings should—but generally have not so far—offset the appropriate interest and depreciation on the extra investment in the solar heating system, which, in the cases reported, ranged from $1,000 (S/3) to $4,500 (S/30).

These cases point up the dependence on competitive ability in relation to fuel costs and the obvious fact that solar space heating will be more attractive where fuel costs are higher. Put in another way, one may calculate from fuel savings how much additional investment would be justified. Based on conditions (fuel costs, degree-days, interest rates, etc.) typical in the north-eastern United States, one such calculation (S/93) comes to the conclusion that the investment in the solar heating system (including storage) may be up to 130 per cent higher than in conventional heating equipment to break even.

HEAT STORAGE (GR/17)

The importance of heat storage has already been mentioned in relation to solar water and space heating. As will be obvious in later sections, other applications, such as space cooling and power generation, would also benefit from improved heat storage.[7]

Since solar energy is available for a limited period and only during the day, the heat storage problem is a vital issue. In fact, "any improvements in the present methods of storing solar energy will have wide applications and open the way to extensive and more economic utilization of sun's heat" (GR/17). There is considerable room for improvement in, and for reducing the cost of, heat storage systems. Relatively little progress appears to have been made in this important field, perhaps because of insufficient effort and lack of ideas.

The magnitude and nature of the heat storage problem may be viewed in the light of several factors. One of them is the locality or region of proposed application, since this determines the number of hours of sunshine available and its intensity. Another is the end use of the energy, which determines whether the storage desired should be at a comparatively higher or lower temperature. Water and space heating, for example, require only modest temperatures (one of the reasons for their relative success), while temperatures would have to be much higher for cooking or running certain solar engines after sunset.

A third factor is the period for which storage is necessary or desirable. For certain uses, such as cooking at night, effective storage for a few hours may be a great improvement. Or the period may be a few days to tide over cloudy spells, as is often the case in water and space heating. For many purposes, however, and space heating in particular, it would be desirable to find an economic solution to the problem of storing heat during the long hours of summer sunshine for use during the following winter months.

A key consideration in the storage system is the material in which the heat energy is stored. The materials can be divided into those (such as water or rock pebbles) which store energy in the form of sensible heat and those that undergo a change of state or physico-chemical changes within the practical range of operating temperatures. Storage by means of hot water in an insulated tank or of air-heated rock piles is simple and frequently used, but it is bulky, taking some four per cent of the total house volume to store enough heat for just two days or less in a temperate climate. Even such short storage requires perhaps 25 or 50 tons of insulated rock pebbles, and when large quantities of energy are to be stored these systems are not cheap. In fact, attempts to make, for example, a whole basement into a heat storage reservoir appear to have been limited to scale model tests (S/20).

Storage space—and with it heat losses and insulation costs—can be reduced considerably, however, by using suitable storage materials which undergo a chemical or physical change upon the introduction of heat from the collector and later give up heat in a reverse change, such as from solid into liquid and vice versa. A few such materials have been tried, and Goldstein (S/7), for example, has surveyed a large number on purely thermo-dynamic grounds from the point of view of the maximum storage capacity in order to isolate physical and chemical processes

[7] Energy storage problems in general are considered in relation to power generation in the last section.

having potential application for heat storage at temperatures ranging from 30° C to 200° C. The various materials and processes differ, for example, with regard to whether the transition takes place abruptly at a certain temperature or gradually, and some may not in fact be reversible so that mechanical stirring becomes necessary. Much remains to be done to find materials and processes that are most suitable technically and, especially, economically. The advantages must not be more than balanced by unduly high investment in the new storage materials themselves, at least not for practical applications on the ground.

Solar drying (GR/15)

Solar energy can be used in several ways for drying agricultural and other products. The simple spreading of the material on the ground for direct exposure to sunshine has of course been practised for ages and involves no special equipment. The drying may be speeded up and better controlled in flat-plate collectors, another form of direct exposure drying. Solar drying may also be indirect, by solar heating and circulation of air, in which case it becomes similar to space heating but less demanding with regard to temperatures and heat storage. In addition, mirror-type collectors can be used for drying (evaporation), as is done in Burma and India for concentrating palm juice to produce joggery (unrefined sugar), thereby avoiding transport costs and undesirable fermentation; this simple mirror concentrator, which requires only cheap labour for operation, is estimated to pay for itself in three seasons.

The economic feasibility of more controlled solar drying, as compared with simple direct drying, may be justified by higher quality, cleanliness, time saving, reduced spoilage and other factors. But it may also have to be justified in comparison with electric or fuel heated drying, which can achieve the same and often better results, or in terms of fuel and power savings in combined systems.

Simple direct drying, which now has been studied in some of its scientific aspects, has still been found to be the best, for example, in the drying of properly arranged vine fruit in Australia (S/4); in fact, the conventional natural drying there costs only about half as much as tunnel drying with artificial heat and gives a satisfactory product. A new possible application is the direct solar drying of oil shale in Brazil (S/83), in which the cost (mostly materials handling) is estimated to amount to about one-third of the resulting increase in product value and the result is said to be far superior to fuel-heated drying of the shale prior to retorting. On the whole, however, little effort seems to have gone into the development and improvement of the simple solar drying now used to process enormous quantities of materials. This world use of solar drying, corresponding to an annual thermal equivalent of millions of gallons of oil, would appear to justify a considerably larger development effort.

The indirect method based on solar-heated air has been tried on a limited scale and can be simple as well as advantageous under certain circumstances, as described in two cases of crop drying (S/17, S/53). In one case (S/17), for example, it has been found that a temperature rise of a few degrees cuts the drying time by from 50 to 75 per cent (and with it the chances of grain spoilage) and that the extra cost of the solar energy collection can be recovered by power savings in from one to five years. In both cases, however, electric fans are used to circulate the heated air, and this would be a serious limitation in most less developed areas.

Solar cooking (GR/16)

Solar cooking is frequently referred to as an appealing practical application of solar energy. The users commonly envisaged are the individual households in poor villages and rural areas in the less developed regions.

Much work has gone into the study and design of solar cookers. Many types have been made and tested in laboratories in several countries, such as the Netherlands (S/24), Portugal (S/110), the United Arab Republic (S/75), the United States (S/87, S/100, S/101) and others including Burma, India, Japan, Lebanon and the Soviet Union. Some types have been field tested, especially in the case of the so-called Wisconsin cooker, on a fairly large scale in Mexico (S/87). Few are in commercial production. Generally, to quote Löf (GR/16), "solar cooker development appears to be in an uncertain, but potentially significant, state".

The uncertainty lies less in the scientific and technical end than in the economic and user end. To be economically acceptable among poor people (unless financed or subsidized by government or other sources), solar cookers have to come down in cost to a few dollars (compared with current costs of $10 or more), and even so it is not certain that they would become popular. The drawbacks may as well be recognized from the outset; they are easier to pin down than the benefits.

A major disadvantage is that solar cooking can be performed only when the sun shines, unless supplemented with heat storage, which adds to the cost; and at least in several countries the main meal is eaten at night rather than in the middle of the day, a custom among many which may not be easy to change. Except with complications and extra costs, the cooking also has to be done in the heat out of doors, possibly in view of hungry or curious bystanders. These are among the reasons for failures of tests undertaken in villages in India, for example, and they indicate that anthropologists and sociologists also have a role in introducing solar cookers, as has actually been the case in the Mexican tests. Moreover, the individual economic incentive may be lacking, at least if the present cash cost of household fuel is nil, as is usually the case in the widespread use of dried animal dung, twigs and agricultural waste materials gathered by people who might otherwise be underemployed.

The advantages are more obvious to those who buy kerosene and other fuels and who may recover the solar cooker cost rather quickly through fuel savings. In broader terms, the widespread adoption of solar cookers may lift a burden from underprivileged people, save animal dung for more valuable use as fertilizer and avert indiscriminate fuel collection leading to erosion and other economic injuries. The potential significance lies largely in these factors and in promising technical progress.

The solar cooking devices are simple. They are of two basic types, both able to reach temperatures (up to about 250° C) required in normal cooking processes. One is the focusing or direct-type cooker often called simply a solar cooker, which is based on a focusing collector concentrating radiation on to the food or cooking vessel (S/24, S/87, S/100); it acts essentially like an open fire. The other is the oven-type cooker, or simply a solar oven—an insulated box with a transparent window exposed to the sun which has the radiation intensified by flat reflectors either outside (S/101) or inside (S/75) the glass cover; it is the equivalent of a fuel-fired oven. A hybrid has now been designed by Prata (S/110) in an attempt to combine the advantages of both; it is basically a drum-like oven with a small window into which is concentrated radiation from focusing collectors. They all differ in their use of materials and detailed arrangements, but could all be manufactured in less developed countries, possibly with a minimum of imported materials.

Each basic type has its own characteristics, advantages and disadvantages. The focusing solar cooker, which is even made like an inverted umbrella with the pot at the handle (S/100), concentrates high heat and is suitable for boiling, stewing, grilling and frying (and, with adaptation, also for baking and roasting). It has to be turned every fifteen to thirty minutes, goes out of operation during cloudy spells and easily loses heat to the surroundings, especially when it is windy; but it does bring a litre of water to boiling point in about fifteen minutes and provides up to about 500 watts of effective cooking power (S/87) even in the winter. The Wisconsin cookers (S/87), which have been made non-commercially by the hundreds, have an estimated factory price of $16 in medium-quantity production and a modified version might be brought slightly below $9 in mass production (using aluminized plastic film on reinforced plastic shell). The umbrella type (S/100) retails for about $30 and might be reduced to $10 or $15 at greater production in the country of use, while the Indian cooker came to about $14-17. New designs may reduce the costs further as indicated by a Fresnel-type segmented reflector cooker demonstrated in Rome.

