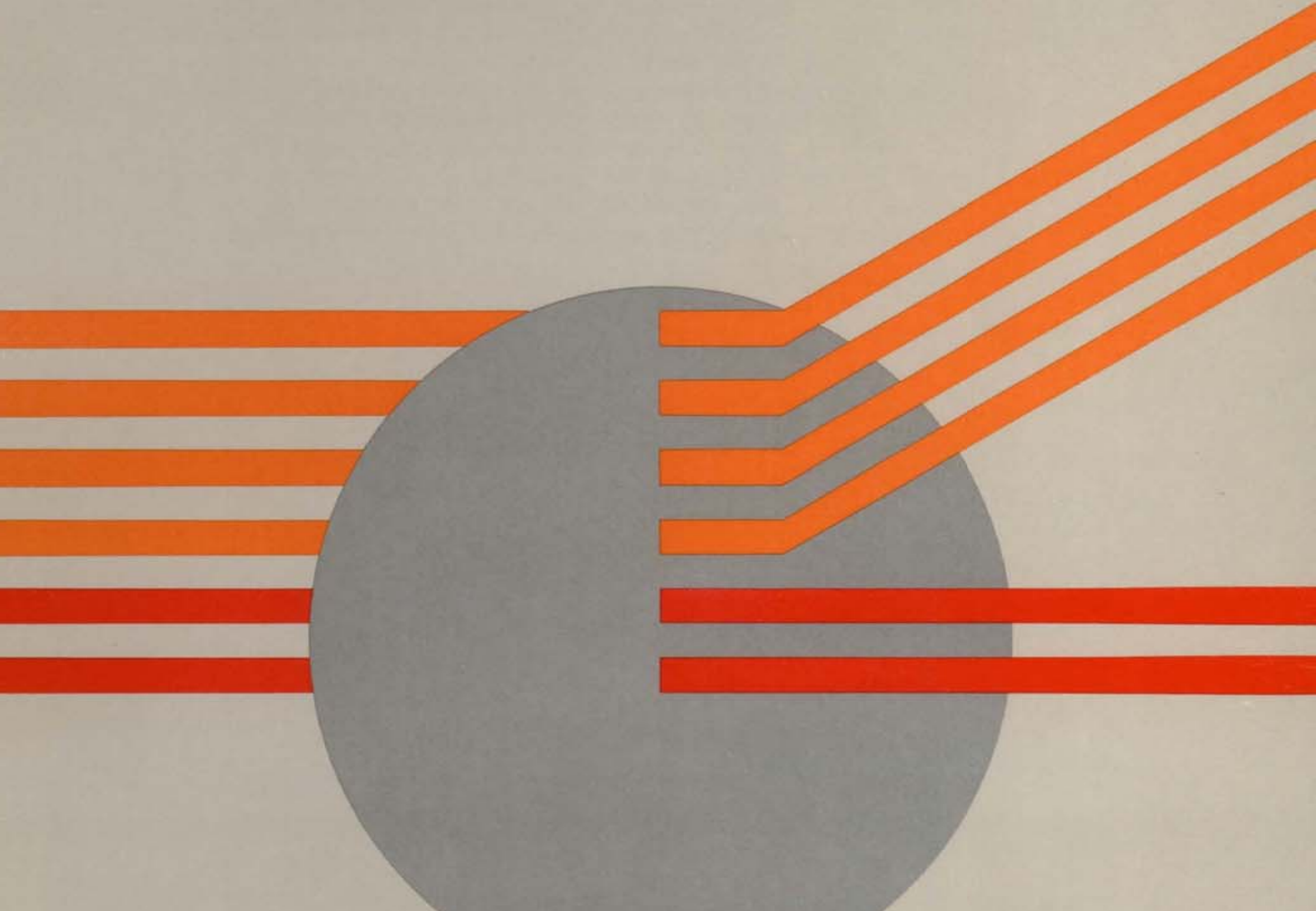
Energy Research

Directions and Issues for Developing Countries



CANADA

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ERRATUM Table 4, page 54

The values given in columns 3, 7, and 8 are in tonnes not kilograms.

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The Energy Research Group

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Abstract

The final report of the Energy Research Group surveys energy research and suggests priorities for developing countries. The report is based on three premises: energy research must be related to research on the entire economy and society; energy sources must be studied in the context of demand for them; and energy saving is as important as energy production.

The report begins by examining the environment for research in developing countries and the role played by governments, research institutions, producers, and international funding agencies. Various approaches to energy demand management and conservation are outlined and illustrated with examples of opportunities for certain common types of equipment.

The Group goes on to pinpoint research priorities for various energy sources — liquid, gaseous, and solid — as well as thermal energy, motive power, and electricity. Of the many pervasive environmental effects of energy production and use, the report focuses most closely on three environmental issues related to energy: deforestation and desertification, the greenhouse effect, and acid rain. The general conclusions of the report are summarized in three final chapters.

Résumé

Le rapport officiel du Groupe de recherche sur l'énergie fait un bilan de la recherche en ce domaine et propose des priorités pour les pays en développement. Trois prémisses sont d'abord posées : la recherche énergétique doit être liée à des recherches économiques et sociales globales, les sources énergétiques doivent être étudiées dans le contexte de la demande d'énergie, enfin, l'économie d'énergie est aussi importante que la production d'énergie.

Dans sa première partie, le rapport examine l'environnement de la recherche dans les pays en développement et le rôle que jouent les gouvernements, les instituts de recherche, les producteurs et les agences internationales de financement. On y aborde différentes méthodes de gestion de la demande d'énergie et de l'économie d'énergie, des exemples servant à illustrer les avantages de certains équipements communément utilisés.

Le Groupe va jusqu'à définir des priorités de recherche pour certaines sources d'énergie — liquides, gazeuses et solides — de même que pour l'énergie thermale, la force motrice et l'électricité. Parmi les nombreux effets négatifs de la production et de l'utilisation de l'énergie sur l'environnement, le rapport retient plus particulièrement trois problèmes environnementaux : le déboisement et la désertification, l'effet de serre et les pluies acides. Les trois derniers chapitres du rapport résument les conclusions générales du Groupe.

Resumen

El informe final del Grupo de Investigaciones Energéticas examina las investigaciones sobre energía y sugiere prioridades para los países en desarrollo. El informe está basado en tres premisas: las investigaciones energéticas deben estar relacionadas con las investigaciones sobre todos los aspectos de la economía y de la sociedad; las fuentes de energía deben estudiarse dentro del contexto de su demanda; y el ahorro de energía tiene tanta importancia como la producción de energía

El informe comienza analizando las condiciones imperantes para la realización de investigaciones en los países en vías de desarrollo y el papel de los gobiernos, instituciones de investigación, productores y agencias internacionales que otorgan fondos. Se esbozan varios enfoques relativos a la gestión de la demanda de energía y a la conservación de energía, ilustrados con ejemplos de las oportunidades existentes para ciertos tipos de equipos.

El Grupo continúa señalando prioridades de investigaciones para varias fuentes de energía — líquidas, gaseosas y sólidas — así como energía térmica, fuerza motriz y electricidad. Entre los muchos efectos ambientales globales de la producción y uso de energía, el informe hace énfasis sobre todo en tres problemas ambientales relacionados con la energía: la despoblación forestal y el avance de los desiertos; el efecto de invernadero; y las lluvias ácidas. Las conclusiones generales del informe se resumen en tres capítulos finales.

Contents

Preface

In 1981, the International Development Research Centre (IDRC) carried out a preliminary study of the energy problems of developing countries and the response of donor agencies to those problems. Among other things, this exercise was aimed at exploring new directions that IDRC itself might take in supporting energy-related research. The study revealed that, although many developing countries and donor agencies were actively involved in energy research, much of that research tended to be poorly conceived and weakly coordinated. Moreover, the research was often of limited relevance to the needs of developing countries.

Specifically, one of the impressions gathered in the Centre's study was that the research concentrated on "hardware" rather than on the social and economic viability of the relevant technology. To be sure, there was some work on energy planning, but this was largely in the form of technical assistance with little local input. Another impression was that a large proportion of foreign aid for energy research was used in developed countries and, even when used in developing countries, it was under the direct control of expatriates. Finally, there was an impression that the global allocation and the overall purpose of aid funds for energy research were unknown. As a result, donor efforts were poorly coordinated and research choices were largely ad hoc. This resulted in great variability in the quality of the research findings and in a high probability that much of the research that had been undertaken was of limited relevance to the energy needs of the developing countries. In the light of these impressions, IDRC saw potential benefits in making an authoritative and independent arrangement to review as fully as possible those energy research strategies that were of direct relevance to developing countries and to recommend useful directions for developing countries' energy research.

Further impetus for the implementation of this arrangement came from the United Nations Conference on New and Renewable Sources of Energy held in Nairobi in August 1981. At that conference, the Right Honourable Pierre Elliott Trudeau, then Prime Minister of Canada, stressed the importance of research in providing solutions to the energy problems of developing countries. Mr Trudeau also announced that an additional CA $10 million would be made available to IDRC to permit an expansion of its support for energy research. This report is the result of a project funded by the Centre using part of those additional resources.

In April 1982, IDRC hosted a meeting of donor agencies engaged in funding energy research. This meeting, chaired by Ivan Head and Enrique Iglesias, confirmed the earlier impressions of the disarticulated, hardware-oriented nature of energy research funding and discussed alternative mechanisms to improve its effectiveness. These included, most notably, the idea of a technical advisory committee, a high-level group to comment on the direction of energy research. Its conviction being reinforced by this meeting, IDRC decided to seek advice on priorities in energy research from a group of energy specialists from developing countries.

Meanwhile, the United Nations University (UNU) had undertaken work on renewable-energy technologies and convened a conference on energy alternatives in January 1979. This experience led to the development of a research effort on the concept of integrated rural energy systems that involves the social, economic, cultural, environmental, and health as well as technological aspects; and to an energy planning and policy research program that emphasized the analysis of the demand side and the satisfaction of basic human needs. As a result of this work and its active involvement in the Nairobi Conference, UNU realized the need for a reliable and objective assessment of energy research and technology relevant to the Third World. To satisfy this need, the University planned to establish an energy research and technology assessment group.

After a series of discussions on the subject, UNU joined IDRC in convening the Energy Research Group as a first step in the search for priorities among the topics to be tackled later in individual assessment studies. As a result of these requirements, a comprehensive and ambitious mandate was drawn up, spanning policies as well as technologies over the entire field of energy.

The Group has prepared this report in fullfilment of that mandate. The report is more than the indication of priorities that IDRC and UNU originally expected: it is an authoritative review of the state of knowledge on energy research and its applications. It analyzes the causes of the success or failure of research strategies and identifies those that are worth pursuing. The Group has made a major contribution to the creation of the "informed user" for whose emergence it pleads.

Official and donor interest as well as investment in energy research have declined in the 1980s with the fall in oil prices. As the Group points out, however, the development process consists of energy transitions: in this sense, developing countries had energy-related problems long before the oil crisis and will have them long after. Thus, this report has more than passing relevance. In addition, the Group's approach in preparing it is a model that could be applied with profit to other fields of knowledge.

The International Development Research Centre and the United Nations University take pleasure in releasing the Group's report to all users of energy research on and in developing countries: governments, funding agencies, research workers, and, indeed, all who wish to contribute in a timely and sensitive fashion to the attempts by developing countries to provide for their energy needs.

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Acknowledgments

Our foremost debt is to Pam Dagenais, project assistant in the Group's secretariat. Attending meetings in remote corners of the world is a tiresome chore and bureaucratic procedures make it even more insufferable; however, Pam went to considerable lengths to ease our rigours and to humanize the administrative machinery. Every member remembers her for her kindness and solicitude. She ran the ERG secretariat with clockwork precision and streamlined its linkages with the Social Sciences Division, the Office of the Comptroller General and Treasurer, and the Office of the Secretary and General Counsel in the International Development Research Centre (IDRC), whose assistance is gratefully acknowledged. Pam was assisted by Judy Lewis, whose warmth and good humour we all appreciated.

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Ralph Torrie, our assistant coordinator, ably orchestrated the administration and, especially, the refereeing and revision of the review papers. We are immensely grateful to the authors of the papers we commissioned (appendix 2) and to the referees (appendix 3), whose prompt and unstinting help went far beyond the claims of professional courtesy.

The ERG project owes much in its conception to Andrew Barnett, Maurice Levy, and Tony Tillett. Its success reflects their vision and farsightedness. Amitav Rath and Walter Shearer, as observers for IDRC and the United Nations University respectively, smoothed our relations with the sponsors.

We would like to express our special gratitude to those who helped us draft this report, although none of them may be able to recognize his or her contribution to it: Andrew Barnett, Ramesh Bhatia, Bharat Bhushan, Susan Bogach, John Chesshire, Peter Elkan, Gilena Graça, Steven Graham, José Roberto Moreira, Adilson de Oliveira, and John Surrey.

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Our other debts are impossible to acknowledge in detail. We have been in touch with over 900 persons over the life of the project: from all we have received much help and goodwill. If this report meets some of their expectations, it will give us particular satisfaction.

Chapter 1 Introduction

The Energy Research Group was convened by the International Development Research Centre and the United Nations University to survey energy research and to suggest energy research priorities for developing countries. This report is intended to fulfill that mandate. The report is based on three premises: (1) energy research must be related to research on the entire economy and society; (2) energy sources must be studied in the context of demand for them; and (3) energy saving is as important as energy production. The report is based mainly on published information. It does not cover engineering and technological details, does not go into regional and national variations, and excludes areas where confidentiality of information or lack of knowledge makes it difficult to judge research.

The Energy Research Group was convened in August 1983 with the following terms of reference:

(1) To carry out a thorough review of energy-related research and technology relevant to developing countries.

(2) To survey the existing and likely capability in developing countries to conduct, finance, diffuse, and use energy research and development.

(3) To survey the energy-related research and technology in developed countries, its relevance to developing countries, the terms on which access to it is available, and ways of using it for the greatest benefit of developing countries.

(4) To disseminate the views of the Group and its members, to invite informed opinion, and to provoke discussion on the energy-related issues facing developing countries and the relevant research results.

(5) To recommend priorities in the conduct and utilization of energy-related research in light of its findings regarding resources for the consideration of decision-makers, researchers, and other interested parties.

(6) To recommend means by which the allocation of resources available for energy-related research can be determined and improved, nationally and internationally.

The survey of research commissioned by the Group in fulfillment of terms of reference (1), (2), and (3) consisted of 103 reviews (Appendix 2). Although many of them are referred to in the present report, this is neither a summary of them nor a review of research. The approved reviews, which are being published separately, form the background of this report and are a valuable survey of energy research of interest to researchers as well as practitioners.

It has not been possible within the resources of the Group to fulfill term of reference (4) to disseminate our views or to invite discussion. We recognize the importance of discussion, especially to test our views, and would welcome it if this report or our review papers lead to more lively discussion of the serious energy-related problems of developing countries.

This report covers terms of reference (5) and (6) and, needless to say, the adequacy of its coverage is constrained by the time and resources available. The research funds provided by the International Development Research Centre (IDRC) and the United Nations University (UNU) were generous. The field of energy research is so vast and the diversity of developing countries so great, however, that a comprehensive and accurate identification of research capability and research priorities for all developing countries would have been unrealistic, if not foolhardy, even had our resources been considerably larger. What we have tried to do is to point out the promising directions, not to lay down a master plan.

Basic Premises

The composition of the Group is given in appendix 1, and the approach of the Group to its task is described in greater detail in chapter 2. It is in the nature of a group like ours and of our task that all of us need not agree on everything in this report. However, none of us disagrees on the major aspects or recommendations of the report. The minor reservations, qualifications, and doubts some of us may have on certain specific propositions are not always spelled out in detail because we feel that we also owe a duty to our readers to keep the report clear and simple. We have no hesitation in identifying ourselves with this report.

To sum up the philosophy behind this report, the Group has tried to propagate an integrated approach to energy problems. As a subject advances, researchers subdivide it and go progressively deeper into ever more narrowly defined problems. Energy studies are, at present, a hybrid of many disciplines, and each discipline brings to them its own concepts and methodologies. At this stage, however, it is important for developing countries that energy problems be defined in comprehensive terms, and that new concepts, theoretical formulations, and methodologies be developed. Therefore, we favour a coordinated and systematic exploration of the hidden interconnections between energy and other variables — a preference that is illustrated, for instance, by our emphasis on energy–economy relationships, national energy planning and pricing, and the influence of location patterns on energy consumption.

Next, the Group argues for the study of energy resources and technologies in the context of the demand for them. This has three major implications. First, demand for energy must be treated as an active policy variable, as a potential source of solutions to energy problems on par with supply and technology. It is possible to treat demand as an exogenous variable, determined by the trends in output, incomes, and prices, and to ask what energy sources can meet this projected demand (see, for instance, Wilson 1977; Greene and Gallagher 1980). This type of formulation begins to lose relevance even for the richest industrial countries once the real costs of energy become significant; it is still less appropriate for developing countries in which the supply of energy is likely to be further constrained by limited investment capacity or a strained balance of payments. For them, the demand for energy must be regarded as a variable instead of a parameter: we must ask what style of development will permit the greatest rise in standards of living consistent with realistic constraints to energy — or indeed, any resource constraints? What are the factors that determine demand for energy, and how far can they be influenced? Whose requirements must have higher priority? Thus, demand for energy can be regulated and managed, and the possibilities and limits of energy demand management are a prime subject for research in developing countries.

Second, energy resources and technologies must be studied in the context of their uses, and the alternative resources and technologies that can serve the same use must be studied together. In other words, there are possibilities of interfuel substitution in most energy uses, these possibilities determine the competitiveness of energy sources in those uses, and prospects of competitiveness must play a decisive role in decisions on research on a specific resource.

Finally, energy saved adds to supply just as does energy produced. Research on ways of saving energy has advanced less far and has greater potential than research on energy production, and also has greater relevance to developing countries. Although developing countries are small users and even smaller producers of large-scale forms of energy, their stocks of boilers, for instance, run into thousands, of engines and motors, into millions. Small improvements in the efficiency of these devices can make a large difference to the energy consumption of developing countries. Often, the more efficient use of existing energy sources is less expensive than the expansion of energy supply. Thus, energy conservation deserves high priority.

Unfortunately, the body of research on many such devices has not advanced to the point where we could confidently identify the promising directions of research. This is not the only field in which the Group found itself plumbing the depths of uncertainty; there are many fields in which our judgment is tentative and imperfect. Therefore, we regard this report not as a verdict, but as an education, and offer it as a contribution to the processes of debate that guide national and international decisions. We expect to learn as much from the debate as we did from writing this report.

Coverage

The information we have used is mostly published information: unpublished information is much more difficult to survey. Our coverage of English-language materials has been comprehensive. Our regional surveys covered literature in Chinese, Indonesian, Korean, Portuguese, and Spanish; we also tried to cover literature in French and German. Literature in Russian remains an important gap in our survey. Major research trends are reflected sooner or later in literature in the languages of all industrial countries, and, indeed, of all countries. However, there are national specialities in research, national styles of research, and theories that are popular in particular countries. Their potential importance may be illustrated by the theory of the nonbiological origin of hydrocarbons. It can be traced back to the 1870s in Russia and remained influential in the Soviet Union. In the west, it was never taken seriously until it received unexpected support from data gathered by space probes.

This report does not cover in any detail the production and engineering technologies of the major energy industries — oil, gas, coal, and electricity (thermal, hydro, and nuclear). Initially, the Group seriously considered covering them, but it found that published literature was an imperfect guide to practice in these fields, and that it largely excluded developing countries. An adequate treatment of these technologies would have required the cooperation of enterprises in the energy and engineering industries, and the employment of expensive consultants; it would have been a very different exercise from what the Group was equipped to do. This omission does not reflect the importance of the industries, only the inadequacy of the Group's resources. However, the Group has dealt with the research for the major strategic issues that policymakers are likely to encounter in respect of these industries.

The references in the report are not a survey of literature, and do not aim to do justice to research, either in the world or in the developing countries. They represent the minimum support we considered necessary for our arguments. Among alternative references, we have tried to choose those that are more recent and accessible.

For reasons of time and space, we imposed certain limitations on ourselves. While we have tried to link major research problems to the developing countries for which they are most relevant, we have refrained from going into regional and national details. We have tried to go deep enough into technologies to make a broad judgment of their end-uses, their appropriateness for those uses, their relative priorities and importance, and the promising directions of research; to go deeper into technological complexity, however desirable, was not possible given the breadth of our mandate. Even reaching a broad judgment was difficult where information on technologies was confidential or proprietary, or where research had not gone far enough to provide a basis for judgment. In a number of such cases we have refrained from making a judgment.

Structure

This report is divided into 15 chapters. Following this chapter, the approach of the Group — its assumptions, agreed procedures, and ways of dealing with controversial issues — is described in chapter 2. Chapter 3 presents the Group's analysis of weaknesses in research capacity in developing countries and what needs to be done to build it up. This chapter also deals with the relationship between policy and research.

Then follow two chapters on demand for energy, whose analysis should, in the view of the Group, be the starting point of research on energy. Chapter 4 deals with demand analysis at the level of the socioeconomic system and of energy-using sectors. Chapter 5 deals with research on energy conservation, and lays special emphasis on research on the efficiency of energy-using equipment.

The chapters that follow relate to the principal energy resources and technologies. An attempt has been made to group energy sources by their mutual substitutability. However, substitutability is a matter of degree and can vary from one use to another, so our grouping is rough. Chapters 6–8 deal with liquid, gaseous, and solid fuels respectively, all of which supply energy through combustion; chapter 9 deals with two other thermal sources of energy, namely, geothermal and solar thermal energy. Electricity is covered in chapter 10, while chapter 11 deals with two sources of motive power, wind energy and human energy.

Environmental issues extend far beyond energy, and it would have been impossible to go deeply even into the energy-related ones within the Group's time and resources. However, three major energy-related environmental issues — deforestation and desertification, global warming, and acid rain — are covered in chapter 12.

The detailed conclusions of the Group are too numerous and varied to summarize, and their significance and relevance vary from one developing country to another. They are summarized, therefore, at the beginning of each chapter. However, the more general conclusions of our collective exercise are summarized in three brief, concluding chapters — those on the prerequisites of research in chapter 13, on energy uses in chapter 14 and on energy resources in chapter 15.

Chapter 2 The Approach of the Group

The Energy Research Group consists of 11 energy specialists from developing countries. We have tried to combine a professional and a sociopolitical judgment on research in this report. The Group has concerned itself with building research capacity, without which priority setting in research would be pointless. It has tried to identify promising lines of research from the role of energy in development. It has covered all forms and uses of energy.

The Group started with the following normative assumptions. The growth of production and consumption is essential for a rise in the living standards of developing countries, but deliberate policies are also necessary to relieve poverty and improve income distribution. This concern for fairness extends to the international sphere. The capacity of developing countries for independent decision-making needs to be increased; this requires the internalization of a number of functions and activities that they lack or for which they depend on industrial countries. Economic activities should pass the test of environmental soundness, and they should be conducted efficiently, although efficiency must be defined in the local context.

