I

GEOTHERMAL ENERGY IN THE WORLD ENERGY SCENARIO

GEOTHERMAL ENERGY IN THE EUROPEAN ECONOMIC COMMUNITY

GEOTHERMAL ENERGY IN ITALY

Enrico Barbier

International Institute for Geothermal Research

Pisa, Italy

Lectures given at the United Nations University
Geothermal Training Programme, Reykjavík, Iceland,
Sept. - Oct. 1984.

PREFACE

Since the foundation of the UNU Geothermal Training Programme in 1979, it has been customary to invite annually one geothermal expert to come to Iceland as a UNU Visiting Lecturer. The UNU Visiting Lecturers have been in residence in Reykjavik from about two weeks to about two months. They have given a series of lectures on their speciality and held discussion sessions with the UNU Fellows attending the Training Programme. The lectures of the UNU Visiting Lecturers have also been open to the geothermal community in Iceland, and have always been very well attended. It is the good fortune of the UNU Geothermal Training Programme that so many distinguished geothermal experts with an international reputation have found time to visit us. Their contribution to the Training Programme has been very significant. Following is a list of the UNU Visiting Lecturers from 1979-1984:

1979	Donald E. White	USA
1980	Cristopher Armstead	UK
1981	Derek H. Freeston	New Zealand
1982	Stanley H. Ward	USA
1983	Patrick Browne	New Zealand
1984	Enrico Barbier	Italy

It is a special pleasure to welcome the UNU Visiting Lecturer of 1984, Dr. Enrico Barbier of the International Institute for Geothermal Research in Pisa, Italy. He has for a number of years been the Editor in Chief of GEOTHERMICS, and the deputy director of the International School of Geothermics in Pisa. We hope that his visit to the UNU Geothermal Training Programme in Reykjavik will further strengthen the ties between the international geothermal training centers in Pisa and Reykjavik. In this report are presented some of the lectures that Dr. Barbier gave in Reykjavik in September 1984.

Ingvar Birgir Fridleifsson,
Director,
United Nations University,
Geothermal Training Programme.

GEOTHERMAL ENERGY IN THE WORLD ENERGY SCENARIO

Enrico Barbier

International Institute for Geothermal Research

Pisa, Italy

Lecture given at the United Nations University Geothermal Training Programme, Reykjavik, Iceland, Sep-Oct 1984.

GEOTHERMAL ENERGY IN THE WORLD ENERGY SCENARIO

Table of Contents

GEOTHERMAL ENERGY IN THE WORLD ENERGY SCENARIO

The World Energy Consumption

Table 1 shows the world energy consumption between 1925 and 1982 expressed as a percentage of the primary energy sources.

It is evident that until the 1950s more than half of the energy consumed throughout the world derived from coal, which represented a milestone in the industrial revolution. Coal was the first choice for power generation and industrial steam raising, as well as being a major fuel for domestic heating and the source of town gas. Coal also had an important role in the transportation sector through steam-driven railway engines and ships.

World consumption of coal has always increased slowly but steadily, and still does so. During the last thirty years it has passed from 1.6 billion tons (1953) to the 3.2 of 1983. However, consumption of other fuels, such as oil and gas, have increased far more rapidly, and Table 1 clearly reveals that the percentage represented by coal is slowly decreasing from 81.3% in 1925 to 29.9% in 1982. Even the energy crisis of 1973 had little or no effect on its role in the world energy scenario: from 29.9% in 1973 it passed to 30.5% in 1974 before decreasing again in later years.

The prospects of relaunching coal on a global scale seemed quite promising a few years ago, but have faded somewhat during the last three years. Power generation is by far the largest market for coal, and so far it has been used for this purpose mostly by the countries that produce it, with very little export-

Table 1

Energy consumption in the world as a percentage of primary sources

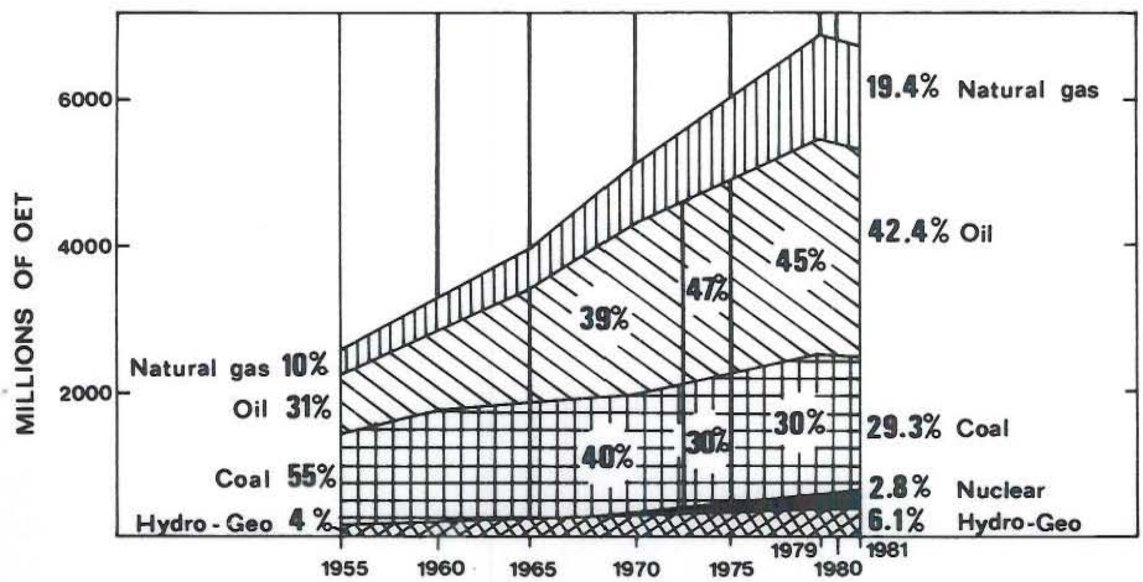
ENERGY CONSUMPTION IN THE WORLD %

Years	1925	1938	1950	1955	1960	1965	1970	1973	1974	1976	1980	1981	1982
COAL	81.3	69.7	58.5	52.1	48.4	39.9	32.8	29.9	30.5	30.2	29.6	29.3	29.9
GAS	3.2	5.5	9.2	10.0	11.9	14.6	16.9	17.2	18.1	17.8	17.4	19.4	19.2
OIL	13.0	20.3	26.5	31.7	33.4	39.0	44.7	46.5	44.7	44.8	44.4	42.4	41.2
HYDRO-GEO	2.5	4.5	5.8	6.2	6.3	5.3	5.2	5.6	6.7 (Hydro-Geo + Nuclear)	7.2 (Hydro-Geo + Nuclear)	6.2	6.1	6.5
NUCLEAR											2.4	2.8	3.2

Source: ENI 1981-1983

Table 2

World energy consumption since 1955



Source: Colombo 1983

ed (only 5% of production).Among the major producers, the USA obtain 52% of their electricity from coal, the USSR 70%, the Federal Republic of Germany 65% and the United Kingdom 70%. The competitive costs of nuclear energy have limited the penetration of coal in the industrial countries that import this fuel. In Japan, for example, only 4.7% of the electricity is coal-derived, in Canada 10% and in France 25%.

There are various factors responsible for the lack of interest in this fuel. Large investments are required to exploit old and new mines, transport costs are higher than for other fuels, the higher capital costs of coal-fired power-stations.The substitution of oil or gas by coal through premature retirement of existing boilers is also clearly less attractive economically and requires greater economic incentive than substitution through normal replacement. Coal is still less convenient to use than oil or gas, and generally retains its historic image of a dusty, dirty fuel. This is indeed a realistic image as coal is one of the most polluting fuels and the increasingly strict environmental regulations lead to additional costs to the producer (and consumer).

The world energy situation is at present so unstable that there are few people willing to take the risk of long-term contracts which are generally based on a coal price that is liable to be much higher than it costs on the spot market. The coal situation is further aggravated by a fall in the price of oil and in the demand for the latter.

One may expect a slow development in the coal sector in future, also as a consequence of the crisis in the steel industry,a major consumer of this fuel.

Table 1 also shows the large increase in consumption of natural gas, from 3.2% in 1925 to 19.2% in 1982. In the years preceding the 1930s, although large quantities of gas were found during oil research, this discovery was considered a research failure and the gas was not utilized. This happened even when a very advanced gas technology was available as the consequence of utilizing the gas extracted from coal. Only in the 30s did industry realize how great an economic value lay in natural gas and began its extensive exploitation. It is logical to ask at this point why it took so long to discover the energy value of natural gas. Probably for the same reasons that delayed for many years the development of geothermal energy throughout the world, rather than the risks entailed with exploration the main causes lie in the limited spreading of knowledge on the subject and the lack of technological curiosity.

Natural gas has so far been a 'domestic' energy source and utilized for the most part in industrialized countries with their own reserves: in the USA natural gas represents 31% of the total energy consumed and in the USSR 25% (1982).

Only 13% of the world gas production in 1983 was exported (of a total of 1460×10^9 m^3), and over three-quarters of this international trade was by pipeline, with the balance exported by sea as liquefied natural gas (LNG). The export of pipeline gas is dominated by four countries: the USSR, the Netherlands, Norway and Canada, whereas export as LNG is mainly conducted by Algeria, Indonesia and Brunei.

Export of gas has been hindered from expansion by the high capital costs required to create the transport and distribution networks, the long-term supply contracts stipulated to amortize capital costs and the reluctance to utilize gas in such important sectors as transport and electricity generation.

There are many advantages offered by natural gas: there are large reserves, sited in quite different geopolitical areas from oil, which is of strategic benefit to consumer countries wishing to diversify their energy suppliers and, finally, gas is a low-polluting fuel.

Table 1 again shows how oil became the world's major source of energy in the mid 1960s and will probably continue so until at least the year 2000, accounting for 35-40% of the total world consumption of energy.

Over half the world's known reserves are located in the Middle East, which will continue to be the major producing area of the world. Following on the energy crisis of 1973 the world's consumption of oil dropped from 46.5% in that year to 44.7% in 1974 to 41.2% in 1982 and 41% in 1983.

Oil will continue to be the major fuel in many markets. Its particular qualities give it many advantages in terms of storage and distribution, as well as flexibility in by-products. But coal and other sources of energy may be used increasingly for industrial purposes, thus leaving more crude oil available for high grade uses such as transportation, or as a chemical feedstock.

Table 1 also reveals the slow but steady development of hydro-power, together with the small contribution of geothermal energy. The latter will, however, be dealt with in greater detail later.

The past hundred years have witnessed the development of hydro for the production of electricity.

During the last 50 years hydro's contribution on a world scale has increased from 2.5% in 1925 to 6.5% in 1982, although in Norway it is now 99% and in South America 55%. The size of hydro-power stations varies greatly from massive units with generating capacities measured in thousands of megawatts to very small systems of a few megawatts. Much attention is currently being given to 'mini-hydro' schemes, i.e. small-scale simple power- plants with generating capacities of around 1 MW. There are a number of areas, especially in rural parts of developing countries, where the installation of such plants appears viable.

Hydro-electricity shares with a number of alternatives the advantage of being an indigenous source of clean and cheap energy. At the same time, it can offer a number of secondary benefits such as flood control, improved irrigation of agricultural land, as well as opportunities for fisheries, better communications and the development of tourism.

The main disadvantage of major hydro schemes is the massive capital expenditure involved, although this can be amortized over very long periods.

Much of the world's untapped hydro potential lies in remote areas and may not be exploited for many years, but its contribution to the energy demand of developing countries could, in various cases, be significant.

Table 1 ends with nuclear energy, which appeared on the world energy scenario at the end of the 1960s; because of its small contribution it is considered included with hydro-geo power until 1976. At the beginning of the present decade nuclear power was already accounting for 2.4% of the world energy demand, and by 1982 had reached 3.2%.

Theoretically the energy released by the fission of 1 kg of the isotope U235 of uranium is equal to that released by the combustion of 2000 tons of oil, that is to say, two million times as much per unit weight. Most nuclear reactors use enriched uranium as fuel.

Knowledge of the world's resources of uranium is still limited but, according to an International Atomic Energy Agency survey, reasonably assured resources in the world, outside state planned economy countries, amount to some 2.6 million tons. Over 85% of these resources are located in 7 countries of which 65% are in the United States and Canada.

In 1980 production of uranium was around 42000 tons. It seems likely that a rapid expansion of nuclear capacity (improbable) during the 1980s and 1990s would be adequately covered.

Nowadays there is in fact a world crisis in this sector:

compared to a total of 495 reactors already operating or being installed in January 1983 in western Europe, USA, Canada and Japan, to a total of 372,060 MW, only 49 new reactors have been ordered, totalling 54,280 MW. It is unlikely that nuclear power will develop at the rate expected in the 1970s; estimates for the future vary considerably, but it is possible that nuclear power's share of the energy supply could rise to as much as 10% by the end of the century. However, much will depend on the degree to which some countries increase their electricity usage. At the same time, political and environmental considerations, partly reflecting such issues as waste disposal and security of supply, as well as the high capital risk involved in an uncertain growth situation, are key factors affecting the development of this industry (Colombo, 1983).

Table 1 showed the world energy consumption expressed in percentages of the various energy sources. Table 2 gives the absolute values, in oil equivalent tons (OET), for the energy consumed since 1955. Table 3 reports the consumption relative to some particular years.

Table 3 reveals a strong increase of 67% in energy consumption between 1962 and 1972, as opposed to the rapid deceleration between 1972 and 1982 to an increase of only 23%, as a consequence of the 1973 energy crisis.

Table 3

World energy consumption of primary sources in selected years.

Million Oil Equivalent Tons	1962	1972	1982
OIL	1275	2655	2900
COAL	1280	1410	1775
NATURAL GAS	430	980	1300
HYDRO	220	315	450
NUCLEAR	+	40	225
OTHER	65++	65	50
Total	3270	5465	6700

+Negligible

++Industrial use of wood, geothermal energy, alcohol from biomass

Source: Shell 1983 - Colombo U. 1983

Table 3 also clearly shows the drop in the contribution of oil to the world's energy requirements during the period 1972- 1982 with respect to the preceding ten years. The increase in oil consumption between 1972 and 1982 was, in fact, 9%, as opposed to the 108% increase between 1962 and 1972.