The solar oven is best suited for roasting and baking, but can also perform other cooking processes. It provides protection from the wind, utilizes some diffuse radiation, can carry over brief cloud periods, loses heat less rapidly (S/75) and can thus keep food warm longer, in effect providing limited heat storage; the latter can be extended by the addition of heat-storing materials (S/101). Moreover, the oven needs turning only every thirty to sixty minutes, is relatively durable and may perhaps be made locally more easily (S/101). But its solar intensification is much smaller and also its effective cooking power so that it requires a much longer time, for instance, to bring water to boiling, as established in comparative tests by the Nutrition Division of the Food and Agriculture Organization (S/116). Also, the oven is likely to be heavier and to require more consumer adaptation for processes not usually performed in ovens. Owing to their still being in the experimental stage, the costs of solar ovens have not yet been clearly established and may be at the same range as for cookers; their future would appear to depend on local fabrication, even using such materials as baskets for the back (S/101), but quality (insulation, reflectors, etc.) cannot be compromised too much, so that in this case, too, small manufacturing rather than improvised handicraft work would seem to be called for. Some flexibility in size is possible, a larger oven being required to hold more than one cooking vessel as in the Prata combination type, which is estimated to cost some $18 in materials alone.

Solar refrigeration for food preservation (GR/18)

Refrigeration—of any kind—can make an important contribution in the preservation of perishable foodstuffs, especially in tropical and semi-tropical areas. The great potential significance of such refrigeration has stimulated technicians to search for ways of using solar energy as a substitute for electricity or fuels where these sources are unavailable or expensive, as is often the case in less developed areas.

The refrigeration systems based on solar energy do not differ in principle from the conventional ones, which use either heat or power and are readily available on the market. Three major types may be distinguished, of which the third has particular interest here. One is the compression cooling machine, usually run by an electric motor, which can be fed by a solar power plant (dealt with in a later section), but otherwise not unique; conversion losses and intermittence of power supply limit the prospects of this form of solar refrigeration. The second method—discovered by Peltier more than a century ago and now gaining interest in advanced countries because no moving parts are required—is also based on electricity, applied to a "thermocouple" acting in a fashion reverse to that of the thermoelectric generator discussed later.

The most promising type suited to a solar operation, however, uses heat directly, in absorption-desorption refrigeration. In this case, heat supplied by a solar collector replaces kerosene or other fuels normally used in absorption refrigerators on the market; the latter are often very simple and may provide formidable competition in many areas, particularly since fuel savings have to compensate not only for the extra cost of the collector, but also for problems associated with operation, efficiency and, especially, the intermittence of energy supply. Absorption refrigeration may be used for cooling a refrigerator box directly (S/70, S/82), or it may be applied to the production of ice for subsequent use in food preservation (S/109), as proved in experimental units; neither type is as yet in commercial production.

A continuous cycle is preferred, but solar energy is intermittent, so an intermittent cycle has been adopted in the simplest system, notably in a small solar refrigerator developed in Wisconsin (S/82). An absorber-refrigerant solution (such as water-ammonia mixture) is heated in a simple focusing collector for two hours to drive ammonia vapor into, and to liquefy it under pressure in, another container in a sealed system. That container is subsequently placed by hand in a refrigerator box, which is kept cool till the next day by the refrigerant absorbing heat there and returning as vapour to the first container. Alternatively, the system may operate under vacuum; this is the case with a more conventional-type refrigerator developed in Israel, in which ingenious use is also made of east-facing and west-facing collectors to effect cycling action.

The simple Wisconsin solar refrigerator suitable for family use is estimated (S/82) to cost about $50, plus perhaps $9 for the collector if it is also used as a solar cooker, while the annual cost would be about $8, not counting the manual operation. Another calculation is made by Oniga (S/70), according to which conventional Brazilian compressor refrigerators cost about $200 and a comparable solar absorption unit with collector (prototype under construction) could cost 20 per cent more owing to electricity savings; in this case attention is given also to a collector in fixed position.

Ice making machines, which hold perhaps the greatest promise at the village level, are larger; one Russian device reportedly produces 250 kilogrammes per day, while a successful French absorption-type solar machine makes 100 kilogrammes per day (S/109). For the latter experimental unit, the investment is reported at about 20,000 new French francs (some $4,100) and, depending on the number of sunny days, the cost per 100 kilogrammes of ice at F.fr. 7 to 10.50, plus labour for operation; according to a detailed survey of the price of ice in different countries this cost is competitive in several areas, especially in Africa (S/109).

Solar air-conditioning (GR/18)

Progress is being made towards fulfilling the dream of using solar energy for air-conditioning. There is no doubt that air-conditioning contributes to work efficiency as well as to comfort; it may well be justified on economic grounds in many cases as more than a luxury. But it is also clear that very efficient cooling, such as that provided by the now conventional, electrically operated vapour compression unit, is not cheap; air-conditioning by the standards demanded in rich countries is out of the question as a widespread application for dwellings in less developed areas.

Fortunately, even moderate adjustment of temperature or humidity or both can make a significant difference. The cooling need not be continuous. And, most significant of all, there is usually a strong direct relationship between the need for cooling and the availability of solar energy; the problem of storage can thus be avoided.

With these factors in mind, fairly considerable efforts have gone into space cooling with, or related to, solar energy, in several countries. These were represented at the Conference by contributions from Australia (S/39), India (S/37), Israel (S/88), the United States (S/82) and France with special reference to the Sahara (S/64, S/76, S/111). To these may be added cases of night radiation cooling combined with space heating systems, referred to above. The work, which is still experimental and does not yet lend itself to clear-cut technical and economic conclusions, ranges over a wide field, from energy utilization proper for cooling machines to architectural design modifications for improved ventilation and air flows in what may be called auxiliary cooling methods.

Space cooling, utilizing energy, may of course be accomplished with systems based on the same principles as those used in refrigerating machines, with the differences that the temperature change is less and the total quantity of heat removal much greater. These systems include those based on power-driven vapour compression (with which economic comparisons are sometimes made as in S/37 and S/39) and the related jet pump cooling (both requiring high temperature), as well as dehumidification and absorption-desorption systems; the latter two may be of particular interest for solar energy application, especially when adapted to use low-temperature heat from flat-plate collectors.

No house has apparently been built yet with a closed-cycle absorption-desorption cooling system run on solar energy, but several studies have been made. In India, for example, it has been found that a carefully designed solar operated air-conditioning unit using an ammonia-water absorption system and flat-plate collectors appears to be economically feasible in New Delhi (S/37). The solar collector cost is of crucial importance, and this has also been found to be the case in a similar study of prospects for solar air-conditioning in Australia (S/39).

A house has been built in Israel (S/88), however, using an open absorption cycle. In this house, the east wall acts as collector and dries absorbent material in the morning while air is drawn in through, and gives up humidity in, the hollow west wall which acts as a heat rejector; in the afternoon their roles are reversed. It has been difficult to make the same wall alternatively an effective collector and a rejector. The system has the advantages of requiring no mechanical parts and no electricity, but the cooling effect has been found negligible in this particular house and the experiments have been suspended for the time being.

Alternatively, in hot dry areas with sufficient water, air may be cooled by water evaporation, at the cost of increased humidity unless the cooler, moist air is led through hollow walls, as proposed in one paper (S/76). Or some cooling may be achieved by night radiation with storage of cool air, by arrangement of air flow patterns, by use of "cold" and "hot" selective surfaces and, of course, by improved designs generally (S/111).

A particular case of "climatization" (S/64) involves simultaneous control of temperature and humidity as well as production of fresh water through distillation for application in greenhouses; the scheme may come to play a significant role, particularly in isolated desert locations.

Solar distillation producing fresh water (GR/19)

With the growing shortage and rising cost of fresh water in many areas and the hampering effect of lack of water on economic development, there is a clear trend of rapidly increasing interest in the possibilities of converting seawater and brackish water into fresh water by solar distillation and other processes. Artificial solar distillation is the simplest process, in effect duplicating under more controlled conditions the evaporation and precipitation taking place on a huge scale in nature's hydrological cycle.

Many countries have research projects devoted to solar distillation, represented in the Conference by papers from Chile (S/23), France (Algeria) (S/89, S/107), India (S/115) Italy (S/113), Spain (S/73), the United Arab Republic (S/63), the United States (S/14, S/28, S/29, S/77, S/85) and the Soviet Union (S/119). Progress is being made, but there is also considerable dispersion and duplication of effort, particularly as regards small solar stills which lend themselves to local handicraft work and are used in large numbers, for example, in Algeria (S/107).

While the present-day cost of solar-distilled water can be reasonably estimated, the possible extent of application cannot, largely because the prospective areas of economic desalination have never been properly surveyed. It is indicative to find Nebbia (S/113), for example, expressing the opinion that a world-wide investigation of the market for solar stills—and for solar energy equipment in general—would be very useful. Among the scattered information on current and permissible water costs—which obviously vary greatly with location and type of use but which do set upper limits for demineralized water—one paper, for example, indicates that irrigation water costs $0.20 per cubic metre in the Canary Islands (S/73) and fresh water for drinking as much as one dollar per cubic metre on the Spanish south-east coast, while in the sunny Antofagasta region of Chile, some mines are reported to pay the staggering sum of $15 per cubic metre of fresh water (S/23). Perhaps it is not surprising that a solar distillation plant—producing 22,500 litres per day and apparently the largest so far anywhere—was built in this region; possibly more surprising, however, is the fact that it was installed some eighty years ago and reputedly operated for about forty years at good efficiency even by present-day standards. The lack of progress in efficiency may be discouraging, but progress cannot be pushed very far in simple solar distillation; at least advances have been made in new materials and especially in scientific understanding. These may help to reduce costs and make solar distallation applicable in many areas, even if the optimistic goals set in the United States (S/29) of ten cents per cubic metre for municipal water and three cents for irrigation water are never reached.