The report represents the unanimous position of the Group. However, the Group recognizes a number of issues on which the state of knowledge permits the holding of equally valid alternative judgments.

The members of the Energy Research Group come from a wide range of backgrounds. Some can be classified as scholars, professionals, administrators, politicians; most are somewhere in between. We found ourselves at various times to have been involved in teaching, research, politics, journalism, and management. There were, however, two elements that united us: we are nationals of developing countries working in developing countries, and we have taken a serious interest in some aspect of energy — more serious than just forming a judgment or making a pronouncement. Most of us either studied, taught, or managed it. These common features shaped our conception of what we could and should do.

Active public concern with energy is over a decade old; during these years, much has been written about what developing countries should do or have done to them (for instance, United Nations 1981; World Bank 1981, 1983a; World Bank and Food and Agriculture Organization 1981; Bhagavan and Carlman 1982; Mwandosya et al. 1983; Commission of European Communities 1984; Goldemberg et al. 1985). The Group asked itself what, if anything, it could add to the considerable body of deliberations and recommendations that had preceded it.

The Group had two basic models to follow. One was a purely professional review of research needs based on the technical gaps in knowledge (for an excellent example relating to combustion research, see Smoot and Hill 1983). This approach was not really applicable to our subject, which does not have well-defined boundaries, a recognized peer group, or a broad consensus among the principal practitioners. The second model was in the form of a social and political comment. This model was indispensable, since there is no way of prescribing research priorities for development without bringing in social and political criteria. However, both the composition of the Group and the conditions of its formation required that a professional judgment be combined with a sociopolitical one. Thus, the Group had to work out its own approach, which calls for some explanation.

Points of Departure

Pathology of Research

To begin with, the Group could not take its terms of reference literally and limit itself to setting energy research priorities. As initiators and practitioners of research in developing countries, we were convinced that unless the effectiveness of research institutions in developing countries was improved, and unless they were integrated into the productive and policy-making processes, setting research priorities would be self-defeating. Although our views on research may not be definitive, we have been compelled to set down the beginnings of a diagnosis in chapter 2.

Research Trajectories

The point of setting research priorities is to lead resources — researchers, funds, equipment — toward desirable or promising subject areas. Research, however, is often a venture into the unknown; it can go wrong in a number of ways. Research problems are conceived in terms of paradigms currently among communities of researchers — paradigms that are not always appropriate for efficient solutions. Research is partly a social phenomenon, and communities of researchers often display elements of crowd — or hunting-pack — psychology: pioneers who tackle new problems or try out new methodologies and instruments are often followed by hordes of imitators. This bandwagon effect is, for instance, seen frequently in the influence exercised by developed-country paradigms on research in developing countries; it is reinforced, in this case, by the considerably larger material and social rewards to research published or recognized in industrial countries (Cooper 1973). Expenditure on research is an investment, and is susceptible to the same forces that cause waste in investment, such as possibilities of profit and aggrandizement. These sources of waste would persist even if priorities were correctly set.

Hence, the Group felt that as researchers we should point not simply toward areas of priority research but also toward the promising directions or approaches. Lest we were in danger of forgetting the risks of such an undertaking, we reminded ourselves of Werner Von Siemens's state-of-the-art review of electricity research. The founder of the well-known power equipment firm, Siemens und Halske, was a considerable inventor in his own right. After reviewing experiments all over the western world (including a battery-powered boat floated by Jacobi on River Neva in Russia), Siemens concluded that batteries were unlikely to serve as a basis for the widespread use of electricity, and concentrated on the development of "magneto-electric machines," or dynamos. His judgment has been justified by the insignificant role of batteries after a hundred years of development. But he also concluded that lighting with carbon or metal wires was impractical since "the light so generated is too weak, requires much electricity and labour, and can hardly be called electric light'' (Siemens 1880); he, therefore, concentrated on the development of electric candles and lighted the German Parliament with them. On 21 October 1879 — almost as Siemens wrote those words — Edison put a carbon filament inside an evacuated bulb and demonstrated an invention that put arc lights to sleep forever.

Thus, we make our assessments of promising directions of research with modesty and caution, and claim no infallibility for them. We have also tried not to stray too far beyond our own expertise and not to speculate. This means that we could not be equally specific in all areas. We have, nevertheless, ventured to make judgments that we hope will make research more effective.

A Lay View

The Group decided that energy research priorities should be derived from the place of energy in the development process, and not from any intrinsic characteristics of energy. Thus, we decided to bring under its purview some research that energy analysts do not always cover — for instance, research on human energy and on energy-using devices. We also decided to focus on energy demand and energy use as indicators of priority.

Although all are academic or professional specialists, the members of the Group tried to transcend technical standpoints, reach a broad consensus, and supplement our technical knowledge with an awareness of the socioeconomic choices facing developing societies and the conflicting interests that constrain those choices. We tried to reach an agreement on the ideological assumptions that should govern our common socioeconomic judgments; these assumptions are described in the section ''The Great Uncertainties'' later in this chapter.

All Forms and Uses of Energy

Following its mandate, the Group tried to cover all forms of energy as well as all uses. We have ignored some energy forms that are unlikely to be significant in the medium and the long run (e.g., ocean thermal energy conversion). We have left out a number of energy uses or user devices (e.g., turbines, jet engines), largely for lack of time, but also because research and development is sometimes confined to a small number of producers and is difficult to observe from outside.

Unlike many scholars, including some of our members and reviewers, we have not taken any position on the question of renewable versus exhaustible resources. The use of exhaustible resources involves their allocation among succeeding generations. It entails a value judgment that no simple optimization rule can help us avoid. The Hotelling principle, that the net price (excluding the extraction and production costs) of an exhaustible resource must increase at a rate equal to the rate of interest, is applicable only under restrictive conditions and is not very useful in practical situations. There is no easy way of making intergenerational comparisons of utility (see, Umaña 1984). However, the moral choice has to be made by those who determine the intergenerational allocation. The bulk of exhaustible resources is consumed by industrial countries, and given the organization of industrial markets, lower consumption of fossil fuels by developing countries now is by no means likely to make more of such fuels available to future generations in those developing countries. Thus, the choice is not the developing countries' to make; nor is the moral judgment that the choice imposes.

This does not mean, however, that the developing countries will not suffer the consequences of resource exhaustion. If, therefore, efforts come to be made to regulate the rate of global resource exhaustion, the developing countries have a clear interest in contributing to them. Further, countries that exploit any exhaustible resources (including fossil fuels) for their own use or exports, have to decide how rapidly to exhaust the resources. They have a researchable problem of intertemporal choice in resource exploitation, whether they treat it as one of intergenerational allocation, or balance-of-payments management, or analyze it in any other way they choose. It is a crucial problem for countries with exhaustible resources to export.

Normative Assumptions

The determination of energy research priorities calls for a utilitarian approach, for a review of the proximate practical objectives rather than the promise or fascination of research. At the same time, it was impossible for the Group to take a narrowly client-oriented view both because the potential clients — governments, funding agencies, producers, etc. — were many and because their objectives were subject to debate. The best that the Group could do, therefore, was to work with a set of goals that would be broadly shared in developing countries. Of these ideals, which are discussed below, some may look as laudable as universal motherhood, others as polemical as zero growth. Some of the judgments expressed in this report will inevitably generate controversy. We welcome controversy as the thorny path to truth but, to be fruitful, controversy should start with the same initial premises. We thought it best to articulate ours, first, to help in the process of our own consensus and, then, in the hope of steering debate in more constructive directions.

In the centuries preceding the rise of modern industry, the comfort in which people lived and the labour they expended to make a living depended on their relationship with the land. It is self-evident that a surplus of food beyond the consumption of the food-producing population was essential at all times to the existence of urban concentrations of people who did not produce their own food. Where high levels of fertility were achieved or where there was an abundance of fish, fowl, and fruit, the people lived well or had ample leisure; under harsher conditions, they had to work harder for a more meagre living.

In regions where a surplus beyond the subsistence requirements of the food-producing population could be produced, a part of the population pursued other occupations such as trade, government, religion, and warfare: some thereby achieved considerable wealth and prosperity. Thus, mechanisms were built into some preindustrial societies that generated economic inequality.

The innovation of modern mechanical techniques led to enormous increases in the productivity of human labour. These not only made possible concentrations of wealth and income that were unimaginable in the preindustrial world, but also raised the incomes of the working populations through the reinvestment of that wealth in activities that required labour. This process of economic growth, by now, almost encompasses the greater part of the populations of the countries that are considered industrialized.

In the rest of the world, the processes of growth of productivity and incomes have affected only a part — often a small part — of the population, and have generated large differences in wealth and lifestyle between those who have benefited from the global tide of productivity growth and those who have not. Among those who have not, levels of poverty and distress are found that are no longer inevitable, and that constitute a blot and a shame in view of the levels of prosperity of their neighbours near and distant.

A significant expansion of the output of goods and services is obviously necessary if the standards of living in developing countries are to be raised. Energy, as we emphasized earlier, is an intermediate product, and concern about it makes sense only in the context of the need for greater production and consumption. Thus, growth in developing countries is a necessary condition of improvement in their people's condition.

We also believe, however, that in developing countries mechanisms exist that lead to an uneven distribution of the benefits of growth. Inequalities arising from the concentration of property are as prevalent in developing as in industrial countries, and the forces that increase wages and reduce inequality are not as strong in developing countries as in some industrial countries. There are other disequalizing forces, however, that are characteristic of, or stronger in, developing countries. Ownership of industry and business tends to be concentrated in narrow social groups. Political power is held by small groups and converted into economic power. Access to education is unequal, and there are wide variations in the quality of the education available to the rich and the poor. Growth is confined to the commercialized sectors of the economy, and leaves untouched those engaged in subsistence gathering, hunting, and agriculture. Land is an important avenue of enrichment, and its ownership is not open to large segments of the rural population. In urban areas, poor housing, insecurity, and uncertainty of employment combine to deprive the poor of the possibilities of asset accumulation. The consequence of all these forces is evident in the widespread poverty, distress, and squalor even in some of the most prosperous and dynamic of the developing countries. These tragedies of growth are, in our view, often avoidable, and their extreme features are largely remediable even within the present resources of developing countries.

We do not believe that poverty or inequality can be removed or even significantly reduced by action in the field of energy alone. However, most types of action have a technological component, including action to influence poverty or inequality, and all technology has an energy component. The implications of action for income distribution and the provision of basic needs can be important, should be explored, and should be considered in formulating energy policies. Further, action in the field of energy can improve productivity and provide the means for improvements in income distribution and the quality of life. More important, extremes of poverty and inequality introduce elements of instability and brittleness in societies that make their smooth and rapid development impossible. This is why poverty alleviation must form an essential component of development policy, of which energy policy is a part.

The advent of modern industry has led to the emergence of a large number of new products, activities, and occupations, many of which are largely confined to industrial countries. This specialization, together with the concentration of industrial production in industrial countries, gives them considerable influence on the fortunes of developing countries — influence exercised not only by the governments but also by large transnational corporations with headquarters in industrial countries. It is reasonable to expect that these governments, as well as corporations, should exercise their power over developing countries with restraint, fairness, and justice, for instance, in trade, finance, and technology transfer. In this sense, we favour a fairer world economic order.

We also recognize, however, that the world is divided into nation-states; and, whatever the level of international assistance, the development of a nation-state depends largely on efforts of its own people and within its frontiers. It is, therefore, essential for the development of countries that they internalize certain activities and capabilities; they should rely on themselves in a few essential respects. On what precisely these are, and where the line is to be drawn between self-reliance and autarky, there is room for difference of opinion. However, there is greater accord on the existence of a class of essential activities. The capacity of government to make independent decisions in energy policy in the national interest is an obvious example. From it follows the need for the research capacity required to make informed decisions and for the productive capacity to sustain and utilize research. Thus, self-reliance is a prerequisite for the economic and technological adjuncts of national sovereignty.

It is impossible to consider large questions of policy, including energy policy, without becoming aware of externalities. The use of fossil fuels by some harms others in various forms, such as acid rain and pollution. We believe that the disutilities and inequities arising from economic activities should be brought firmly into the calculation of net benefits and that such activities should pass the test of environmental soundness.

Externalities arise not only between people living together in this world but also between generations. For instance, the quantity of fossil fuels available on this planet is strictly finite; whoever uses any today reduces the available potential supply to the coming generations (Georgescu-Roegen 1976). While we do not conclude from this fact that there should be a rapid shift from exhaustible to renewable resources, we must stress the need to take account of the interests of coming generations.

We share a preference for efficiency in the sense that, if an activity can be undertaken with a lower resource input, it should be. This preference may sound trite; it is also unspecific because there is no unique measure of efficiency. Measurement in terms of a single factor — for instance, labour productivity — can be misleading where there are a number of inputs; and there is an infinite number of ways of weighting such inputs to get a measure of efficiency. Weighting them by their prices is a convenient convention, but prices are not invariant. In particular, many developing countries are import-dependent in energy and face extremely unequal chances of expanding exports. The resulting variations in the shadow cost of imports may make research on and investment in import substitutes, including energy, worthwhile in some developing countries, even when international costs at current exchange rates do not support them. A long view must be taken to anticipate future turning points in such decisions; for instance, a country that expects its balance of payments to worsen may take advance action to develop alternative energy technologies even before they become economic at the ruling exchange rate. More generally, a usable concept of efficiency must take account of multiple inputs and must be adapted to local conditions and national objectives.

The Great Uncertainties

The consensus on which this report is based was arrived at by means of an iterative process. Within the framework of a number of guidelines and of the coverage worked out by the entire Group, a set of statements defining a certain unitary position was first developed; it was then modified, expanded, and refined on the basis of members' reactions to three successive drafts. This interaction did not produce any basic disagreements, but there were a number of future or hypothetical situations on which it was found that a number of alternative judgments could be held with more or less equal confidence. Among these were some of the most fundamental questions in the energy debate. Let us give four illustrations.

The future price of oil In the past 12 years, a battery of technologies has been investigated, developed, or updated in anticipation that oil prices would continue to rise. If they did so continue, a number of substitute resources and technologies would become competitive at different oil price levels; the faster the rise in oil prices, the earlier such resources and technologies would become competitive, and the earlier the research and development (R&D) to improve them would be justified. On the other hand, if oil prices remained below the level at which substitutes become workable for a long time to come, investment in research on substitutes would be premature, if not wasted. Strong convictions about the future course of oil prices are encountered among researchers; not surprisingly, they are correlated with the researchers' convictions about the desirability of research on alternatives. However, if we look into the question in detail, the mechanism of oil price determination is complex and obscure (Singer 1983, 1985). Even if it were transparent, variables, such as rates of technological progress and of oil discovery, enter the mechanism whose future course is most uncertain (Adelman et al. 1983). Under these conditions, a broad variety of alternative convictions can be held about future oil prices with equal justification.

The future rate of warming The possibility that rising carbon dioxide concentration may radically change regional climates and lead to the submergence of extensive coastal areas by melting the Antarctic ice sheet is extremely disturbing. The view one takes of this danger must profoundly influence one's convictions on "benign" energy sources like hydrogen and nuclear energy. However, the degree of uncertainty of future carbon emissions is high and increases as projections extend into the future. In a group of projections generated from plausible values for a limited number of variables, the standard deviations of projected carbon emissions were found to be about equal to the means for 2025, and 30–60% higher than the means for 2075 (Edmonds and Reilly 1985b). Thus, the possible values are spread across a very wide spectrum. Insofar as some of the independent variables can be changed by policy, which may itself be influenced by the policymakers' view of the dangers of global warming, carbon emissions are inherently unpredictable. Even if they were predictable, the relationship between them and global climate is itself under debate, as is discussed in the second section of chapter 12. Here again, a number of judgments could be made with equal confidence.

Global growth and cycles Broadly speaking, the faster the growth of aggregate demand in the rest of the world, the easier it is for developing countries to export and earn the resources needed for imports, including imports of energy. The quarter century after World War II saw a relatively rapid growth in world demand, and also in imports of oil by oil-importing developing countries. Their demand for oil was cut by subsequent rises in oil prices, but also by the slower growth in the industrial countries after 1973. In the future, too, the more sluggish the world economy, the more common balance-of-payments problems will be among developing countries, and more of them will be justified in investing in oil substitutes for import substitution, even when such substitutes are not competitive on the international market. Hence, the attractiveness of oil substitutes to developing countries depends, not only on world oil prices as indicated, but also on world growth.

Although it is surmised that world growth proceeds in cycles, the forces that drive the cycle are not well-enough understood for reliable prediction (Freeman et al. 1982).

Direct versus indirect subsidies It is a reasonable principle of economic policy that a subsidy intended to improve income distribution is better given in the form of generalized income that can be spent on a range of commodities than of a subsidy that is conditional on the consumption of a particular commodity. However, the difficulties of applying this principle in various countries are serious. The conditions in each country are peculiar to it, and a judgment has to be made regarding the feasibility of applying the principle. Here again, the body of experience does not give sufficient grounds for arriving at a balance between the optimal and the feasible, and a number of alternative judgments can be held with equal validity.

These are only some of the issues on which the Group members could see the validity of a range of alternative views. On these, as well as other issues, the neutral stance of this report is based on the admissibility of rational differences, which does not preclude strong views being held by individual members.

Chapter 3 Research and its Environment

Research needs to be useful as well as sound; the extent to which it is depends on the effective interaction of the "doers," directors, and users of research.

Governments are institutions for resolving conflicts; whatever their philosophy, the central role of energy, the scale of energy investments, and the import costs of, or export earnings from, energy force governments in developing countries into action on energy. Energy policy has to take a forward view of feasible futures, choose among them, and select instruments for achieving national objectives; research can improve decisions at each step. For research to effectively assist policy, however, it is essential that it be done by well-endowed, professional research institutions capable of giving independent advice. The government should be an informed buyer rather than an owner of research.

Technologically sophisticated observation of their environment is within the capacity of many firms in developing countries, and needs to be encouraged. Government assistance should be directed to building this capacity, and not to R&D as such, and to creating competitive market structures that induce firms to innovate rather than to generating particular innovations. Research institutions working for small firms should be in close touch with some producers, and should carry innovations to the point where the risks of commercializing them are minimized.

For effectiveness, research institutions need to accumulate experience, diffuse intellectual skills, ensure efficient use of their intellectual assets, and bring together diverse disciplines to bear upon problems. Program funds to them should be directed toward building intellectual and material assets in specific areas of research; projects should be designed to exploit those assets. Directors of research institutions play a crucial role in coordinating researchers and problems, programs and projects. Training and communications are essential to good quality in research.

International funding agencies play a neutral to negative role in building research capacity in developing countries. Large-scale, site-specific research required for investment projects is funded by large investment funding agencies, whereas small-scale research, generally unrelated to production or commercialization, is funded by small funding agencies. They are not responsible for the lack of connection between policy, production, and use on the one hand and research on the other that is characteristic of developing countries: that disconnection arises from the dominance of multinational corporations in the production of capital-intensive energy equipment, the weakness of domestic firms in developing countries, and the passive energy policies of developing-country governments. However, international funding agencies also reinforce this disarticulation, and do little to remedy the weaknesses of research institutions in developing countries.

This chapter is focused on energy research. Much that is said here, however, will have wider application.

Research has two features that are crucial but difficult to define: utility and quality. If it is to be subjected to any social or economic evaluation, research must directly or indirectly serve a practical use; but that is not enough. Research that leads to wrong conclusions can do harm, and the more important its application, the greater the harm it can do. Hence, research has to be both useful and sound.

Research is an intermediate input that may be used in policy formulation, production, or consumption. In these activities, it must reduce risks attendant on decisions, or expand options, or reduce costs, or improve the quality of goods and services. Its usefulness can only be judged in terms of one or more of these consequences.

However, all of these consequences are in spheres outside research. Thus, the benefits of research are contingent on the downstream users — policymakers, producers, or funding agencies. They must be skilled at using research and at translating it into practical decisions; these skills require some training in the disciplines that go into research. We shall emphasize the importance of informed users in generating good research in various industries, notably oil and power, but the point is more general: the broader the training of research users, the greater the use they will be able to make of research. For instance, surface tension may appear to a lay mind as too abstruse a subject to be of practical use, but it has at least two applications even within the field of energy, namely, in the prevention of scaling in power plant boiler tubes, and in economizing hot water in washing and cleaning.

As important as the informed user is the informed director of research, who needs to be informed for a different reason. Knowledge is not organized on any principle of utility but on the basis of theories and tools. Hence, any practical problem requires a decision on what field of knowledge should be applied to it, and often has to be divided into subproblems that can be tackled by individual researchers or small teams; conversely, the results obtained have to be integrated into practical solutions. This subdivision of problems and integration of results calls for a special expertise in the director of research.

An attempt is made in the following sections to spell out the implications of these principles in terms of the principal institutions that use and produce research.

Governments

Governments do or commission a great deal of policy-oriented research, while much more research that they do not pay for is done for them by researchers who seek to influence policy. Although their wisdom and power vary greatly, governments are basically institutions for resolving conflicts and regulating competition in the political field. The role they play in the resolution of conflicts ranges from extreme laissez-faire to comprehensive intervention. Whatever their ideological complexion, however, energy-related problems have forced almost all governments into action in many fields, such as the following.

The balance of payments Management of foreign exchange reserves is always in government hands. The rise in the price of oil forced a number of developing-country governments to adopt a variety of corrective policies such as import regulation, import substitution, export promotion, exchange-rate variation, and international borrowing and lending. Although oil prices have eased, a number of developing-country governments continue to have serious payments problems either on account of oil imports or debts contracted to pay for oil or energy-related equipment. Payments problems of developing countries have been exacerbated by a fall in the real prices of primary products and a rise in real interest rates, as well as by import restrictions of some industrial countries. Insofar as energy imports or exports make the balance of payments of a developing country vulnerable, it will have to pursue active corrective policies.

National resource management For energy resources that are depletable or have a limit to sustainable yields, governments must decide who exploits them, at what prices, how fast, how they should be taxed or subsidized, how they are to be rationed in the event of a shortage, and how the issue of economic rents should be treated.

Gestation lags and lumpiness Some types of energy-based production (e.g., development of coal mines, oil exploration and production, construction of power plants), as well as changes in consumption patterns that require the replacement of equipment stocks, take many years, and have to be planned well in advance. The large minimum size of certain types of energy investments also raises problems of matching the time patterns of demand and supply. Even if they are privately owned, investment in them is influenced by entrepreneurial expectations of return, which are strongly influenced by government policies. Thus, government action based on a forward view can make energy investments more timely and less costly.

Essential needs Essential commodities, including energy, have to be shared in the event of shortage, or if a rise in their prices causes widespread hardship.

Monopolies Natural or otherwise, monopolies call for regulation to prevent high prices or inefficiency. Monopolies, including state-owned ones, are common in the energy sector. In addition, a number of countries, especially small ones, face noncompetitive suppliers in the import of oil and buyers in the export of resources.