Table 4 shows the total energy consumption (again in Oil Equivalent Tons) for the industrialized and developing countries. From this Table we obtain Table 5, in which it is interesting to note that:

- in 1962 the OECD countries, together with the USSR and Eastern Europe, consumed 81% of the total energy, and the developing countries only 19%;
- in 1972 this figure was 82%, as opposed to the 18% of the developing countries;
- in 1982 the industrialized countries consumed 77%, and the developing countries 23%.

Table 4

Total energy consumption for developed and developing countries in selected years.

Million Oil Equivalent Tons		1962		1972		1982	
OECD Countries+			2105		3445		3550
USSR & Eastern Europe			550		1060		1625
OPEC	Developing countries	40	615	100	960	225	1525
Others		575		860		1300	
Total			3270		5465		6700

+EEC-Austria-Finland-Iceland-Norway-Portugal-Spain-Sweden-Switzerland-Australia-Canada-Japan-New Zealand-Turkey-USA-Yugoslavia.

Source: Shell 1983- modified.

Table 5

Percentages of world energy consumption for developed and developing countries in selected years.

	1962	1972	1982
OECD-USSR-Eastern Europe	81%	82%	77%
Developing countries	19%	18%	23%
Total	100%	100%	100%

The greatest increase in the energy consumption of the developing countries occurred, therefore, between 1972 and 1982.

The World Energy Reserves

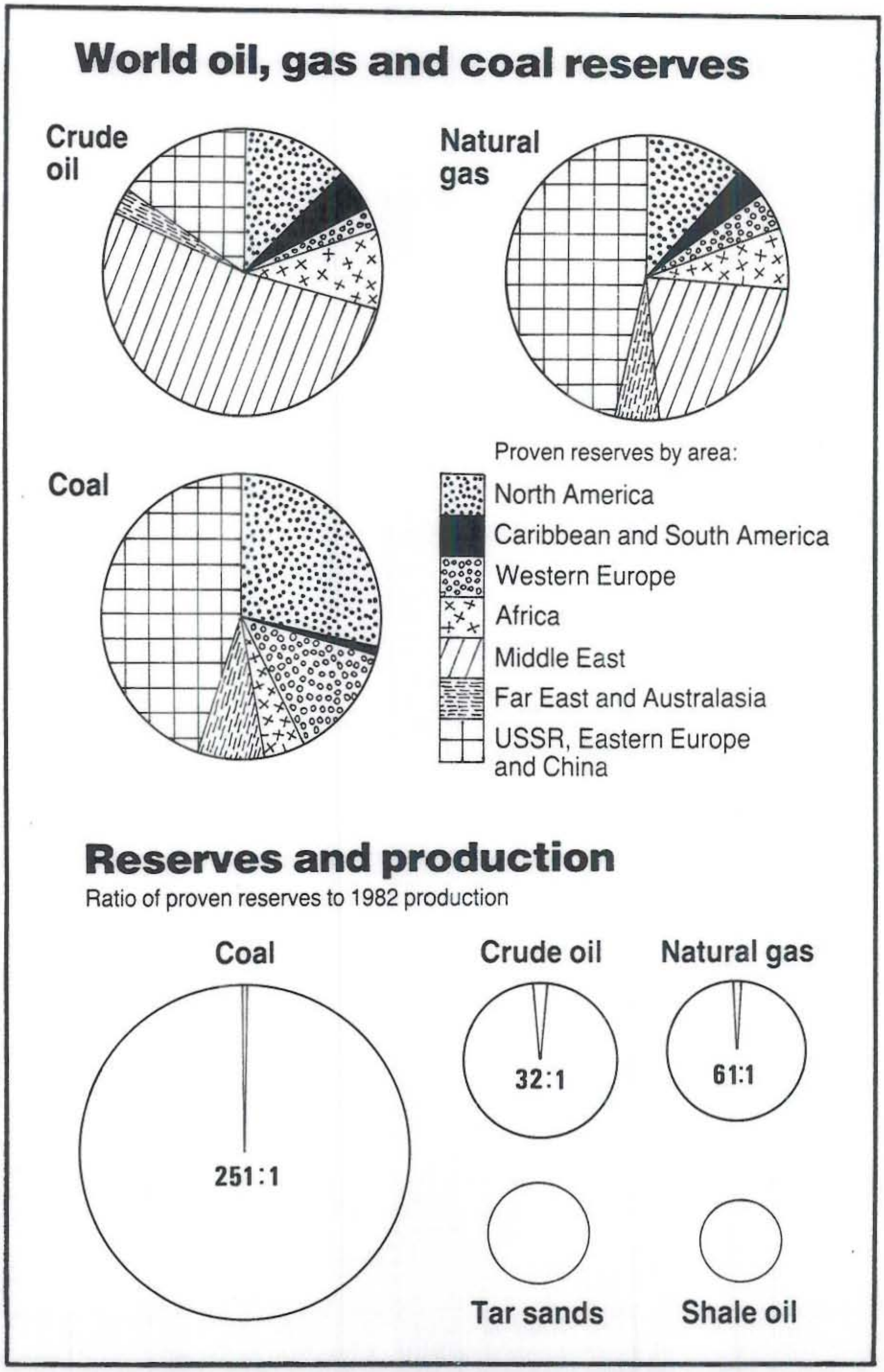
The proven world energy reserves, as regards fossil fuels, are given in Table 6, which also indicates their geographical location.

This Table also shows , as mentioned earlier, that more than 50% of the world's oil is located in the Middle East, whereas about 50% of the coal and 50% of the natural gas are found in the USSR, Eastern Europe and China.

Various hypotheses could be forwarded for the lifetime of these reserves. Assuming that they will be extracted at the rate of world production in 1982, and taking this figure as a reference equal to 1, then the coal reserves could be estimated to last a further 251 years (1982 production = 1.8×10^9 OET,

Table 6

Proven world oil, gas and coal reserves



Source: SHELL 1983

reserves 452 x 10^9 OET), natural gas for 61 years (1982 production = 1.3 x 10^9 OET, reserves 79.5 x 10^9 OET), while oil would last for a further 32 years only (1982 production = 2.9 x 10^9 OET, reserves 93.3 x 10^9 OET).

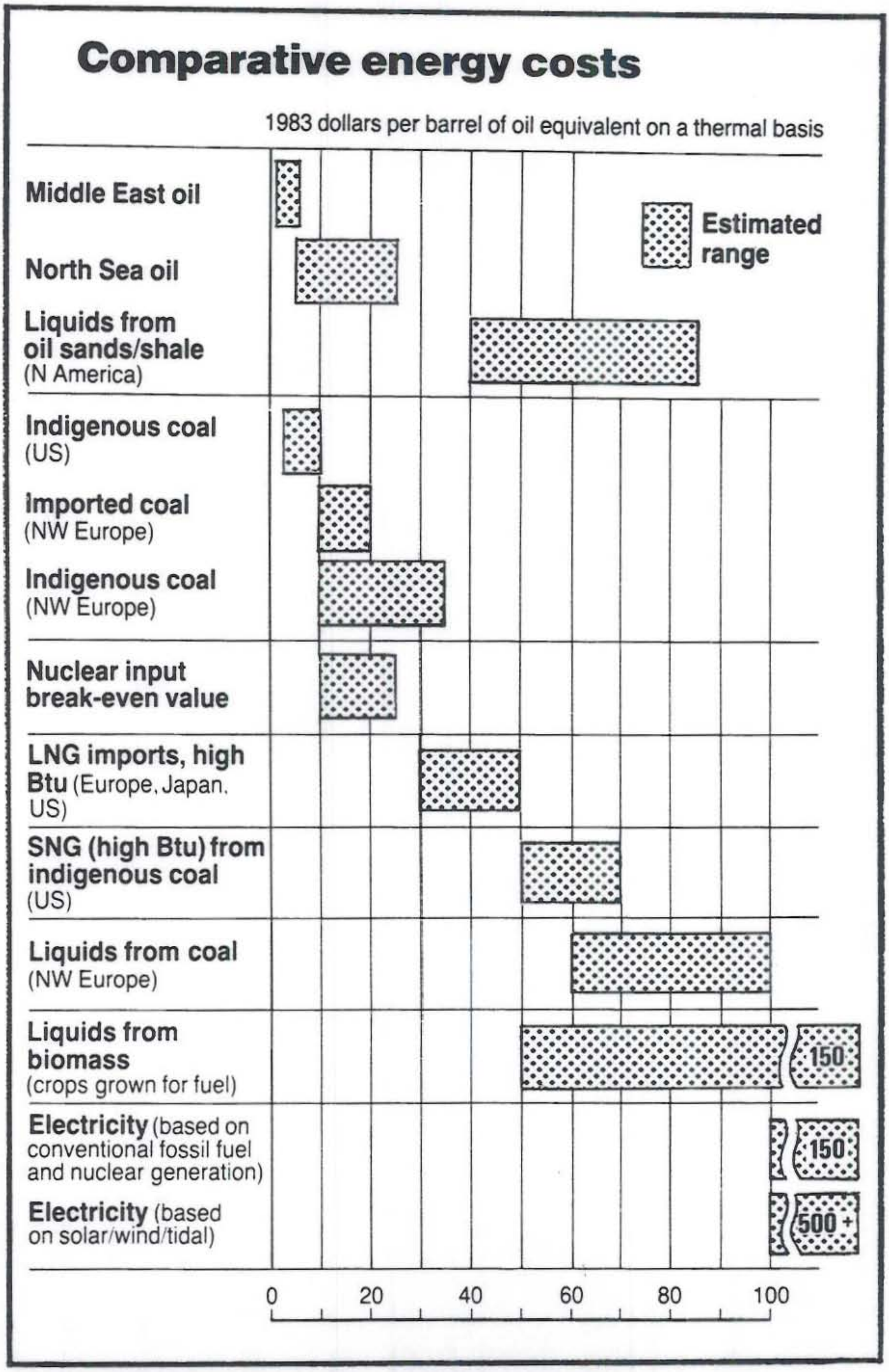
Production of oil from tar sands and oil shales is low at the moment and in the experimental stage, and the proven reserves amount to 41 x 10^9 OET for the former and 27.4 x 10^9 for the latter.

Comparative Energy Costs

Table 7 is a comparison of the costs of the various energy sources, heat generation being equal. The Table shows the cost range of one barrel of oil equivalent (OEBBL) on a thermal basis (1 barrel of oil = 137 kg x 10,000 kcal/kg = 1,370,000 kcal). Although not cited in Table 7, the average world cost for geothermal energy can be estimated at 140 $ for the energy of 1 OEBBL, assuming the transfer to heat of geothermal-derived electricity. This value corresponds to about 8.8 US cents/kWh,which happens to be the cost of geothermal power production in the Japanese power-stations (Kaneko 1983). For geothermal power-stations of roughly 20 MW, the estimates are at present roughly 9.6-12.6 US c/kWh (Djibouti, Abdallah et al.1984); for 4 MW power-stations they are 8.4-11.8 c/kWh (Guadeloupe, Jaud and Lamèthe, 1984). These figures cannot be generalized, as they are tied to local geological and economic situations.

Table 7

Comparative energy costs



Source: SHELL 1983

In Table 8, which shows the energy costs of the developing countries, a rise in the cost of oil is clearly accompanied by a rise in the import bills of these countries. Concern is again mounting over the ability of many developing countries to pay for their energy needs without constraining growth and future investment. In 1972 (see Table 8) only 8% on average of the oil importing developing countries' export earnings were required to cover the cost of oil imports. By 1978 this percentage had risen to 20%.

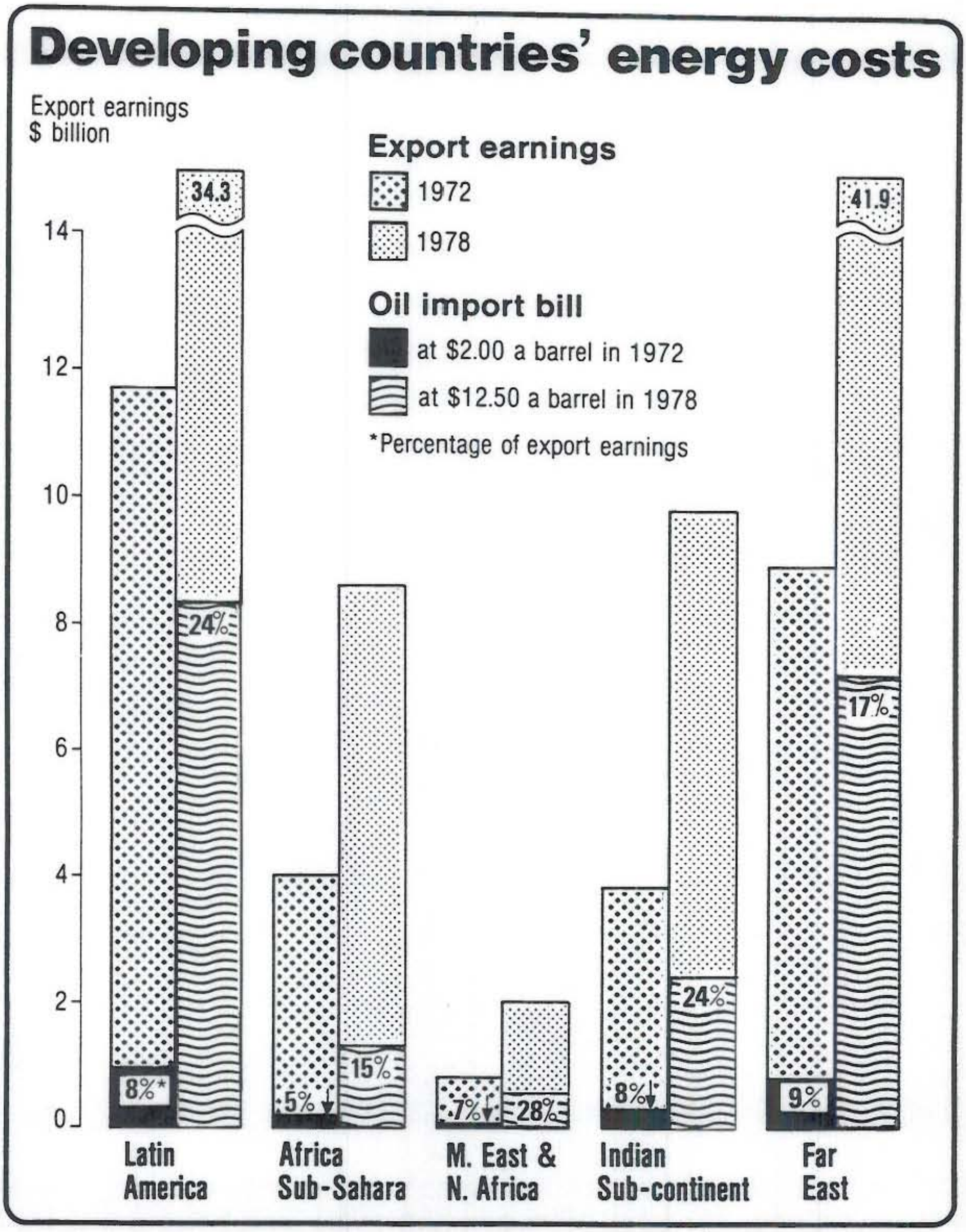
Geothermal Contribution to Electricity Generation

Table 9 shows the installed electric power throughout the world in 1981. From this Table we then obtain Table 10, which gives the total electrical installed power in 1981 divided between developed and developing countries.