The numerous small distillers, of family size for providing drinking water, are all based on the flat-plate collector principle and are essentially simple. Provided with insulation on the bottom or at the back, they usually consist of a black heat-absorbing surface that evaporates saline water; the vapour in turn condenses into fresh water on the transparent cover and runs off it into separating troughs. There are many variations, as described in the technical papers, in the detailed arrangements and in the types of material used.

The small distillers produce about seven to eight litres per square metre of evaporating area in summer and one litre in winter, averaging some four to five litres per day and one and a half to two cubic metres per year per square metre. Costs vary with location, construction and types of materials used; plastic covers, for example, are lower in initial cost but, having less durability, are not necessarily so in ultimate cost. With glass covers, the initial cost is of the order of $15 to $30 per square metre and may be reduced to some $10 to $20, which, with a lifetime of twenty years, would give an optimistic cost of some $0.25 to $0.70 per cubic metre of fresh water or, more realistically now, $1 to $2, plus operating labour (GR/19). The labour cost is likely to be disregarded in the operation of family-size units, which can easily be increased in capacity by adding to size. These small distillers, of course, have the advantages that cost of water distribution is avoided (provided saline water is available nearby) and that they do not require power and skilled labour. They have a definite role in supplying drinking water.

Large-scale solar distillers face a much more difficult situation, at least in the capacity range beyond 50,000 litres a day. They must usually be competitive with fresh water transported from more distant sources or with other demineralization processes, of which there are many, or with both. In particular, the need for a low initial investment or a long life or both is indicated to keep the product cost down, but attention must also be paid to maintenance and operating labour costs.

The large solar distillers so far tried are mainly of the single-effect type, as in the case of those installed by the United States Office of Saline Water at Daytona Beach, Florida (S/85). The latter range in size up to 3,000 square feet and afford an opportunity to study different designs and materials as well as the many variables to be taken into account even in such an apparently simple device as a basin-type still (S/77, S/107, S/119). The large but simple distillers are basically an extension of the small ones; they obviously afford some economy of size, but unfortunately drop in efficiency, so that only a much lower investment per square metre is permissible (S/107). For production of less than a million cubic metres per year, for drinking and industry, an investment of $4 to $20 per sqaure metre may be acceptable, and, for city supply, up to $2 per square metre (GR/19), which is about one-tenth of the cost of the new large installation at Daytona Beach and one-fifth of the cost used in cost calculations on plants with a capacity of 100,000 US gallons per day (S/85). With a very long life and on best performance, the latter plants (yet to be built) may be expected to produce at some $0.30 to $0.65 per cubic metre ($1.22 to $2.44 per 1,000 gallons) in the near future, according to these calculations. Simple basin distillers thus would be out of the question as suppliers of fresh water for irrigation and many other large uses, unless radical improvements are found.

The large solar distillers can incorporate various refinements, such as forced convection and multiple-effect distillation (S/14), thereby improving efficiency but adding to investment cost if not to product cost. The most optimistic calculation of all in this category is undoubtedly one arriving at a cost of about $0.08 per cubic metre of fresh water (S/28) and at no cost at all if the distillation is combined with power production and the power is sold at about eleven mills per kilowatt-hour (S/15), but this scheme would be based on a plastic collector cover one square mile in size put together in one piece.

Technically, it is of course possible to use concentrating collectors for the production of steam subsequently to be condensed to fresh water. Though not promising in itself, this steam production may be combined, as considered by Baum (S/119) with production of electricity and also with demineralization by electrodialysis.

Whichever type of solar distiller is used, the collector is the big item requiring cost reduction. The most radical way of getting around this problem is to use a lake or the sea as the collector, as in the so-called Claude process which uses the thermal energy of the sea (basically falling outside the scope of the Conference) and a surface condenser to produce fresh water after drawing steam through a vacuum chamber (and driving a turbo-generator on the way) in a low-pressure, low-temperature differential system. A land-based pilot project, essentially using this system, has been drawn up in Chile (S/23). More promising is a similar system based on an artificial "solar pond" as the heat collector, dealt with in a later section, since power production would be the major consideration.

Indeed, for large-scale evaporation or distillation with solar energy, the Claude-type process may hold the best future, particularly when combined with power production. Simple solar distillation on a large scale appears less promising at the moment and may in certain circumstances be better carried out by multiplication of small individual units, which would also save the cost of distribution from a central unit.

Solar furnaces for high temperature processing (GR/20)

With high-precision optics, solar radiation can be concentrated on a small surface to give temperatures of up to some 3,500° C. This is being done in several so-called solar furnaces, most of them in the capacity range of from two to three kilowatts (heat), located mainly in France, Japan, the United States and the Soviet Union. Up to now, solar furnaces have been used predominantly for materials testing and research purposes, as is evident from the technical papers submitted by authors from France (S/35, S/36, S/48, S/52, S/66, S/81, S/108), Japan (S/21, S/57) and the United States (S/5, S/16, S/25, S/79) and also from interventions by participants from Australia, the United Kingdom and Yugoslavia. For many of these purposes the small scale is sufficient, because the temperature achieved depends on the quality of the installation and not on its size.

From the point of view of practical application, interest centres more on the possibilities of using solar furnaces for small-scale refining of minerals and for certain chemical processes; in these applications the limitations of scale and relatively high initial cost may not be serious, if the product is sufficiently valuable or if the application overcomes the obstacle of transportation from remote mining areas. Indeed, experience on a semi-industrial scale is available from a seventy-five-kilowatt solar furnace built in 1952 at Montlouis in France (S/81) and, to some extent, from a big furnace built in 1958 primarily for materials research in the United States (S/79). Another plant, of seventy kilowatts and costing $102,000 (plus skilled labour), in Japan is in the same category (S/21). But even these are small compared with a 1,000-kilowatt solar furnace under construction at Odeillo-Font-Romeu near Montlouis in the French Pyrenees; it is expected to produce, for example, two to three tons of valuable ultra-refractory oxides per day (S/81). The solar furnace can be and is used to treat and produce a great variety of materials, including various pure chemicals, monocrystals and pure or rare metals, in demand by modern technology for nuclear reactors, semi-conductors and many other purposes (S/52). In fact, the solar furnace does have some special advantages, besides its ease in reaching high temperatures quickly notably, absence of contamination permitting preparation of pure products and high quality.

The solar furnace also has limitations, perhaps the most serious being the nature of the energy supply itself. The intermittent availability of sunshine makes it necessary, for example, to apply only methods and materials adaptable to this situation (S/81), and of course makes it possible to utilize the plant only less than half the time during the year, since it would not be practical to store high-temperature heat. Because of the predominance of interest and depreciation on the initial investment, which cannot as yet be discussed with any generality in terms of cost per kilowatt installed, the limited utilization factor also has a significant influence on the process cost. Other limitations are of a technical nature, such as the smallness of the heat receiving surface, difficulties of distributing the heat in the material and the like.

Great advance has been made, as demonstrated by the technical papers and discussions, in the technology and operation of solar furnaces. The numerous considerations to be taken into account include such factors as the type and construction of the solar energy concentrator, the tracking mechanism to keep the radiation focused, the arrangements at the receiver or furnace proper (direct reception, cavity, etc.) and various materials arrangements and measurements, as well as the choice of construction materials. It may be noted, for example, that in large furnaces a fixed concentrator is used in order to keep the target or furnace in a fixed position and that radiation is reflected on to the concentrator by large plane mirror assemblies (heliostats) following the sun; both are made of numerous segments. Small systems require only one set of reflectors which can now be made of hard, light-weight plastics spun into perfect shape. Great strides, spurred on by space research, have also been made in the use of aluminium, which has certain advantages over glas-mirrors, for example in the reflection of ultra-violet radiation useful in photo-chemical reactions as distinct from heat applications.

Mechanical and electric power from solar heat engines (GR/9)

Solar heat can, in theory, be readily converted to mechanical power—for direct use as in water pumping and for further conversion to electricity—by means of piston and turbine engines along the lines of well-known principles. This general field of technology has, however, been the subject of so much work that perhaps it lends itself less readily to new breakthroughs—and with them significant applications—than do the direct conversion systems covered in the following sections.

Little use has been made of solar energy so far for the production of power, although many model devices have been designed in various countries and actually proved workable. This lack of success may be traced to several factors, including weaknesses inherent in the source itself (notably intermittence and low density), inadequate engine development and prohibitive collector costs, as well as competition from inexpensive gasolene engines and other conventional devices. Some promising progress indicates, however, that the way may already be opening for practical applications, notably of small-scale units in less developed areas, and that it may be well worth while to intensify work in this field.

For both economic and technical reasons, it is useful to distinguish between small power units, of less than, say, ten-kilowatt capacity, and potential units in the megawatt class. The small units could best take advantage of the free distribution of solar energy by collection and transformation at the point of use. They can fill a definite need—for water pumping, lighting and other purposes not characterized by exacting demand for continuity and storage—in less developed areas otherwise lacking power, and therefore permit a relatively flexible range of costs as well as technical approaches utilizing both high- and low-temperature heat. Megawatt units, however, would almost certainly have to compete with conventional power units producing electricity at low cost, say, less then ten mills per kilowatt-hour; they remain to be built and tried in practice, but some interesting possibilities of large area collectors (operating at low temperature) have now been proposed to get around the problem, and prohibitive cost, of concentrating collectors on a large scale. It is noteworthy that, except for a 1,200 to 2,200-kilowatt project designed in the Soviet Union, but costing some $2,000 per kilowatt and, therefore, remaining on the drawing board, no large plant based on focusing collectors giving high temperature has been seriously considered in recent years.