Conflicts of interest Large projects such as dams, mines, and transmission lines affect so many people that governments must act as arbitrators between social and economic interest groups. Although the general principle of gainers compensating losers is well understood, the quantum of compensation and the mechanisms for raising and distributing it permit many variations.

Energy Policy

The pervasive and critically important role of energy in national economies indicates that the identification of energy issues and energy policy development are important areas of study by governments, researchers, and the development community. Energy policy analysis, planning, and management must be improved to ensure that major energy policy initiatives, programs, and projects that are being implemented have the greatest beneficial impact and effectiveness. Because most developing countries devote at least one-third of public sector investments to energy, and a number of oil importers have spent 50% or more of their export earnings on petroleum imports in recent years, even small improvements in the efficiency of energy supply and utilization are desirable.

Energy planning, broadly interpreted, denotes a series of steps or procedures by which the myriad of interactions involved in the production and use of energy may be studied and understood within an explicit analytical framework. Planning techniques range from simple manual methods to sophisticated computer modeling. The complexity of energy problems has forced increasing reliance on the latter approach. Energy policy analysis is the systematic investigation of the impact of specific energy policies or policy packages on the economy and society at all levels. Energy management, which includes both supply and demand management, involves the use of a selected set of policies and policy instruments to achieve desirable energy and economic objectives.

An important aim of energy research in developing countries must be to upgrade the quality of energy planning, policy analysis, and management. In particular, such studies must also focus on methods of enhancing the effectiveness of energy policy implementation. To better understand the role of energy research, we begin by identifying some of the broad goals of energy policy as seen from the national perspective.

The broad rationale underlying national level planning and policy-making of all kinds in developing countries is the need to ensure the best use of scarce resources to further overall socioeconomic development and improve the welfare and quality of life of citizens. Energy planning is, therefore, an essential part of national economic planning, and should be carried out and implemented in close coordination with the latter (Munasinghe 1980). However, the word planning, whether applied to the national economy or the energy sector in particular, need not imply a rigid framework along the lines of centralized and fully planned economies. Planning, whether by design or deliberate default, takes place in every economy, even in those where market forces reign supreme. In energy planning and policy analysis, the principal emphasis is on the detailed and disaggregated analysis of the energy sector, its interactions with the rest of the economy, and the main interactions within the various energy subsectors themselves.

Energy policy analysis and planning must be developed to meet the many interrelated and often conflicting overall national objectives as effectively as possible. Specific goals usually include: determining the detailed energy needs of the economy and meeting them to achieve growth and development targets; choosing the mix of energy sources to meet future energy requirements at lowest costs; minimizing unemployment; conserving energy resources and eliminating wasteful consumption; diversifying supply and reducing dependence on foreign sources; meeting national security and defence requirements; supplying the basic energy needs of the poor; saving scarce foreign exchange; identifying specific energy demand or supply measures to contribute to possible priority development of special regions or sectors of the economy; raising sufficient revenues from energy sales to finance energy sector development; stabilizing prices; preserving the environment; and so on.

Thus, the role of governments in energy and energy-related fields will inevitably be large, and if their policies are informed by rational macroeconomic calculations, the returns in the form of improved resource allocation and reduced risk can be high (Munasinghe 1984a). Getting the big decisions right requires a policy framework. In respect of energy, it will consist of a projection, or a view of the future; a plan, or an outline of problems and proposed solutions; and the instruments to be used to implement the solutions.

Projections

The long gestation lags in energy investments and structural changes in consumption are the primary reason for making projections. Such projections should look forward at least as far as the maximum gestation lags, if not somewhat longer. For instance, 15- to 20-year projections are not uncommon for electricity, and similar or longer time spans would be justified for coal.

It is possible to make naive projections by extrapolating past trends; they minimize information requirements, and are not always less accurate than projections based on more sophisticated methods. The purpose of projections, however, is not simply to generate a set of future estimates, but also to give a better understanding of the processes involved. Hence, it is advisable to use models for projection that bring in the energy-using sectors as well as the major macroeconomic constraints; indeed, there is not much point in projecting energy except in the context of a view of the future for the economy as a whole.

It is commonplace but worth emphasizing that a projection requires external judgment, and that it does not improve judgment but simply spells out its implications. Making a judgment about the future remains an act of imagination, however much it may be supported by information. Information relates to the past and present, and reading the tendencies that are inherent in history is one part of the skill required to make good projections. In addition, however, discontinuities between the past and the future must be foreseen and incorporated into projections. To cite an example of a misinterpreted discontinuity, many oil-importing developing countries coped with the 1973/74 rise in oil prices by borrowing in the short term and increasing exports and replacing imports over the longer term. This strategy was remarkably successful, and when oil prices rose again in 1979/80, it was repeated. However, the circumstances had changed. The oil-import ratios of the developing countries were higher in 1979 than 1973 and left less room for further import substitution, and the opportunities for further export growth were also more limited. As a result, freshly contracted debt could not be serviced, and a number of developing countries faced insurmountable debt problems (Campbell 1983).

The discontinuities arising from oil prices were beyond the control of the developing countries that were affected by it. However, there are also controllable discontinuities. In modeling language, there is a distinction between exogenous and instrumental variables; and if projections on exogenous variables point to unworkable or unacceptable futures, discontinuities have to be introduced into instrumental variables to lead to better or more realistic future outcomes, which is the essence of planning. However, the pace of change depends on the magnitude of the discontinuities introduced, on which there is often debate among planners. For instance, such a debate underlies the recent global energy projections. The world faces an unacceptable future in the form of declining oil supply and rising levels of atmospheric carbon dioxide. Some futurologists have looked for the minimum changes in the current lifestyles and power relations required to make the future endurable, while others have pointed toward more fundamental changes (Goldemberg et al. 1985). Projections at the national level would similarly open debate on desirable futures, and debate on these is essential for robust and widely acceptable choices to emerge.

Plans

The purpose of projections is to sort out feasible from infeasible futures: the purpose of plans is to select an optimal future out of the realizable ones, and to work out the steps needed to realize it. Planning has a long history, and a baggage of inherited connotations. To prevent misunderstandings arising from such associations we should clarify that by plans we do not mean 5-year plans; for the purpose of energy management, a country would need a number of interrelated plans for various time spans extending to much longer periods. Nor do we mean central direction of all economic activities. Among developing countries, there are some with a considerable degree of central direction whose performance in the field of economy or energy has been perfectly creditable. Such direction, however, is not essential. What is essential is selective state intervention in respect of activities where governments must be active to avoid major disruptions that arise from the mismanagement of energy: such disruptions are too serious in recent history to need to be highlighted.

Recent experience gained in modeling for integrated national energy planning and policy analysis has led to a more hierarchical analytical framework that recognizes at least three distinct levels of analysis, including energy–macroeconomic, energy sector, and energy subsector, as well as the interactions among them. This approach also gives a better policy focus. More recently, the availability of microcomputers has provided analysts in developing countries with a relatively cheap, powerful, and flexible tool to develop and apply some of these ideas (Munasinghe et al. 1985). At the highest and most aggregate level of the hierarchical approach to modeling, it must be clearly recognized that the energy sector is a part of the whole socioeconomic system. Therefore, energy planning requires analysis of the links between the energy sector and the rest of the system. The second level treats the energy sector as a separate entity composed of subsectors, e.g., electricity, petroleum products, biomass, and so on. This permits detailed analysis of specific end uses with particular emphasis on interaction among the different energy subsectors, substitution possibilities, and the resolution of any resulting policy conflicts. The third and most disaggregated level in the hierarchy pertains to planning within each of the energy subsectors. Thus, for example, the electricity subsector must determine its own demand forecast and long-term investment programs.

Instruments

Planning should result in the development of a flexible and constantly updated energy strategy that can meet the national goals discussed earlier. Such a national energy strategy may be implemented through a set of energy supply and demand management policies and programs (Munasinghe 1983).

To achieve the desired national goals, the policy instruments available to Third World governments for optimal energy management include: physical controls; technical methods; direct investments or investment-influencing policies; education and promotion; and pricing, taxes, subsidies, and other financial incentives. Because these tools are interrelated, their use should be closely coordinated for maximum effect.

Physical controls are most useful in the short run when there are unforeseen shortages of energy. All methods of limiting consumption by physical means, e.g., load shedding, rotating power cuts in the electricity subsector, reducing or rationing the supply of gasoline, or banning the use of motor cars during specified periods, are included in this category. However, physical controls can also be used as long-run policy tools.

Technical means used to manage the supply of energy include the determination of the most efficient means of producing a given form of energy, choice of the least-cost or cheapest mix of fuels, research and development of substitute fuels such as coal, natural gas, or oil from shale, the substitution of alcohol for gasoline, and so on. Technology may also be used to influence energy demand, for example, by promoting the introduction of more efficient energy conservation devices such as more fuel-efficient automobiles, better stoves for woodfuel, and by research into and promotion of solar heating devices, etc.

Investment policies have a major effect on both energy supply and consumption patterns in the long run. The extension of natural gas distribution networks, the building of new power plants based on more readily available fuels such as coal, or the development of public urban transport networks are just some of these policies. It should be noted that many of them may well be undertaken by sectors other than energy — examples are investments in transportation facilities or the systematic installation or electrification of deep-well irrigation pumps. Close cooperation between the energy administration and planning authorities of these other sectors is obviously necessary.

The policy tool of *education and promotion* can help to improve the energy supply situation through efforts to make citizens aware of cost-effective ways to reduce energy consumption, of the energy use implications of specific appliances or vehicles, and of the potential for substitution of energy by capital (e.g., proper insulation).

Taxation and subsidies are useful policy instruments that can also profoundly affect energy consumption patterns in the long run. For example, countries that have imposed high taxes on gasoline have generally had significant results in terms of reduced automobile use, more efficient vehicle fleets, and so on. Subsidies have similarly encouraged energy-saving capital investments.

Policy Research

If a policy framework comprising the above three elements — projections, plans, and instruments — is created, it will generate substantial research requirements. Policy research is not uncommon in developing countries. Although it was prevalent in a number of them even earlier, many more recognized its need in the wake of the serious energy problems that arose in the 1970s. Others were forced to produce plans before international funding agencies to justify investment projects for funding. International research funding agencies also looked kindly on policy research as a relatively low-cost way of getting involved with policymakers. Thus, policy research has not suffered from neglect. However, its quality could be improved; and quality improvement calls for organizational changes.

If properly articulated, a policy framework should have a considerable effect on research, and research on policy. Yet, our reviewers have found that the connection between national priorities and the activities of research centres is tenuous if not absent (Bhushan 1984; Torres 1984). Most research in developing countries is funded by the state. When the government wants inputs to policy, it invariably does so in a hurry, and it does not get them with the speed it wants from independent research institutions. (Gestation lags in research are longer than in policy formulation, and the trade-off between speed and quality is often different for researchers and policymakers.) Many governments also like to have an influence on the views of research institutions. Hence, they have tended to disfavour independent research centres, and either set up captive research institutes or hire consultants. Both are more responsive to immediate demands, but the quality of their research suffers.

The faster the results are required, the less time there is for fresh research, and the greater the reliance on inherited knowledge. Unfortunately, neither consultants nor official research organs are well organized for accumulating knowledge in depth. Both tend to move quickly across widely separated areas as required to skim the available information; neither systematically stores knowledge in libraries, data bases or people. The result is repetitive and derivative work; and especially in socioeconomic research, repetition generally means regurgitation of conventional wisdom.

The first need of competent policy research in developing countries is independent, professional research institutions that can act as a repository of knowledge. That the present-day independent institutions do not serve the needs of policy is an organizational and political failing that can be corrected. Among the corrective measures required, the following are the more basic ones.

First, government funding should not be channeled primarily into captive research institutions and, among funded research institutions, it should not unconditionally cover all forms of expenditure. It should go into the funding of the infrastructure of research institutions, especially those parts of it that are crucial to the quality of research, such as the library, instrumentation, experimental facilities, computation facilities, and training of personnel. The funding of personnel should support specialists available for policy research as first priority: such specialists and their projects should be attached to adequately endowed research institutions. The salaries and other terms should be uniform to encourage active interflow between policymakers, researchers working on policy, and other researchers.

Second, it is important that the government become an informed buyer of research. The persons responsible for buying and judging research in the government should be trained and experienced: they should, in fact, be interchangeable with the persons who produce research for them, and should interchange positions with them from time to time. Governments often draw upon experienced people from enterprises and research institutions, but the reverse flow is equally important if policymakers are to be competent judges of research. Policy-making is responsible and often technical work; many governments in developing countries try to ensure the supply of high-quality personnel for it by setting up specially privileged administrative cadres or hiring expensive consultants from outside. It is not enough, however, to ensure a high intelligence quotient in the government; it is also necessary to feed the intelligence with knowledge to be acquired outside the government from time to time.

Third, socioeconomic research provides fruitful ground for policy research even if it is not directly relevant or if it is unsympathetic to government policy. The costs of collecting socioeconomic information on a large scale can be very high, and unless the government subsidizes it, integrated macrolevel research is likely to suffer as it does in many developing countries. The government can stimulate socioeconomic research both by collecting and publishing statistical and other information, and by financing the collection and publication of such information by research institutions.

We should, at this point, address the question of policy research and dissent. Research that is a direct input to policy is only a part of socioeconomic research; much research also arises as a result of the routine activities of researchers as well as of a critique of policies. In societies with mechanisms for peaceful changes in policymakers or in policies, critique tests the robustness of policies and expands the range of policy alternatives available. Where change is not institutionalized, however, policy critique is often looked upon as a threat to authority and suppressed.

Because we are in favour of systematic and peaceful change in our societies, we need hardly say that our sympathies are not with brittle, unrepresentative regimes. The capacity to advance knowledge and to use it in policy is a resource that is not readily available to governments that do not tolerate intellectual dissent.

Freedom of Maneuvre

Broadly speaking, the larger a country, the less its dependence on the outside world, and the greater its freedom of maneuvre in policy-making. Further, the economic benefits of research depend on its scale of application; this is a major reason why research tends to be concentrated in large countries. Most developing countries are, however, small. If they are to acquire greater freedom to formulate policy, they should have closer association with research done by their neighbours, and they would need to coordinate policies among themselves. If they are to acquire greater capacity to do and use research, they would need to share the costs, facilities, and benefits of research. As it happens, almost all developing countries are concentrated in Africa, Asia, and Latin America; most of their neighbours are other developing countries, and regional cooperation among them also implies south–south cooperation.

Producers

Producers are the practitioners and the major repository of production technology. However, all producers of goods and services are not producers of new or improved technology. Intensive technological investigations tend to be centred in research and teaching institutions. Within industries, technological innovation tends to concentrate in industries where the same or similar processes are capable of making a wide range of products, namely engineering, electricals and electronics, and biotechnology.

The absence or relatively small size of these innovative industries in developing countries is one reason for their relatively unimportant role in innovations. It is not the only one, however; there are other and, in our view, more remediable reasons. We discuss the possibilities of action in three spheres: research and development (R&D), technological capacity, and the technological infrastructure.

Research and Development

It is customary to lament the tendency of producers in developing countries to rely on imported technology and not to develop their own (Cooper 1973; Stewart 1977). In the field of energy, we have encountered some outstanding instances of R&D-led innovation, such as alcohol-powered cars and charcoal smelting of iron in Brazil (Torres 1984). By and large, however, both the extent and the effectiveness of R&D in developing countries leave room for improvement.

R&D, as commonly understood, has two components. The first involves trying processes on a small scale, or prototypes produced singly or in batch, with the objective of minimizing the costs and reducing the risks of large-scale development. The second is development to embody the results of research into a workable production system. Applied research is well understood and is common in developing countries; in fact, it may be argued that there is too much of it and too little of development. There is a suggestion of this in the breakdown of the 365 research projects in new and renewable sources of energy in Latin America enumerated by the Inter-American Development Bank and the Institute for the Integration of Latin America in 1981. Only 7% of them were directed toward "mass development," i.e., commercialization, and only 28% were large projects that may eventually have substantial energy substitution impacts. However, many were in areas where it was too early to commercialize the results of research.

Most, perhaps all, of the projects in Table 1 are not ones being executed by producers; one of the reasons for the imbalance between applied research and commercialization in developing countries is that public funds are more liberally available to research institutes that are not attached to producers, and many of which are state owned. Producers are given tax incentives for spending on R&D, but their R&D is seldom directly funded. The reasons given are various: for instance, that producers' R&D would contribute to their profits, therefore they should fund it; the results of the R&D would not become generally available; producers are under private ownership; etc.

The policies in developed market economies are different; in many, public funds are actively allocated to R&D in private firms. The reason is that the competitive advantage thereby gained by private firms is seen to be a national advantage in international competition. Further, governments can influence the direction of research if they fund it directly, but not if they release funds for it through tax incentives. The governments in France, Japan, and the USA have been particularly effective in influencing the course of technological development to some of their energy industries.

Thus, the use of public funds to fund the complete chain of R&D in producer firms is an instrument that developing countries could use more purposively to generate new technologies that are appropriate to their own circumstances. Such a strategy may not work where the producer firms are multinational ones: they may ignore national research needs, and concentrate R&D in their mother countries. The emergence of national producer firms is a prerequisite of a national R&D strategy.

Development is not just a matter of funding, however, but requires special managerial skills. It involves setting up large plants in the case of process indus-

Table 1. Distribution (%)[a] of 365 research projects on new and renewable sources of energy in Latin America, 1981.

	Argentina	Brazil	Colombia	Costa Rica	Mexico	Uruguay	Average
Type of research							
Basic research	22	14	27	23	25	45	26
Research and development	66	81	61	73	68	55	67
Mass development	12	5	12	4	7	0	7
Type of technology							
Simple, small, low-impact	55	21	58	35	46	41	41
Complex, intermediate, high-impact	32	44	4	27	27	4	31
Complex, large-scale, high-impact	12	35	38	38	27	55	28

Source: Inter-American Development Bank and Institute for the Integration of Latin America (1981).
[a] Totals may not add to 100 due to rounding.

tries, and mass production facilities in the case of product industries. The plants almost always require large external inputs, and the task of the development manager consists of coordinating the inputs so as to set up plants cheaply for high-quality production. This coordination requires the combination of technological and commercial expertise — expertise of the informed buyer. This is why it is impossible to separate development from the producer.

Thus, the emphasis needs to shift from R&D projects to building the capacity of producers in developing countries to carry out R&D or to develop, commercialize, and disseminate products based on the research of others (Munasinghe 1984b).

Technological Capacity

R&D is a statistical category created in the search for the sources of innovation. However, whether a producer innovates or not does not invariably depend on whether he has an R&D department, or how much he spends on it. What matters is whether he observes and reacts to his business environment in technological terms. The more rapid the rate of technological change, and the smaller the firm, the more important this monitoring function becomes. Changes in science, technology and the market bring about rapid changes in the external environment of a firm. A firm that does not monitor and anticipate the changes experiences them as a victim of unexpected shocks; but a firm that studies them can adapt its technology to changing circumstances and turn the threats into opportunities. An R&D facility is a resource, though not the only one, for working out and speeding up technological responses to external shocks (Freeman 1982).

The benefits of monitoring the environment and translating it into product and process changes are evident even if a firm is substantially dependent on outside sources for its technology. Thus, technologically sophisticated observation is within the capacity of many firms in developing countries, and deserves to be encouraged both directly and indirectly — for instance, through cooperative industrial monitoring centres, consultants, libraries, etc.

One of the aspects of this trained observation is learning from the market. Technological interaction between buyers and sellers is an important source of innovation in industrial countries; it is a strong feature of technological development in oil, coal, and power industries, for instance. Thus, it is useful to build the capacity to learn from experience, not only in the equipment-manufacturing industries, but also among the oil producers, coal-mining enterprises, and power plants of developing countries.

External Conditions

In the preceding two sections, we have emphasized R&D and technological capability as two aspects of technological adjustment to the economic environment. Of these, the development of technological capability is open to a much larger proportion of producers; both for them and for those who do R&D, external sources of ideas are very important in the process of innovation — more important than their own contribution in fact (Pavitt 1984). The link between innovation and the information that went into it is, however, not direct or predictable; instead, key information is often provided through unrelated research (Munasinghe 1984b). Thus, research outside the business sector can strongly contribute to innovation (as discussed in the next section), but frequent interaction between technologists in industry and those engaged in scientific research is essential. This interaction is much facilitated by previous student–teacher or collegial relationships between the two groups, and is much more frequent and effective if it is verbal. Both the availability of scientists outside firms for consultation and their direct participation have been found to contribute to innovation (Price and Bass 1969).

Major innovations are few and far between; more often, a line of technological improvement is perceived and exploited over long periods. This is how the efficiency of thermal power plants has been raised by progressively increasing steam temperature and pressure, the capacity of draglines has been raised in coal mines, or the efficiency of photovoltaic cells has been improved. In this type of incremental change, example and emulation are important, and emulation is more probable if a producer has technologically sophisticated competitors to observe. The considerable discussion on the effect of market structure and technological change is not conclusive (Kamien and Schwartz 1982). What matters, however, is not the precise market structure, but whether producers have to reckon with technologically sophisticated competitors.

Taking a look across developing countries, we can hardly say that one type of ownership is superior to another: there is a great variety of ownership patterns, and variations in performance seem to be as great within each ownership type as between them. However, ownership undoubtedly affects technological capacity through the autonomy of the management, its technological sophistication, its openness to information from outside, and the flexibility of organization that is required to make quick organizational changes within the firm.

Small Producers

The foregoing refers to large industrial producers who can afford substantial technologically trained labour and technological resources on their own. Far more numerous are small producers, for whom research is full of risk. The outcome of research is uncertain: some research projects may bring superprofits, whereas others may lead to losses. A small producer can undertake fewer research projects, and is more vulnerable to unexpected losses on research (Casimir 1983).

The norm in many sectors in developing countries is, however, a multiplicity of producers who are too small even to contemplate research. It would be wrong to assume that innovations come only from research, or from large producers. If research is done for small producers, however, it is important that they should use the results of research. In energy, for instance, at least three sets of research programs — those on charcoal, woodstoves, and woodlots — are aimed at small producers. We must ask ourselves what are the conditions of success in improving the technology for use by numerous small producers with low technological capability.

First, few innovations are confined to a single stage in the production process. Product innovations generally require process changes, and changes in one part of a process require consequent changes in other parts. In a large company that internalizes the entire chain of innovation, these structural adjustments are brought about by the interaction between different departments of the company, for instance, the R&D section, the engineering department, the procurement department, and other line departments. In fact, the ability of a large company to innovate depends crucially on the degree of coordination between those sections that generate ideas and those that embody them in production. Where the producers are small, these two functions are necessarily separated: ideas must come from outside research institutions, and must be implemented by the producers. This makes the coordination of the two more difficult, but no less necessary. It is essential that the researchers be in close touch with some producers, from the outset, and thus have feedback from potential users of research. The lack of intimate contact between the two often leads to the premature transfer of innovations, before they are ready for commercial development, and, hence, to failure.