Considering electrical consumption only, Table 10 shows that the developing countries consumed 11% of all the electricity generated throughout the world in 1981. This figure is lower than the 23% ascribed to these countries as regards the total energy consumed (Table 5). We can thus conclude that a lower percentage of primary energy sources is converted to electricity in the developing countries. (Note that I have compared the 1981 electricity data with the 1982 data for primary energy sources, as no electricity data were available for 1982).

Table 8

Developing countries' energy costs



Source: SHELL 1980

Table 9

World Electrical Installed Power in 1981, Megawatts

Western Europe	450,000
Eastern Europe (excluding USSR)	100,000
USSR	250,000
Asia (excluding USSR & Japan)	130,000
Japan	150,000
North America	700,000
Central America	5,000
South America	60,000
Africa (excluding South Africa)	20,000
South Africa	20,000
Australia & Oceania	25,000
Total	1,910,000

Source: UN Economic Commission for Europe, 1982

Table 10

Electric Power Installed in the World in 1981, Megawatts

Developed countries	Developing countries	Total
1,695,000	215,000	1,910,000

The world installed electric power of geothermal origin, at the end of 1982, is shown in Table 11, along with some very conservative estimates for 1986 and 1990. Figures were obtained directly from the countries quoted in the Table.

The world geothermal electric power at the end of 1982 was about 2800 MW (2,792,500 kW). By comparison, the world electrical power in 1981 was 1,910,000 MW (Table 9). Geothermal energy thus represents 0.15% of the world electric power. (I have again compared 1982 with 1981 data (total power), but the geothermal figures are so small, and the total power figures so large that the percentage is not affected to any appreciable extent).

This is obviously a very small figure and indicates that geothermal energy plays a very minor role on the world energy scene. However, if we distinguish between industrialized and developing countries, then the contribution of geothermal energy is clearly shown to be entirely different.

In the industrialized countries, where the installed electrical power reaches high figures (tens or even hundreds of thousands of MW), geothermal energy is unlikely, in the mid-term (10 years), to count for more than a few percent, at the most, of the total.

In the developing countries, with an as yet limited electrical consumption but good geothermal prospects, the electrical energy of geothermal origin could, on the contrary, make quite a significant contribution to the total.

Table 12 compares these two situations.

Table 11

Geothermal energy in the world: present status and future prospects. Electricity generation, Megawatts.

Country	Geothermal electrical installed power 1982	1986	1990
Azores (Portugal)	3	?	?
Chile			30
China	4	7	10
El Salvador	95	95	150
Ethiopia			5
Greece		3	100
Guatemala			15
Iceland	41	71	71
India			5
Indonesia	30	60	92
Italy	440	500	700
Japan	215	400	1400
Kenya	30	30	30
Mexico	180	580	1200
New Zealand	202	252	302
Nicaragua	35	35	180
Philippines	570	1100	1300
Turkey	0.5	20	?
USA	936	1800	4370
USSR	11	61	71
West Indies (French)		5	5
Total	2792.5	5024	10,036

Source: Barbier E. & Fanelli M., 1983

Table 12

Total electrical installed power vs geothermal for some developed and developing countries

	Total Electrical Installed Power (1981), MW+	Geothermal Electrical Installed Power (1982), MW	% of the Total Installed Power
Industrialized countries			
Italy	48,000	440	0.9
Japan	150,000	215	0.1
USA	652,000	936	0.1
Developing countries			
El Salvador	502	95	18.9
Nicaragua	370	35	9.5
Philippines	4,755	570	11.9
Kenya	541	30	5.5

+Source: UN Statistic Yearbook 1981(1983).

With regard to the geothermal power-plants, a total of 121 units were in operation throughout the world in 1982, each unit consisting of one turbine and an electric generator. Their size is given in Table 13. (That is, 121 units out of a total power of 2559 MW reported by Di Pippo(1983) for June 1982. This figure is lower than the power calculated by Barbier & Fanelli for the end of that same year, given in Table 11 (2792 MW)).

Table 13

Number of units in geothermal power-stations in the world,1982

```
         0      5       10      15      20     25      30      35      40

  5 MW   ============================================================38
  5- 10  =============9
 10- 20  =================================================32
 20- 30  =========================16
 30- 40  =======5
 40- 50  ==1
 50- 60  =========================16
 60- 70
 70- 80
 80- 90
 90-100
100-110  ====3
110-120
120-130
130-140  ==1
140-150
```

Source: Di Pippo R., 1983

This Table shows that 80% of the units were smaller than 30 MW. The biggest, 135 MW, is installed in The Geysers field, in California.

With regard to the type of unit, at the end of 1982, 46% were dry steam, 26% single flash, 13% dual flash and 9% multiple flash. Only 6% were binary cycles (Di Pippo,1983).

Research in geothermal energy is being conducted all over the world. The effort expended in this sector varies from country to country, depending on the financial resources and, at times, the political and social stability.

Table 11 gives some rather conservative estimates of the future geothermal electric power that will be installed by 1986 and possibly by 1990. The figures relative to 1986 are obviously much more reliable as we are dealing in this case, at a distance of only a few years, with known geothermal fields and plants already under construction.

References

ABDALLAH A., GANDINO A. and SOMMARUGA C. (1984) Technical-economic studies of geothermal projects: the Djibouti case. Seminar on Utiliz. of Geoth.Energy for Electric Power Produc. and Space Heating. Florence, 14-17 May 1984. Geothermics, 14, 2/3, 1985, in press.

BARBIER E. and FANELLI M. (1983) International Institute for Geothermal Research, Pisa, Italy.

COLOMBO U. (1983) Energy: industrial competition and technological development (in Italian). ENEA News Bulletin, October, Rome, p.10-30.

DI PIPPO R. (1983) Overview of worldwide geothermal power development. Geothermal Resources Council Bull., May, USA, p.3-9.

ENI (Italian State Oil Holding) (1981) Energy & Hydrocarbons, Rome.

JAUD Ph. and LAMETHE D. (1984) The Bouillante geothermal powerplant, Guadeloupe. Seminar on Utiliz. of Geoth.Energy for Electric Power Produc. and Space Heating. Florence, 14-17 May 1984. Geothermics, 14, 2/3,1985, in press.

KANEKO M. (1983) National outlook in Japan for geothermal energy development. Ministry of International Trade & Industry, Tokyo.

SHELL BRIEFING SERVICE (1980) Energy in Profile, Dec.1980, London.

SHELL BRIEFING SERVICE (1982) The energy spectrum, no.3, London.

SHELL BRIEFING SERVICE (1983) Energy in Profile,no.5, London.

U.N.ECONOMIC COMMISSION FOR EUROPE (1982) Seminar on the medium-term and long-term prospects for the electric power industry, V.V.Ezshevich's gen.report, London 26-30 Oct. 1981. UNECE, Geneva.

U.N. STATISTIC YEARBOOK 1981 (1983) United Nations, New York.

GEOTHERMAL ENERGY IN THE EUROPEAN ECONOMIC COMMUNITY

Enrico Barbier

International Institute for Geothermal Research

Pisa, Italy

Lecture given at the United Nations University Geothermal Training Programme, Reykjavik, Iceland, Sep.Oct. 1984.

GEOTHERMAL ENERGY IN THE EUROPEAN ECONOMIC COMMUNITY

Table of Contents

GEOTHERMAL ENERGY IN THE EUROPEAN ECONOMIC COMMUNITY

Introduction

Ten countries belong to the European Economic Community (Fig.1).Table 1 shows the population of these 10 countries and their installed electric capacity.

Table 1

Population and electric power in the EEC countries

	Population (millions)	Electric installed power MW (1981)
Belgium	10	11,127
Denmark	5	6,758
Federal Rep. of Germany	60	84,630
France	54	69,900
Greece	10	5,952
Ireland	3	3,332
Italy	56	47,616
Luxembourg	0.4	1,305
The Netherlands	14	18,473
United Kingdom	54	70,158

Source: UN Statistic Yearbook 1981 (1983)