Focusing collectors, because of their higher temperature and consequent engine efficiency and because of advances in new plastic and aluminium reflectors, may nevertheless still find use in conjunction with very small heat engines, such as a new type of hot-air (Stirling) engine exhibited on model scale in Rome, as well as in some special applications. It is interesting to note, for example, that a scheme has been worked out (S/27) for an (expensive) fifteen-kilowatt solar engine for use in space, where the radiation intensity is higher and also completely predictable, with some indications of possible adaptations for use on the ground.

Recent efforts for terrestrial applications have been devoted more to avoiding the high cost of focusing collectors, by use of collectors with lower or no concentration and fluids (other than steam) and engines adapted to low-temperature heat. This is the case, for example, with the Italian Somor solar pump, which essentially uses a flat-plate collector modified with mirrors on the side to provide some concentration and sulphur dioxide instead of steam; this device has been put on the market, at a cost apparently exceeding $1,000 per kilowatt.

Possibly the most significant development, now reported from Israel (S/54) and demonstrated in Rome, is a small turbine-solar power combination based on a new type of collector and turbine and operating on a heavy fluid (monochlorbenzene) with a lower boiling point than water. In this power "package", with a capacity of from two to ten kilowatts, the turbine achieves an efficiency (15 to 20 per cent) three times that of conventional small steam engines and turbines; the solar collectors, in units twelve metres long, are in the form of inflated plastic cylinders, half of whose inside surface is aluminized to focus the radiation on a "selective black" receiver tube running through the cylinder to a heat storage system providing a constant temperature (150° C) for the turbine. During the night, it operates at a reduced load. The initial cost is estimated (S/54) at from $513 to $1,435 per kilowatt installed and the product cost at from 34 to 52 mills per kilowatt-hour (with the collector accounting for more than two-thirds), at full use of the power output; this compares favourably with power costs from other small prime movers in many areas.

As suggested by d'Amelio (S/99), perhaps even simple flat-plate collectors can become adequate in harnessing solar radiation to drive solar engines economically, if one not only substitutes a heavy fluid with low boiling point for water but puts together with water an immiscible, or non-mixing, secondary fluid evaporating at a lower temperature and drawing heat from the water acting as a large heat exchange contact surface in the "boiler". After going through and driving the engine, the vapour is cooled and condensed by pumped water and returned to the collector in a closed system.

Another, and more radical, way of cutting the collector cost is the "solar pond", which has been proposed and is being experimented with in Israel (S/47); if successful, it may cut the cost from something like $20 to $1 per square metre and thus put solar power in an entirely different category, for rather large-scale production. Essentially, the solar pond is a flat-plate collector with a black-bottom absorber to take up heat but with layers of water of different densities (salt content) stratified in such a way that the water is heavier towards the bottom, so that heat at the bottom (reaching 90° C in experiments) is not lost by convection through upper layers and to the atmosphere as happens in normal ponds. The major technical problems being worked on and remaining to be solved include the effective extraction of heat from the bottom, prevention of layer mixing due to stirring by the wind and other causes, and keeping a large pond clean.

If these problems can be solved, it is estimated (S/47) that low-temperature heat from a "solar pond" one sq. kilometre in size could be used to produce power at ten mills per kilowatt-hour. Such a large pond, it is claimed, could give some 30 million kilowatt-hours per year at 1.5 per cent over-all conversion efficiency, or the equivalent of a 6,000-kilowatt plant at 58 per cent load factor. In an indirect calculation, based on a power price of ten mills, it is estimated that $1,080,000 can be invested in the "pond" collector, while at a price of twenty mills, the investment could go up to $4.5 million. As in most large solar power plants operated on low-temperature water (cf. Claude process), fresh water can also be produced as a by-product in this case estimated at 500 cubic metres of fresh water per year at $0.02 per cubic metre.

In conclusion, then, it appears that electricity can be produced via mechanical energy from solar energy at a cost of only some fifty mills per kilowatt-hour (with present technology), except perhaps in large installations based on low-temperature differentials. Located on sea coasts and in similar areas, the latter may convert salt water to fresh water in the same process and thus help to solve water as well as power shortages.

Direct conversion of solar heat to electricity (GR/10)

Up to now, electricity has been produced from heat exclusively by going through the stage of mechanical energy driving turbines and piston engines. Recently, however, a great deal of research has gone into the direct conversion of heat into electricity in following up a phenomenon long known in principle but hampered in practical application by an extremely low conversion efficiency and other problems. This situation has now changed with the rapid progress being made in solid state physics, the development of new materials having special physical properties (especially semi-conductors) and other advances. Most advanced countries are taking part in this development, though not necessarily relating it to solar energy as the source of heat.

Solar heat may be converted directly to electricity by means of thermoelectric converters or "thermocouples" (S/10, S/12, S/55, S/84, S/103, S/118) and of thermionic or thermoelectronic converters (S/78, S/90). Both require relatively high-temperature heat, obtainable from concentrated solar radiation (and other heat sources), or rather a high-temperature differential between a hot and a cold end, and are subject to the thermodynamic limitations of this cycle (nevertheless, the efficiency has been raised from one per cent or less to some ten per cent in a recent advance towards the theoretical efficiency of about thirty-five per cent). Both have the advantages of simple operation and also of not requiring any moving parts, as well as of light weight, rugged construction and possibly long life. They are still in the experimental stage, spurred on by space research, and appear most suitable for small loads from a few watts up to a few kilowatts, or sufficient for irrigation pumping, communications purposes and various small power uses in remote areas.

In thermoelectric generators, an electric current is produced by heating one junction in a circuit or hoop of two different metals or semi-conductors and by keeping the other junction cool (such as by pumped water in the case of water pumping). The efficiency depends greatly on the metals used, with which several of the technical papers are concerned. Another basic factor is the temperature achieved and endurable by the metals; high-concentrating collectors seem called for, though one French experiment (S/55) is based on flat-plate collectors. Several small units, of less than one kilowatt, are already operating, such as the one in Wisconsin which is coupled with a simple plastic reflector (S/103).

In at least one case (S/12), the fabrication of small thermoelectric generators is reportedly moving from development into manufacturing, with such purposes in mind as water pumping in less developed areas. Although it may still be too early to draw definite economic conclusions, it is indicated in this case, as a best estimate at this time, that the cost of electric power from a solar thermoelectric generator in the 50- to 1,000-watt range is about 70 to 100 mills per kilowatt-hour. This cost may be reduced substantially with mass production and long life.

The cost prospects are more uncertain for thermionic converters. They operate by the heating (up to some 2,000° C) of a cathode, which then emits electrons to a cool anode spaced at an extremely small distance away, in a vacuum tube or in a chamber filled for example with cessium vapour to neutralize the space charge between the electrodes. Among the difficulties are the creation and maintenance of a vacuum, protection of high-temperature cathodes from oxidation and achievement of sufficiently high temperature with cheap enough solar reflectors; some of these problems (such as oxidation) are less pronounced in space applications, for which much of this work is being carried out and in which cost is less important. The cost of the converter alone may be in the order of $2,000 per kilowatt (S/90), but with further advance and mass production, costs might be brought down significantly.

Direct conversion of solar light to electricity (GR/10)

Solar radiation has a unique quality in that a large part of it comes as light, and this light (or high-energy photons) can be converted directly to electricity in photoelectric converters. The latter are of two types. One is the photo-galvanic (or photo-chemical) cell, which unfortunately has not yet become practical but which, if successful, would also solve the storage or intermittence problem; it is not dealt with further here. The other is the physical photo-voltaic cell, photo-electric cell, or popularly, solar battery.

Photo-voltaic conversion underwent a breakthrough in 1954, when the so-called silicon solar cell was introduced and the conversion efficiency was raised from a fraction of one per cent to some six per cent. Much progress has since been made, and the devices are produced on an industrial scale in a number of countries.

Perhaps the most spectacular application of solar cells is in space, where they are powering satellite radio transmitters, in one case after more than three years. They are also used in large numbers on the ground for such small-power purposes as powering radio receivers and other communications. In Japan, for example, six repeater stations and eight lighthouses were equipped in the period from 1958 to 1960 with solar batteries (S/11). The solar cells in these various applications are connected with storage batteries to regulate the current and also to provide power in the absence of sunlight.

Long widely used in photographic exposure meters, the solar cells now producing power operate in the following manner. An electric current is produced when sunlight strikes a light-sensitive material in a barrier-layer photovoltaic cell made up of materials having different valence, such as silicon with a valence of four, arsenic with five and boron with three; the light strikes down to the (p—n) junction of layers separating negative electrons from positive charges and an electric current is sent through wires connected to the layers. Most solar cells have so far been based on monocrystal silicon cut into thin wafers, but, as demonstrated by the technical papers (S/11, S/40, S/44, S/56, S/65, S/106, S/118), several materials have been experimented with.

Power from photocells is still too expensive for ordinary home consumption, and is used mainly for small power loads in special applications. It is characteristic that initial cost is usually measured per watt rather than per kilowatt. But costs have been reduced considerably, partly by increased efficiency (now reaching some 12 to 14 per cent) through so-called gridded cells and modified spectral response (S/44, S/65). In the United States, for example, it is indicated that the cost of silicon cells per watt of capacity has fallen from \$500 in 1958 to \$275 in 1960 and to \$175 in 1961 (S/65), while the present cost in Japan is about \$130 per watt (fully mounted, with battery and controls) and is expected to be reduced shortly by one-third (S/11). Even at these costs, the resulting power is competitive in certain situations where the alternatives would be uneconomic transmission lines for low power (S/11, S/44), or no power at all.