Second, the internalization of the entire chain of innovation in a large enterprise ensures that it reaps the benefits of innovation as long as imitators do not cut into its market: there is a direct link between the investment in innovation and the benefits from it. Where the producers are small, this chain is broken; the costs of innovation are incurred by a research institution while the producers reap the benefits. The research institution may try to appropriate part of the returns from the innovation through royalties. However, the volume of the returns that can be appropriated depends on how long the producers to whom the innovation is transferred can retain its exclusive use. Innovations are generally copied so rapidly by small-scale producers that it is difficult to restrict their use to a few. Even if it is possible, rapid diffusion and equal access for all producers may be held to be in the public interest. The public interest, together with the difficulty of capturing the benefits of innovation, argues for a public subsidy to R&D for small-scale enterprises.

Third, the introduction of innovations is often risky. The risk-taking capacity of small producers is limited, and the cost of failure is greater for them because of their undercapitalization and the keen competition they face. Hence, the transfer of innovations to small producers must be accompanied by a mechanism for eliminating or reducing the attendant risks. Innovations for small producers have to be proved and debugged to a greater extent than for large ones and may, even then, need to be supported by risk-avoiding or risk-sharing mechanisms.

Finally, insofar as the introduction of an innovation requires capital or technical skills, the access to it will vary among small producers according to their command of these two factors. In general, the strong and technologically more capable producers are better able to take up innovations. Thus, the benefits of innovations tend to be distributed unequally, and increase the unequal distribution of resources among small producers.

Thus, research for small producers faces peculiar problems. Policymakers in a number of developing — and even some industrial — countries are aware of these problems, and have tried to solve them in various ways. A comparative review of their experiments would be of considerable practical value.

Equipment Manufacturers

The international conventional power plant market is extremely oligopolistic and not keenly competitive. Of the world power equipment exports, 70% come from 14 firms in five industrial countries — the Federal Republic of Germany, France, Japan, the U.K., and the USA. The firms build spheres of influence in developing countries through subsidiaries; there is even less competition within each market than internationally (Surrey and Chesshire 1984). In the circumstances, it is less necessary than in more competitive markets for an industrial country to push the exports of its national firms, which are more or less satisfied by the even-handed funding of projects by multilateral institutions. As Table 2 suggests, however, national bilateral aid is extensively used to finance purchases of power equipment from the donor country.

Table 2. Loans and export credits to developing countries for energy investments: A. 1975–81 (US $ million).

	Coal	Uranium	Oil and gas	Electricity	Other	Total
Multilateral institutions	**376**	**17**	**1748**	**14511**	**528**	**17180**
World Bank	92	–	1357	8491	451	10391
African Development Bank	–	–	–	234	–	234
Asian Development Bank	51	–	120	1779	–	1950
Inter-American Development Bank	233	–	262	3141	77	3713
European Investment Bank	–	17	9	866	–	892
Export credits	**493**	**45**	**9687**	**24548**	**591**	**35364**
Austria	–	–	28	490	–	518
Belgium	43	41	184	206	–	474
Canada	123	–	473	2995	–	3591
France	10	4	4653	3201	15	7883
Germany, Federal Republic	182	–	113	4415	–	4710
Italy	–	–	53	369	–	422
Japan	24	–	1052	1279	538	2893
Korea, Republic	–	–	–	6	–	6
Netherlands	–	–	3	601	4	608
Spain	–	–	328	140	–	468
Switzerland	–	–	20	720	–	740
U.K.	36	–	524	4806	–	5366
USA	75	–	2256	5320	34	7685
Total	**869**	**62**	**11435**	**39059**	**1119**	**52544**

Sources: African, Asian, and Inter-American development banks annual reports; Duersten (1983); and World Bank (1980a, 1983a).

Table 2. Loans and export credits to developing countries for energy investments: B. 1980–82[a] (US $ million).

	Energy development	Oil	Gas	Coal	Nuclear	Hydro-electricity	Electricity transmission and distribution	Fuelwood and charcoal	Alcohol	Geothermal	Technical cooperation[b]	Biogas	Solar energy	Unspecified	Total
Multilateral institutions	**197**	**1494**	**842**	**1135**	**50**	**2639**	**4157**	**122**	**276**	**85**	–	–	–	**771**	**11768**
World Bank	189	1244	324	504	–	1473	1898	–	250	76	–	–	–	506	6464
International Development Association	8	142	123	525	–	203	752	100	–	–	–	–	–	172	2025
African Development Bank	–	29	–	31	–	23	30	–	–	–	–	–	–	1	114
AfDB (African Development Fund)	–	–	–	–	–	2	29	12	–	–	–	–	–	10	53
Asian Development Bank	–	–	158	–	50	175	580	–	–	–	–	–	–	52	1015
AsDB (Special Fund)	–	5	66	–	–	8	207	10	–	–	–	–	–	29	325
Inter-American Development Bank	–	50	155	75	–	682	498	–	26	9	–	–	–	1	1496
IDB (Special Operations)	–	24	16	–	–	73	163	–	–	–	–	–	–	–	276
OPEC	–	**117**	**47**	**23**	–	**401**	**131**	–	–	–	–	–	**5**	**872**	**1596**
Bilateral concessional	–	75	47	1	–	332	83	–	–	–	–	–	–	616	1154
Multilateral concessional	–	42	–	12	–	56	48	–	–	–	–	–	5	219	382
Multilateral nonconcessional	–	–	–	10	–	13	–	–	–	–	–	–	–	37	60
Governments	**70**	**660**	**449**	**1775**	**61**	**1930**	**1231**	**26**	**11**	**172**	**(807)**	**8**	**2**	**1440**	**8642**
Australia	3	–	–	3	–	3	–	–	–	–	12	–	–	1	22
Austria	–	22	–	–	–	7	–	–	–	–	–	–	–	144	173
Belgium	–	–	–	–	–	–	–	–	–	–	–	–	–	13	13
Canada	6	57	–	–	–	76	106	–	–	–	(30)	2	–	64	341
Denmark	–	7	–	–	–	–	30	–	–	–	2	–	–	1	40
Finland	–	–	–	–	–	2	7	–	–	–	–	–	–	3	12
France[c]	13	63	11	40	35	179	56	3	–	–	(90)	6	1	196	693

(continued)

Table 2B concluded.

	Energy development	Oil	Gas	Coal	Nuclear	Hydro-electricity	Electricity transmission and distribution	Fuelwood and charcoal	Alcohol	Geothermal	Technical cooperation[b]	Biogas	Solar energy	Unspecified	Total
Germany, Federal Republic	–	65	3	170	–	310	234	–	–	–	111	–	–	217	1110
Italy	–	–	–	–	–	–	–	–	–	5	(18)	–	–	82	105
Japan[c]	–	203	371	1169	9	884	339	–	11	132	(244)	–	–	387	3749
Netherlands	–	6	5	1	–	6	48	11	–	–	(52)	–	–	19	148
New Zealand	4	–	–	–	–	–	–	–	–	4	6	–	–	4	18
Norway	–	3	1	–	–	13	2	–	–	–	(36)	–	–	5	60
Sweden	–	–	2	–	–	61	5	1	–	–	(6)	–	–	25	100
Switzerland	2	–	–	–	–	8	–	–	–	–	1	–	–	1	12
U.K.[c]	–	165	41	273	–	97	27	5	–	22	(118)	–	–	27	775
USA	42	11	–	5	–	94	77	6	–	–	(75)	–	–	206	516
European Economic Commission[d]	–	58	15	114	17	190	300	–	–	9	6	–	1	45	755
Export credits[e]	–	**5553**	**1325**	**411**	**2123**	**1686**	**850**	–	**42**	**63**	–	–	–	**6384**	**18437**
Total	**267**	**7824**	**2663**	**3344**	**2234**	**6656**	**6369**	**148**	**329**	**320**	**(807)**	**8**	**7**	**9467**	**40443**

Sources: Compiled from tables 5, 6, and 7 in Organisation for Economic Cooperation and Development (1984).

[a] New and renewable sources of energy also include, in addition to those separately listed — hydropower, fuelwood, alcohol, and geothermal — biogas, solar, wind, ocean, peat, oil shale and tar sands, and draught animal power. However, only small amounts were reported for the latter categories under the Creditor Reporting System (CRS) on which this table is based. They are included under "unspecified."

[b] Data on technical cooperation are only partially reported under CRS and have been estimated from Organisation for Economic Cooperation and Development (1984), but cannot be allocated to subsectors. The costs of technical cooperation are included in the project costs in the case of multilateral institutions.

[c] Includes also nonconcessional development lending: France — US $170 million; Japan — US $1514 million; U.K. — US $150 million.

[d] Includes European Investment Bank (US $413 million).

[e] Includes only officially guaranteed credits with maturity over 5 years.

Market concentration is even greater with nuclear power plants. Of the 194 reactors built in market economies up to 1984, 132 were supplied by four firms — two from the USA, one from France, and one from Canada, all countries with large indigenous nuclear power programs (Desai 1984). The East European market is served by the Soviet Union, which itself has a large nuclear capacity (Chung 1985). The influence of host-country governments on the export of equipment and technology is much greater in the case of nuclear plants than of conventional electrical plants, because of the implications for nuclear proliferation. The resulting difficulty of obtaining technology has led a number of developing countries, including Argentina and India, to develop their own capabilities in nuclear power plant construction.

The oil and gas equipment markets are more competitive, but in most types of oil equipment, U.S. firms predominate. In recent years, however, oil development in the North Sea, Southeast Asia, and China has led to the emergence of oil equipment manufacturers in France, Japan, and the U.K., and these are often supported by official and unofficial loans from their countries in their penetration of the world market.

In coal mining, local conditions vary a great deal, and local adaptation of machinery and user-learning are important. The machinery produced in each country is related to the local conditions, and markets for equipment are largely national. However, Japan, whose own coal output is small, has developed a strong mining equipment industry based on exports. The Federal Republic of Germany, Japan, and the U.K. are the principal exporters, and exporters in each country are supported by their national governments and banks.

Thus, the manufacturers of energy equipment derive their competitive strength from the mastery of technology of one sort or another. They depend to a varying degree on exports, and exports to developing countries generally form a small proportion of their total exports. The markets are often divided into spheres of influence. Where they are competitive, exporters are helped by official and unofficial loans from within their countries.

Under these conditions, some of the larger developing countries can build domestic production of equipment by closing off imports, but given the small domestic markets, their domestic firms remain technologically dependent. Their entry into the international market is constrained both by their technological dependence and by the connections between equipment makers and their national funding agencies. Equipment makers in these developing countries that have a large domestic output of energy may be able to change this and eventually enter international markets, but to do so they would need to develop their own technological capacity, and their countries would need to give substantial international credits. In view of the scales involved and the important role of governments, cooperation among neighbouring developing countries may be of particular benefit in this area.

Research Institutions

We said earlier that the technological capacity of producers lay in making technological responses to their socioeconomic environment. Research and training institutions are the repositories of accumulated knowledge and of the skills necessary for advances in it. The problems for them to tackle must arise from the conditions in their countries and societies, and the solutions they look for must arise from their accumulated knowledge and experience. They must be in touch with government and industry for utilization of their research. They should serve a number of functions.

Accumulation of experience The quality of research closely depends on researchers' accumulated experience. The experience accumulates from sustained application to meticulous research, which requires good facilities. Governments and producers have a relatively use-oriented and short-term approach to knowledge, and are poorly suited for accumulation of experience. Research institutions serve as reservoirs of expertise on which other users can draw. A minimum concentration of expertise is required if it is to serve as a critical mass.

Diffusion of intellectual skills The amount of work a researcher can do in a lifetime is limited. For advances in knowledge, it is essential that researchers work together, that they improve their skills and pass them on to succeeding generations of researchers, and that they educate those who are not engaged in research. Research and training institutions should provide the mechanism for the transfer of intellectual skills.

Efficient use of intellectual assets The knowledge residing in research institutions is public and widely accessible; their location should be designed for the broadest and fullest utilization of their assets — libraries, classrooms, instrumentation, etc.

Juxtaposition of diverse disciplines Radical insights often come from the coupling of ideas from unrelated disciplines. Many practical problems require bringing together diverse fields of knowledge. Broad-based research institutions should serve as the places where unrelated disciplines come together.

Research Funding

What distinguishes — or should distinguish — research institutions from research facilities in business and government is the greater breadth and depth of knowledge they bring to bear on the problem, and the breadth and depth must be based on superior research facilities — libraries, laboratories, computation facilities, etc. These are precisely the assets against which result-oriented project funding discriminates. Funding agencies, national and international, endeavour to buy research at its marginal cost, which consists mainly of personnel costs. The result is levels of personnel that are not supported by the infrastructure, and the quality of research suffers. Project funding also orients researchers toward a series of unrelated, short-term research projects, and prevents them from developing depth.

The utilitarian approach leads to institutions that are too narrowly specialized. Priority areas of research keep changing, whereas institutions have a natural urge to perpetuate themselves. If funds are given for new subject areas to old institutions with unfashionable specialization, the funds may be in danger of being diverted to the old areas. Hence, the tendency is to start new institutions for new subject areas. Disciplines, however, do not follow social priorities, but are always being redefined for efficiency in research. Growing subjects keep dividing and redividing so that each remains researchable by a small number of researchers who can communicate with, check on, and learn from one another (Menard 1971). Thus, proliferation of institutions locked into specializations that are defined in utilitarian terms leads to poor research and low productivity.

The need to make a long-term investment in knowledge and to make research respond to the changing needs of society are twin objectives that are difficult to combine. Many solutions have been tried out across the world, and none is ideal. Lip-service has often been paid to program funding. However, funding agencies in democratic countries have to answer questions from their governments and their fellow-citizens about the utility of their activities, and need to be able to judge and demonstrate results within reasonable time periods. They prefer project funding because they can monitor and control short-term projects more easily than programs. If they are to be persuaded to fund programs, program funding also needs to be combined with a method of evaluation.

The foregoing considerations point, in our view, toward a funding system with the following elements.

Growth by accretion Large, multidisciplinary institutions have the advantages of shared facilities, greater possibilities of interaction among researchers and, consequently, of greater breadth in research. At the same time, institutions must change in response to changing directions of demand. The solution to this problem is not to proliferate small, new research institutions, but to let old ones grow by accretion of programs designed to meet new demands.

Program funds as an investment The institutions should be given long-term funds to cover all requirements, material and human, of new areas required. New programs should be set up only if adequate backup, in terms of material facilities, is available for quality research.

Projects for return on the investment Projects should not be regarded as a method of funding research, but as a way of putting investment, in the form of program funds, to use. When new programs are considered, the volume of projects they may attract should be assessed. Choice among and allocation between programs should be based on the volume of projects they may be expected to generate.

Decentralized direction of programs If programs are to succeed, autonomy and continuity of their direction are paramount. Research institutions should be run as cooperatives of programs. At the same time, active management of programs is essential to drive them forward toward efficient implementation of projects.

Centralized planning and resource allocation The short-term allocation of researchers and other mobile resources would follow the project requirements. If researchers are to be utilized fully, however, and if their careers are to mould them into skilled and experienced resource persons, successive programs must be selected so that experience is acquired in useful directions. Further, research takes time, whereas its users want results quickly. This gap between what is needed and what is possible can be partially bridged by anticipation: research programs can be launched in advance of projected demand for them. The forward vision and management of resources that this building of experience and knowledge requires are the tasks of institutional management.

Directing Research

In our view, the unit of research management should be a program, which should be funded for a fairly long period — 5–10 years — and then continued or expanded on the basis of the projects it attracts, or disbanded. It should be the instrument of converting the investment made in it into project output. If it is to serve this function, a program must have considerable autonomy in the way it spends its budget, recruits its personnel, seeks projects, and carries them out. Hence, we envisage that most administrative functions and power should be in the hands of program directors; they should have both autonomy and control.

The position of program directors would be one of great responsibility. They would be responsible, on the one hand, for dividing up assignments into research tasks that can be tackled by individual researchers or teams and, on the other, for coordinating their output and putting it in a form that can be useful to the client. Hence, program directors will need both technical and managerial expertise, and would everywhere be a rare breed that must be nurtured carefully.

If program direction functions well, the overall direction of research institutions will be relieved of most day-to-day management. Their task will essentially consist of managing common resources — including funds for allocation between programs, which may come from either external program grants or internal earnings from projects — and forward planning.

Research and Training

Research and training differ from each other in a number of significant ways:

- The object of research is to produce high-quality inputs for users; the object of training is to improve the intellectual capability of students. Research has a training effect and training can have a research component. If research is used for training, there is a danger that the results would be poor and wasteful; if, on the other hand, students are used in research, they may be given work with a negligible training element.
- The time spans involved are different. To ensure and monitor the students' progress, training is generally broken into short, uniform periods. The time span of research is more flexible and generally longer.
- Although this is not an absolute difference, the focus in teaching is on the individual student and the individual teacher; in research, it is generally essential to form teams and coordinate the work of individuals. To be useful in teaching, problems have to be small enough to be tackled by a single student in a fairly short period. No such restrictions can be placed on actual research assignments; in research, it is the size of the team that has to be tailored to the problem.

In these ways, research and teaching can both suffer if they are too closely integrated. However, separation is also undesirable; both are complementary. They require similar material facilities. Research can lead to the restructuring of teaching in more relevant directions; conversely, teaching can lead a researcher to question and test her or his ideas. Hence, it is desirable that research and teaching should be done in sister institutions that share facilities and interchange personnel.

Research Communication and Informatics

Research is intended to add to knowledge, but it can also rediscover knowledge. Whether it adds new knowledge depends on how well informed researchers are on the current state of knowledge. While one of the purposes of education and training has been to give all researchers a minimum initial stock of knowledge, the degree of knowledge varies considerably between researchers in the same field; access to comprehensive libraries and to experienced colleagues is highly unequal between research institutions, and those in developing countries suffer in this respect. The poor state of communications in developing countries contributes to the inequality of access.

Recent technological advances in informatics have, however, created the possibility of reducing this inequality (Munasinghe et al. 1985). Computer-based techniques of information storage and retrieval are being applied to libraries. The currently available systems are either small and limited in capacity or large, custom-made, and expensive. One reason why cheaper and more standardized systems have not emerged is that major libraries in industrial countries are old and large, the costs of converting their cataloguing systems are high, and their manual cataloguing systems impose special requirements on their computerized successors. These constraints are less applicable to the newer and smaller libraries that are common in developing countries. It is in their interest to promote the development of, and to adopt, computer-based cataloguing systems of greater versatility and use to researchers.

The same informatics and computer-based technologies are also making the transfer of information easier and cheaper. The use of satellites has brought down the capital costs of communication networks considerably, and the information that can be transmitted can be aural, visual, or coded (e.g., written). The extension of these cheap and convenient communications to developing countries must await the renovation of their existing telecommunication networks and the installation of terminal facilities. However, the enormous potential benefits of better applications of computers and communications to energy research, in the form of improvement in its quality and the prevention of duplication, are obvious.

Prevention of duplication is of even greater interest to research users and to funding agencies than to researchers, for better acquaintance with the state of knowledge can save wasteful expenditure on repetitive research. Hence, research users and funding agencies should look upon expenditure on libraries, communications, and research networks as ways of increasing the effectiveness of their total expenditure on research.

International Funding Agencies

Paradoxically, the international funding agencies form the only group on whose activities we have comprehensive statistical information; it throws an interesting light on their activities.

Investment

Agencies fund two types of activities: investment and research. The total concessional and nonconcessional loans for energy investment from developed market economies to developing countries in 1975–1981 amounted to US $92 billion, of which multilateral loans were US $17 billion, bilateral concessional loans were about US $10 billion, commercial bank loans were about US $30 billion, and the remaining US $35 billion consisted of nonconcessional suppliers' credits (estimated from World Bank 1983a). Except for equipment being manufactured in a few of the larger developing countries, principally Brazil, China, India, Mexico and the Republic of Korea, virtually all large-scale energy-producing and transforming equipment was imported by developing countries, and almost all that was imported was financed to a substantial extent by loans and export credits. Thus, loans of one kind or another financed a high proportion for energy investment in many developing countries.

More detailed estimates are available from two sources and are summarized in Table 2; both are deficient. For 1975–81, we do not have a breakdown of bilateral official loans. For 1980–82, the figures of export credits include only officially guaranteed credits with a term over 5 years: officially guaranteed credits under 5 years, estimated to be about half as much as those over 5 years, and credits without an official guarantee, for which no figure is available, are excluded.

The striking feature of these figures is that almost all multilateral loans go to energy production (as against energy saving); and a high proportion of them goes to electricity. Their share in loans is also higher for electricity than for other industries. The power industry has certain characteristics that make it attractive to funding agencies. Its plants are neatly packaged, and their capital costs are easy to predict. Its technology is standardized, and it is more difficult (though not impossible) to mismanage. In most developing countries, demand for power has been growing rapidly, so a power plant is less likely to suffer from lack of demand. Finally, power plants are simply connected to grids; power needs no special marketing effort as long as demand for it is growing. However, these features would make loans to the power industry attractive to all funding agencies, and not simply the multilateral institutions. Developing countries prefer to borrow from multilateral institutions because of the somewhat lower interest and appreciably longer terms they offer, and as preferred lenders the institutions take the pick of power loans.

On the other hand, because of their favourable lending terms, the multilateral institutions are not popular with competing funding agencies, whether they are national official agencies or private banks; and the political pressure of these competitors keeps the multilateral institutions out of the markets in which their competitors are specially interested.

International lending for nonconventional energy investments is extremely small, and is confined mainly to charcoal, alcohol, and geothermal, all of which are relatively large-scale industries. Much of the funding comes from multilateral institutions.

Research

The information on research funding is not nearly as detailed as on investment finance. The only data that give us comparative information of the kind we need relate to a set of projects in the member countries of the Asian Development Bank (Table 3). We have divided the agencies into five types: the international banks, the United Nations family, the submultilateral institutions, the national agencies of the large industrial countries that manufacture electrical plants, and the smaller national agencies that are in the business of funding research per se.

The only area of research that is popular with all agencies is macroeconomic studies. The emphasis on macro studies has a rationale: they are essential for putting micro proposals for investment and research into perspective. It stands to reason that a funding agency would want to get a picture of the macroeconomy and the macroenergetic flows before it decides what to fund at the micro level. However, the macro focus also reflects the symbiotic relationship between the funding

Table 3. An analysis of externally financed energy research projects in Asia[a] (numbers of projects).