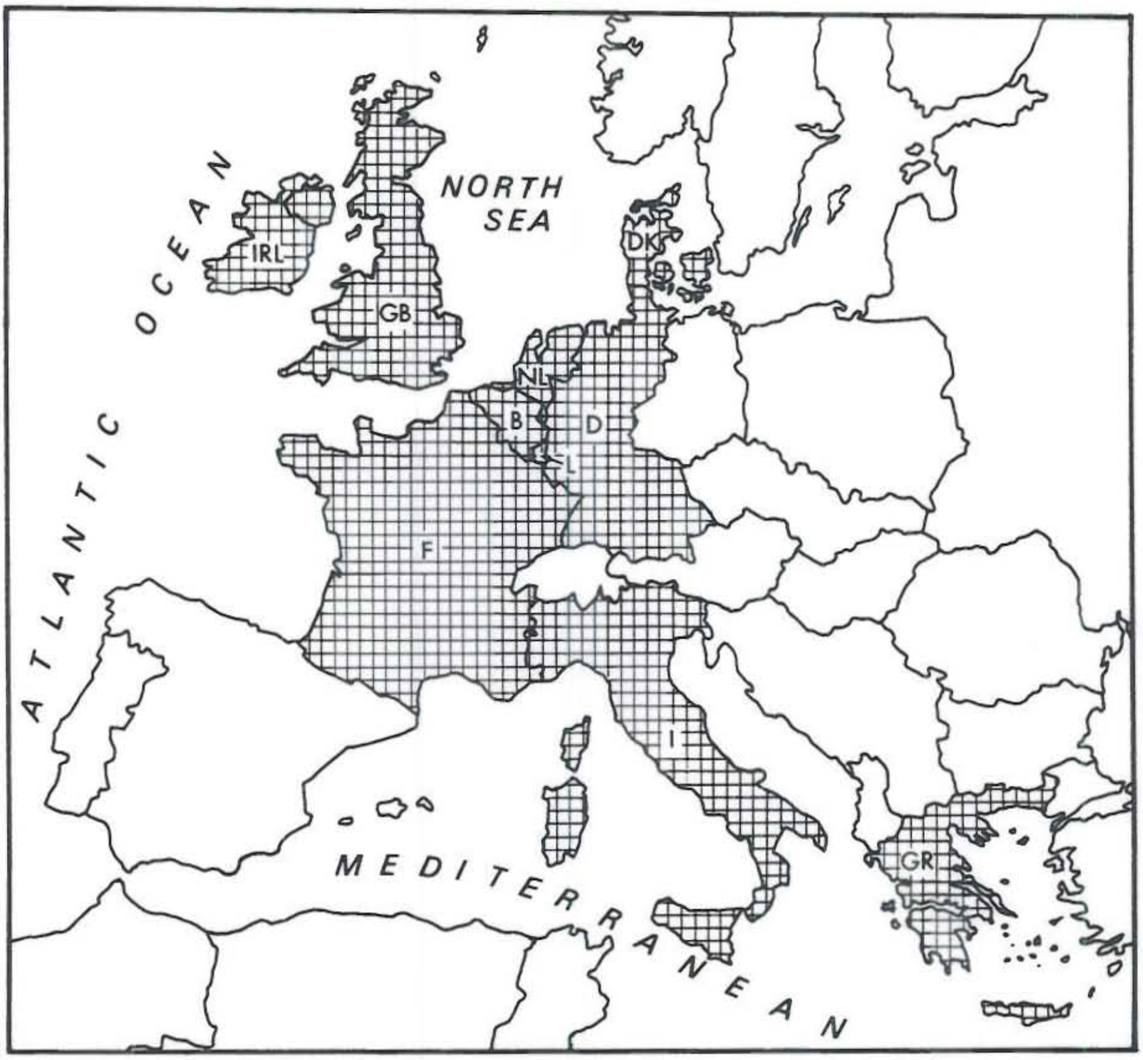


Fig.1

The European Economic Community Member States

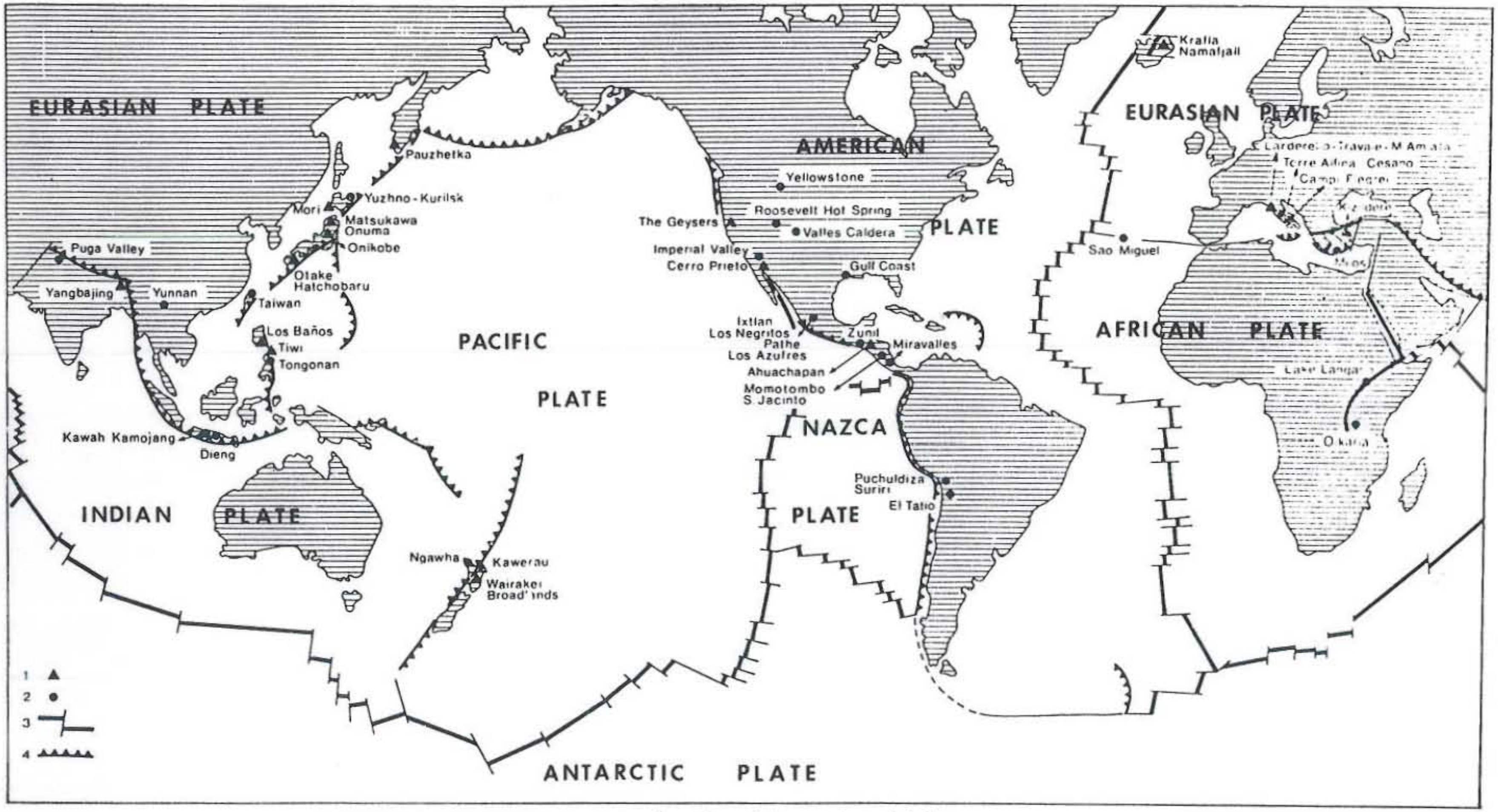
The energy crisis has obviously encouraged all the member countries of the EEC to search for non-conventional sources of energy. The Community is, in fact, severely dependent on third countries for their energy supply: in 1981 the Community consumed about 1 billion Oil Equivalent Tons (OET), about 50% of which was imported (world-wide consumption during that year was 6.7 billion OET). Forty percent of the entire EEC energy demand is in district heating, agriculture and industrial processing.

As one of the non-conventional energy sources, geothermal energy could make a contribution to oil savings, especially in the direct use of geothermal heat for district heating, agriculture and industrial processes. Note that warm and quite large aquifers (30°-80°C) have been discovered in almost all the countries of the Community. Their utilization in the above- mentioned sectors, which absorb about 40% of the entire Community energy demand, could lead to considerable savings in imported fuel.

The EEC geological outline

The geological setting in Europe, and hence the geothermal situation, is tied to the geodynamics of the Eurasian plate (Figs.2 and 3).

Western Europe, which is the area of the EEC states, has on the whole a very old, rigid continental crust characterized by:



Location of the geothermal fields.

1 : Exploited high temperature fields.
2 : Known high temperature fields not yet exploited.
3 : Spreading ridges, continental rift zones and transcurrent faults.
4 : Subduction zones.

Fig.2

Plate tectonics and geothermal fields

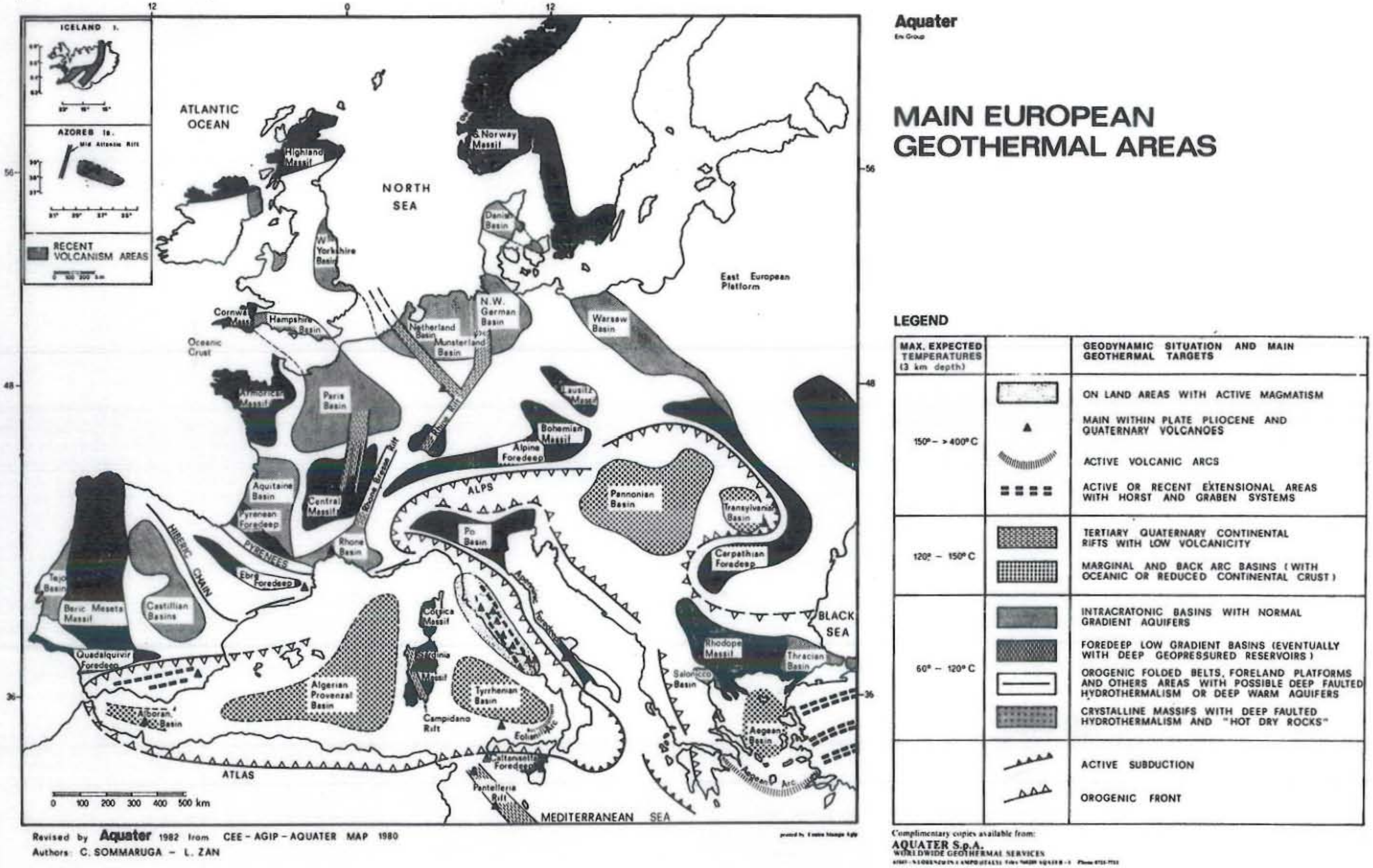


Fig.3

Main European geothermal areas

- Crystalline massifs (usually Paleozoic) with deep-faulted hydrothermalism and potential for 'hot dry rock' tests.
  These are: Highlands, U.K., Cornwall, U.K.; Armorican, France; Central Massif, France; Corsica, France; Sardinia, Italy; Rhodopean Massif, Greece; Bohemian and Lausitz, Czechoslovakia; South Norway; Beric Meseta, Spain.

- Sedimentary intracratonic basins, with normal geothermal gradient aquifers. These are: Wessex, Southampton, U.K.; East Yorkshire, U.K.; Northern Ireland, U.K.; Danish; NW Germany; Musterland, FRG; The Netherlands; Paris, Aquitaine, France; Thrace, Greece; Warsaw, Poland; Castillan, Spain; Tejo, Portugal.

- Sedimentary foredeep basins, with low gradient aquifers (eventually with deep geopressured reservoirs).
  These are: Alpine-Molasse foredeep; Pyrenean; Po Valley,Italy; Caltanissetta, Italy; Carpathian, Hungary; Quadalquivir, Spain.

- Continental rifting, Rhine graben; Rhone rift valley; Campidano valley, Sardinia; Pantelleria rift.
  Rift valleys,and particularly the Rhine graben, were long considered promising zones, due to above normal gradients (40°-50°C/km), but exploratory holes showed varying reservoir performances. In these areas commercially viable development is highly site specific and it still awaits the advent of a successful wildcat to allow for clear resource validation.

The Mediterranean area, where the Eurasian and African plates collide, is covered by a younger crust, and shows the typical features of the subduction of the African beneath the Eurasian plate. This is in fact the area of the Eolian and Hellenic trenches, the Tyrrhenian, Algerian-Provençal and Aegean marginal basins, and a system of tensional horsts and grabens (Tuscany, Latium and Campania, Italy) with associated active and recent volcanism.

One important outcome of the rather irregular distribution of these geothermal areas is that the majority of the EEC states are bound to a low enthalpy geothermal outlook, e.g. to direct uses of heat, whereas the high enthalpy sources, eligible for electricity generation, are limited to central and southwest Italy and Eastern Greece.

The EEC activity in the geothermal sector

The EEC has promoted and financed geothermal research since 1975 in the form of:

- R & D programmes (1975-1983), with EEC support totalling 24 M US$ (rate of exchange Sep. 1984)
- Demonstration projects (1979-1983), with EEC support totalling 32 M US$.

The total financial support given by the EEC in the period 1975-1983 was ,therefore, 56 M US$.

R & D programmes

The first R & D programme was launched in 1975 and completed in 1979. Its five targets were:

- compilation of an EEC inventory of geothermal data
- improvement of exploration methods
- utilization of hot water sources (low enthalpy)
- steam sources
- hot dry rocks (HDR)

During this programme the Community signed 700 contracts on a cost-sharing basis with Universities, research organizations, public and private industry. The financial contribution of the EEC amounted to 10 M US$ (Strub, 1980).

The second R & D programme began in 1979, after completion of the first, and ended in 1983. Its four targets were:

- geological, geophysical and geochemical investigations in selected EEC areas
- subsurface problems of hydrothermal resources
- surface problems related to the use of hydrothermal resources
- hot dry rocks.

During this programme, the Community signed 90 contracts with a financial support of 14 M US$ (EEC,1983a).

The total EEC financial support for R & D from 1975 to 1983 was 24 M US$ (Sep.1984).

Demonstration projects

In 1979 the EEC began financing Demonstration Projects in the sector of geothermal energy.

A Demonstration project is one that has already passed the research stage, but it held back by technical and economic problems. It must be on an industrial scale and economically viable.

EEC support never exceeds 49% of the cost of the entire project and has been given essentially to drilling.

A total of 164 proposals were received between 1979 and 1983 of which 78 were financed; the total cost of the accepted proposals was 332 M $ (Sep.1984) and EEC support was for 32 M $ (Gerini, 1984).

Fifty percent of the EEC contribution must be paid back in a maximum of 8 years should the resource be successfully exploited.

The financial support given to the 78 proposals was as follows:

Domestic heating	22	Million US$
Electricity generation	6	" " US$
Greenhouses & other	4	" " US$
Total	32	Million US$

A brief description will now follow of the geothermal activities in the countries of the Community with a committment in this field (EEC,1983b; EEC,1983c; Gerini,1984).

Belgium

Three wells have been drilled into the Carboniferous karst limestone horizon in Hainaut area. The reservoir was first discovered in 1978 by a 5403 m well during geological exploratory drilling at St.Ghislain. The well was later re-activated in order to study the reservoir from the geothermal standpoint. It is an artesian flow with a yield of 150 m^3/h at 73°C.

Since then another two 1500 m wells have been drilled for research and demonstration purposes: in Douvrain, 1447 m, 150 m^3/h of water at 66°C; in Ghlin, 1580 m, 200 m^3/h of water at 68°C. All three of these wells could be utilized but, due to a lack of public and private interest, only one is being exploited at present.

The Netherlands

Feasibility studies are now being conducted on several district heating projects. The most important of these includes the drilling of two wells (production + reinjection) in an area north of Rotterdam to exploit the reservoir of detrital deposits at a depth of about 3000 m.

Note, however, that the energy charges for agriculture are being kept low at the moment, so that there is little incentive to use geothermal heat, at least in this sector.

Denmark

Three wells of more than 3000 m depth have been drilled in northern Denmark, but the Permian-Jurassic sandstone reservoirs have not come up to expectations because of compaction, sealing and recrystallization phenomena, which were underestimated in preliminary studies (temperature between 67°C at 1800 m and 105°C at 3200 m).

The geothermal programme in this country is now being revised.

Federal Republic of Germany

Four Demonstration Projects have received EEC support. One in the Rhine rift valley, which failed to find a productive horizon and the other three in karst limestones of the pre-Alpine basin, where water at 39°C was found at 585 m. The last three projects seem promising.