Further significant cost reductions will have to be made, from the current investment of \$100,000 or more per kilowatt, for this power to reach large-scale application. Remarkable strides are being made in this direction. One of them is in the form of experiments with concentration of the solar radiation, by which it has been shown (GR/10) that output can be increased twentyfold; but with intensive concentration of radiation, the solar cell has to be cooled in order to avoid the damaging effect of heat on its efficiency.

Other strides include the search for materials other than pure silicon, which is very expensive, and in particular for replacement of monocrystal silicon with polycrystal silicon applicable with inherently inexpensive deposition techniques. Several papers (S/44, S/56, S/106) indicate the possibilities of a radical departure with thin cadmium-sulphide films, which may come to place photo-electric cells in an entirely new category and perhaps eventually bring the cost below \$1,000 per kilowatt, or within the range of economic feasibility for home use.

COMBINED USE OF VARIOUS ENERGY SOURCES, AND ENERGY STORAGE PROBLEMS

The intermittence of supply has been repeatedly noted as perhaps the most serious limitation to the practical utilization of solar energy and wind power for many power purposes.[8] Except where the intermittence does not greatly matter, as in water-pumping for irrigation, or is otherwise permissible, this limitation may have to be circumvented before widespread application can be found for purposes requiring continuous supply or supply at a specific time. Ideally, the limitation is overcome by finding an economical way of storing the energy (or useful energy product) of the one source considered. Or several energy sources may be combined, at the cost of multiplication of devices converting raw energy into a useful and interchangeable form.

It is impossible to store raw solar or wind energy as such for subsequent conversion to electricity. The closest form, in the case of solar energy, would be storage of heat, but this would require a high degree of insulation for high-temperature heat and the solution of other problems, and has apparently not been undertaken in practice beyond the point discussed above in connexion with solar heat engines. Rather, in the single-device system, the raw energy is converted and the product stored.

The most familiar method is, of course, the use of electric storage batteries. They have a useful role for small power purposes; unfortunately, they have no significant economy of scale and have not been the subject of any recent technological breakthrough promising a really drastic reduction of cost, estimated by Evans (GEN/3) at $13.50 per kilowatt-hour of storage capacity on an annual basis.

More promising, perhaps, is the considerable work devoted to so-called fuel cells. As described in the technical papers, they may be divided into two types, based on electrolysis and thermal regeneration, respectively.

In the first category are the hydrogen-oxygen cell systems (GEN/3 and 9), in which electricity (produced from solar or wind energy or other sources) is used to electrolyse water (or other chemicals in comparable systems) into hydrogen and oxygen then stored separately; the two gases may subsequently, at any time, be recombined to produce electricity in a fuel cell, which has the advantages of no moving parts, and, particularly, of high efficiency. The electrolyser and the generating cell have not so far been combined in one apparatus (GEN/9), and no cell is yet on the market. Although certain problems remain to be solved, fuel cells in this category may become highly significant (also for higher efficiency in use of conventional fuels), particularly with reductions in their cost. Evans (GEN/3), for example, suggests that the annual cost of the fuel cell plus electrolyser may come down from about $100 to $30 per kilowatt even for rather small units, while Bacon (GEN/9) estimates the over-all capital investment at roughly $325 per kilowatt for a 100-kilowatt installation; he finds the system premature for less developed countries and also doubts its ability to compete with diesel power in small units except where oil is relatively expensive. Much research is, however, going on in this field, and it is being closely watched in many quarters.

The thermally regenerative fuel cells (GEN/2 and 14) or thermally reversible galvanic cells are based on a closed cycle and recharged by heat rather than by external electric current. They combine in one device electric generation, regeneration (or separation of lithium hydride or other chemicals for later recombination and power generation) and storage; they are still in an early experimental stage but may find significant applications in conjunction with highly concentrated solar radiation providing the heat.

Other research, related to solar energy, attempts to find solutions through photo-chemical conversion and storage (GEN/2), including photolysis rather than electrolysis for separation. If successful, these processes would also solve the storage problem. However, practical results useful for wide energy applications are still eluding the photochemical approach and photo-chemistry other than that taking place in nature's photosynthesis.

In fact, as concluded by Daniels (GR/2), "it is clear that there are no new technological advances in energy storage, now in sight, which are likely to lead to striking economic advances". But he finds that encouraging progress in basic science may eventually lead to useful devices.

In the meantime, practical solutions of the intermittence problem may be found by combining different energy sources; that is, by obtaining energy other than from one self-contained source. There are many possibilities in this direction.

Large-scale electrical networks may readily absorb intermittent output, as discussed in connexion with wind power. The intermittent sources then save fuel and conserve water. Similar principles may be applied on a smaller scale, such as in the mechanical storage provided by pumping water to a higher elevation for later production through a small water turbine. Or air may be compressed for later use of the mechanical energy. Another way would be to store hydrogen gas, produced by electrolysis based on power from wind or solar energy, for use in place of other fuels in combustion engines.

The combinations may be carried further, so that the power needed is produced entirely from local energy

[8] This section is largely limited to power purposes, heat storage for heat applications having been considered above in connexion with solar energy alone. Geothermal energy is naturally stored in the ground and does not raise problems of intermittence.

sources, as discussed in detail by Golding (GEN/5). There is much to be said for this approach (besides the fact that it eliminates distribution costs), as a way of overcoming intermittence and especially of providing power for the numerous small communities in the less developed areas depending on muscle power and lacking even simple amenities. A prerequisite in those conditions is a careful consideration of the various types, and timing, of power demand, so that the best economic use is made of the different devices and local energy sources and that essential loads requiring precise timing are covered, if in fact intermittence is not altogether permissible.

The problem of intermittence may, however, be overstressed and with it the storage of energy, which can be far more costly than the energy production itself. This appears to be the case particularly with regard to rural communities in under-developed areas, where, as pointed out by Kapur (GEN/8), the question of intermittence is less important and where "what is needed to be done is to create conditions for work and productive effort to the maximum extent possible within the present limitation of research and development".

ANNEXES

ANNEX 1

AGENDA

United Nations Conference on New Sources of Energy
Solar Energy—Wind Power—Geothermal Energy

21 to 31 August 1961

Monday, 21 August

5.00 p.m.

OPENING SESSION

Tuesday, 22 August

10.00 a.m.

I. GENERAL SESSION: NEW SOURCES OF ENERGY AND ENERGY DEVELOPMENT

II. TECHNICAL SESSIONS ON NEW SOURCES FOR POWER PURPOSES

II.A. *Geothermal energy*

4.00 p.m. II.A.1. Prospection of geothermal fields and investigations necessary to evaluate their capacity: Description of known fields—preliminary prospection—investigation for evaluation

III. TECHNICAL SESSIONS ON SOLAR ENERGY FOR PURPOSES OTHER THAN POWER

III.A. Solar energy availability and instruments for measurements: Radiation data—networks—instrumentation

Wednesday, 23 August

10.00 a.m. II.A.2. Harnessing of geothermal energy and geothermal electricity production:

(*a*) Methods and equipment for harnessing geothermal energy

(*b*) Utilization of geothermal energy for power generation

III.B. New materials in solar energy utilization: Plastics, metals, glass, selective surfaces and other materials

3.30 p.m. II.A.3. Utilization of geothermal energy for heating purposes and combined schemes involving power generation, heating and/or by products:

(*a*) Utilization for heating purposes

(*b*) Combined schemes and by-products

III.C. Use of solar energy for heating purposes:

1. Water heating
2. Space heating

Thursday, 24 August

10.00 a.m. II.A.4. Review and summary of geothermal energy problems and findings: Plenary session

II.B. *Wind power*

4.00 p.m. II.B.1. Studies of wind behaviour and investigation of suitable sites for wind-driven plants

III.C. Use of solar energy for heating purposes (*continued*):

3. Solar drying
4. Solar cooking
5. Heat storage

Friday, 25 August

10.00 a.m. II.B.2. The design and testing of wind power plants:

(*a*) Design

(*b*) Testing

III.D. Use of solar energy for cooling purposes:

1. Food preservation by refrigeration
2. Space cooling and dehumidification

4.00 p.m. II.B.3. Recent developments and potential improvements in wind power utilization:

(*a*) For household and other individual uses

(*b*) For community purposes (isolated units and units in combination with conventional power sets)

(*c*) For use in connexion with electrical networks

III.F. Use of solar energy for high-temperature processing (solar furnaces): Equipment—research—potential uses

Monday, 28 August

10.30 a.m.	II.B.4. Review and summary of wind power problems and findings: Plenary session II.C. *Solar energy*	
4.00 p.m.	II.C.1. Use of solar energy for mechanical power and electricity production: (*a*) By means of piston engines and turbines	

Tuesday, 29 August

10.00 a.m.	II.C.1. Use of solar energy for mechanical power and electricity production (*continued*): (*b*) By direct conversion to electricity by means of: (*i*) thermoelectric converters (*ii*) photo-electric cells	III.E. Use of solar energy for production of fresh water: Small and large-scale distillers
4.00 p.m.	II.D. Combined use of various energy sources and energy storage problems: 1. Combined use of various energy sources 2. Energy storage problems	

Wednesday, 30 August

10.00 a.m.		III.G. Review and summary of solar energy problems and findings related to purposes other than power: Plenary session
4.00 p.m.		III.G. (*continued*) and II.C.2. Review and summary of solar energy problems and findings related to power and other purposes: Plenary session