				National agencies		
	Banks	UN family	Sub-multilaterals[b]	Large countries[c]	Small countries	Total
Energy	**23**	**38**	**4**	**11**	**11**	**87**
Data, assessment, and planning	14	13	1	3	6	37
Demand and prices	1	2	0	0	0	3
Rural energy	0	2	0	1	1	4
Resources, equipment, and technology	1	2	0	3	2	8
Conservation	2	3	2	1	0	8
Personnel and training	5	14	1	2	1	23
Socioeconomic studies	0	2	0	1	1	4
Industry	**0**	**3**	**0**	**1**	**0**	**4**
Transport	**2**	**7**	**0**	**0**	**0**	**9**
Oil	**11**	**2**	**1**	**0**	**0**	**14**
Exploration	4	0	1	0	0	5
Refining	2	0	0	0	0	2
General	5	2	0	0	0	7
Electricity	**37**	**16**	**3**	**38**	**10**	**104**
Generation	4	2	1	1	3	11
Small hydropower	3	3	2	4	1	13
Distribution	4	0	0	1	0	5
Rural electrification	3	2	0	4	1	10
Nuclear power	0	1	0	0	0	1
Other (including training)	23	8	0	28	5	64
Natural gas	**7**	**1**	**0**	**4**	**4**	**16**
Coal, lignite, peat	**5**	**9**	**0**	**4**	**6**	**24**
Renewable energy	**1**	**5**	**1**	**8**	**3**	**18**
Biomass energy	**2**	**4**	**1**	**3**	**1**	**11**
Woody fuels	**4**	**14**	**3**	**5**	**6**	**32**
Wood	4	13	0	5	6	28
Charcoal	0	1	1	0	0	2
Woodstoves	0	0	2	0	0	2
Biogas	**0**	**1**	**3**	**0**	**1**	**5**
Producer gas	**0**	**0**	**1**	**0**	**1**	**2**
Ethanol	**0**	**1**	**0**	**2**	**0**	**3**
Vegetable oil	**0**	**0**	**2**	**0**	**0**	**2**
Solar	**1**	**3**	**7**	**2**	**1**	**14**
Photovoltaic	0	0	3	1	0	4
Other	1	3	4	1	1	10
Wind	**0**	**2**	**0**	**0**	**6**	**8**
Geothermal	**3**	**1**	**0**	**3**	**4**	**11**
OTEC[d]	**0**	**0**	**0**	**0**	**1**	**1**
Storage	**0**	**1**	**0**	**0**	**0**	**1**
Total	**96**	**108**	**26**	**81**	**55**	**366**

Source: Compiled from Asian Development Bank (1984).

[a] Excluding China, Mongolia, and The People's Democratic Republic of Korea.

[b] The submultilaterals include Commonwealth Fund for Technical Cooperation; Commonwealth Heads of Government Regional Meeting; European Community; Organization of Petroleum Exporting Countries; and South Pacific Commission.

[c] Large countries are defined as those with an electrical plant manufacturing base (i.e., Canada, Japan, U.K., and USA).

[d] OTEC = ocean thermal energy conversion.

agencies and the governments. The funding agencies, by and large, prefer to work closely with the governments and to use the governments' power to get things done. The governments look to international agencies for money, jobs, and travel abroad for their personnel. The research that can be done within governments or state-related institutions naturally relates to policy. Thus, the interests of governments and funding agencies coincide in policy-related research.

Within the United Nations Organization, there are specialized agencies and regional economic commissions. The specialized agencies tend to concentrate on subjects within their own specialization: the International Labour Organisation on manpower and training, the Food and Agriculture Organization on agriculture, forestry and firewood, and so on. The scarcity of funds for the United Nations system in the 1970s and 1980s led to considerable competition among agencies for outside funds, which, among other things, took the form of entering areas that were popular with funding agencies. Energy was one of these areas in the 1970s.

Because national governments are organized into specialist ministries, like the United Nations, their funding of energy investment and research also tends to depend on the influence and bargaining power of ministers and ministries. The only difference is that the energy economy impinges on the government in the form of demands from producing and consuming sectors. The distance between the latter and the United Nations, however, is much greater.

Leaving the United Nations agencies aside, the research funding agencies divide themselves into two groups: those belonging to countries that produce power plants, and others. The difference in their research funding patterns is remarkable. A high proportion of the former's projects is related to areas where they would expect to fund investments. Electricity is by far the most important, but oil, gas, and coal also figure. Among the renewables, those in which large-scale technologies have been or can be developed are favoured: for instance, geothermal or alcohol.

The focus of the independent research funding agencies, on the other hand, is resolutely toward small-scale, stand-alone technologies: biomass, wood, biogas, and solar. These are also technologies that have few established producers in developing countries into which to feed. Hence, the research is liable to remain unapplied and ineffective.

The question then needs to be asked: why do the independent funding agencies not move into the field of big energy? The answer is twofold. First, in big energy, there is an unbroken chain from the equipment manufacturers in industrial countries to the producers in developing countries. Governments of developing countries enter this chain as owners of the firms that buy equipment or as guarantors of their debts, while the investment funding agencies enter it as lenders. They fund primarily the research needed to make their funding decisions. Because that research is site-specific, it is shown as research in developing countries. It is project-specific rather than generic, however, and often it is done by consultants from abroad. Independent research funding agencies have no function in the chain of investments. Second, they are also much smaller than investment funding agencies. The funds of most of them would cover the cost of but few feasibility studies, pre-investment surveys, or detailed project reports.

In this way, the field of energy research gets divided between the large and the small research funding agencies. Large-scale, site-specific research required for investment projects is funded by large investment funding agencies, while small-scale research, generally unrelated to production or commercialization, is funded by small funding agencies. They are not responsible for the lack of connection between policy, production, and use on the one hand and research on the other that is characteristic of developing countries: that disconnection arises from the dominance of multinational corporations in the production of capital-intensive energy equipment, the weakness of domestic firms in developing countries, and the passive energy policies of developing-country governments. However, international funding agencies also reinforce this disarticulation, and do little to remedy the weaknesses of research institutions in developing countries.

Chapter 4 Demand Analysis and Management

The demand for energy grows in the process of development, both because it involves an expansion of production and consumption, and because the structure tends to become more energy-intensive. Hence, it is important to study the factors that determine demand.

Energy statistics in most developing countries are sparse and poorly organized, and permit only aggregated and imprecise analysis. Research within the limits set by data must be pursued in the short run, but efforts should also be made to improve the data base for estimating more detailed and reliable relationships. Energy balances are one form in which detailed energy statistics can be organized, but they do not yield any analytical results by themselves.

The income elasticity of energy consumption summarizes a relationship but is silent on the factors that decide or change it. The same is true of translog functions, which seek to measure the substitutability between energy and other inputs. Input–output models portray the relationship between production and consumption on the one hand and energy use on the other in great detail, and permit the study of a great many hypothetical situations. They exclude other influences, however, and by measuring flows in terms of value, mix up changes in quantity and price. Engineering or technoeconomic models seek to disentangle the two by working in terms of physical quantities. However, the behaviour of producers and consumers cannot be accurately portrayed in physical terms. It depends on money value, and is essentially volatile. Thus, there is no perfect way of studying aggregate energy demand.

The volatility and complexity of human behaviour that destabilize aggregate demand relationships similarly affect more disaggregated relationships. In the latter, it is easier to deal with a number of influences together but not always easy to unravel their individual effect. The scope for two types of microlevel demand studies is particularly great, i.e., those that place energy demand in the context of overall household consumption decisions and those that look at fuelwood collection as a part of work allocation within rural families.

Energy demand models can be used to study and manipulate total energy intensity by means of policy measures, of which taxes and subsidies are the principal ones. The design of taxes and subsidies that combines social justice with precision of impact calls for ingenuity and is a challenge for research. Taxes and subsidies on individual fuels often have strong unintended substitution effects; more neutral and better targeted measures need to be devised by researchers.

Average cost pricing, based on historical costs, is common in large-scale energy industries. It distorts profit levels, investment patterns, and competition among energy sources. Research is needed into improved price regulation, and into the use of market structures to regulate prices and to stimulate technological change.

An agricultural surplus is essential to sustain population outside agriculture. Labour productivity in agriculture is too low to generate a significant surplus in *many countries in Africa and a few in Asia. Raising it must have a high priority in their development; it would require the replacement of, and assistance to, human labour by inanimate energy inputs. Studies of the relationship between agricultural output and total energy inputs are not fruitful, and disaggregation and conceptual innovation are necessary. Study needs to be extended to peripheral agricultural systems like arid coarse-grain cultivation and perennial tuber cultivation. Studies of mechanization could benefit by distinguishing between peak and off-peak operations. Research to improve the efficiency of mechanical and nonmechanical techniques hold particular interest: for instance, studies to extend minimum-tillage agriculture to developing countries. Energy efficiency can also be raised by using energy-intensive agricultural inputs more efficiently: for instance, fertilizers, water, and pesticides. One way of increasing their efficiency in use is to breed plants for that purpose.*

Much research has gone into energy conservation in industry in developing countries; energy-intensive industries have also been identified. By similarly targeting big energy users among their industries and adapting the available knowledge, developing countries can increase their industrial energy efficiency.

Transport forms the link between energy policy, trade policy, and environment policy. Research must create a basis for the coordination of the three. Location patterns determine transport requirements, and there is not much flexibility in their relationship. Besides, it is difficult to increase the transport capacity of roads and railways in already developed areas. Hence, it is better to plan location of activities and people decades ahead to reduce eventual transport requirements. The best location patterns depend on two opposite considerations: keeping cities small can reduce suburban traffic, but concentrating economic activities in a few places can make infrastructural investment in transport more economical. Short-term traffic management presents researchable problems in the rationing of limited traffic capacity and in the coordinated use of pricing and taxation of fuels, vehicles, and roads. Research is similarly promising into variations in transport intensity, economics of vehicle size, and railroad competition. Being capital-intensive, railways offer a good subject for research toward improving their utilization, especially research into traffic scheduling and communication, rate structure, and quality of service.

Energy-consuming households can be classified into collectors, producers, and buyers of energy; their behaviour patterns differ, as do the methods of studying them. Demand theory developed in industrial countries can fit buyers, but concepts for the study of collectors and subsistence producers need to be developed. Allocation of human labour to alternative uses is central to the behaviour of collectors and producers. System boundaries in their studies need to be broad enough to cover their dealings with neighbouring towns, and to throw light on variations across regions and classes. Research on fuelwood collection needs to be linked with more direct observations of the environment, and research on its use with its product: for instance, with the quality and composition of food cooked with it.

The growth in the output of goods and services, which is an essential part of development, will normally require increases in energy consumption to sustain it. In addition, there are a number of structural changes embodied in development that tend to raise the energy intensity of national income.

- As people become prosperous, the energy they use for lighting and for appliances increases. Some appliances (e.g., electric fans, radios) begin to be acquired at fairly low income levels, others at higher income levels. Thus, even if household energy consumption for cooking does not rise, consumption for other purposes continues to rise with income; and this new demand is mainly for electricity. Electricity is also the major source of motive power in industry. Because 60–70% of the energy of fuels is wasted in transformation into electricity, the shift in final energy mix toward thermal electricity implies a faster growth in the demand for primary fuels.

- Many developing countries face the need to intensify agriculture to produce food for growing populations and to deal with constraints on the availability of arable land. All the major means of agricultural intensification — water, fertilizers, pesticides, machines — consume energy.
- A sustained rise in general living standards requires a rise in the productivity of workers, and many of the known ways of increasing productivity involve the use of greater energy per worker.
- As developing countries raise their incomes, their demand structures and production patterns shift toward industry, and the growth of industry requires a rise in energy consumption.
- A rise in the standard of living entails greater consumption of goods and, hence, more transport. In addition, urbanization and industrialization place an increasing distance between the producer and the consumer — and the worker and the place of work. Thus, transport requirements rise more than in proportion to production.

Energy is, therefore, a vital input that can constrain development — and its constraining effect can be reduced by means of structural changes that reduce the energy intensity of total output, interfuel substitution to replace scarcer with more abundant forms of energy, and energy conservation to increase the overall energy efficiency. Of these, we shall deal with energy conservation in the next chapter; here, we deal with the analysis of energy demand, first at the aggregate level and next at the level of user sectors — agriculture, industry, transport, and households.

Aggregate Demand

In the analysis of energy demand, researchers have to choose between methods with low requirements of data and computation, which give quick but limited results, and more powerful methods capable of giving more detailed and consistent results which, however, require investment in data collection and computation and which are sensitive to the quality of the data and the computational models. Among the former are studies of the energy–gross domestic product (GDP) relationship and microeconomic demand studies. Among the latter are macroeconomic models with an input–output base and technoeconomic models directed toward end-use analysis. The choice is not entirely between the quick-and-dirty and the slow-and-clean. Microeconomic studies can exploit available data more fully, or use data from special surveys tailored to the problem, whereas large macroeconomic models often have to use data of varying quality and reliability thrown together for the sake of completeness. Microeconomic studies can also accommodate a greater variety of functional forms and, therefore, allow a closer approximation to underlying relationships, whereas large, multiequation models have, until now, been largely confined to linear functional forms and simple relationships. Both types of studies are likely to be affected by the recent increases in the computing power and miniaturization of computers. The effect may be even greater in developing countries in view of the emergence of low-cost microcomputers. Hence, both macro and micro demand studies hold a promise of advances in the coming years.

The choice of methods is limited by the availability of data in the short run; in the longer run, however, an effort should be made to remove this constraint by gathering more detailed information for use in more sophisticated models. One possible format for collecting detailed information on energy flows is furnished by energy balances.

Energy Balances

National energy data, if they are disaggregated, can be tabulated in the form of an energy balance. An energy balance disaggregates energy by its components. For each component, it equates consumption with the sum of production, international trade, and changes in stocks. It disaggregates consumption by various uses, distinguishing between energy used for transformation and energy put to final use.

Energy balances have been published for OECD countries by the Organisation for Economic Cooperation and Development (OECD) from the 1950s onward. In the 1970s, the International Energy Agency (IEA), an affiliate of OECD, stimulated interest in energy balances among developing countries. The energy balances it commissioned were presented and discussed at a workshop in 1978 and have recently been updated to 1982 (International Energy Agency 1979a, b, 1984).

The Organización Latinoamericana de Energía (OLADE), founded in 1973, has similarly stimulated interest in energy balances for Latin American countries. As a result of its efforts, energy balances have been compiled for all member countries of OLADE, except Barbados, Cuba, and Paraguay; for a number of them, energy balances are available annually from 1970. The quality of the statistics also has improved over time. The degree of detail available, however, varies from country to country (see, e.g., El Salvador 1980; Organización Latinoamericana de Energía 1981; Chile 1982; Instituto de Economía Energética 1982, 1983). A network of energy researchers working under the aegis of the European Community developed a schema for an integral energy balance sheet, i.e., a set of interrelated energy balances covering the entire energy system from resources to useful energy consumption (Commission of European Communities 1984). The energy balances worked out under the leadership of OLADE are also being extended by incorporating estimates of useful energy.

An energy balance is essentially a tabular representation of energy production and consumption statistics. In its preparation, questions regarding detail and consistency have to be answered that provide a useful starting point for national energy studies. An energy balance itself does not contain any information on the determinants of final energy consumption, and is, therefore, not sufficient for projection, planning, or modeling exercises. A time series of energy balances, however, would give time series of consumption by sectors, which can be used to study the behaviour and the determinants of sectoral consumption. These sectoral studies can provide submodels that, together, can be used to project or plan national energy production, transformation, and consumption (see, e.g., Moscoso and Barbalho 1983). The techniques applied to each sector can be adapted to the availability of data and the causative mechanisms involved; for instance, it is possible to use very different models for agriculture, industry, transport, and households. Thus, energy balances, if constructed with a consistent methodology over a number of years, provide a flexible framework for national energy studies. However, if independent sectoral models are developed, the estimates they provide are unlikely to be mutually consistent, and a further mechanism for assuring their mutual consistency would have to be introduced.

The Energy–GDP Relationship

At the most aggregated level, energy consumption may be taken to depend on the GDP, which measures the value of output of final goods and services in an economy. A great many studies of the energy–GDP relationship have been carried out, both across countries and over time. The results vary a great deal, and yield elasticities in a wide range above and below unity. The elasticities in the 1970s are generally lower than in previous years (Siddayao 1985; Leach et al. 1986). They typically show, however, that the income elasticity of energy consumption is higher for low-income than for high-income countries. This result is the basis of projections that predict a rise in developing countries' share of global energy consumption (Martin and Pinto 1979). Before this or any other conclusion can be drawn from GDP elasticities of energy consumption, it is necessary to ask what these elasticities mean, and how they are determined.

In a process that undergoes no technical change or substitution among inputs, energy consumption would be proportional to output, and its output elasticity would be exactly equal to one. Hence, if the elasticity is found to differ from unity, it must be due to four possible causes.

- Technological improvements may lead to a fall in energy intensity of output; this is mainly why energy elasticities for industrial countries are found to be below unity. The substitution of more energy-intensive technologies would tend to counteract this tendency.
- Changes in the structure of GDP may lead to a shift toward more or less energy-intensive sectors. For instance, the relatively rapid growth of industry and transport in developing countries is one factor behind their high GDP elasticities of energy consumption.
- Changes in the composition of energy consumption may change the average efficiency of energy use. In developing countries, commercial energy typically replaces noncommercial energy, which is often excluded from statistics; there is, thus, a purely statistical rise in energy consumption, and in the estimated GDP elasticity of energy consumption over time. For instance, the inclusion of fuelwood in energy consumption leads to a significant fall in cross-country GDP elasticities (Strout 1983). Even if it is included, its replacement by kerosene, gas, or electricity would generally raise energy efficiency and reduce output elasticity.
- Changes in lifestyle may lead to a change in the (direct or indirect) energy intensity of consumption. Although this effect would be reflected in the elasticity, it emanates from consumption rather than production.

Because the effects of these four phenomena are mixed up in energy–GDP relationships, it is difficult to say what the elasticities mean. Especially where major structural breaks are involved, e.g., during the oil crises, summary energy–GDP elasticities have proved unstable and unreliable for any predictive purposes.

Substitution Among Inputs

The use of energy–GDP elasticities assumes a stable relationship between the GDP and total energy consumption. There are, however, possibilities of substitution between various forms of energy, and between energy and other inputs. Substitution among inputs can be explicitly taken into account in production functions. There are a number of production functions in use; the one that has been applied most intensively to energy is the translog production function developed by Christensen et al. (1973). It has been applied to a number of industrial countries, and has generated a large range of estimates of price elasticities and elasticities of substitution (Hudson and Jorgenson 1974; Berndt and Wood 1975, 1979; Griffin and Gregory 1976; Ozatalay et al. 1979; Pindyck 1979, 1980). The major difference among their results is that some of them conclude that energy and capital (i.e., plant and equipment) are substitutes, while others find them to be complements. Thus, they make different predictions regarding the effect of a rise in energy prices: the first set predicts greater investment in capital goods; the second, less. Recently, Gibbons (1984) has sought an explanation of the difference in results in quality variations among capital goods.

Translog models have found very limited applications in developing countries (cf., however, Uri 1981; Apte 1983). There is no difficulty in applying them at the industry level, where developing countries have relatively abundant data. In view of the difficulty of interpreting the elasticities of substitution yielded by them, however, there can be doubts about their operational usefulness.

Input–Output Analysis

An input–output table portrays the flows of inputs and outputs across the entire economy, just as an energy balance portrays the flows of energy in the economy. An energy balance may be regarded as consisting of the columns of an input–output table relating to energy sources with two differences: the units used in an energy balance are either physical units or units of energy, whereas an input–output table is in value terms; and an energy balance gives figures for energy sectors in a more disaggregated form than an input–output table.

An input–output table, since it shows the sales of one sector or industry to another, is also called the transactions matrix. If the inputs into each industry are divided by its output, a matrix of input–output coefficients is obtained, which is also called the technology matrix. This technology matrix is a highly versatile tool.

- It can be used to calculate both direct and indirect effects of a change in output.
- It shows the link between the outputs of final goods (i.e., goods that are consumed or invested) and intermediate goods (i.e., goods that are used to produce other goods). It can be used to work out the implications for all other industries of a change in the output of a single industry.
- A change in technology can be represented as a change in input–output coefficients, and its implications for the entire economy can be worked out by modifying the technology matrix. Thus, it can be used to estimate the impact of energy-saving technologies or of interfuel substitution on the economy.
- It ensures mutual consistency between the outputs of various industries.
- Finally, as a part of linear programing models, it can be used for economywide

optimization and for analyzing the effects of constraints, for example, the need to balance trade or to ration limited supplies.

As a result of these advantages, input–output analysis forms the basis of models used in developed market economies for macroeconomic forecasting. Material balances, which may be regarded as a variant of input–output tables, have also formed the basis of planning in the Soviet Union and other centrally planned economies.

The application of input–output analysis to energy problems was pioneered by the Energy Research Group at the University of Illinois (Bullard and Herendeen 1975); a small body of specialized work has grown from their methodology (Bullard et al. 1978; Casler and Wilbur 1984). A major application of energy input–output analysis has been in the calculation of direct and indirect energy intensities, as well as of embodied and disembodied energy intensities of goods (Costanza and Herendeen 1984).

Applications of input–output analysis to developing countries have come mainly from two centres — MIT Energy Laboratory and Brookhaven National Laboratory. The input–output models developed by Blitzer and his associates for development planning (Blitzer et al. 1975; Taylor 1979) have been applied to Egypt (Choucri and Lahiri 1984), Jordan (Blitzer 1984), and Mexico (Blitzer and Eckhaus 1983). In the technology matrices developed by the Brookhaven group, the energy sector is greatly elaborated, energy flows are measured in energy units, and energy consumption is measured in terms of useful energy (i.e., final energy consumed multiplied by the efficiency of utilization). This approach has been applied to Egypt, Peru, Portugal, and the Republic of Korea (Mubayi and Meier 1981).

The large-scale computations required by detailed input–output models have been one reason why even their applications to developing countries have not been common in developing countries (see, however, Subba Rao et al. 1981; Vanin and Graça 1982; Behrens 1984). However, the miniaturization and fall in the cost of computers have now made these techniques feasible in developing countries as well (cf., Munasinghe et al. 1985).

Engineering Approaches

Economic approaches to energy problems are characterized by the primacy given to the effects of income on output and prices. These basic economic relationships, however, portray human behaviour which is extremely volatile. Besides, they must be formulated in value terms, which make it impossible to distinguish changes in quantity and in price. Dissatisfaction with these instabilities has led to models that rely on technological constants.

In these models, final energy consumption F is decomposed as follows:

$$F = uA/e$$

where A is the level of activity, u the useful energy required per unit of activity, and e the efficiency of energy utilization. The advantage of this decomposition is that u is expected to be invariant with respect to the form of energy, and that the rate of interfuel substitution is expected to be equal to 1 when fuel inputs are reckoned in terms of useful energy.

The level of activity may be the level of production of a commodity or service, or a "need" in the case of a consumer. Thus, the models seek to replace the behaviourally determined demand for energy by a normatively defined requirement of energy. Perhaps the most prominent of such models is the series of MEDEE models (Chateau and Lapillonne 1978, 1979, 1984; Lapillonne 1983). They have been applied inter alia to the European Community (Commission of European Communities 1983), Brazil (Prado 1981), Ecuador (Instituto Nacional de Energía 1984), Portugal (Neto et al. 1980), and Quebec (Québec 1984).