France

France is the Community country which has made the greatest progress in domestic heating uses of geothermal energy. Geothermal fluids in the Paris basin and other sedimentary basins in France, which are now being explored or exploited, are not the result of a particularly high geothermal gradient, nor is this the case anywhere else in North Europe (except for Iceland). The gradient is more or less normal,i.e. around 35°C/km.

Many hundreds of deep boreholes have been drilled in the Paris basin for oil exploration, and several small oil-fields have been discovered. The characteristics of all potential reservoirs are consequently well-known.

With the depletion of the productive oil wells and the advent of the energy crisis, it seemed more convenient to utilize the warm waters associated with the oil in these wells.

One of the biggest aquifers in the Paris area is the 1300-1700 m deep horizon of Dogger limestone, a regular, continuous formation capable of supplying 200 m^3/h at 70°C with one well only and 20 g/l of salts on average.

So far reinjection has posed no problems in this aquifer. This is undoubtedly the largest geothermal target in Europe, covering a total of 15,000 km^2 and extending as far as the United Kingdom.

At the moment in France there are 42 domestic heating projects operating on geothermal water in the 35°-76°C temperature range, in Paris and its surrounding areas and in Aquitaine. So far 100,000 apartment equivalents (200 m^3 each) are heated in this way, with an energy savings of 100,000 OET/yr.

The French objective is to heat 800,000 apartment equivalents by 1990, thus saving about 1 million OET/yr (Varet, 1984).

According to the Bureau de Recherches Geologiques et Minières (BRGM), the French geothermal resource is <u>not</u> renewable in human time, because the earth heat flow in the Paris basin, for instance, takes 50 years to replace the heat exploited in 1 year by a well doublet.

An average project in the Dogger limestone of the Paris basin has the following characteristics:

- 2 wells (production + reinjection), each 1800 m deep, deviated;
- the power exploitable is about 10 MW_t = 0.9 OET/h at a reinjection temperature of 27°C;
- the heat exchangers, in titanium, are close to the wells;
- possibility of heating 3000 apartment equivalents;

- the geothermal resource covers 40% of the maximum power required and 80% of the total heat needed. The remainder is supplied by back-up fuel boilers.
- the energy savings is estimated at 3000 OET/yr;
- the life of the doublet is assumed to be 30 years;
- the investment costs are in the range of 4.9 - 6.0 M$, of which 1.6 - 1.9 M$ is for the two wells and 2.8 - 3.9 M$ for the surface plants.

The following is a comparison of the selling prices of energy in France:

1 kcal geothermal energy with government financial support.. 1.5 US cents

1 kcal geothermal energy without government financial support.. 1.8 US cents

1 kcal electricity	4.7 US cents
1 kcal oil	2.8 US cents
1 kcal coal	1.5 US cents
1 kcal natural gas	1.7 US cents

All these prices are excluding taxes (Varet,1984).

The French government offers some attractive incentives and subsidies to geothermal operators. These are:
- government grants for the geothermal feasibility study, covering up to 50% of the costs;
- government grants for 20% of the cost of the first well.A fur-

ther 70% is added if the well proves sterile. Local administrations may provide further aid.

- mid- and long-term coverage of risks inherent to exploitation;
- these subsidies are integrated with special loans covering as much as 80% of capital costs of the geothermal project.

United Kingdom

Britain is an extremely stable area without active volcanism. In this situation the development of geothermal resources depends upon the occurrence of permeable rocks in deep sedimentary basins or the successful development of the Hot Dry Rock concept. The average geothermal gradient is about 25°C/km, but two belts of above average heat flow extend across northern and soutwestern England. In these areas the gradient can reach 30°C/km or more.

Utilization of non-conventional energy sources is not so vital in this country, which attained energy self-sufficiency in 1980. However, the British government has, with some foresight, stated that geothermal and wind energy take priority over other renewable forms of energy. In the 1981-82 Fiscal Year 12 million dollars were thus allotted to geothermal research, and a further 17 million dollars added recently for the Hot Dry Rock project in Cornwall, to be spent in the next 3 years.

Hot water exploitation

The principal surface manifestations of geothermal activity in the U.K. are in Carboniferous rocks at Bath and Bristol, where the relatively high temperatures (47°C at Bath and 24°C at Bristol) are caused by the deep circulation of meteoric waters.

At the moment hot water research is under way in the Wessex basin (Southampton), where a hot aquifer (76°C) has been discovered at 1700 m depth in Triassic sandstone. The utilization project consists of the heating of a residential centre and some public buildings.

Hot Dry Rocks

The United Kingdom is the only EEC country which has so far made a serious committment in economic (see above) and technological terms in the Hot Dry Rock sector. It is well-known that the pioneering effort in this field was carried out at the Los Alamos National Laboratory (USA) in the early Seventies, but the work in Cornwall has developed specific aspects of the problem. The concept is, of course, very simple: anywhere on Earth the temperature increases as greater depths are reached. In some areas there will be hot water or steam occurring in natural porosity or in fractures, but the more common situation will be a more or less impermeable rock.

Once a process is developed for producing fractures and flow paths through the rock, the heat content of the rocks could be extracted and transferred, by fluid flow, to the surface utilization plants. The most complex aspect of the entire project is to succeed in creating an artificial geothermal reservoir at depth by pumping pressurized water through specially drilled boreholes until a system of fractures develop in the rocks (Los Alamos), or to facilitate hydraulic fracturing by pre-treatment with explosive charges at bottomhole (Cornwall).

Two boreholes have been drilled to a depth of 2000 m and a temperature of 80°C in the Cornish granite. The interconnection of the wells was achieved by pumping water at flow-rates as high as 100 kg/s at pressures of 140 bars, following an explosive pre-treatment process. The system was circulated for several months to measure the size and efficiency of the structure. Peak, but unsustained flow has been achieved, but steady production and low water losses are still to be attained (Batchelor,1983).

The fracturing pattern is difficult to localize. Television observation reveals cracks in the bores themselves, but how these cracks spread between the bores is more uncertain. Microseismic observations have suggested that hydrofracturing had opened the fractures beneath the bores and movement was noted there, but no evidence appeared of interconnecting flow paths.

At present some 4.5 million dollars of the new 17 million will be spent on drilling a third 2000 m hole, and the most logical move would be to extend it slightly below the bottomhole depth of the present bores into the zone affected by microseismic events. A key problem now will be to determine the exact fracture regime. Open fractures definitely exist, because 180 l/s of thick gel can be pumped down the hole; the trouble is that at present relatively little of it comes back up the second hole, and the problem will be that of bringing the gel up from the third programmed hole.

The cash (17 million $) will also be used to prepare for a 6000 m well not included in the present 7-year programme. In

Cornwall the HDR experts argue that low temperature sources, which are geographically common, may be more economic sources of energy, and the scientists working on the same research at Los Alamos seem to confirm this opinion. In fact, in order to evaluate the economic viability of future HDR electric power-stations, a Los Alamos report (Murphy et al.,1984) reached the conclusion, based on the results of a model, that a 75 MW_e HDR generating station can sell electricity at the bus bar for 4.9 US c/kWh. According to this report this is a highly competitive price, compared to the 6.3 c/kWh for oil-fired steam and 7.6 cents for diesel-electric. Only coal and nuclear stations, at 3.4 and 3.6 c/kWh, are expected to be cheaper than HDR stations.

Greece

Greece and Italy are probably the only member countries of the EEC that have vapour-dominated fields.

Greece first began exploratory work in 1970, directed at exploiting its geothermal potential (Vrouzi,1984).

Ten areas have been identified as being of specific high enthalpy geothermal interest. Five wells have been drilled on Milos, to a depth of 1000 m, and production tests show that 24 MW_e could be sustained using these wells. A 3 MW_e power-station will begin operating by the end of 1984. The potential geothermal-electric capacity for Greece has been estimated conservatively at 350 MW_e minimum, which would be extremely satisfactory for the country. This figure would indeed cover 15% of the electricity consumed at present. Energy demand on Milos is at present about 4 MW_e. Excess energy produced in future will be transmitted by underwater cable to the mainland and nearby islands.

In the non-electric sector, greenhouse and space-heating projects were launched in 1981. The first is already implemented, and the second will eventually exploit a sandstone reservoir in Macedonia.

Italy

This country has been producing electricity from geothermal steam on an industrial basis since 1913.

At present ENEL and AGIP carry out jointly geothermal research of new fields, with the exception of the Tuscan areas where ENEL operates on an exclusive basis.

As regards electricity generation, by December 1983 the Italian geothermal capacity was 456 MW and 3450 t/h of steam were available. The electrical energy generated via geothermal in 1983 was 2.7 billion kWh.

According to the Italian Energy Plan, in 1990 a further 1.5 billion kWh/yr will be added to the present production, giving a total of around 4.2 billion kWh/yr. Maximum total production realistically expected in Italy in future is about 1000 MW_e for 50 years of operation (Carella et al.,1984).

As for the non-electric uses of geothermal energy, Italy has nowadays three important centres of utilization of this source. They are in:

- Larderello (Tuscany), whose domestic, industrial and greenhouse heating saves about 10,000 OET/yr of high-grade fuel;
- Mt.Amiata (Tuscany), where greenhouse and space-heating and a drying plant save 35,000 OET/yr of fuel;
- Abano Basin (Veneto), where domestic heating saves 15,000 OET/yr.

Considering other projects now under way, including district heating in Vicenza, Milano and Ferrara, a total of 85,000 OET/yr of high-grade fuel will be saved in Italy by 1990 (Carella et al., 1984).

CONCLUSIONS

Heat extraction from low enthalpy geothermal deposits in the EEC, as witnessed by commercial development of space-heating systems in France and less so in Italy, has already demonstrated the feasibility of mining technologies and operational heat processes, but as yet marginal economic viability. In France exploitation of different resource settings (brackish waters in the Paris Basin, fresh waters in the Aquitaine Basin) leads to two contrasting catchment and utilization modes:

- geothermal doublets (production + reinjection well) with large and concentrated heat loads in the Paris basin,

and

- single wells, combined in many cases with heat pumps, supplying reduced and dispersed heat demands in Aquitaine.

The significant achievements in France have certainly been made possible by a number of conditions:

- a thorough involvement of the state in support of geothermal sources;
- early resource inventories, deriving mainly from the release of oil data;
- legislation to codify geothermal exploration and exploitation;
- various types of incentives;
- a willingness on the part of city authorities and public housing organizations to change from conventional fossil fuels to other cheaper sources despite the risks and high initial investment;
- existence of qualified operators.

According to this model, the geothermal market is likely to be long dominated by a tendency to heat existing apartment blocks and condominiums. This restricts the utilization of geothermal heat to large urban areas.Cascade uses remain an exception and, for the time being, industrial (process heat) and agricultural users (greenhouses) are generally by-standers rather than potential end users, unless more flexible utilizations and optimized economic ratios render the geothermal resource more attractive.

Resource and reserve assessments carried out at national and EEC levels, and based on the compilation of existing reservoir data from oil and gas exploration or from geothermal exploratory boreholes, will continue with the ultimate aim of creating a resource data base and estimating the heat recoverable from aquifers.

At present a saving of 2 million OET/yr throughout the EEC in non-electric uses seems a realistic target for the early 1990s.

With regard to electricity generation, the only countries of the EEC with commercially viable resources by 1990 will probably be Italy and, to a lesser extent, Greece. The high-grade fuel saved at that point will amount to around 1 million OET/yr.

References

BATCHELOR A.S.(1983) Hot dry rock geothermal exploration in the United Kingdom. Camborne School of Mines, Redruth, Cornwall, June 1983.

CARELLA R., PALMERINI C.G., STEFANI G.C. and VERDIANI G. (1984) Geothermal activity in Italy: present status and prospects. Seminar on Utilization of Geothermal Energy for Electric Power Production and Space Heating. Florence 14-17 May 1984. Geothermics, 14, 2/3,1985, in press.

EUROPEAN ECONOMIC COMMUNITY (1983a) Introduction. 3rd Int.Seminar on the Results of EC Research & Demonstration Projects in the Field of Geothermal Energy. Munich 29 Nov.-1 Dec. 1983, Report EUR 8853EN (Extended summaries).

EUROPEAN ECONOMIC COMMUNITY (1983b) Geothermal News Bull., Sep. 1983, no.2.

EUROPEAN ECONOMIC COMMUNITY (1983c) Les projets de demonstration des Communautes Européennes dans le domaine de l'energie géothermique. 3rd Int.Seminar on the Results of EC Research & Demonstration Projects in the Field of Geothermal Energy. Munich 29 Nov.-1 Dec. 1983, Report EUR 8853EN (Extended summaries), 241-261.

GERINI G.(1984) Demonstration projects of the European Communities in the field of geothermal energy. Seminar on the Utilization of Geothermal Energy for Electric Power Production and Space Heating. Florence 14-17 May 1984. Geothermics, 14, 2/3, 1985, in press.

MURPHY H., DRAKE R., TESTER J. and ZYVOLOSKI G. (1984) Economics of a conceptual 75 MW hot dry rock geothermal electric power-station.Seminar on the Util. of Geoth. Energy for Electric Power Production and Space Heating. Florence 14-17 May 1984. Geothermics, 14, 2/3, 1985, in press.

STRUB A. (1980) Opening address. Proc.2nd Int.Seminar on the Results of EC Geoth. Energy Research. Strasbourg 4-6 March 1980, Reidel Publ.Co., Dordrecht, Holland.

UNITED NATIONS STATISTICAL YEARBOOK 1981. United Nations, New York (1983).

VARET J.(1984) La géothermie basse energie en France. Geothermal Seminar, Ferrara (Italy), 11-13 April 1984.

VROUZI F.(1984) Research & development of geothermal resources in Greece. Present status and future prospects. Seminar on Utiliz. of Geoth. Energy for Electric Power Production and Space Heating. Florence, 14-17 May 1984. Geothermics, 14, 2/3, 1985, in press.

GEOTHERMAL ENERGY IN ITALY

Enrico Barbier

International Institute for Geothermal Research

Pisa, Italy

Lecture given at the United Nations University Geothermal Training Programme, Reykjavik, Iceland, Sep.-Oct. 1984.