Thursday, 31 August

10.00 a.m.	CLOSING SESSION	

ANNEX 2

CHAIRMEN AND RAPPORTEURS

Chairman	Agenda item
H.E. Signor Egidio Ortona Ambassador Extraordinary and Plenipotentiary Director-General, Department of Economic Affairs Ministry of Foreign Affairs Government of Italy	Opening session
Dr. Ibrahim Helmi Abdel-Rahman Director Institute of National Planning 5 Sh. Zaki Cairo, United Arab Republic	III.B
M. Pierre J. Ailleret Directeur général adjoint de l'Electricité de France 12 place des Etats-Unis Paris XVIème, France	II.D
Mr. H. Christopher H. Armstead Senior Co-ordinating Engineer Merz and McLellan Milburn, Esher Surrey, England	II.A.2
Dr. Freddy Ba Hli Director-General Union of Burma Applied Research Institute Kanbe, Yankin P.O. Rangoon, Burma	III.C.3 III.C.4 III.C.5
Professor Valentin A. Baum Deputy Director Krzhizhanovsky Power Institute Head of Heliolaboratory Leninsky Prospect 19 Moscow, USSR	III.F
Dr. Emanuele Cambilargiu Professor of Wind Dynamics School of Engineering Montevideo, Uruguay	II.B.2
Dr. Averardo Chierici Director-General "Larderello" S.p.A. Lungarno Pacinotti 16 Pisa, Italy	II.A.4
Dr. Farrington Daniels Professor Emeritus, Chemistry Solar Energy Laboratory Engineering Experiment Station Mechanical Engineering Building University of Wisconsin Madison 6, Wisconsin, USA	II.C.2 III.G
Sir Vincent Z. de Ferranti Chairman, International Executive Council of World Power Conference Henbury Hall Macclesfield Cheshire, England	I
Mr. Andrew J. Drummond Chief Research Physicist The Eppley Laboratory, Inc. 12 Sheffield Avenue Newport, Rhode Island, USA	III.A
Professor Carlo Garbato 15 Via Pietro A. Mascagni Milan, Italy	II.A.3
Professor Julio G. Hirschmann Vicerrector Universidad Técnica Federico Santa María Casilla 110-V Valparaiso, Chile	III.E
Dr. K. Langlo Chief, Technical Division World Meteorological Organization Geneva, Switzerland	II.B.1
Professor Henri Masson Doyen de la Faculté des Sciences de Dakar Dakar, Senegal	II.C.1
Mr. Roger N. Morse Officer in Charge Commonwealth Scientific and Industrial Research Organization Engineering Section P.O. Box 26 Highett, Victoria, Australia	III.C.1 III.C.2
Senhor Teodoro Oniga Director, Centre for Studies in Applied Mechanics (CEMA) Ladeira dos Tabajaras, 94—Apart. 705 Guanabara Rio de Janeiro, Brazil	III.D
Mr. David Owen Executive Chairman Technical Assistance Board United Nations, New York	Closing session
Mr. Peder Gerhard Poulsen-Hansen General Manager Association of Danish Electricity Works Chairman, Danish Wind Power Committee Livjaegergade 22 Copenhagen, Denmark	II.B.3
Mr. Frank E. Studt Principal Scientific Officer New Zealand Department of Scientific and Industrial Research P.O. Box 8018 Wellington, New Zealand	II.A.1
Professor M. S. Thacker Director-General Council of Scientific and Industrial Research New Delhi, India	II.B.4

Rapporteur	Agenda item
Professor Valentin A. Baum Deputy Director Krzhizhanovsky Power Institute Head of Heliolaboratory Leninsky Prospect 19 Moscow, USSR	II.C.1(*b*)
Profesor Pedro Blanco Director Comisión Nacional de Energías Especiales Ortega y Gasset, 40 Madrid 6, Spain	III.A
Dr. Gunnar Bodvarsson Chief, Department for Natural Heat State Electricity Authority P.O. Box 40 Reykjavik, Iceland	II.A.3
Dr. Farrington Daniels Professor Emeritus, Chemistry Solar Energy Laboratory Engineering Experiment Station Mechanical Engineering Building University of Wisconsin Madison 6, Wisconsin, USA	II.D.2
Father Emmanuel S. de Breuvery, S.J. Director Resources and Transport Branch Department of Economic and Social Affairs United Nations, New York	I II.A.4 II.B.4 II.C.2—III.G
Dr. John A. Duffie Director Solar Energy Laboratory Mechanical Engineering Building University of Wisconsin Madison 6, Wisconsin, USA	III.B
Profesor Jesús Ruiz Elizondo Comisión Nacional de Energía Nuclear Ana María Mier No. 13 México 12, D.F., México	II.A.1
Mr. Edward W. Golding The Electrical Research Association Danes Inn House 265 Strand London, W.C.2, England	II.B.1 II.D.1

Rapporteur	Agenda item
M. Cyril Gomella Ingénieur conseil 5, rue Berthezène Algiers, Algeria	III.E
Dr. Ulrich Hütter Professor, Technische Hochschule Stuttgart Holzgartenstrasse 9A Stuttgart-N., Württemberg Federal Republic of Germany	II.B.3
Dr. George O. G. Löf Consulting Chemical Engineer 512 Farmers' Union Building Denver 3, Colorado, USA	III.C.2 III.C.3 III.C.4
Dr. Kailash N. Mathur Director Central Scientific Instruments Organization Council of Scientific and Industrial Research Rafi Marg New Delhi 1, India	III.C.5
Dr. Isao Oshida Director Kobayashi Institute of Physical Research 2431 Kokuburji Kitatama-gun Tokyo, Japan	III.C.1
Mr. John H. Smith Geothermal Engineer Ministry of Works P.O. Box 8024 Wellington, New Zealand	II.A.2
Dr. Harry Tabor Director National Physical Laboratory of Israel Danziger Building Hebrew University Jerusalem, Israel	II.C.1(a) III.D
M. Félix Trombe Directeur de recherches Centre national de la recherche scientifique 37, boulevard Saint-Michel Paris V^{ème}, France	III.F
Dr. Louis Vadot NEYRPIC-SOGREAH Grenoble (Isère), France	II.B.2

ANNEX 3

REGISTERED ATTENDANCE AT THE CONFERENCE

By country or territory[a]

Afghanistan	2
Argentina	1
Australia	4
Austria	1
Belgium	7
Bermuda	1
Bolivia	2
Brazil	2
Bulgaria	1
Burma	1
Canada	3
Ceylon	1
Chile	4
China (Taiwan)	3
Colombia	2
Congo (Leopoldville)	2
Czechoslovakia	2
Denmark	2
Ecuador	2
El Salvador	4
Federal Republic of Germany	7
Fiji	1
France[b]	57
Gabon	1
Ghana	3
Greece	5
Hungary	2
Iceland	4
India	11
Indonesia	1
Iran	1
Iraq	1
Israel	11
Italy	87
Ivory Coast	1
Jamaica	1
Japan	14
Jordan	1
Kenya	1
Lebanon	4
Libya	1
Luxembourg	2
Madagascar	1
Mali	3
Mexico	3
Morocco	5
Netherlands	5
Netherlands Antilles	1
New Zealand	5
Niger	2
Nigeria	3
Pakistan	1
Peru	1
Philippines	3
Poland	2
Portugal	1
Saudi Arabia	3
Senegal	4
South Africa	2
Spain	7
Sudan	1
Sweden	9
Switzerland	6
Tanganyika	1
Thailand	2
Tunisia	1
Turkey	1
Union of Soviet Socialist Republics	2
United Arab Republic	8
United Kingdom of Great Britain and Northern Ireland	16
United States of America	63
Uruguay	1
Venezuela	1
Yugoslavia	3

United Nations specialized agencies and international agency

Food and Agriculture Organization of the United Nations	8
International Labour Organisation	1
United Nations Educational, Scientific and Cultural Organization	2
World Health Organization	1
World Meteorological Organization	3
International Atomic Energy Agency	1

[a] Classified by place of residence, except for those with embassy addresses, representatives of specialized agencies of the United Nations and others, such as students or research workers abroad indicating home addresses.

[b] Including eleven from Algeria.

ANNEX 4

LIST OF CONFERENCE PAPERS

By agenda item[a]

Agenda item I. New sources of energy and energy development

GENERAL REPORT: Rapporteur, E. S. de Breuvery, GR/1(GEN).

Social aspects of the sources of energy (A long-range view): *I. H. Abdel-Rahman* (UAR), GEN/11.

The abundance of natural energy and the choice of the means of harnessing it: *P. J. Ailleret* (France), GEN/12.

Reflections on the economic value of geothermal energy, wind power and solar energy, especially after conversion to electrical energy: *A. M. Angelini* (Italy), GEN/1.

Energy as a factor in the progress of under-developedc ountries: *H. Hartley* (UK), GEN/4.

Socio-economic considerations in the utilization of solar energy in under-developed areas: *J. C. Kapur* (India), GEN/8.

Problems of energy supply in under-developed countries with special regard to new sources of energy: *H. F. Mueller* (Federal Republic of Germany), GEN/7.

New sources of energy in the world energy economy: *B. C. Netschert* and *G. O. G. Löf* (USA), GEN/10.

New sources of energy and energy development: *M. S. Thacker* (India), GEN/15.

Agenda item II.A.1. Prospection of geothermal fields and investigations necessary to evaluate their capacity

GENERAL REPORT: Rapporteur, J. Ruiz Elizondo, GR/3(G).

The technique of testing geothermal wells: *V. V. Averiev* (USSR) G/74.

Geothermal drillholes—physical investigations: *C. J. Banwell* (New Zealand), G/53.

Structural study of the roccastrada zone in prospecting for steam by geophysical, gravimetric and electrical methods: *F. Battini* and *P. Menut* (Italy), G/26.

Physical characteristics of natural heat resources in Iceland: *G. Bodvarsson* (Iceland), G/6.

Exploration of subsurface temperature in Iceland: *G. Bodvarsson* and *G. Palmason* (Iceland), G/24.

Prospecting of geothermal fields and exploration necessary for their adequate exploitation performed in various regions of Italy: *R. Burgassi* (Italy), G/65.