The family kinship of the MEDEE models with other normative approaches to energy problems is evident: for instance, with soft energy approaches that predicate a shift away from fossil fuels and conservationist approaches that emphasize the possibilities of energy conservation unrelated to costs (e.g., Goldemberg et al. 1985). Technology determines what is possible; social and economic variables determine which of the possibilities will be realized. Conviction that the world ought to change more radically or rapidly goes naturally with a technological approach; realization that the rate at which it can change is limited by behavioural and institutional factors is often associated with economic and sociological approaches. Both are necessary and neither by itself is sufficient to change the world. This is recognized, for instance, in the MEDEE-3 model, which incorporates a consumer choice function. Progress in macro models of energy hinges less on the discovery of physical constants, and more on the improvement of the specifications of behavioural functions.

Demand at the Micro Level

The traditional economic theory of demand is mature and has changed little in recent years (cf., Goldberger 1967). The major determinants of *consumer* demand are known to be income and price, to which may be added special variables relating to each situation: for instance, family size and composition where the demand is personal rather than family-based; or the price and supply of substitutes where these are important. The determinants of *industrial* demand are related to the economic objectives of industry as well as to the specific processes in which inputs are used. They can be studied in the context of a generalized model of industrial production, called the production function, or of industry-specific process models. More recently, the effects of the quality of energy supply on demand have emerged as a promising area of research, especially in view of the chronic energy shortages in developing countries (Munasinghe and Schramm 1983). Here, we shall deal with models of consumer demand.

While the theory of demand is well established, the estimation of demand functions presents serious problems of four kinds (Deaton 1978; Deaton and Muellbauer 1980; Wold 1982). First, what is observed in reality is the quantities purchased and sold; from them, it is difficult to disentangle influences that emanate from the buyers and those that come from the suppliers. Second, the regression techniques available for estimation restrict the functional forms that can be assumed between demand and its determinants. If a summary measure of influence, such as elasticity, is required, the functional form is even further restricted. Graphical techniques can be employed to investigate the functional form of relationships, but they are not always effective where a large number of variables is involved. Third, there is the problem of disentangling the relative influence of determinant variables where a number of them are involved; this problem is often difficult and sometimes insoluble. Finally, multivariate relationships require a large body of data and relatively computation-intensive regression techniques which, until the advent of the microcomputer, were within reach only of researchers working in the small number of institutions with mainframe computers.

As a result, a high proportion of energy demand studies in developing countries uses bivariate methods involving tabulation and two-dimensional graphics (Desai 1985; Howes 1985; Leach 1985). Applied to field surveys, bivariate techniques are highly productive. If a survey generates information on n characteristics, $n(n - 1)/2$ bivariate tables can be obtained from it; variation of frequency intervals can expand the range even further. At least a few of them are likely to show some relationship. Thus, bivariate techniques are a relatively fail–safe way of getting results. For the same reason, they are also not very rigorous. There is always a possibility that bivariate techniques might miss detecting a multivariate relationship or give a misleading impression of it.

Thus, both multivariate and bivariate techniques yield approximations of variable quality. Statisticians and econometricians have put a considerable effort into refinement of estimation techniques in the last 60 years. If it has not led to a high level of reliability, the difficulty lies as much in the complexity and variability of socioeconomic phenomena as in the techniques themselves. However, we would point to two directions of research that hold promise in regard to the analysis of developing-country energy problems.

The first is research on the consumer allocation problem. Consumers cannot continue to spend more than their incomes over sustained periods; in this sense, there is a budgetary restriction on their total expenditure. Further, the consumption of different commodities shows specific relationships with income. For instance, if a commodity is a necessity, poor consumers spend a higher proportion of their income on it than rich consumers, and vice versa for luxuries, as was noted by Engel in 1857 (Houthakker 1957). These twin observations have formed the basis of a theory of the consumer's allocation of the budget (Pollak and Wales 1978). In its applications to developing countries, however, it is also necessary to bring in the effects of price changes (Weisskopf 1971; Sener 1977). Income and price effects on commodity groups, including fuel and light, have been estimated for the Philippines; the Republic of Korea; Taiwan, China; and Thailand (Lluch et al. 1977). A study of Indian data also estimated the separate effects of size of family (Ray 1980). This body of literature illustrates the way in which the household consumption of energy can be regarded as the outcome of a budget allocation decision. Further applications to developing countries would call for modifications to the models. In particular, the budget limit in developing countries cannot always be assumed to be a monetary limit, but may be a limit in terms of labour time or farm area, as we shall argue in the section "Transport" later. The character of the limits may vary at different income levels. What should be emphasized, however, is the need to place household consumption in the context of the overall consumption decisions of the households.

The second direction relates to the study of the family as a decision-making unit. It is commonly observed that family farms use more labour per hectare than farms that hire labour (see, e.g., Deolalikar and Vijverberg 1983). Within the family, it is observed that women and children commonly predominate among the collectors of fuelwood (Reddy 1982; Cecelski 1984). It is clear that there are social and economic rules of work allocation and consumption between different members of the family, which are different from the rules that operate within a business firm, for instance. These rules also depend on the income level; work allocation in poor families is very different from work allocation among the rich. The knitting together of these frequent but stray observations into theory has attracted researchers in diverse disciplines, including economics (Simon 1957; Pollak and Wachter 1975; Becker 1981; Mack and Leigland 1982; Pollak 1985), sociology (Demos and Boocock 1978), anthropology (Pryor 1977), and history (Laslett 1972). No unified picture has emerged, yet, from these diverse approaches. Fuelwood collection, however, can be recognized as an aspect of work distribution within the family, and its study is likely to be advanced by a synthesis of various theoretical approaches to the family.

Demand-based Policies

The relationship between energy use and final demand can, in principle, be used to reduce the energy intensity of gross national expenditure by shifting expenditure from more to less energy-intensive components of final demand. This can be done:

- by influencing the components of final demand themselves; for instance, by means of taxes and subsidies on final goods (i.e., consumer goods or capital goods);
- by influencing the determinants of final demand; for instance, incomes through taxes and subsidies; and
- by influencing the regional distribution of final demand and thereby reducing transport inputs; for instance, by means of location control.

Direct and Indirect Taxes

For simplicity, we may confine this discussion to taxes; subsidies can be regarded as negative taxes.

Under certain reasonable assumptions about consumer preferences, it can be shown that a proportional tax on their incomes would leave consumers better off than taxes on the commodities they purchase, if the revenue from both were the same. This well-known proposition of the theory of public finance, together with the fact that an income-related tax can be made progressive, argues for a preference for direct over indirect taxes (Newbery and Stern 1985).

However, in practice, all countries rely a great deal on commodity taxes, developing countries probably more so than industrialized market economies. This preference is based on administrative convenience. Administratively, the fewer the taxpayers the easier it is to collect a tax; producers, processors, or traders on whom commodity taxes are levied are fewer and offer a more compact target than the general population. The tax base for direct taxes can be contracted by introducing a high threshold for tax exemption, but if a large proportion of the population is tax-exempt, problems of identifying newly eligible taxpayers, as well as preventing tax evasion by unidentified taxpayers, become serious. Further, income is a much more imprecise tax base than the volume of goods produced or traded.

More principled reasons can also be given for a commodity-based approach. For instance, it can be argued that poverty leads to undesirable deprivation, but deprivation of some goods, for example, food, clothing, and shelter, is more serious than deprivation in general: this is the basis of the basic-needs approach. Conversely, it can be argued that the deprivation of some goods, such as alcoholic beverages, is not serious for anyone, and that a reduction in the consumption of luxuries is not serious for the rich. This argument can form the basis of taxes on luxuries and subsidies on necessities. However, such commodity-specific taxes and subsidies cannot easily be confined to a specific income class; they affect all purchasers, whether they are rich or poor.

A subsidy on basic necessities has the further shortcoming that it takes no account of the fact that, as a person or a household consumes more of it, additional quantities of it become less essential. Ideally, a subsidy on a basic necessity should be specific to the poor consumer, and should apply only to a certain minimum purchase. A better approximation to such a subsidy is obtained by rationing, which assures a fixed minimum quantity to all at a subsidized price. The restriction that it imposes on consumer choice can be removed by making rationing quotas salable, and thereby allowing those poor who do not need the ration to convert it into freely disposable income. However, although it is simpler to administer than a subsidy based on personal income, it requires an administrative machinery that can reach down to each household. Further, rationing of subsidized goods brings into being a dual market, and the administration has to be strong enough to prevent the leakage of subsidized supplies into the unsubsidized market. Thus, the efficient administration of subsidies calls for a level of integrity and sophistication in the government that is not within reach of all developing countries.

In all countries, there are many more consumers than producers; and making consumers happy helps all governments, whether they are democracies or dictatorships. Thus, they control prices, which involves subsidizing the consumer at the expense of the producer; or they subsidize consumer goods. The revenue for the subsidies usually comes from taxes on goods, for it is easier to tax a small number of producers (or importers) than a large number of consumers. Thus, indirect taxes, indirect subsidies, and cross-subsidies through price control become the norm in developing countries, and if the subsidies benefit the poor, it becomes difficult to reduce or remove them. Thus, rigidities are introduced in the price structure that make it useless for resource allocation.

If this danger is to be avoided, it is necessary to shift from indirect to direct taxes and subsidies for the regulation of income distribution. It is the people who are poor, not commodities, and it is at the level of people that poverty must be alleviated. Agreed, there are practical difficulties: income is easy to conceal and difficult to estimate, the poor are too numerous to reach directly, taxes and subsidies create incentive effects that reduce their efficacy. However, there must also be practical solutions. The rich are few, and have identifiable markers: houses, cars, consumer durables, children's education, etc.; a composite index of these may be no less accurate than a direct estimate of income. The poor are many, but particularly vulnerable sections of them — for instance, single parents, widows, orphans — are not that many, and are easily identifiable. Employment registration is not too difficult an administrative chore; and where all those who are employed are registered, an annual subsidy is not difficult to administer, as long as it is kept simple. These are not necessarily good or generally applicable suggestions; but, surely, it is not beyond the ingenuity of researchers to work out better, more ingenious, and practical methods of poverty alleviation than indirect taxes and subsidies.

Taxation of Energy Sources

Policies affecting the prices of energy sources, especially oil products and electricity, are common in developing countries. Although they are not always instituted with demand management in view, their effects on demand are obvious; they are also often unintended and undesirable. More generally, the government influences prices through taxes and subsidies. However, direct controls on prices are not uncommon, especially where the energy industries are publicly owned.

The different energy sources — oil products, gas, electricity, coal, and firewood — exhibit different market structures and, hence, offer different conditions for taxation and subsidization.

Oil products are typically sold by a small number of companies that extend their distribution activities all the way to the consumer, at least for transport fuels. Oil products are the joint products of refineries, so it is impossible to allocate production costs to them precisely. Hence, there is much flexibility in pricing them. The only restriction on their relative prices is that the resulting demand pattern should not differ greatly from the pattern of supplies from the refineries. However, refinery product patterns can be changed, up to a point, by making small and acceptable changes in the product specifications, and it is possible, although costly, to change the patterns further by installing ancillary processes like cracking and visbreaking. It is also possible to balance the supply and demand patterns by importing or exporting refined products. Hence, considerable freedom of maneuvre is available in fixing the relative prices of refined products, as well as in taxing or subsidizing them.

The way in which this freedom of maneuvre is generally used is in the form of taxes on gasoline, on the grounds that it is used by rich car-owners, and subsidies on kerosene, on the grounds that it is used by the poor for lighting. Both have considerable substitution effects. Where the taxes on gasoline engines are high, the uses and development of gasoline engines are restricted. Gasoline engines can be miniaturized more than diesel engines and would be more widely used in small-scale applications, for example, irrigation pumps, if the price of gasoline were nearer to that of diesel oil. The development of diesel cars has been stimulated by lower taxes on diesel oil; insofar as they catch on, the progressiveness of the tax on gasoline is eroded. Here, a better tax base than gasoline is available, i.e., cars; a shift of the tax from gasoline to cars would be better targeted on the rich and be more difficult to avoid.

The subsidization of kerosene leads to its use for less essential purposes, such as cooking, by those who are not so poor. It leads to the adulteration of diesel oil, for up to 20% of kerosene can be mixed with diesel oil without noticeable side effects. It also prevents the emergence of alternatives to kerosene, such as electricity which gives light of a better quality. Unlike with gasoline, it would be impossible to make this subsidy more specific by shifting it to user equipment, for the number of kerosene lamps is too large. It may be questioned if lighting, by itself, is a fit base for a subsidy to the poor. If it is held to be so, the impact can be made more specific to the poor by salable rationing quotas giving them subsidized access. Even so, a subsidy on kerosene will lead to its substitution for other forms of lighting; such a substitution effect can be removed only by giving a subsidy that is neutral between all illuminants (cf., Reddy 1978).

The question may be asked whether a tax should not be levied on all oil products to encourage their replacement by renewable energy (Lovins 1977). The point of discriminating against nonrenewables is intergenerational equity: the more oil is consumed now, the less would be available to future generations. The direct effect of a tax, however, is not to transfer anything from one generation to a later one but to transfer purchasing power from the buyers of oil to the government in the same generation. It is only insofar as the tax reduces the demand for oil by directing it to other forms of energy that it will actually transfer oil to a future generation. It is better, where necessary and appropriate, to organize interfuel substitution directly and to tailor taxes and subsidies to it, than simply to impose a tax on nonrenewables. Further, the reduction of oil consumption by a developing country in one generation would do nothing to make more available to it later (except for oil within its own frontiers — but that is an argument for importing oil as much as for reducing its consumption). A differential tax on oil is, therefore, not justified on these grounds. The idea of a subsidy on renewables or on imported fuels may, however, have a stronger basis in particular national circumstances.

Unlike oil products, the taxation of other energy sources is not widespread or systematic. Taxes on coal or electricity are not unknown, but their purpose is generally confined to revenue raising. Taxes on wood or charcoal are known but not very common. Insofar as the burning of wood and coal generates considerable smoke and pollution, an opportunity is perhaps being missed here. Bulk fuels entering urban areas could easily be taxed at the city gate, and differential taxation of wood and coal could be used to encourage the use of charcoal and soft coke.

Pricing

In many developing countries, the major energy-producing industries, coal, oil, and electricity, are entirely or substantially state-owned. Even where they are not, their market structure often obliges the government to intervene in price formation. Thus, pricing is the most actively used instrument of demand management in developing countries (Munasinghe 1983). However, the use of this instrument is commonly vitiated by average pricing based on historical costs.

Among other things, average cost pricing gives the wrong incentives (or disincentives) to producers. Once the price ceases to be an indicator of investment requirements, other regulators of investment have to be brought in. Typically, under diminishing returns or when there is excess demand, average costs are below marginal costs, and prices set on the basis of average costs are too low to justify investment that would lead capacity to grow pari passu with demand. To persuade enterprises to make sufficient investment in the circumstances, governments introduce various investment incentives: for instance, low and stable interest rates, generous depreciation and investment allowances, and cross-subsidies for high-cost production. Each of these distorts the investment pattern in favour of the industries that are thus favoured and within those industries, in favour of capital-intensive technologies and projects.

Pricing based on historical costs leads to an imbalance between depreciation reserves and investment funds required for replacement. When equipment prices are rising, depreciation provisions fall short of replacement requirements; investment then needs incentives of the kind mentioned earlier. In the less common converse case, depreciation exceeds replacement requirements.

Among large-scale sources of energy, geographically uniform pricing favours those whose transport costs are low. Thus, pricing practices probably contributed to the penetration of the markets for coal by oil. Conversely, if prices were made to reflect transport costs, energy markets would be less monopolized and a larger variety of energy sources would be able to hold market segments.

The underpricing and undercosting of energy produced by large, centralized enterprises reduces the competitiveness of small, decentralized, renewable energy forms and prevents them from capturing the markets they would under fairer competitive conditions. As was argued in the section on aggregate demand, lowering prices of particular commodities is not the best way of helping the consumer or of promoting equity. It is necessary to get away from average cost pricing and to rethink the regulation of prices charged by natural or politically created monopolies.

The economists' rule in these conditions is long-run marginal-cost (LRMC) pricing. Marginal costs are those that vary with output. However, in the long run all costs become variable. Thus, the difference between average and long-run marginal costs lies basically in the fact that, whereas average costs are generally understood to be costs that have been incurred, marginal costs are those that probably will be incurred. Thus, the major implication is that cost estimation should be forward-looking instead of backward-looking. The difference is likely to be unimportant in the case of inputs that are purchased frequently; for instance, raw materials. It can, however, be substantial for durable goods such as machinery. In the case of multiproduct firms, LRMC pricing involves, in addition, that the prices of their products should be at least equal to the costs that can be attributed to each: that is, that there should be no cross-subsidization of products. Finally, just as utilities should charge marginal costs for what they sell, they should be prepared to pay marginal or avoided costs for what they buy.

Thus, although full-blooded LRMC pricing may sound esoteric and intelligible only to thoroughbred economists, it provides a benchmark value for pricing and has a number of practical implications; for example,

- product prices should reflect attributable costs: prices should vary from place to place to reflect transport costs;
- enterprises should be prepared to pay avoided costs for what they buy; and
- depreciation write-offs should be based on replacement costs, and not on incurred costs.

These rules are not more complicated than average cost pricing; they can be enacted, and they can be enforced by auditors. They are not the only possible rules, and one cannot be sure how they would work in practice. The point is that fresh research is called for on principles of price regulation and their applications to the energy industry.

Market Structure

The rules we discussed above are rules to enforce minimum prices to protect small energy producers; the concern of governments is usually to fix the maximum prices to protect the consumer. Average cost pricing is popular among regulators because it is considered minimum cost pricing. However, there are many ways of increasing prices without increasing profits; padding of costs is not uncommon where prices are controlled. The remedy for cost inflation should be sought, not so much in price regulation, but in competition. Competition does not always have to be there; often the possibility of competition is enough to keep prices down (Baumol et al. 1982; Spence 1983). The way to keep prices down should be looked for in the market structure, and not in price regulation. The search for market structures to ensure effective competition should extend to energy industries as well.

A corollary of competition is that entry should be free, and that no special favours should be shown to one enterprise against another. This condition is often violated in developing countries. It is virtually impossible to separate business from politics in any country; in developing countries where politicians set up or capture enterprises to enrich themselves, or vice versa, this is impossible. State enterprises are often set up to keep foreign enterprises out or to deal with them on more equal terms. Once set up, however, they have a privileged position and prevent the growth of competitors. Thus, irrespective of ownership, an arm's length relationship between government and business is essential for fair competition.

Agriculture

Agriculture may be viewed as an activity that produces useful biomass. The biomass it produces can be put to a wide variety of uses — food, fodder, fuel, fertilizer, and industrial raw materials. Its output is so diverse that it can supply most of the needs of rural populations locally. Many agricultural systems in developing countries are self-sufficient to a high degree (although the countries themselves are often not self-sufficient in agriculture). The trade flows of the systems with other areas are small; consequently, the cost of infrastructure, e.g., roads and power supply, that is needed to support such flows is high. Although the costs of infrastructure vary and are relatively more manageable for high-income countries and for densely populated areas, they are a major constraint on the rate of rural development. A country that invests in rural infrastructure tends to see low returns in terms of output and trade. One that invests in urban infrastructure may thereby build industrial output and trade faster, but may face problems of dualism between urban and rural areas and of rural–urban migration.

The agricultural systems of developing countries display two common features: a high proportion of population in agriculture, and low value of output per worker, which in turn sets a limit to rural living standards. In those developing countries where the bulk of food intake comes from cereals and roots, 0.25 t/year per adult head would provide a quantitatively (though not qualitatively) adequate diet; 1 t per agricultural worker would provide enough, approximately, for four adults or for a family of husband, wife, and three children. In practice, the agricultural population in countries with an output of under 1 t per agricultural worker is largely engaged in subsistence production; all countries that have significant levels of urbanization and industrialization have output per agricultural worker of over 1 t.

In Table 4, we list the countries where food productivity per agricultural worker is less than 1 t/year. The table has its imperfections. To add roots and tubers to grains, we have divided root output by three and derived its approximate dry equivalent. We had figures of all agricultural workers, not of workers engaged in food production. To make the two figures comparable, we tried to estimate the food that would be produced if all agricultural land were under food crops: we divided food output by the area under food crops and multiplied it by the area under all crops. We could not get a direct estimate of the latter, so we used two imperfect substitutes: area under major crops, and area under cultivation. Both are incomplete estimates of area under all crops. Thus, our estimate of the area under all crops and, hence, of national food productivity is lower than it should be, but the underestimation is not too great. More serious is the assumption that the area under other crops

Table 4. Potential productivity per agricultural worker in terms of food, 1983.

Country	Agricultural workers (1000) [1]	Weighted food output (1000 t)[a] [2]	Food productivity (kg) [3 = 2/1]	Area under food crops (1000 ha) [4]	Area under crops[b] (1000 ha) [5]	Area under cultivation[c] (1000 ha) [6]	Potential productivity I[d] (kg) [3 × 5/4]	Potential productivity II[e] (kg) [3 × 6/4]
Botswana	315	31.0	0.099	164	166	1360	0.100	0.820
Mauritania	436	54.5	.125	173	174	208	.125	.150
Cape Verde	59	9.8	.166	15	17	40	.188	.443
Lesotho	604	148.8	.246	154	154	298	.246	.476
Somalia	1563	261.7	.167	344	536	1116	.260	.542
Gambia	239	65.8	.275	87	90	160	.284	.506
Mali	3416	975.2	.285	1789	1899	2058	.303	.328
Bhutan	619	186.9	.302	132	136	98	.311	.224
Burkina Faso	3117	1219.7	.391	2559	2658	2633	.406	.402
Guinea	1867	687.2	.368	637	708	1574	.409	.909
Haiti	1981	694.4	.351	783	947	897	.425	.402
Mozambique	2560	983.0	.384	1535	1808	3080	.452	.771
Swaziland	190	62.1	.327	66	98	138	.486	.684
Rwanda	2394	1139.8	.476	736	791	1034	.512	.669
Burundi	1746	1104.2	.632	850	900	1306	.669	.971
Nepal	6612	4506.0	.682	2543	2605	2332	.699	.625
Kenya	5248	3278.5	.625	2890	3349	2310	.724	.500
Liberia	532	358.0	.673	307	367	371	.805	.813
Tanzania	6269	5211.8	.831	4460	5210	5200	.971	.969
Bangladesh	26804	23598.3	.880	11669	12889	9136	.972	.689
Vietnam	17703	16569.0	.936	7413	7737	7585	.977	.958

Source: Compiled from Food and Agriculture Organization (1984).

[a] Output of food crops has been added in thousands of tonnes. Roots and tubers have been reckoned at 0.3 times the tonnage of other food crops, in proportion to their lower calorie content per unit of weight.