GEOTHERMAL ENERGY IN ITALY

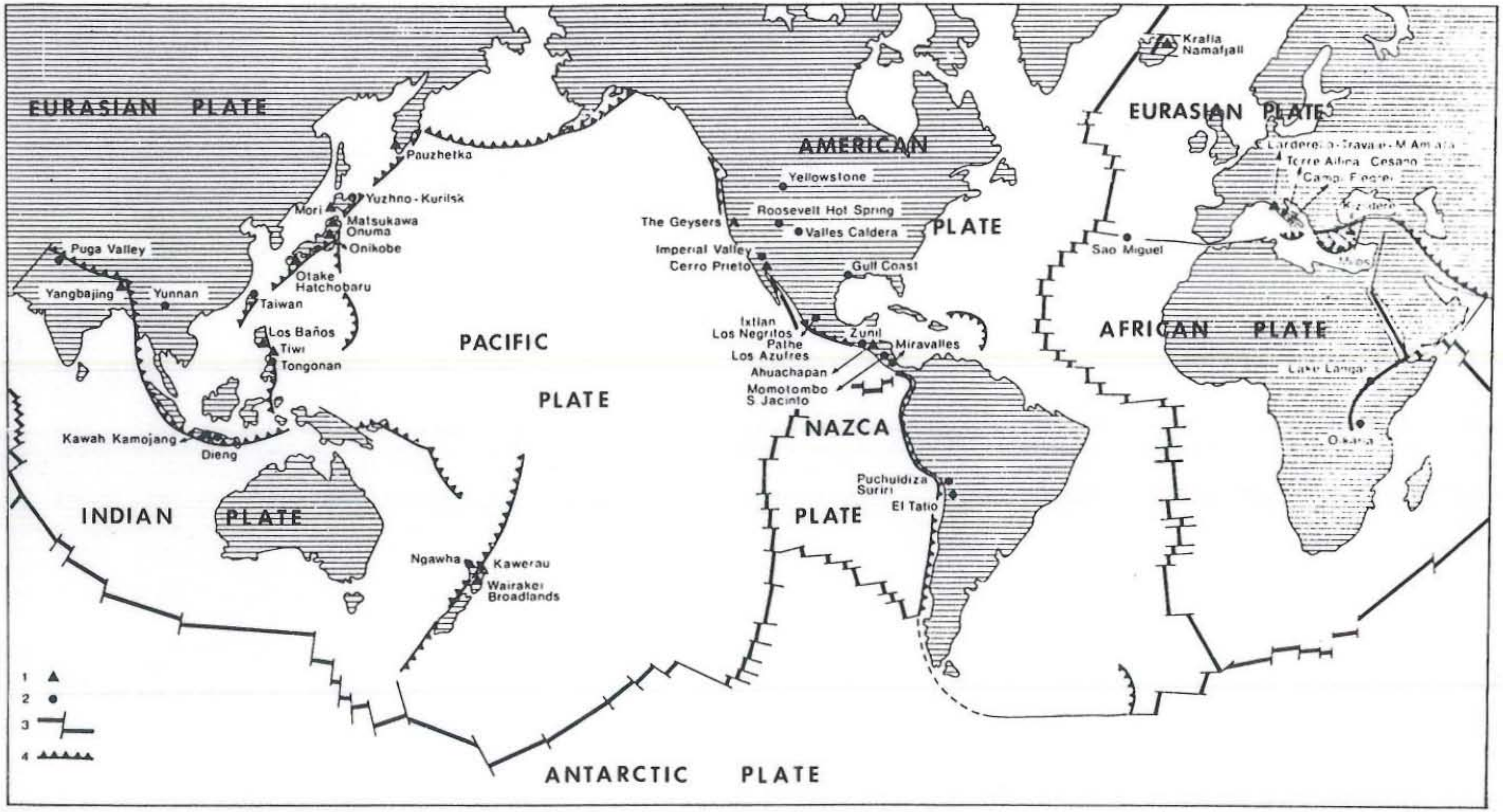
Table of Contents

ITALIAN GEOTHERMAL AREAS

According to contemporary geological theory on plate tectonics, the surface of the Earth consists of a crust split into separate plates that comprise both the ocean floors and continental areas. The crust, which may be from a few to seventy kilometres in thickness, floats above the mantle, which surrounds the core of our planet. During their relative movement the plates may drift apart, forming rifts along their margins through which magmatic effusions rise. On the other hand, the plates may collide, in which case their zones of collision are characterized by mountain-building areas, volcanic archipelagos, and the subduction of one plate beneath another.

These geodynamic phenomena are responsible for the development of terrestrial heat flow anomalies and geothermal fields. It is now common knowledge that the regions with the most favourable conditions for the development of such fields are the Andes Cordillera, the Rocky Mountains, the island arcs of Japan, the Philippines, Indonesia, New Zealand and the Caribbean, the Himalayan chain and the great rifts of East Africa and Iceland (emergent tip of the Mid-Atlantic Ridge) (Fig.1).

The Mediterranean Sea lies right within a collision zone between the European and African plates. Italy, in particular (Sommaruga and Guglielminetti, 1981), can be considered an orogenic arc, with the Apennine chain running from north to south along the peninsula separating two belts of basins. The hot west-



Location of the geothermal fields.

1 : Exploited high temperature fields.
2 : Known high temperature fields not yet exploited.
3 : Spreading ridges, continental rift zones and transcurrent faults.
4 : Subduction zones.

Fig.1

Plate tectonics and geothermal fields

ern belt, along the Tyrrhenian Sea, is characterized by recent or still active volcanic activity and high geothermal gradients. The eastern belt, from the Po Valley to the Ionian Sea, on the other hand, is relatively cold (Fig.2).

The Italian geothermal fields, whether vapour- or water-dominated, are all located within this hot western belt. Other areas of geothermal interest in Italy are tied to tensional events of the Earth's crust, with warm rifts and Tertiary or Present volcanic manifestations, such as those in Sardinia or on the small island of Pantelleria. The volcanic arc of the Eolian islands, north of Sicily, is also of geothermal interest.

ELECTRICITY FROM GEOTHERMAL ENERGY: THE ITALIAN GEOTHERMAL FIELDS UNDER EXPLOITATION

The Italian fields at present under exploitation are those of the Tuscan 'borax region', Larderello and Travale-Radicondoli, and Mt.Amiata (southern Tuscany) (Fig.3).

The Tuscan 'borax' region

The Larderello field has been producing electric energy on an industrial scale since 1913, the first field of its kind in the world.

The 'borax region' covers 200 km^2 and its characteristics are as follows (Carella et al.,1984):

- vapour-dominated system, superheated steam

PRESENT GEOTHERMAL RESEARCH AND EXPLOITATION IN ITALY

Fig.3

- drilled area, 200 km^2
- wells drilled, 628 (June 1983)
- productive wells, about 200
- well depth, 51-4000 m, average 670 m
- maximum output of a single well, 300 t/h, average 15 t/h
- length of pipelines, 115 km
- steam flow-rate, 3200 t/h
- steam pressure, 1.0 - 11.6 bar
- steam temperature, 130 - 267 °C
- gas content of steam (in weight), 1.7 - 14.3%, average 5% = 49 g/kg
- composition of steam in grams/kg: H_2O = 951; CO_2 = 47.5; H_2S = 0.5; CH_4 + H_2 + N_2 = 0.5; H_3BO_3 = 0.3; NH_3 = 0.2
- electricity generating units, 36
- unit rating, 0.9 - 26 MW
- total electrical installed capacity, 427.1 MW (June 1983)
- a further 70 MW are either being installed or programmed.

The geology of the field consists of a caprock of Cretaceous-Oligocenic allochthonous flysch. The reservoir is an evaporitic series, also allochthonous, of Triassic anhydrites and magnesian limestones. Underlying the reservoir is a Paleozoic metamorphic basement, part of which has a fracture-derived permeability.

The high geothermal gradient of the zone, above 300°C/km, is certainly the result of a Pliocene-Quaternary granitic intrusion lying at a depth of 7-10 km from the surface.

Two-thirds of the steam condensate at Larderello and Travale is eliminated by evaporation through the cooling-towers and a part of the remaining third (200 t/h) is reinjected. Reinjection is still in the experimental stage here, and three different situations have been contemplated for conducting injection tests and for eventual selection of the sites for long-term injection (Cappetti et al., 1982):

- peripheral, water-dominated, low temperature zones
- deep parts of the reservoir (2000-3500 m), where temperatures exceed 300°C
- upper parts of the reservoir in productive areas, generally with high temperature, low pressure and good permeability. These seem to be the most favourable conditions for experimenting reinjection aimed at improving heat recovery and maintaining, or increasing where possible, the production rate.

In the 'borax region' 80 to 100% of the water reinjected is recovered in adjacent wells in the form of steam. The steam produced by these wells shows no variation in temperature, and the pressure is slightly above the preceding values; the isotopic composition of the steam and the gas/steam ratios, on the other hand, varied after the reinjection tests began, thus proving that reinjection effectively recharges the reservoir.

With regard to a correlation between seismicity and reinjection, the number of seismic events in the Larderello - Travale area were seen to increase from 1972 to 1982 in correspondence to an increase in the quantity of water injected in the wells (Batini et al., 1984). It seems probable that part of the low-magnitude seismic events ($M \geqslant 2$) is, therefore, induced. However, the data indicate that an increase in quantity of injected water does not produce an increase in the magnitude value, which ranges between 2.5 and 3.2. One could ,therefore, deduce that reinjection probably favours the release of energy and consequently does not permit high tensions to accumulate. Until this hypothesis is confirmed by further studies, one could also formulate another less favourable hypothesis that reinjection leads to an increase in the number of lower energy events but does not modify the energy release mechanism of higher magnitude events. These magnitudes should probably be determined, in this case, by the geodynamic conditions of the area.

Deep drilling in the Larderello geothermal field

Three deep wells have been drilled in the Larderello area since 1974. They are wells VC 11 (2900 m, 320°C), Sasso 22 (4000 m, 400°C) and San Pompeo 2 (3000 m, 395°C at 2560 m).

The target of deep drilling was to find steam in the deep layers of the metamorphic basement (Paleozoic-Precambrian phyllites, micaschists, gneiss). Until 1974 exploratory drilling had instead affected the shallow limestone and anhydrite horizons of the Tuscan nappe (Triassic) and only the uppermost levels of the metamorphic basement.

Seismic reflection data have revealed a first continuous horizon, which corresponds to the top of the metamorphic basement already exploited, and a second deep reflecting horizon (K) 3 to 5 km from ground-level in the Larderello area and 6 - 8 km in the Travale area (Puxeddu, 1984).

This K horizon has a high reflection coefficient which can be indicative of mafic rocks, but these can be excluded in this case. More likely this horizon consists of intensely fractured rocks (micaschists) filled with hot fluids, forming a band some hundreds of metres thick above a Hercynian and Alpine batholith (Batini et al.,1983).

The results obtained from the deep wells can be summarized in the following:

- discovery of a 2nd reservoir, not communicating with the upper 'traditional' first reservoir at present under exploitation. This second reservoir has a different chemism (H_2 + CH_4 15% in weight, instead of about 1%) and much higher pressure values (higher than 240 bars at 2900 m compared with 30 bars at 1500 m);
- existence of an impermeable formation (phyllites) between 2300 and 2900 m, which separates the two reservoirs;

- petrological analyses on cores suggest a late Alpine thermal event which gave origin to the geothermal field and produced the contact aureole observed in the Tuscan basement. This aureole was produced by an Alpine batholith which rose to 3 km from the surface.

The K reflecting horizon can therefore be attributed to the fracturing of the deep basement due to the rise of the batholith and the circulation of high temperature and high pressure fluids (Puxeddu, 1984).

Deep drilling considerations

Some details of technical aspects of the drilling of S.Pompeo 2 well may be of interest to the reader. This well met with temperatures of about 400°C at a depth of about 3000 m, which created serious technological problems for the operators (ENEL, 1984). Sited 15 km south-west of Larderello, this well was initiated on 21 September 1980 and completed on 5 May 1982, at a bottomhole depth of 2967 m.

The drilling rig was a Massarenti 5000, 142 feet high (47 m), with a maximum static hook load (API) of 1,025,000 lb (464 tons), an electric winch powered by 2 Siemens D.C. engines of 600 HP each with a 7000 HP hydraulic brake.

Two Massarenti 1000 Triplex mud pumps were used , diam. 7" x 9", with a max. pressure of 5300 psi (373 kg/cm^2) and flow- rate of 2550 l/min. One pump was powered by 2 Siemens D.C. electric engines of 600 HP each, identical to those of the winch and the other stand-by pump was powered by 2 diesel engines, again 600 HP each.

Drilling proceeded to a depth of 3000 m (well bottom) and was conducted with total loss of circulation from 836 m on, as attempts to plug the fractures were unsuccessful.

Bentonitic mud was used as drilling fluid, except in the interval from 836 to 1200 m. Mud was used to guarantee against eventual failures in the drill-stem. It was also possible to keep variations from well verticality within fairly acceptable limits and avoid excessive friction between the terrain and the drill-stem. Water was simultaneously and regularly pumped into the well from the surface pipings, at rates ranging between 40 and 100 m^3/h, so as to monitor the fractures and improve the quality of the mud.

The bentonitic mud used was 2% "Bentosund 300" bentonite, 2% "Carbocel BR-7" carbossimethyl cellulose and 0.8% NaOH with ferro-chromolignine. It had a Marsh viscosity of 21 seconds and pH 10.

Because of high temperatures, the mud had to be prepared from rapidly degradable products in order to prevent its solidification, but capable of cleaning the well at the same time. Changes in the inclination of the well axis were kept under control with this mud.

The wellbottom was cleaned with nitrogen. This is the cheapest gas compatible with those contained in the geothermal fluid. Air would have triggered explosions because of the high concentrations of H_2 and CH_4.

Several drill-string failures were caused by extensive corrosion. The steel had become very fragile and after only 12 days, at 2500 m depth, corrosion had created wide holes within the strings. It is apparently the result of the progressive impoverishment of the carbon content of the steel, along with intergranular microfractures. The atomic hydrogen produced by the reaction between the gas in the well and the metal of the string is the cause of the observed failures.