Geothermal prospecting for endogenous energy: *R. Burgassi*, *F. Battini* and *J. Mouton* (Italy), G/61/Rev.1.

[a] Under each agenda item, the general report of the rapporteur, which bears the same title as the agenda item, is listed first and is followed by the relevant individual papers. The latter are arranged in alphabetical order by author; each entry gives title of paper, author, country and document symbol.

Document symbols have been abbreviated by the elimination of the prefix "E/CONF.35/" which should precede the sub-symbols "GR", "GEN", "G", "W" and "S" in all full references.

The contribution of geophysical methods to the survey of geothermal fields: *J. J. Breusse* (France), G/25.

Geochemical aspects of thermal springs in El Salvador: *G. Christmann* (El Salvador), G/10.

Geothermal energy in Mexico: *L. F. de Anda*, *J. I. Septien* and *J. R. Elizondo* (Mexico), G/77.

Geological environment of hyperthermal areas in continental United States and suggested methods of prospecting them for geothermal power: *L. C. Decius* (USA), G/48.

Investigations for geothermal power at Waiotapu, New Zealand: *N. D. Dench* (New Zealand), G/17.

Scientific factors in geothermal investigation and exploitation: *D. Doyle* and *F. E. Studt* (New Zealand), G/55.

Review of geothermal activity in El Salvador: *F. Durr* (El Salvador), G/11.

Operations research and possible applications to geothermal exploration programming: *F. Durr* (El Salvador), G/20.

Geothermal drillhole schemical investigations: *A. J. Ellis* (New Zealand), G/42.

Natural steam geology and geochemistry: *G. Facca* and *F. Tonani* (Italy), G/67.

Preliminary investigation of the Rabaul geothermal area for the production of electric power: *A. C. L. Fooks* (New Zealand), G/12.

Geology of New Zealand geothermal steam fields: *G. W. Grindley* (New Zealand), G/34.

The present position regarding the utilization of geothermal energy and the role of geothermal energy from the viewpoint of energy economy in Japan: *H. Harada* and *T. Mori* (Japan), G/57.

Geology and geothermal energy in the Taupo Volcanic Zone, New Zealand: *J. Healy* (New Zealand), G/28.

Isotope geology in the hydrothermal areas of New Zealand: *J. R. Hulston* (New Zealand), G/31.

Alternative methods of determining enthalpy and mass flow: *R. James* (New Zealand), G/30.

Sampling of geothermal drillhole discharges: *W. A. J. Mahon* (New Zealand), G/46.

Photogeology applied to natural steam exploration: *E. Marchesini* (Italy), G/69.

Thermal anomalies and geothermal fields related to recent plutonism in Tuscany: *G. Marinelli* (Italy), G/58.

Geology of The Geysers Thermal Area, California: *J. R. McNitt* (USA), G/3.

Sampling and analysis of gases in natural-steam wells: *R. G. C. Nencetti* (Italy), G/76.

Water collection and analysis from thermal sources and vapour manifestations: *R. G. C. Nencetti* (Italy), G/73.

Methods and apparatus used for wellmouth measurements in the Larderello geothermal zone when a new well comes in: *R. G. C. Nencetti* (Italy), G/75.

The hyperthermal waters of Pauzhetsk, Kamchatka, as a source of geothermal energy: *B. I. Piip, V. V. Ivanov* and *V. V. Averiev* (USSR), G/38.

Results and power generation implications from drilling into the Kilauea Iki Lava Lake, Hawaii: *D. E. Rawson* and *W. P. Bennett* (USA), G/5.

Chemical analysis and laboratory requirements: experience in New Zealand's hydrothermal areas: *J. A. Ritchie* (New Zealand), G/29.

Known geothermal fields in Japan: *M. Saito* (Japan), G/1.

Methods used in exploring geothermal fields in Japan, with particular reference to geophysical methods, their role and results: *K. Sato* (Japan), G/23.

Geophysical prospecting in New Zealand's hydrothermal fields: *F. E. Studt* (New Zealand), G/33.

Prospecting of hydrothermal areas by surface thermal surveys: *G. E. K. Thompson, C. J. Banwell, G. B. Dawson,* and *D. J. Dickinson* (New Zealand), G/54.

Preliminary evaluation of geothermal areas by geochemistry, geology and shallow drilling: *D. E. White* (USA), G/2.

Chemical prospecting of hot spring areas for utilization of geothermal steam: *S. H. Wilson* (New Zealand), G/35.

Agenda item II.A.2. Harnessing of geothermal energy and geothermal electricity production

General report: Rapporteur, J. H. Smith, GR/4(G).

II.A.2(*a*). *Methods and equipment for harnessing geothermal energy*

The development and performance of a steam-water separator for use on geothermal bores: *P. Bangma* (New Zealand), G/13.

The prevention of blowouts and other aspects of safety in geothermal steam drilling: *R. S. Bolton* (New Zealand), G/43.

Air drilling in geothermal bores: *R. Contini* and *U. Cigni* (Italy), G/70.

Methods of exploitation of geothermal energy and the equipment required: *R. Contini* (Italy), G/71.

Geothermal drilling practices at Wairakei, New Zealand: *S. B. Craig* (New Zealand), G/14.

Silencers for geothermal bore discharge: *N. D. Dench* (New Zealand), G/18.

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GR/13(S)	English and French	III.C.1	Oshida, I.
GR/14(S)	English and French	III.C.2	Löf, G. O. G.
GR/15(S)	English and French	III.C.3	Löf, G. O. G.
GR/16(S)	English and French	III.C.4	Löf, G. O. G.
GR/17(S)	English and French	III.C.5	Mathur, K. N.
GR/18(S)	English and French	III.D	Tabor, H.
GR/19(S)	French and English	III.E	Gomella, C.
GR/20(S)	French and English	III.F	Trombe, F.
	Individual papers[a]		
GEN/1	French and English	I	Angelini, A. M.
GEN/2	English	II.D.2	Marcus, R. J. and Wohlers, H. C.
GEN/3	English	II.D.2	Evans, G. E.
GEN/4	English and French	I	Hartley, Sir Harold
GEN/5	English	II.D.1	Golding, E. W.
GEN/6	English	II.D.2	McCully, C. R.
GEN/7	English and French	I	Mueller, H. F.
GEN/8	English and French	I	Kapur, J. C.
GEN/9	English	II.D.2	Bacon, F. T.
GEN/10	English and French	I	Netschert, B. C. and Löf, G. O. G.
GEN/11	English and French	I	Abdel-Rahman, I. H.
GEN/12	French and English	I	Ailleret, P.
GEN/13	English	II.D.2	Melzer, H.
GEN/14	English	II.D.2	Werner, R. C. and Ciarlariello, T. A.
GEN/15	English and French	I	Thacker, M. S.
	Geothermal energy		
G/1	English	II.A.1	Saito, M.
G/2	English	II.A.1	White, D. E.
G/3	English	II.A.1	McNitt, J. R.
G/4	English	II.A.2(*b*)	Armstead, H. C. H.
G/5	English	II.A.1	Rawson, D. E. and Bennett, W. P.
G/6	English	II.A.1	Bodvarsson, G.
G/7	English	II.A.3(*a*)	Mizutani, Y.
G/8	English	II.A.2(*b*)	Bruce, A. W.
G/9	English	II.A.2(*b*)	Einarsson, S. S.

[a] With the exceptions noted below, each individual paper is accompanied by a bilingual summary (English and French) bearing the same symbol plus the word "summary". The exceptions are the papers under agenda item I and W/34, S/76, S/80, S/89, S/112, S/116, S/118 and S/119.