[b] Sum of all areas for the crops listed in Food and Agriculture Organization (1984) for which figures were available. The area under fruit and nuts was not available.

[c] Area defined by Food and Agriculture Organization (1984, table 1) as arable land plus land under permanent crops. Arable land is defined as "land under temporary crops (double-cropped areas are counted only once), temporary meadows for mowing or pasture, land under market and kitchen gardens (including cultivation under glass), and land temporarily fallow or lying idle" (Food and Agriculture Organization 1984:3).

[d] Potential productivity I = Food productivity × Area under crops/Area under food crops.

[e] Potential productivity II = Food productivity × Area under cultivation/Area under food crops.

could produce the same yields of food if it was made to produce food crops. Nevertheless, for our gross indicative purposes, we believe we have got reasonable figures.

The picture they reveal is not so reasonable, however. Except for one country (Haiti) in Latin America and four (Bangladesh, Bhutan, Nepal, and Vietnam) in Asia, all low-productivity countries are in Africa, and they are spread all over the continent. Five other African countries (Chad, Comoros, Ivory Coast, Malawi, and Zaire) had productivity between 1 and 1.1 t.

Table 4 probably does not tell the whole story. The productivity figures at the top of the table are so low that families could not be sustained on agricultural food production alone. Clearly, agricultural workers in those countries are likely to be engaged in other activities also; and there must be other sources of food for them — for instance, animal husbandry.

Nevertheless, productivity figures for many African — and some Asian — countries look extremely low; at such low productivity levels, there cannot be much hope of restructuring their economies. Raising agricultural productivity must come high among the priorities for these countries — and among research priorities.

However, agriculture should not cease to be a priority area once productivity of 1 t/year is attained. A number of densely settled industrializing countries, for instance, China, Egypt, and India, have productivities between 1 and 2 t. For them also pushing up the productivity level must remain important.

The low living standards make the rural population susceptible to urban pulls when the urban demand for labour is growing. Migration to urban areas is not in itself undesirable. It is a major cause of a general rise in productivity and living standards, and has characterized the development of all industrial countries. However, where the growth in urban employment is in services rather than in the production of goods, some countries have experienced a fall in agricultural output without a compensating rise in other output and, consequently, a growing import dependence in food; and urban employment has been shared among partially employed rural migrants. Thus, a sustained rise in agricultural output per worker makes development more manageable.

Any such increase will have implications for the demand for labour: a rise in labour productivity would reduce labour requirements and would lead to growing unemployment unless total output were to rise. A rise in productivity will normally also raise real income, increase the total demand for goods and services, and raise output and employment. However, its positive and negative effects on employment need not cancel out; nor do they always occur in the same place. Hence, employment implications of productivity growth would need to be investigated and taken into account in any development program.

Further, growth in output and productivity may have serious implications for income distribution. Agriculture is a land-intensive industry, and except in socialist countries, land is not equally or commonly owned. Where land ownership is unequal and wage employment is common, the benefits of productivity increase would go to landowners unless wages also rose concomitantly or some other form of redistribution (e.g., of land) were applied. Thus, agricultural development can lead to a serious worsening of income distribution. Hence, the distributive implications of development programs need always to be studied and taken into account.

In recent times, the growth of agricultural productivity in a number of developing countries has been accompanied by rapid increases in the consumption of commercial energy, especially oil. This oil dependence has made agricultural systems as vulnerable to external shocks as other parts of the economy, and made agriculture a part of the total policy problem of dealing with such shocks.

Types of Energy Inputs

In a number of early studies, energy inputs to agriculture were aggregated; in some, the output of agriculture was itself aggregated in energy terms (see, e.g., Makhijani and Poole 1975; Leach 1976; Pimentel 1980). These highly aggregated studies showed that food production systems that achieved high productivity of human labour also showed high inputs of other types of energy to output. More careful analysis may lead to more qualified conclusions (cf., Smil et al. 1983). However, new conceptual formulations and models would go further to make the analysis of energy use in agriculture fruitful.

Perhaps the starting point of this formulation should be the disaggregation of agricultural processes and the involved energy inputs. A methodology that disaggregates the processes and inputs has been developed and applied to rice cultivation by Reddy (1985). Referring to agricultural systems in general, we should first distinguish between direct and indirect energy inputs; the more important among the latter is energy used in irrigation, fertilizers, and pesticides. Direct energy inputs can be further divided into mobile and stationary inputs. The type of input determines the possibilities of substitutions among fuels and among inputs; the totality of processes, together with the substitution possibilities within each, determines the technological options available.

Unmeasured inputs

Agriculture depends on crucial inputs of solar energy, carbon dioxide, nitrogen, and water from the environment. It would be possible to measure these inputs only in highly controlled, experimental conditions; thus, most agricultural studies do not measure them, and work in terms of partial models.

The existence of uncontrolled and unmeasured inputs has long been recognized; it was to deal with them that statistical techniques of factor analysis were developed. Simply put, the influence of such factors can be isolated and separately investigated if variations in them are reflected in different samples; then, variations among samples can be used to study the effect of uncontrolled factors and variations within samples can show the effect of controlled ones.

The general lesson is that it is useful for agricultural studies to encompass a wide range of variations and to stratify their observations in order to bring out the effect of uncontrolled variables such as climate and soils. There is a synergism between macro and micro studies that exclusively macro or micro studies are likely to miss. This is true of studies of energy use in agriculture: although studies for a single village or a smaller entity may be easier for a researcher or a small team to manage and may get funds more easily, a number of comparable, simultaneous studies in varying circumstances would be more illuminating (cf., Dumont 1957).

One axis of variation missed in agricultural research is the three major food production systems of the world: the seasonal cereal agriculture of the Eurasian land mass; the perennial tuber agriculture of wet Africa, Southeast Asia, and the Pacific; and the seasonal coarse grain agriculture of arid Africa. The Eurasian system, developed over millennia, has been adapted to a wide range of environments, and has also diversified its technologies as a result of its mechanization in the industrial countries. The other two systems, on the other hand, have remained static in technology and productivity, and are declining under competition from the products of the first system. The decline in agricultural production in parts of Africa and the rising food imports into Africa and some Pacific countries are reflections of this technological stagnation. The possibilities of adaptation and improvement of the peripheral agricultural systems are a research area of considerable importance to a number of developing countries.

Mobile inputs

Mobile inputs are inputs required for soil preparation; sowing; weeding; spreading of manures, fertilizers, and pesticides; harvesting; and transport of output. Human labour is essential to these operations for guidance and decision-making, but it can be replaced by animal-powered or mechanical equipment in physical tasks, and its productivity can thereby be increased.

When the length of the agricultural season is determined by weather or by the succession of multiple crops, shortening the time spent in soil preparation and in harvesting can raise yields. Hence, these operations tend to have the peak energy input requirements, and speeding them up can increase returns.

The use of animals in plowing speeds up soil preparation; this is their primary use in most agricultural systems. Although the first harvesters in the USA were drawn by horses, the use of animal-powered devices in harvesting is virtually unknown in developing countries. Animals are used mainly in preharvest operations (and for threshing in some regions), and their use has a sharp seasonal peak.

Human labour inputs have two peaks — in sowing and in harvesting. Hence, these were the first operations for which mechanical devices to raise human productivity were developed in industrial countries in the form of tractors and combine harvesters, respectively. Tractors and, less commonly, harvesters have been introduced in some areas of developing countries, notably in Brazil, China, India, and Turkey.

The effects of mechanization on labour use are different according to whether it is introduced in peak operations or below-peak operations. It reduces the person-hour requirements in all operations, but it does not release workers if introduced in below-peak operations. If introduced in peak operations, however, it releases workers for the whole year. In other words, mechanization of below-peak operations creates seasonal unemployment, whereas mechanization of peak operations creates perennial unemployment. Thus, tractors and harvesters raise fears of unemployment that do not accompany other forms of mechanization. Mechanization of peak operations can raise productivity per worker in a way that mechanization of other operations cannot, but for that productivity increase to be realized, the workers rendered surplus should be absorbed in employment created by production increases, or elsewhere.

As pointed out earlier, a rise in productivity will raise real income, output, and employment, and will tend to offset the labour displacement effects of mechanization. Hence, the direct effects of mechanization, which will always displace labour, may be different from the total effects. It is, therefore, not surprising that the large volume of research in this area is inconclusive (see, e.g., Hayami and Ruttan 1971; Poleman and Freebairn 1973; International Labour Organisation 1974; Binswanger 1978; Berry and Cline 1979). Despite being heavily plowed, this area of research could benefit from fresh work based on a clearer conceptualization of direct and indirect effects of mechanization.

The possibilities of agricultural mechanization are constrained by topography, soil characteristics, and water supply. For instance, level land with light or easily broken soils is easier to plow mechanically. Differences in these ground factors lead to unevenness in the spread of mechanization. The adaptation of technological systems to the variety of local conditions in developing countries calls for widespread applications of research.

The interrelations between equipment design, tillage conditions, and performance have been studied and have led to progressive improvements in the design of tractors, harvesters, and implements. With the rise of oil prices, the energy efficiency of equipment was added to the parameters under study (Taylor 1977). Comparable work on draft animals and implements is meagre and little known (cf., Ramaswamy 1979; Ward et al. 1980).

Finally, tillage itself is an input to agriculture that can be optimized. With the rise in oil prices, possibilities of reducing the tillage inputs have attracted considerable attention in the mechanized agricultural systems (cf., Wittmus et al. 1975). Similar possibilities of optimizing tillage undoubtedly exist in the agricultural systems of developing countries, and call for exploration.

Stationary inputs

Agricultural activities after harvesting are stationary; energy inputs to them may be called stationary inputs. The energy-intensive activities among them are three postharvest operations: drying, threshing, and milling.

Of these, threshing and milling are mechanical operations similar to lift pumping, and can use the same forms of energy. The volume of research on them has been much smaller than on irrigation, but all the technologies and forms of energy for pumping are applicable to them. We shall discuss pumping more fully in the next section. Discussion of solar dryers is to be found in chapter 9.

Indirect inputs

Indirect inputs consist of the energy used to produce the goods and services used in agriculture. The principal ones are water, fertilizers, and pesticides. One way of reducing the indirect energy inputs is to increase the output response to water and other inputs. The difference between the actual responses and responses in controlled experiments is so great that considerable improvements in responses can apparently be achieved by changing the methods and timing of application (see, for instance, Rogers 1983).

Energy use in irrigation has attracted a great deal of research (Meta Systems Inc. 1980; Bhatia 1984a, b). In lift irrigation, there are a large number of alternative technologies that can use solid, liquid, and gaseous fuels; electricity; solar energy; and wind power. Some of these, like solar energy and wind, are dependent on local ambient conditions. Each technology has different scale variations and scale-dependent capital costs. Finally, the depth and volume of water supply vary from place to place; so do prices. In the circumstances, the mapping of appropriate technologies for each combination of conditions is an impossibly complex task. The numerous cost–benefit analyses take different cuts into this tangled seam of facts, but do not suffice to order them in a manageable way. It might be better if, instead of trying to define the market segments of each technology in advance, each was allowed to carve out its segment in competition with the others. If they are to do so, market distortions introduced by economically inefficient pricing, such as average cost pricing of electricity, need to be removed. Hence, policy-oriented pricing studies are prerequisite to the emergence of better market structures in irrigation.

There is another set of issues that cannot be addressed in the farm-level studies of irrigation: optimum scale and spatial distribution of irrigation devices. Generally speaking, gravity irrigation is cheaper and less energy-intensive than lift irrigation, but only on a much larger scale. It also tends to be inefficient owing to poor matching of water supply and demand. Further, most lift irrigation devices are subject to economies of scale, some more than others, but there are limits to the size of all. Finally, the lower the water table the greater the minimum power required to lift it. These three factors lead to optimal spatial distributions of devices that are almost never realized in practice, but that could be approximated better by correct pricing practices. Hence, water pricing and water allocation rules are of as great a consequence to energy efficiency as energy pricing itself. This is a grossly underresearched area.

Policy

We have given above a classification of energy inputs to agriculture. For policy purposes, it is necessary to combine them into technological alternatives and to make or induce choices among them at the aggregate level (for a description and application of a methodology for doing so, see Reddy 1985). These choices often relate to energy sources; for instance, a decision to mechanize involves the substitution of mechanical for human or animal power. While it essentially involves interfuel substitution at the farm level, it requires policy formulation when it has macroeconomic implications for total employment, balance of payments, and energy resource use.

Policies can also be devised to increase the efficiency of energy use in agriculture. Three areas appear most promising in this regard.

First, increase in land yields raises the productivity of all energy inputs that are related to the area cultivated: inputs to plowing, application of fertilizers and pesticides, and irrigation.

Second is an increase in the productivity of indirect energy inputs, especially water and fertilizers. There is a vast difference between the average and the best-practice efficiency of irrigation (Bos and Nugteren 1974). Large-scale canal irrigation in the tropics often involves vast evaporation and percolation losses even before the water reaches the farm. On the farm itself, the technique of water application has a considerable effect on its effectiveness. The underpricing of irrigation water in many developing countries encourages its inefficient use. Among fertilizers, the development of highly concentrated, water-soluble fertilizers (principally urea) has increased the efficiency of nitrogen uptake to 50% or more. However, the intake of phosphorus by the first crop is usually below 10%, and of potassium, 20–40%. Although the total uptake is higher because of phosphorus and potassium retention in the soil, considerable improvements in total fertilizer absorption are still possible (Food and Agriculture Organization 1978). Here again, the widespread subsidization of fertilizers can encourage their inefficient use.

Finally, increases in the efficiency of use of the indirect energy inputs, especially water, fertilizers, and pesticides, are closely dependent on the development of cultivars that can utilize them efficiently and on soil chemistry. Thus, research on the three — energy inputs, cultivars, and soils — should be closely coordinated. Biotechnological research to increase yields and the intensity of land utilization is particularly promising as a means of energy conservation.

Industry

In respect of the range of energy sources, as well as the processes and devices in which they are used, industry is more versatile than other sectors. In transport, the need to make vehicles light, fast, and safe has led to the predominance of internal combustion engines, and research also has been concentrated on them. The size of domestic energy-using equipment, on the other hand, is constrained by the size of the household. Energy use in industry is not so constrained by considerations of size or portability. The range of options available for energy conservation and interfuel substitution is also correspondingly greater in industry.

Producers in industrial countries, especially the larger firms among them, do a great deal of research on their technologies and processes, including energy-related options. Some of the results of this research are proprietary. Others are embodied in the equipment they produce, and information on them is given to potential buyers. Some of the information is published in industrial journals and conference proceedings. Published information is, by itself, voluminous, especially for energy-intensive industries like steel and cement; and to evaluate it within the time and resources of the Group would have been impossible.

Hence, the Group limited itself to reviewing three types of research. First, there is research that presupposes no or little industry-specific knowledge, and that deals with general measures of demand management discussed earlier in this chapter. Second, there is research on types of energy user and storage equipment, which in our view holds much promise for developing countries. The scope of both these types extends beyond industry, therefore they are dealt with in the next chapter. Finally, there is research on energy intensity of industries, which is dealt with next.

Energy-intensive Industries

Energy-intensive materials, taking direct as well as indirect energy requirements into account, have been identified on the basis of input coefficients for the USA; the 17 most energy-intensive ones among them are listed in Table 5. Energy-intensive materials are defined as relatively homogeneous commodities whose direct and indirect production processes require unusually large amounts of primary energy (Strout 1985). The global energy consumption of these materials is calculated on the assumption that the USA's energy coefficients applied all over the world; on that assumption their energy consumption amounted to 27% of global commercial energy consumption, and a much higher proportion of world industrial energy consumption. Thus, concentrating energy conservation efforts on industries producing energy-intensive materials, or shifting the demand pattern away from these materials, would make a quick and significant contribution to a reduction in overall energy intensity of production. Recycling of energy-intensive materials would similarly reduce overall energy intensity.

Table 5. World production of principal energy-intensive materials (1000 t), 1969–71 (3-year means) and 1979–80 (2-year means).

Commodity group	Energy coefficient (tce/t)[b] [1]	Average annual production 1969–71 [2]	Average annual production 1979–80 [3]	Average annual energy use[a] 1969–71 [4 = 1 × 2]	Average annual energy use[a] 1979–80 [5 = 1 × 3]	Ratio 1979–80 to 1969–71 [5/4]
Petroleum refinery products	0.21	2186004	2982677	459061	626362	1.364
Wood pulp	0.99	101216	124922	100204	123673	1.234
Paper and paperboard	0.40	127291	174250	50916	69700	1.369
Chemical fertilizers (NPK)	0.77	71484	121796	55043	93783	1.704
Insecticides, fungicides, etc.	3.63	1620	2760	5881	10019	1.704
Plastics and resins[c]	5.38	29294	58599	157602	315263	2.000
Synthetic rubber	5.46	5015	9022	27382	49260	1.799
Cellulosic synthetic fibres	8.10	3510	3279	28431	26560	0.934
Noncellulosic fibres	9.45	5097	10413	48167	98403	2.043
Hydraulic cement	0.32	570333	861902	182507	275809	1.511
Building bricks[cd]	0.26	473766	442133	123179	114955	0.933
Steel products[e]	1.87	582033	723649	1088402	1353224	1.243
Primary copper	4.47	7394	9394	33051	41991	1.270
Primary lead[f]	1.10	3923	5580	4315	6138	1.422
Primary zinc	3.04	5208	6296	15832	19140	1.209
Primary aluminum	8.97	10217	15613	91646	140049	1.528
Primary magnesium	13.55	220	371	2981	5027	1.686
Primary tin	1.42	220	234	312	332	1.064
Total energy use in 17 nonfuel commodity groups[a]				2015851	2743326	1.361
Percentage of world total primary energy production				26.9	26.8	0.996
World total primary energy production[g]				7504410	10254408	1.366

Source: Strout (1985).

[a] Assuming the use of U.S. 1967 technology, industrial structure, product mix, and relative importance of imported intermediate products.

[b] Tonne coal-equivalent = 7 Gcal = 29.3 GJ.

[c] Coverage probably less complete than for other commodities.

[d] Bricks converted to metric tonnes at factors of 2038 t/million standard bricks or 2.0 t/m^3.

[e] Crude steel equivalent.

[f] Includes secondary antimonial lead in 1979–80.

[g] Hydro, geothermal, and nuclear electricity included at thermal generating station equivalent, assuming 25% generating efficiency in both years.

Such steps would, indeed, be incumbent on a number of developing countries, for in industrial countries the per capita consumption of the 10 most energy-intensive materials in 1979/80 was in the range of 1–2 t/year; in developing countries with incomes under US $1000/head, it was typically 100 kg or less. Income elasticity of energy-intensive materials eventually declines but this effect is evidently only at high income levels. Production of energy-intensive materials on a large enough scale to raise the per capita consumption of developing countries to the levels current in industrial countries would entail such a large increase in global energy consumption that the saving of both energy-intensive materials and energy is likely to be a necessary part of the growth strategy of developing countries.

Although it may be assumed that those industrial goods that are energy-intensive in industrial countries will also be energy-intensive in developing countries, their relative weight will vary from one developing country to another. Thus, the list of industries on which conservation and substitution measures must be concentrated has to be worked out individually for each developing country. Apart from energy-intensive materials, such a list may well include industries that, although not energy-intensive, consume a large proportion of the energy used in a country because of their large size: for instance, food and drink, or textiles in many developing countries.

It also cannot be assumed that the energy intensity of an industry will be the same in industrial and in developing countries. Technology varies from country to country and from plant to plant, and it is necessary to work out conservation and substitution strategies in the context of the local industry. Considerable research has been done on energy use in the more energy-intensive industries such as steel, cement, and fertilizers (see, e.g., Metals Society 1981; Mudahar and Hignett 1982; United Nations Industrial Development Organization 1985). The research on individual industries is too voluminous for the Group to have surveyed, and would be best utilized by each country or industry to suit its own interests.

Policy

The general approach to a policy on a national or subnational scale is to start by energy audits of particular industries, to pinpoint those measures that would result in the most significant energy savings, and to devise policies to promote them. The measures are usually classified into three types (Tunnah 1985).

Housekeeping measures The actual measurement of energy flows in an industrial plant, such as an energy audit involves, will suggest ways of increasing energy efficiency that require no investment; for instance, through adjustment of the excess air rate in furnaces, of temperature in chemical reactions, of loading rate in continuous processes.

Measures requiring minor investments Although investment in more modern equipment for large, energy-intensive industries can save considerable energy, investment in small equipment for using and converting energy, such as motors and boilers, can have an equally significant impact on energy consumption where such equipment is used in large numbers. Equipment that can use waste heat also has a similarly large energy-saving potential. In the Group's view, both these types of equipment hold considerable promise in developing countries; they are therefore discussed in greater detail in chapter 5. Finally, better insulation and prevention of energy wastage generally require small amounts of investment in an individual plant but can make a significant difference overall. Opportunities for such small energy savings tend to get neglected; compared to large energy-saving investment for which fiscal and financial promotion measures are well developed, measures for small, heterogenous energy-saving investments are underdeveloped. This is an area where research could be of particular benefit to developing countries.

Measures requiring major investments The technology of major energy-using industries has developed in energy-saving directions as energy prices have risen; plants of the latest vintage are highly energy-efficient, for instance, in steel, aluminum, and cement. Thus, the replacement of old plants by new ones can lead to considerable energy savings. More generally, the establishment of new plants that are likely to make a significant difference to a country's energy consumption needs to be looked at from a national point of view because the effect of the investment decision on energy consumption would persist for decades. Fiscal measures to promote energy efficiency, such as tax credits, investment allowances, and accelerated depreciation, may be effective where there is competition and the economic prospects of an enterprise depend on its profits. If monopolies or public enterprises are significant in the industrial structure, however, more direct regulation to promote energy efficiency may be necessary.

It would thus appear that a great deal of knowledge about energy use and conservation exists and more is continuously being generated in industry; what is required is not so much fresh research in developing countries but collection of information, its dissemination, and its application to specific plants.

Transport

The dominance of oil-fired internal combustion engines has made transport the crux of the strategic problem of oil dependence of developing countries. The countries where development began in the 19th century built up railway networks, but many countries of Latin America and Asia, whose development gathered pace in the petroleum age, depend exclusively on road transport and oil. Thus, we have tried, in Table 6, to identify the developing countries with a high transport intensity. It may be expected that product prices would adjust themselves to transport costs and that transport intensity would not vary much; in fact, the variation is enormous. It may well be due to differences in relative prices; figures given by Moavenzadeh and Geltner (1984), as far as they are comparable, show smaller differences. Other factors suggested are variations in the size of the country, structure of production, location patterns, the degree of motorization, and the rate of exchange. The variation is intriguing, and forms a starting point for an inquiry into its causes and into policy options.

For developing countries, transport forms the link between energy policy, trade policy, and environment policy. It thus provides a base for integrated policy formulation. Current research, however, provides a poor basis for such policy formulation. The volume of research is comparatively small, and much of it relates to modes of transport and transport technologies rather than to the uses of transport. The poverty of research is rooted in the poverty of data: even for industrial countries, the degree of disaggregation in the data is not great.