Drilling of the well S.Pompeo 2 brought to light the following two rather important problems:

- the absolute necessity of checking well verticality in order to limit friction on the drill strings. This can be achieved with reasonable success by using special muds at all times during drilling. Unfortunately this is an effective but expensive solution wherever there is a continuous loss of circulation. Furthermore, the mud tended to boil because of the high temperatures in the well (above 300°C), as occurred during breaks in drilling when the pumps were no longer cooling the well;
- corrosion of the materials used in the well. The steps taken to combat this were:

  avoidance of materials liable to corrode under tension

  controls on the pH of the mud

  preventing the escape of geothermal fluids from the fractures met during drilling by pumping alkaline water into the well.

Considering past experience of severe breakages in other wells, the results were acceptable, but still unsatisfactory as far as widespread corrosion of steel is concerned.

Mt.Amiata

The Mt.Amiata area in southern Tuscany was discovered in 1958, and lies about 80 km south-east of Larderello. The explored area covers about 46 km^2, with the following characteristics (Carella et al., 1984):

- vapour-dominated system, slightly superheated steam
- drilled area, 46 km^2
- wells drilled, 68
- productive wells, 8 (June 1983)
- well depth, 346 - 3500 m
- length of pipelines, 7 km
- steam flow-rate, 280 t/h
- steam pressure, 2.5 - 9.8 bar
- steam temperature, 130 - 205°C
- gas content of steam averaging 17% by weight
- composition of steam similar to that at Larderello
- electricity generating units, 3 (exhausting-to-atmosphere)
- unit rating, 3.5 - 15 MW
- total electrical installed capacity, 22 MW (June 1983) (Carella et al.,1984).

The geological situation in this field is very similar to that of Larderello, the greatest difference being the presence of Pliocene-Quaternary volcanic manifestations that are not known at Larderello. These volcanites, along with the volcanic chimney, are considered recharge areas of the geothermal reservoir. The gravity anomaly is again negative, and the geothermal gradient relatively high (100°C/km), although lower than in the Larderello area.

A deep drilling programme in the Mt.Amiata area (Piancastagnaio field), similar to that under way at Larderello, has revealed the existence of a continuous productive horizon in the 2500-3500 m depth range, about 2500 m below the productive horizon exploited at present. The temperature of the reservoir fluid ranges between 330° and 350°C, and pressure is about 200 bar.

The first wells proved productive and now produce a quantity of fluid equal to about 15 MW. A development project for an area of 27 km^2, based on research data, will be completed within the next decade and will lead to an increase in electric capacity of 100 MW.

ITALIAN GEOTHERMAL AREAS NOT YET UNDER EXPLOITATION

As a result of studies and exploratory drilling, the following geothermal fields have been discovered in Latium (north of Rome) (Carella et al., 1984)(Fig.3):

Latera

Out of 9 wells drilled, so far 4 are productive, with a water, steam and gas (CO_2) mixture at a temperature of about 210-220°C, and salinity of the order of 12 g/l. It has been estimated that about 1000 t/h of fluid are available, corresponding to more than 29 MW. An 8 MW power-station is now being installed.

Cesano

Four out of the seven wells drilled proved productive; each have a capacity ranging from 3 to 5 MW_e. However the fluid is a brine made up of steam and water with 350 g/l of salts, little gas and a temperature of 140 - 220°C. It is uncertain yet whether this fluid will be utilized, because of the potential effects on the environment of its extremely high salt content (sodium and potassium sulphates).

Torre Alfina

The nine wells drilled have revealed a water-dominated reservoir with a gas cap of CO_2, and temperatures of about 150°C at depths between 220-550 m. Utilization is problematic because of the very high gas content (95% by weight) and consequent effects on the environment.

Phlegraean Fields geothermal area (Campania Plain, Naples)

This is the most promising of the unexploited areas as far as high enthalpy fluids are concerned (Fig.4).

The first geothermal studies in the Naples region (southern Italy) were conducted in 1939, resumed in the period 1949- 1954 and again in 1978, indicating the presence of a hot salt water-dominated system (325°C at 1800 m). After a further few years of prospectings, research is now concentrated in the area of the Phlegraean Fields (Patria Lake, north-west of Naples), where 11 wells have been drilled so far.

The Phlegraean Fields is a volcanic area located in the centre of a large Quaternary graben which forms the Campania Plain (80 x 40 km). The Pliocene-Quaternary tensional tectonics has caused the collapse of the Tyrrhenian belt with the formation of the graben and the uplift of the Apennine chain. The Mesozoic formations have sunk within the graben to about 3000-4000 m. The geophysical data indicate the existence of a smaller scale horst and graben structure inside this large graben.

The trachytic volcanism of the area is coeval with, or slightly younger than, the formation of the graben (about 1 Myr ago).

The Phlegraean Fields area is made up of several eruptive centres, with predominantly pyroclastic materials, mainly located on the rim of one of the main volcanic structures, a caldera some

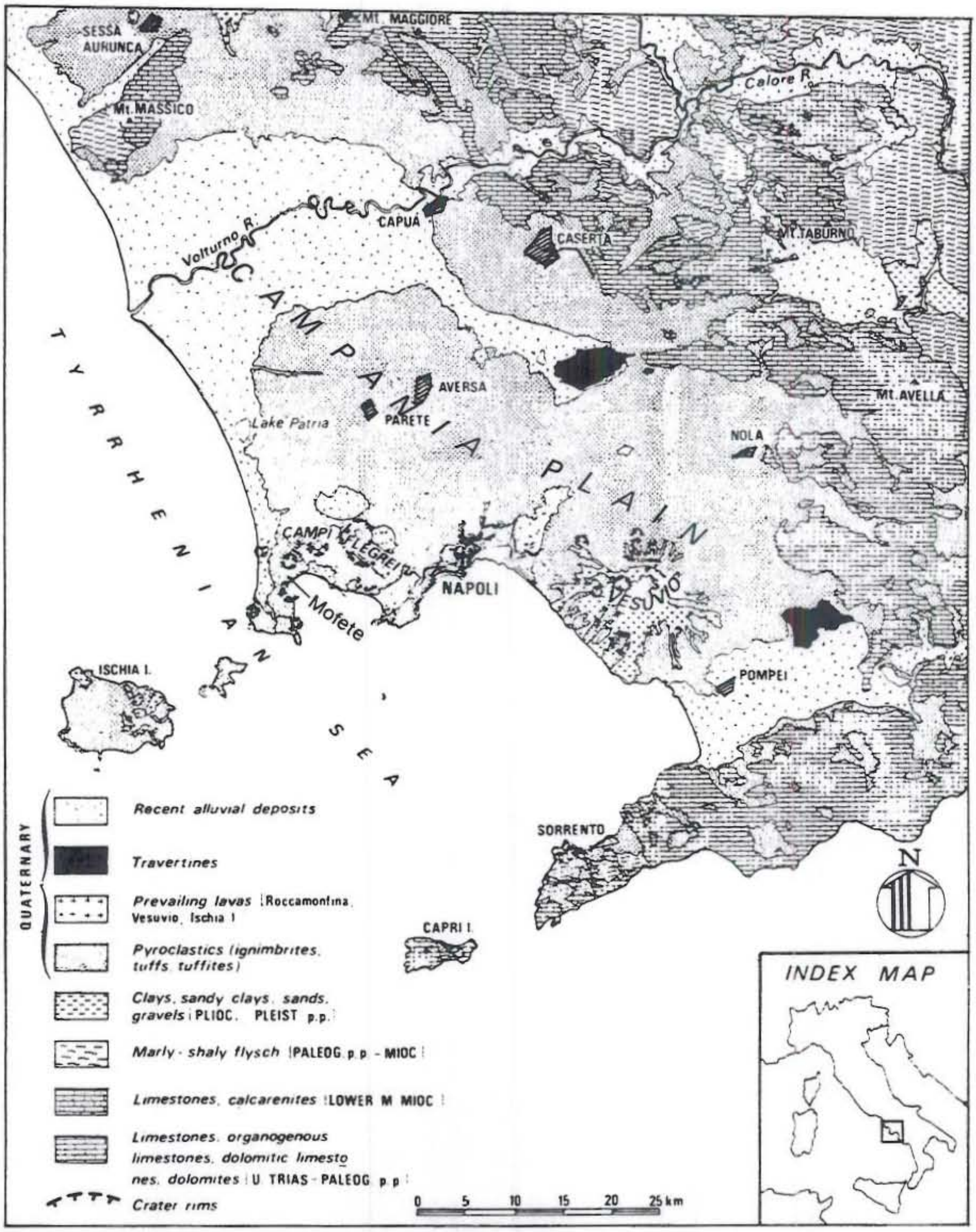


Fig.4

Geological map of the Campania region (Naples)

13 km wide formed by the collapse that followed the partial emptying of a magmatic chamber (35,000 years ago). The higher density of the eruptive centres follows the eastern border of the caldera, and the ascent of deep alkaline magma took place along this alignment.

The most recent volcanic activity was the eruption and formation of Monte Nuovo in 1538 AD.

A recent geological model assumes the existence of a magmatic chamber centred in the Pozzuoli Gulf with trachytic liquids at the top and convective cells of trachybasalts at the bottom. The temperature is presumed between 1000°C at the top and 1200 °C at the bottom. The top of the chamber is inferred to be at 3000 m depth, above the Mesozoic limestones, because there are no fragments of these rocks in the eruptive products.

This active magmatic body is presumed to be responsible for the vertical movements (bradyseism) in the Pozzuoli area (upward movement since 1982: 1.6 metres).

Mofete geothermal field has been localized in the Phlegraean Fields area, north-west of Naples and on the western border of the 13 km wide caldera. Gravity data for the Phlegraean Fields indicate a regional subcircular low centered in the Gulf of Pozzuoli, surrounded by a ring of higher values. The electric resistivity is low at shallow levels, as a result of the presence of hot saline waters. The magnetic susceptibility is low in altered rocks but in good agreement with the resistivity lows.

The seismic data are difficult to interpret. Geochemical surveys show that the thermal waters of the area are a mixture of local meteoric waters and deep hot waters of marine origin. Fumaroles and hydrothermal activity are present on the sea- bottom in the Gulf of Pozzuoli as well as on land at the Solfatara, Agnano and in the Mofete area.

Seven wells have been drilled in the Mofete field since 1978, 3 vertical and 4 directionally drilled. Their depth ranges between 800 and 2700 m.

Three reservoirs have been discovered, all three in volcanic rocks, and their permeability is due to faulting and fracturing. The location in the area of these reservoirs is erratic and unpredictable.

The shallow reservoir (550 - 1500 m deep) has water with salinity ranging from 40 to 76 g/kg at the surface, and bottom temperature in the range 230°-308°C. It is represented by fractured volcanic rocks.

The intermediate reservoir (1900 m deep) has low salinity fluids of about 38 g/kg and reservoir temperature of 340°C. It is in a metamorphosed volcanic-sedimentary complex.

The deep reservoir (2700 m deep) hosts hypersaline fluids, about 516 g/kg of salts (at the surface) and a bottom temperature of about 360°C. It is in the metamorphosed volcanic-sedimentary complex.

The reservoir fluid in the Mofete field is in a single phase (liquid) under static conditions, with a dissolved CO_2 content between 1 and 5% by weight. The fluid is in two-phase state under dynamic conditions. The enthalpy is between 228 and 384 kcal/kg (950 - 1600 kJ/kg), flow-rates between 9 and 35 t/h of steam and wellhead pressures between 5 and 23 bars (Carella and Guglielminetti, 1983).

At the moment the Mofete area is known to contain fluids whose potential is a few tens of MW_e, provided a suitable reinjection system is installed (Carella et al., 1984).

Exploitation of this field must be approached with some caution because of the possible geodynamic effects of fluid extraction, the presence of a large-scale bradyseism in the area and the high population density.

Vulcano island

The volcanic arc of the Eolian islands, in the southern Tyrrhenian Sea, is affected by the Calabrian subduction. A steam field was discovered on the island of Vulcano at 200 m depth in 1953, with temperatures around 200°C. Deeper wells, reaching 1500 m, are now being drilled for a combined production of electric energy and desalinated drinking water.

NON-ELECTRIC USES OF GEOTHERMAL ENERGY IN ITALY

The direct use of geothermal heat on an industrial scale in Italy first began in 1827, when Francesco Larderel had the ingenious idea of utilizing the natural steam of the present

Larderello area to heat the boron-enriched waters of the local natural pools, and to collect the boric acid left after this operation. Until then the local woods and forests had provided the fuel required to concentrate these waters, but wood supplies were becoming scarcer and more expensive.

Apart from balneotherapeutic applications, geothermal heat is now used in Italy in space- and greenhouse-heating in the following sites (Fig.5):

Abano (Padua)

The 65 - 87°C water produced from about 120 wells (250-400 m depth) is used in balneotherapy, and also for heating about 75 hotels and many private homes (using heat exchangers). Together with Galzignano (see below), it replaces 15,000 OET/yr of oil.

Galzignano (Padua)

A total of 20,000 m^2 of greenhouses (ornamental plants) are heated by the warm water (65°C) produced by a 300 m well.

Larderello

A total of 348,000 m^3 of residential buildings and offices, along with 15,000 m^2 of greenhouses, are heated at Larderello and other localities mainly by low temperature and low pressure steam. Together with Castelnuovo (see below) it saves 10,000 OET/yr of high grade fuel.