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G/10	English	II.A.1	Christmann, G.
G/11	English	II.A.1	Durr, F.
G/12	English	II.A.1	Fooks, A. C. L.
G/13	English	II.A.2(*a*)	Bangma, P.
G/14	English	II.A.2(*a*)	Craig, S. B.
G/15	English	II.A.2(*a*)	Innes, I. A.
G/16	English	II.A.2(*a*)	Fooks, A. C. L.
G/17	English	II.A.1	Dench, N. D.
G/18	English	II.A.2(*a*)	Dench, N. D.
G/19/Rev. 1	English	II.A.2(*a*)	Hunt, A. M.
G/20	English	II.A.1	Durr, F.
G/21	English	II.A.2(*a*)	Woods, D. I.
G/22	English	II.A.2(*a*)	Niijima, R.
G/23	English	II.A.1	Sato, K.
G/24	English	II.A.1	Bodvarsson, G. and Palmason, G.
G/25	French	II.A.1	Breusse, J. J.
G/26	French	II.A.1	Battini, F. and Menut, P.
G/27	English	II.A.3(*a*)	Lindal, B.
G/28	English	II.A.1	Healy, J.
G/29	English	II.A.1	Ritchie, J. A.
G/30	English	II.A.1	James, R.
G/31	English	II.A.1	Hulston, J. R.
G/32	English	II.A.3(*a*)	Lindal, B.
G/33	English	II.A.1	Studt, F. E.
G/34	English	II.A.1	Grindley, G. W.
G/35	English	II.A.1	Wilson, S. H.
G/36	English	II.A.2(*a*)	Karlsson, T.
G/37	English	II.A.3(*a*)	Bodvarsson, G. and Zoëga, J.
G/38	Russian/English	II.A.1	Piip, B. I., Ivanov, V. V. and Averiev, V. V.
G/39	French	II.A.3(*b*)	Lenzi, D.
G/40	English	II.A.2(*a*)	Smith, J. H.
G/41	English	II.A.2(*b*)	Hansen, A.
G/42	English	II.A.1	Ellis, A. J.
G/43	English	II.A.2(*a*)	Bolton, R. S.
G/44	English	II.A.2.(*a*)	Smith, J. H.
G/45	English	II.A.3(*a*)	Sigurdsson, H.
G/46	English	II.A.1	Mahon, W. A. J.
G/47	English	II.A.2(*a*)	Foster, P. K., Marshall, T. and Tombs, A.
G/48	English	II.A.1	Decius, L. C.
G/49	English	II.A.2(*a*)	Fisher, W. M.
G/50	English	II.A.2(*b*)	Zancani, C. F.
G/51	English	II.A.2(*a*)	English, E. F.
G/52	English	II.A.3(*a*)	Kerr. R. N., Bangma, P., Cooke, W. L., Furness, F. G. and Vamos, G.
G/53	English	II.A.1	Banwell, C. J.
G/54	English	II.A.1	Thompson, G. E. K., Banwell, C. J., Dawson, G. B. and Dickinson, D. J.
G/55	English	II.A.1	Doyle, D. and Studt, F. E.
G/56	English	II.A.3(*b*)	Kennedy, A. M.
G/57	English	II.A.1	Harada, H. and Mori, T.
G/58	French	II.A.1	Marinelli, G.
G/59	English	II.A.3(*a*)	Lindal, B.
G/60	English	II.A.2(*b*)	Saporiti, A.
G/61/Rev. 1	French	II.A.1	Burgassi, R., Battini, F. and Mouton, J.
G/62	English	II.A.2(*b*)	Chierici, A.
G/63	French	II.A.3(*b*)	Garbato, C.
G/64	English	II.A.2(*b*)	Saporiti, A.
G/65	French and English	II.A.1	Burgassi, R.
G/66	French and English	II.A.2(*a*)	Minucci, G.
G/67	English	II.A.1	Facca, G. and Tonani, F.
G/68	French and English	II.A.2(*b*)	Di Mario, P.
G/69	English	II.A.1	Marchesini, E.
G/70	English	II.A.2(*a*)	Contini, R. and Cigni, U.
G/71	French and English	II.A.2(*a*)	Contini, R.
G/72	English	II.A.2(*b*)	Villa, F. P.
G/73	French	II.A.1	Nencetti, R. G. C.
G/74	Russian/English	II.A.1	Averiev, V. V.

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S/14	English	III.E	Grune, W. N., Collins, R. A. and Thompson, T. L.
S/15	English	II.C.1(*a*)	Hummel, R. L.
S/16	English	III.F	Glaser, P. E.
S/17	English	III.C.3	Buelow, F. H.
S/18	English	III.A	Truhlar, E. J., Latimer, J. R., Mateer, C. L. and Godson, W. L.
S/19	English	III.C.2	Benseman, R. F.
S/20	English	III.A	Allcut, E. A. and Hooper, F. C.
S/21	English	III.F	Sakurai, R., Shishido, K., Kamada, O. and Inagaki, K.
S/22	English	III.B	Oshida, I.
S/23	Spanish/French	III.E	Hirschmann, J. G.
S/24	English	III.C.4	Stam, H.
S/25/Rev.1	English	III.F	Marcus, R. J. and Wohlers, H. C.
S/26	English	III.C.1	Sobotka, R.
S/27	English	II.C.1(*a*)	Macauley, B. T.
S/28	English	III.E	Hummel, R. L.
S/29	English	III.E	Howe, E. D.
S/30	English	III.C.2	Bliss, Jr., R. W.
S/31	English	III.C.1	Robinson, N. and Neeman, E.
S/32	English	III.A	Sapsford, C. M.
S/33	English	III.B	Edlin, F. E. and Willauer, D. E.
S/34	English	III.A	Yellott, J. I. and Kokoropoulos, P.
S/35	French	III.F	Trombe, F., Foëx, M. and Henry La Blanchetais, Ch.
S/36	French	III.F	Vuillard, G. E.
S/37	English	III.D.2	Ashar, N. G. and Reti, A. R.
S/38	English	III.C.1	Morse, R. N.
S/39	English	III.D.2	Sheridan, N. B.
S/40	English	II.C.1(*b*)(*ii*)	Pearson, G. L.
S/41/Rev.1	French	III.A	Perrot, M. and Touchais, M.
S/42	English	III.B	Gaumer, R. E.
S/43	English	III.B	Edwards, D. K., Gier, J. T., Nelson, K. E. and Roddick, R. D.
S/44	English	II.C.1(*b*)(*ii*)	Wolf, M.
S/45	French and English	II.C.1(*a*)	Touchais, M.
S/46	English	III.B	Tabor, H., Harris, J., Weinberger, H. and Doron, B.
S/47	English	II.C.1(*a*)	Tabor, H.
S/48	French	III.F	Le-Phat-Vinh, A.
S/49	English	III.C.2	Pleijel, G. V. and Lindström, B. I.
S/50	English	III.C.1	Abou-Hussein, M. S. M.
S/51 (*not issued*)			
S/52	French	III.F	Trombe, F. and Foëx, M.
S/53	English	III.C.3	Davis, Jr., C. P. and Lipper, R. I.
S/54	English	II.C.1(*a*)	Tabor, H. and Bronicki, J. L.
S/55	French and English	II.C.1(*b*)(*i*)	Michel, R. G.
S/56	English	II.C.1(*b*)(*ii*)	Ravich, L. E.
S/57	English	III.F	Noguchi, T., Mizuno, M., Nakayama, N. and Hayashi, H.
S/58	French and English	III.C.1	Geoffroy, J.
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S/60	English	III.A	Venkiteshwaran, S. P.
S/61	English	III.A	Gräfe, K.
S/62	English	III.A	Elnesr, M. K. and Khalil, A. M.
S/63	English	III.E	Hafez, M. M. and Elnesr, M. K.
S/64/Rev.1	French and English	III.D.2	Trombe, F. and Foëx, M.
S/65	English	II.C.1(*b*)(*ii*)	Prince, M. B.
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S/67	English	III.C.2	Engebretson, C. D.
S/68	English	III.C.1	Tanishita, I.
S/69	French	III.A	Peyturaux, R.
S/70	French and English	III.D.1	Oniga, T.
S/71	French and English	III.B	Francia, G. F.
S/72	French and English	III.C.1	Savornin, J.
S/73	Spanish/French	III.E	Fontán, L. and Barasoain, J. A.

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S/74	English	III.A	Flach, E. F. and Mörikofer, W.
S/75	English	III.C.4	Abou-Hussein, M. S. M.
S/76	French and English	III.D.2	Crausse, E. and Gachon, H.
S/77	English	III.E	Löf, G. O. G.
S/78	English	II.C.1(*b*)(*i*)	Hatsopoulos, G. N. and Brosens, P. J.
S/79	English	III.F	Cotton, E. S., Lynch, W. P., Zagieboylo, W. and Davies, J. M.
S/80	French	III.A	Perrin de Brichambaut, C.
S/81	French	III.F	Trombe, F. and Foëx, M.
S/82	English	III.D	Chung, R. and Duffie, J. A.
S/83	English	III.C.3	Talwalkar, A. T., Duffie, J. A. and Löf, G. O. G.
S/84	French and English	II.C.1(*b*)(*i*)	Perrot, M. and Touchais, M.
S/85	English	III.E	Strobel, J. J.
S/86	French and English	III.B	Vachet, P. and Mercier, J.
S/87	English	III.C.4	Duffie, J. A., Löf, G. O. G. and Beck, B.
S/88	English	III.D.2	Adler, S., Levite, G. and Tabor, H.
S/89	French	III.E	Lejeune, G.
S/90	English	II.C.1(*b*)(*i*)	Wilson, V. C.
S/91	French and English	III.B	Peyches, I.
S/92	English	III.A	Schöffer, P., Kuhn, P. M. and Sapsford, C. M.
S/93	English	III.C.2	Olgyay, A.
S/94	English	III.C.2	Yanagimachi, M.
S/95	French	III.A	Gondet, M.
S/96	English	III.C.1	Andrassy, S.
S/97	English	III.C.1	Whillier, A. and Richards, S. J.
S/98	English	III.A	Page, J. K.
S/99	English	II.C.1(*a*)	d'Amelio, L.
S/100	English	III.C.4	Löf, G. O. G. and Fester, D. A.
S/101	English	III.C.4	Telkes, M. and Andrassy, S.
S/102	English	III.C.1	Mathur, K. N. and Khanna, M. L.
S/103	English	II.C.1(*b*)(*i*)	Breihan, R. R., Daniels, F., Duffie, J. A. and Löf, G. O. G.
S/104	English	III.B	Daniels, F. and Breihan, R. R.
S/105	English	III.A	Ramdas, L. A.
S/106	English	II.C.1(*b*)(*ii*)	Rappaport, P. and Moss, H. I.
S/107	French	III.E	Gomella, C.
S/108	French	III.F	Achard, J. C.
S/109/Rev.1	French and English	III.D.1	Trombe, F. and Foëx, M.
S/110	French and English	III.C.4	Prata, A. S.
S/111	French and English	III.D.2	Trombe, F. and Henry La Blanchetais, Ch.
S/112	English	III.C.2	Fukuo, N., Kozuka, T., Iida, S., Fujishiro, I., Irisawa, T., Yoshida, M. and Mii, H.
S/113	English	III.E	Nebbia, G.
S/114	English	III.C.2	Löf, G. O. G., El-Wakil, M. M. and Chiou, J. P.
S/115	English	III.E	Khanna, M. L. and Mathur, K. N.
S/116	English	III.C.4	Food and Agriculture Organization, Nutrition Division
S/117	English	III.A	Drummond, A. J.
S/118	English	II.C.1(*b*)	Baum, V. A., Borovikova, R. P. and Okhotin, A. S.
S/119	English	III.E	Baum, V. A.

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