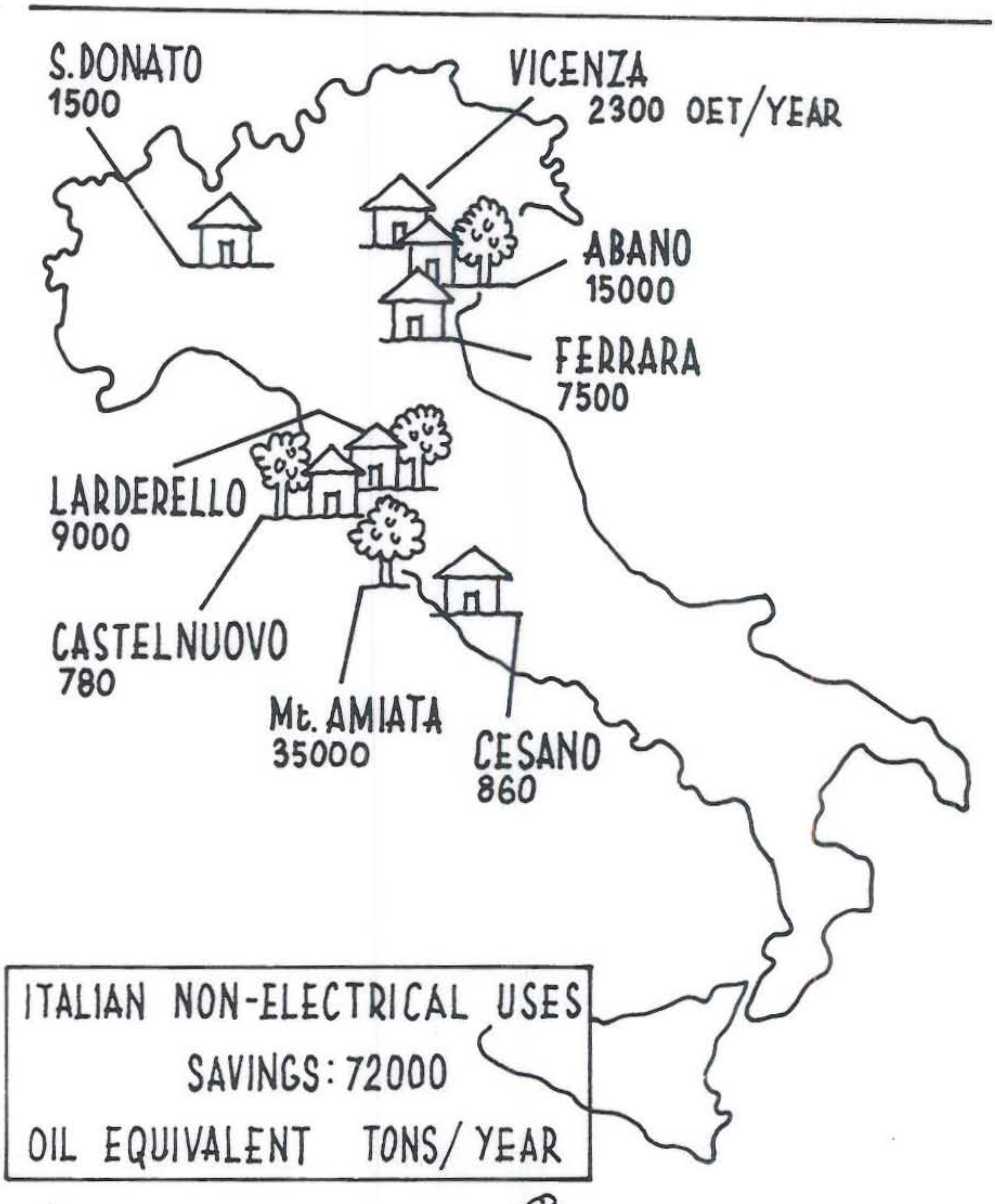


Fig. 5

Non-electric uses of geothermal energy in Italy

Castelnuovo Val di Cecina

Buildings covering 200,000 m^3 are heated by low quality steam. The steam from shallow wells, whose flow-rate has gradually decreased to non-commercial levels, is condensated in a contact condenser and the hot water (95°C) carried to a heat exchanger.

Mt.Amiata

This project, launched in 1982, consists of the multi-purpose use of geothermal energy (electric and non-electric).

The steam discharged from Piancastagnaio 15 MW_e geothermal power-station is condensated, instead of being exhausted into the atmosphere, because of its high percentage of uncondensable gases (21% by weight). The resulting hot water (90°C) is used to heat 220,000 m^2 of greenhouses. The uncondensable gases (mainly CO_2 and H_2S) are discharged in a 50 m stack built onto the condenser. The energy saving is estimated at 35,000 OET/yr.

The areas in which plants are now being built for direct uses of geothermal energy are the following:

San Donato Milanese

Two wells have been drilled, one for production and the other for reinjection. The wells reached 2200 m through alternations of Pliocene sands and clays. Production is estimated at 50-100 m^3/h of salty water (76 g/l) at 62°C. It will probably be exploited for district heating (467,000 m^3). It is expected to replace from 800 to 1500 OET/yr.

Vicenza

This project, now in the stage of being implemented, provides for the heating of 656,000 m^3 of private homes and 462,000 m^3 of military and prison buildings. One well has been drilled to 2590 m depth into a known aquifer within Mesozoic limestones, with temperatures of about 70°C. The water has a rather low salinity, so that reinjection will not be required, and it can also be used directly for domestic water supplies. It will replace about 2300 OET/yr, equal to 65% of present consumption in this area.

Ferrara

This project, also being implemented, consists of the space-heating of 7000 apartments by means of two existing wells, one for production (250 - 400 m^3/h of water at about 100°C) and the other for reinjection. Heat exchangers will be used at wellhead. A total of 7500 OET/yr will be saved, equal to 60% of present consumption.

Cesano

Work is now under way on implementing this space-heating project for the local Military Infantry Academy, using the fluid from a high-salinity geothermal field discovered some years ago in this area. The fluid has a temperature of 140 - 220°C and salinity in the 70 - 350 g/l range (sodium and potassium sulphates). The project requires a flow-rate of 300 - 400 t/h to heat about 350,000 m^3. Heat exchangers and a reinjection well will obviously be required. The estimated saving is about 900 OET/yr.

CONCLUSIONS

At present ENEL and AGIP carry out jointly geothermal research of new fields in Italy, with the exception of the Tuscan areas, where ENEL is sole operator.

With regard to electricity generation, by December 1983 the Italian geothermal capacity was 456 MW , with 3480 t/h of steam (mostly superheated) available. The electric energy generated in the geothermal power-plants was 2.7 billion kWh in 1983.

According to the Italian Energy Plan, by 1990 a further 1.5 billion kWh/yr will have been added to the present capacity, thus totalling about 4.2 billion kWh/yr.

In order to reach this objective about 150 new wells must be drilled by 1990, totalling 400,000 metres and with a financial outlay of 500 million dollars, at current prices. Considering the cost of research, modernization of the old power-stations and construction of new ones, it is estimated that attainment of the Energy Plan target will mean a total investment of 1 billion 1983 dollars (ENEL, 1983).

The maximum electrical production that can realistically be expected in future in Italy from geothermal energy is about 1000 MW_e, for 50 years of operation (Carella et al., 1984) (Fig.6).

As regards the non-electric uses of geothermal energy, some drawbacks do exist, and must be taken into due consideration (Calabrò and Trambaioli, 1984),viz.:

- extremely large investments are required to recover and extract fluid from the wells, and mining risks are very high in non-traditional geothermal zones;

- utilization of geothermal fluids in industrial processes generally involves modifications to the plants, which lead to a protraction of the normal amortization times;

- the minimum well output, for exploitation to be economically viable, is now considered to be about 15,000 Gcal/yr in Italy (corresponding to a flow-rate of 42 t/h of water with a temperature drop of 40°C). Moreover, it is difficult to find the geothermal resource and a heat demand both on the well site, and geothermal energy can obviously be transported for limited distances;

- potential users in Italy are rarely well informed of the possibilities offered by geothermal energy, nor is there an industrially advanced technology available for utilizing fluids that have a very high salt content or are liable to attack materials.

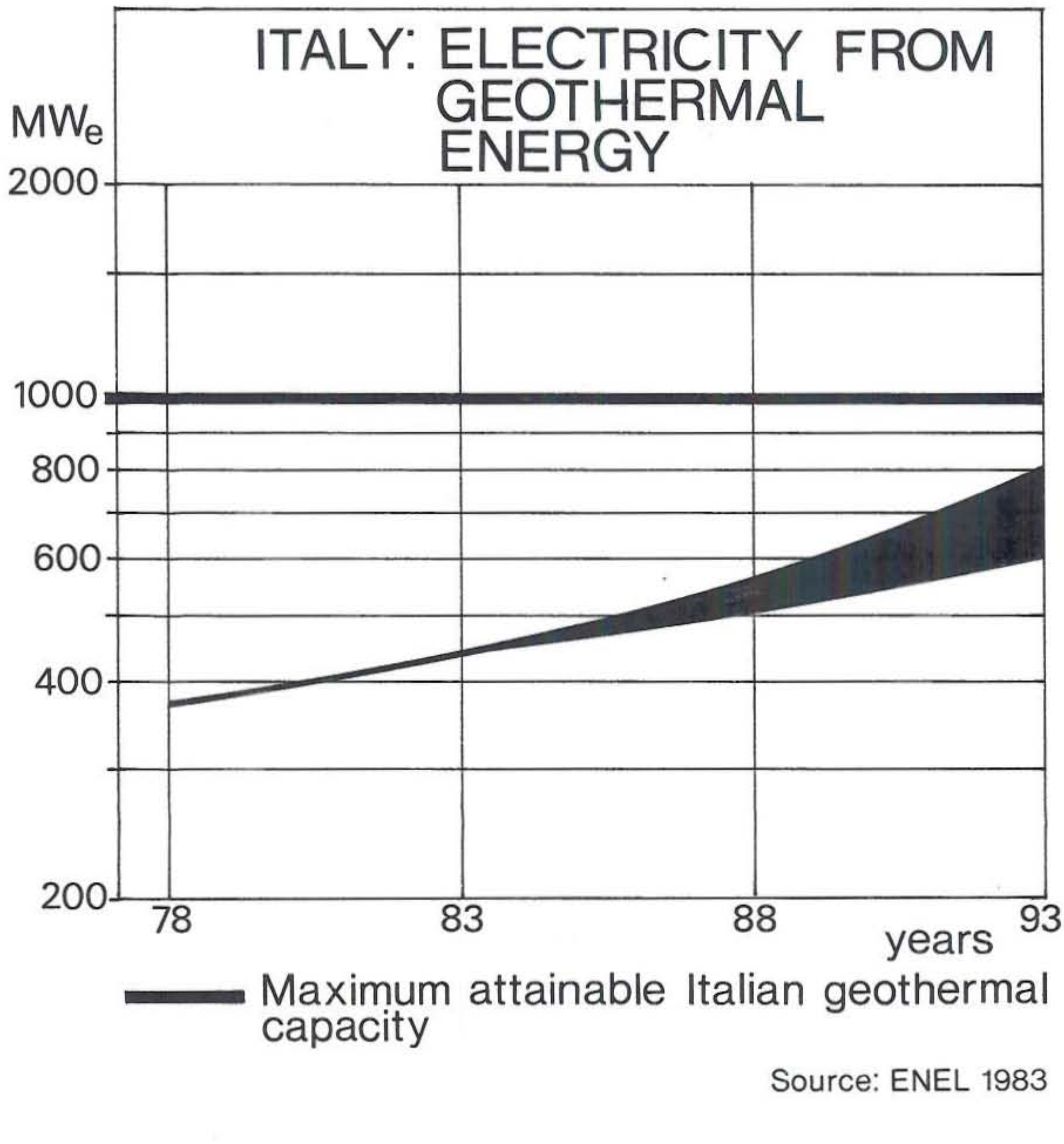

ITALY: ELECTRICITY FROM GEOTHERMAL ENERGY
MWe
2000
1000
800
600
400
200
78
83
88
93
years
Maximum attainable Italian geothermal capacity
Source: ENEL 1983

Fig.6

The National Energy Plan envisages a savings, by 1990, of 300,000 Oil Equivalent Tons per year in the non-electric uses of geothermal energy: current savings can be estimated at about 60,000 OET/yr (72,000 by 1987) and a more realistic value for 1990 is a saving of about 85,000 OET/yr (Carella et al., 1984).

References

BATINI F., BERTINI G., GIANELLI G., PANDELI E. and PUXEDDU M. (1983) Deep structure of the Larderello field: contribution from recent geophysical and geological data. Mem.Soc.Geol.Ital., 27, in press.

BATINI F., CONSOLE R. and LUONGO G. (1984) Seismological study of Larderello-Travale geothermal area. Seminar on Utiliz. of Geoth. Energy for Electric Power Production and Space Heating. Florence 14-17 May 1984. Geothermics, 14, 2/3, 1985, in press.

CALABRÒ G. and TRAMBAIOLI G. (1984) Non-electric uses of the geothermal resource: economic considerations. Seminar on Utiliz. of Geoth. Energy for Electric Power Production and Space Heating, Florence 11-14 May 1984, Report R.15, UNECE, Geneva.

CAPPETTI G., GIOVANNONI A. and RUFFILLI C. (1982) Reinjection in the Larderello geothermal field. BHRA Int. Conf. on Geoth. Energy, Florence 11-14 May 1982, p.395-407.

CARELLA R. and GUGLIELMINETTI M. (1983) Multiple reservoirs in the Mofete field, Naples, Italy. 9th Workshop on Geoth. Res. Engng., 13-15 Dec. 1983, Stanford Univ., California.

CARELLA R., PALMERINI C.G., STEFANI G.C. and VERDIANI G. (1984) Geothermal activity in Italy: present status and prospects. Seminar on Utiliz. of Geoth. Energy for Electric Power Production and Space Heating, Florence 11-14 May 1984. Geothermics, 14, 2/3, 1985, in press.

ENEL, Direzione Studi e Ricerche (1983) Cenni sull'uso dell'energia geotermica: situazione attuale e prospettive future con particolare riferimento all'Italia ed all'America Latina. (In Italian). Convegno su Cooperazione tra Italia ed America Latina nel settore delle fonti di energia nuove e rinnovabili. Rome, 17-20 Oct. 1983, ENEA-IILA.

PUXEDDU M. (1984) Structure and late Cenozoic evolution of the upper lithosphere in southwest Tuscany (Italy). Tectonophysics, 101, 357-382.

SOMMARUGA C. and GUGLIELMINETTI M. (1981) Energia geotermica: impieghi e prospettive. ECOS-ENI, Rome. (In Italian).