Research on transport may be divided into research on transport planning and and on transport management. The management of existing transport systems is made difficult by three facts.

- Transport routes are natural monopolies. As long as a road is underutilized, it is wasteful to build an alternative one. By the time it is fully utilized, there is so much settlement along it that to widen it or to build a parallel road is impossibly costly; it is more attractive to ration road capacity.
- Transport requirements are a function of settlement and activity location patterns. Both road capacity and location patterns are difficult to change and, if mismatched, difficult to do anything about.
- There is considerable investment in transport user equipment; if traffic densities demand a change in modes of transport, new user equipment may call for much scrapping of old equipment and for new investment.

Table 6. Transport intensity of gross domestic product (GDP), 1981.

Country	Energy consumption in transport (1000 toe[a]) [1]	GDP (US $ million) [2]	Transport intensity of GDP (toe/$ million) [1/2]
Costa Rica	467	2630	177.6
Tunisia	1247	7100	175.6
Argentina[b]	10541	64450	163.6
Ecuador	2186	13430	162.8
Kenya	1021	6960	146.7
Sri Lanka	597	4120	144.9
Trinidad and Tobago	1001	6970	143.6
Venezuela	9228	67800	136.1
Panama[c]	473	3490	135.5
India[b]	19730	150760	130.9
Colombia	4255	32970	129.1
Egypt[b]	3375	26400	127.8
Jamaica	372	2960	125.7
Pakistan	3017	25160	119.9
Zambia	398	3430	116.0
Burma	669	5770	115.9
Thailand	4250	36810	115.5
Mexico	25260	238960	105.7
Brazil[b]	25318	248470	101.9
Zaire	540	5380	100.4
Morocco	1406	14780	95.1
Peru	2154	23260	92.6
Zimbabwe	537	6010	89.4
Indonesia	7251	84960	85.0
Bolivia	661	7900	83.7
Korea, Republic	5495	65750	83.6
Chile	2523	32860	76.8
Uruguay	669	9790	68.3
Côte d'Ivoire	581	8670	67.0
Algeria	2611	41830	62.4
Philippines	2321	38900	59.7
Guatemala	459	8660	53.0
Saudi Arabia[b]	7602	153590	49.5
Libya	1269	27400	46.3
Nigeria	2985	70800	42.2
Malaysia	1041	24770	42.0
Bangladesh	431	11910	36.2

Sources: For energy consumption, International Energy Agency (1984); for GDP, World Bank (1982b, 1983b, 1984).
[a] Tonne oil-equivalent (toe) = 10 Gcal = 41.84 GJ.
[b] 1982 figures.
[c] 1980 figures.

For these reasons, it is advantageous to invest in research in transport planning, so that problems of transport management can be avoided or postponed (Thomson 1983).

Transport planning encompasses the planning of national location patterns and regional specialization, town planning and design, and modal choice between and within towns (Meier 1974). All three have energy implications.

The point of planning national location patterns is, in part, to minimize transport flows and, hence, energy inputs. Unplanned cities have often grown in developing countries to a size that narrows down the choice of energy sources for them; for instance, the supply of firewood or charcoal to large cities would involve large quantities and expanding rings of deforestation, or dependence on liquid fuels. The long-term relationship between cities and their hinterland should be anticipated and built into the planning of urban size and location. The investment requirements for railways (including the track and the rolling stock) are much higher than for road transport, but the track capacity is also higher. Hence, railways will be economically justified beyond a certain traffic density. Unlike road transport, there is considerable choice in traction technologies and fuels in railways. One way of saving oil is electric rail traction. In a given situation, the possibilities of substitution between roads and rail traction will be limited by traffic volumes. In the long run, however, location planning can concentrate traffic flows between fewer nodes and make them large enough to justify railways (Inter-American Development Bank 1982; Alston 1984; Moavenzadeh and Geltner 1984).

Bottlenecks in interurban transport are few; and where they arise, they usually permit only limited choices. Bottlenecks in intraurban traffic are, however, much more common. Road capacity is a function of road width and the average speed of traffic. People in developing countries walk more and use personal transport less. There is also more transport of goods and people by means of human and animal traction. All these means of transport are slow and use up much road capacity; at the same time, replacing them by mechanized transport is costly and may have serious effects on employment (Thomas 1981). Various low-cost forms of mechanized transport are used in developing countries that also reduce road capacity in a number of ways: by slow speeds, dangerous driving, more frequent breakdowns, etc. (Ocampo 1982). The result is that many cities in developing countries have experienced a slowing of traffic, reduction of road capacity, and clogging of roads, while others have experienced the squeezing out of slower traffic to the detriment of low-income populations.

These problems are peculiar to developing countries and arise from their economic and transport characteristics; they need to be tackled at the stage of planning. The rise of the use of the personal car led to considerable research on urban design in industrial countries (cf., Buchanan et al. 1980); it was reflected in the new towns, and has made them much easier to live in than the older metropolises. At the same time, the metropolises that did not foresee or could not solve the emerging problems (e.g., the movement of the better-off to suburbs, the depopulation and impoverishment of city centres and the rise of automobile traffic) have experienced shocking social and environmental deterioration. The urban problems of developing countries are different, but lead to equally drastic consequences if not tackled in time.

At the planning stage, it is necessary to work out the implications of the peculiar traffic characteristics of developing countries. For instance, if walking is a common mode of transport, more space for walkers must be provided; failure to do so results in the spillover of pedestrians onto roadways. It is also worth keeping workplaces within walking distance of workers' residences. Thus, although the techniques of town planning in developing countries will be similar to those for industrial countries, the data that go into the plans will be very different, and so also the plans.

However, all problems cannot be resolved through planning. In existing cities where location patterns and traffic flows are given, the traffic must be managed within the available road capacity. Here, there are two basic solutions. First, various techniques of traffic separation and road access restriction are used to ration road capacity (Organisation for Economic Cooperation and Development 1973). However, less coercive ways of traffic management are also available. Governments have at least three bases of taxation available in relation to transport: fuels, vehicles, and roads; of these, road taxation and the financing of highways through tolls are little exploited (Yucel [1974]). In any case, it is worthwhile to look at the pricing and taxation of all three — fuels, vehicles, and roads — together, and to relate them to the needs of traffic management.

Second, it is possible to increase available traffic capacity by means of intermodal substitution; suburban (overground and underground) railways and rapid-transit highways are the major modes used. These modes, when introduced into existing cities, are extremely costly, for systems designed for speed and effective traffic separation have high capital costs, land in cities is expensive, and the systems have to be constructed with minimum disruption to existing patterns of life and work. Their high investment costs make research in their economics and design valuable.

Because of their high cost, however, investment in them can seldom be justified on purely financial grounds, and they generally require sustained subsidies. The subsidies can be justified on distributional grounds where the population that lives on the periphery of the cities and consequently uses the new route for long-distance commuting is poor. Essentially, however, the subsidy to rapid transit is not a subsidy to the poor, but a subsidy to long-distance suburban transport. The supply of such transport facilities also tends to create its own demand by encouraging the settlement of population in the peripheral locations they serve: they shape the vast conurbations as much as they serve them. If the national or regional planning of location patterns, advocated earlier, leads to the saving of costly investment in rapid-transit systems for overgrown cities, its value would be greatly enhanced.

Policy

Energy-related policies can be formulated at three levels in the field of transport: policies to reduce transport intensity of economic and social activities, policies to shift traffic to more energy-efficient forms of transport, and policies to increase the energy efficiency of vehicles, by increasing their size as well as by shifting from road to rail transport.

Transport intensity

As shown above, there are enormous differences in the transport intensity of GDP across developing countries that suggest corresponding scope for its reduction in many countries. Not enough is known about its determinants, however, to provide a solid basis for policy. It can be presumed that transport intensity is determined by location patterns among other things, but precisely how they affect transport intensity is not known. In this area, policy formulation would probably have to await definitive research.

Economies of vehicle size

The rise in oil prices in recent years has generated great interest in increasing the energy efficiency of transport through the use of larger vehicles. In urban passenger transport, larger vehicles are undoubtedly more fuel-efficient. Apart from this, public buses are clearly more accessible to the poor. However, developing countries, in the course of rising incomes, display the same shifts from public to private transport and from buses to personal vehicles as industrial countries. Such shifts take the better-off passengers with a higher capacity to pay away from public transport and contribute to its worsening financial viability. In the cities where public transport has survived and prospered, this has often been due to the growing inconvenience of urban driving; but it has also occasionally been due to the convenience, comfort, and punctuality of public transport. Thus, in the long run, the modal split between private and public transport is influenced less by price and more by quality of service. This fact offers scope for more sophisticated long-term urban passenger transport policies than have generally been attempted.

Although large vehicles may be more energy-efficient, cities in developing countries are often characterized by small buses and other small means of public transport (Ocampo 1982). Clearly, energy costs are not an important determinant of the size of vehicles; other factors such as capital requirements, traffic flow characteristics, and ease of driving enter the picture. Energy efficiency is also affected by factors unrelated to size, such as the state of the roads, the level of congestion, and traffic speed. Thus, it is important that policies oriented toward increased energy efficiency should not be confined to the size variable but take all the major influences in view.

Shift to rail transport

The option of moving traffic from road to rail is attractive for two reasons: both because it increases energy efficiency and because it permits a shift from petroleum-based fuels to other fuels, principally electricity. However, the question of modal split between road and rail transport is altogether complicated. It is true that, by and large, railways require less energy per unit of transport. The reason is basically that rails entail less friction between the vehicle and the roadway than rubber-wheeled transport does. However, less friction also means that at the same speed, a rail-borne vehicle needs a greater distance to stop (or to accelerate). If a rail-borne vehicle has to travel in congested conditions and in the midst of other traffic, as trams do, its advantage in terms of energy efficiency is reduced. Hence, rail transport has by and large survived where it has specialized in high-speed, relatively long-distance transport along dedicated tracks. Further, rail transport is more capital-intensive and requires high-density traffic to be competitive with road transport. Thus, the spatial distribution of traffic density determines the boundary of competition between road and rail transport.

However, in practice, the division of traffic between road and rail is also influenced by their differing minimum scale. Roads can be widened and upgraded as traffic grows; and the investment in road vehicles required to maintain a minimum service is much lower than in railway rolling stock. Thus, demand for transport is met by road transport facilities at low traffic densities, and continues to be so met as traffic density increases. When it increases to a point where a railway would be justified, the road transport system is already in place and its displacement is no longer economic. All the major railway systems of the world were built at a time when motorized road transport was nonexistent or in its infancy. Since road transport grew to maturity, most railway lines have been built where either the initial traffic density made railways the cheaper option (e.g., in the haulage of bulky ores from mines to smelters or ports) or where the traffic density grew so much that it could not be handled by road transport within the existing space limitations (e.g., urban commuter traffic).

This is why, if transport facilities are left to respond to traffic needs as they arise, road transport is likely to gain a larger, and rail transport a smaller, share of the market than would be economically justified. To develop a workable railway system, it is necessary to forecast and plan the major traffic flows in a country for some decades in advance; and to make investments in railways in time to meet the growing demand, the advance projections require research. Even when timely investments are made in railway capacity, their utilization and, hence, the successful functioning of railways depends crucially on three factors.

Traffic scheduling and communications on the railways Because traffic moves about in trainloads, there is always a risk that wagons will be at a different place from where they are needed at any time. Moving them where there is demand requires the use of rail capacity which can be a bottleneck at junction points. Thus, the scheduling of rolling stock and the utilization of track generate complex management problems.

Rate structure As railways are regarded as a public utility, their rates are often subject to public regulation; and rate controls are used to cross-subsidize the transport of various products. However, when railways have to compete with road transport, they tend to lose highly rated traffic and hence the profits from which low-rated traffic is subsidized; this is a major reason why railways make losses. It is important that railway rate structures bear a relationship to actual costs, and if the railways are used to give freight or fare subsidies, these should come explicitly from public funds.

Quality of service The advantage offered by road transport relates to quality of service, speed, and convenience. It is seldom enough for railways to offer lower freights or fares; they also have to offer comparable quality of service. To do so, they should be able and willing to offer both rail transport and the ancillary road transport required to carry goods from one point to another. Thus, in order to be practicable, railways need to be run as a joint road–rail enterprise offering integrated service.

Households

In industrial societies, a consumer is practically always a buyer, with a money income that is spent on consumer goods. Many consumers in developing countries do not fall into this stereotype: some consume goods they produce themselves, others collect them from common lands. There is no common system of analysis applicable to all of them, and it is necessary to distinguish between them in energy research and in other research. It is equally necessary to integrate the analysis of all three to get an idea of total domestic demand.

Collector–Consumers

Fuel in various forms is collected by a large number of consumers in developing countries. It is not the only thing they collect; they also collect water, and often food. Wherever such naturally available products are collected, it is possible that consumption will outrun the naturally available supply, or the carrying capacity (Sahlins 1972; Odum and Odum 1976; Harris 1977). Even before the carrying capacity is reached, the average distance between the consumer's residential base and the sources of supply will increase and so will the time spent in collection. More often, it is the woman in the household whose time is taken by firewood collection and other survival activities (Reddy 1982; Tinker 1984). Many figures have been collected and microlevel evidence amassed on the average collection times of firewood. From these collection times, it is concluded that the collector–consumers would be better off if they became producer–consumers and started their own woodlots. The analysis looks sound and leads to a persuasive policy recommendation, which, however, has proved very difficult to implement.

To our mind, this field of research illustrates the dangers of excessively micro research: the system boundaries have been too narrowly defined. For it has also been found in a number of studies that a major part of the demand for firewood comes from cities. Further, a high proportion of rural energy consumption is in the form of twigs and branches collected nondestructively from trees, whereas urban consumption is mainly in the form of logs obtained by felling trees (Reddy 1982; Reddy and Reddy 1983). If this is so, the responsibility for the depletion of the tree stock lies, not with the collector–consumer, but with the collector–seller: the system to investigate is not the village but the urban–rural complex. Townspeople almost invariably use other fuels as well, so the boundaries should be drawn, not around fuelwood, but around all competing fuels. Further, a significant proportion of the demand for wood is for timber for housing and construction. Thus, the system boundaries must be extended again to include construction materials. Finally, the relative scarcity of firewood varies from place to place and has led to different degrees and patterns of energy transition. Hence, research must encompass regional variations. If extended in these ways, the scope and scale of research projects would be greater, but the lessons to be learned would be richer and the number of policy alternatives that emerge would be greater: for instance, alternatives in terms of fuels, construction materials, and the technologies for producing both. The cost and coordination requirements would also be greater, but one of our arguments throughout this report is that organization should be adapted to the needs of research, and not the other way round.

If broadbased research led to the conclusion that a collector–consumer population was straining the carrying capacity of the land and the pressure could not be relieved by manipulating a third factor such as construction materials, the population would either have to come down or change its technologies and grow wood or cook with greater fuel efficiency. It is unlikely, however, that consideration of all alternatives in related fields will lead to these as the only or best alternatives.

Producer–Consumers

Producer–consumers are also called subsistence producers. Like collector–consumers, they do not buy or sell; so far as they do not, the possibilities of influencing their behaviour are limited. To neither is it possible to apply demand analysis of the type used in developed countries for buyer–consumers. More appropriate theoretical formulations are not available, so a great deal of data gets collected and described without accumulation of knowledge (see, however, Bliss and Stern 1978; Sen 1981).

Attempts to formulate policies affecting producer–consumers (and collector–consumers), for instance, promotion of agroforestry or biogas, have also been slow to yield results. In our view, this also is due to inadequate theoretical understanding of the behaviour of these consumers — of their objectives in life and work and of their allocation of resources.

Their central resource is labour. Unfortunately, economists, anthropologists, and physiologists have followed very different concepts of labour or work, none of which has proved especially fruitful (see the section on human energy in chapter 11). Meanwhile, a great deal of empirical research has been done without commensurate advance in understanding. Theoretical innovations will have to emerge in this area before empirical research can be sensibly interpreted.

Buyer–Consumers

The buyer–consumer is the type that is familiar in developed economies, and for whom the standard demand analysis (referred to in the section on micro-level demand in this chapter) has been devised. This type of analysis is equally applicable to buyer–consumers in developing economies, although the ground conditions and implicit relationships are often different. It can be particularly useful for analyzing the effect of changes in prices, taxes, or subsidies on consumers at different income levels and, thereby, on overall income distribution.

However, if consumers are partly collectors, partly producers and partly buyers as often happens in the case of rurally consumed fuels, the case is much more complex; theoretical formulations for such mixed situations still need to be developed.

Cooking

This is the area of domestic consumption that has attracted the greatest volume of research. The result is a welter of figures that does not yield many significant conclusions. Most of the studies simply measure the total consumption of cooking fuels and, therefore, miss out two aspects that may well be of considerable importance. First, cooking always involves food and drink; there must be a relationship between the quantity of food cooked and the fuel used (Reddy 1982). If, as food surveys show, food consumption of the rich can vary by 1.5 to 3 times that of the poor in developing countries, it may have a considerable effect on fuel consumption. Yet the differences in fuel consumption are not observed to be so pronounced (Leach 1985); so there are probably variations in energy efficiency. Second, there is limited but strong evidence that larger households use less fuel per capita (Bialy 1979; Natarajan 1985). Cooking is a heat transfer process, and it stands to reason that cooking in larger quantities should be more fuel-efficient. It is also possible that there is less wastage and, therefore, also economies of scale in food consumption in larger households.

Most energy research has stopped at the doorstep and failed to penetrate the house; the result is that the proximate determinants of fuel consumption remain uninvestigated, and research is confined to external variables such as income and price. Superficial research can lead only to superficial conclusions. The situation is similar to that in respect of research on food consumption, which also has failed to cross the doorstep, and has generated voluminous figures without leading to further understanding.

Lighting

Lighting is an item of consumption with high income elasticity of demand at low income levels. The poorest households and those without access to kerosene and electricity do without lighting. Among those with access, quality of lighting varies with income. There are many types of kerosene lamps with varying oil consumption per hour and intensity of light. The types of electric lights are fewer, but the intensity and quality of electric lighting do vary with income. The most efficient electric lighting available has an energy efficiency of up to 4 times that of the least efficient; energy-efficient lights are not used more widely because their initial costs are higher. Insofar as they are, there is scope for tax-subsidy mechanisms to increase energy efficiency in lighting; they need to be designed through country-specific or site-specific research. Apart from costs, however, the adoption of energy-efficient lights is also influenced by perceived differences in quality. Research can bring a better balance between the range of available devices and user preferences.

Appliances

Electricity is essential to most of the commonly used domestic appliances. Where electricity is available, a large range of appliances is available with considerable variations in capital and in running costs.

Depending on their initial costs, different appliances will have different market penetration curves related to income levels. The purchases of the cheaper ones like irons, heaters, radios, and fans will begin at fairly low income levels, while the most expensive ones, for example, air conditioners, will be bought at much higher income levels (Brooks 1984). The demand for consumer durables has to be analyzed in terms of stock adjustment models; simple price–income models are not appropriate for them. The demand for energy to run appliances is a derived demand depending on their energy input per hour, their intensity of utilization, and their numbers in stock, and analysis of this demand requires correspondingly complex models and field surveys to provide data for them.

Power demand for air conditioners is already a significant part of total demand, and causes serious peaking problems in some African countries. The demand emanating from cooling devices — fans, coolers, air conditioners, and refrigerators — may be important in other tropical developing countries; certainly daily peaks in summer pose problems in many of them. Solutions may be looked for in a number of directions — for example, climatic adjustments to houses, time-of-use pricing of electricity, and improvements in the energy efficiency of appliances. This entire area has attracted little research.

Rural Households

The only part of rural energy demand that has attracted much research is the demand for cooking and heating fuels (Howes 1985). Demand is a behavioural variable, and a theory of human behaviour must underlie its analysis. The received demand theory, framed in terms of a consumer whose entire income is monetary, is inappropriate for rural households in developing countries.

Part of their income is in the form of collected goods, of which fuels can form an important part. Because collected goods are free (though not necessarily abundant), resource costs do not enter the households' calculations. On the other hand, labour costs do. The perceived labour costs are related to the quantity collected and the distance carried in a nonproportional way: the onerousness of quantities as well as distances is insensitive up to a point and highly sensitive beyond a certain point. It is not possible to value the labour involved in collection at the going wage because the alternative of wage labour is not always open. The unequal employment opportunities for men and women will also affect the alternatives open to them, and are related to the relatively greater role of women in collection. Where alternative wage employment is available, or where money incomes in rural areas have risen as in Egypt or the Republic of Korea, the rural population readily ceases to collect fuel. Thus, it is necessary to explore the relationship between collected fuel (and other collected goods) and their labour costs.

Labour costs have been estimated in terms of labour time, but for the earlier stated reason the perceived labour costs may not be proportional to the labour time. "High" estimates of labour time spent in fuel collection have been at least partly responsible for the research effort that has gone into fuelwood forestry and improved woodstoves. The value that a population places on these innovations will, however, depend on the perceived labour costs, and not on labour time. The object of saving labour time would appeal only to a population that is short of it; for one that has ample labour time or only low-value uses for it, the question to ask is: what are the most valuable uses of labour time that can be found for it?

However, in view of the research on fuelwood forestry and woodstoves, one may ask a different question: where can a use be found for this research? The answer would be, where these activities are commercialized, i.e., where selling firewood is an established rural activity, and where woodstoves are used to cook food for sale. Once they are proven in commercial uses, they are likely to diffuse more easily.

Apart from collected fuels, rural households also burn fuel grown or produced on the farm in the form of crop residues and animal residues. There are occasional references in the literature to cultivated fuel crops (e.g., Pathak et al. 1980); but mostly it is the residues of crops grown for other purposes that are burnt. The residues of some food crops should normally give enough energy to cook the edible part at a fairly low level of efficiency of 10–20% (Desai 1985). It is common, however, for farming households to buy or collect woody fuels for their better quality.

In the case of farming households, too, the behavioural models underlying studies of fuel consumption are inexplicit. Farmers vary in their degree of commercialization. Uncommercialized or subsistence farmers use agriculture to convert their labour into goods and services, just like collectors of fuel, and the model applicable to both would be one of allocation of labour flows. Commercialized farmers, on the other hand, run business enterprises, and may fit theories of the firm or the farm. Most developing-country farmers fall in between, and pose unsolved conceptual problems.

Both collectors and producers obtain combustible biomass from vegetation, and their practices have been the subject of academic concern. This concern, which we shall discuss in the first section of chapter 12, is based on naive models. It is not necessarily misplaced, but the conditions of environmental deterioration need to be defined more closely and their connection with fuel demand more directly observed. Thus, studies of fuel consumption should be integrated with those of the environment.

Further, if biomass-burning practices lead to environmental deterioration, they will be reflected in greater inputs of labour time into fuel collection, in the case of collectors, and declining yields in the case of producers. The research studies must be designed to take in these effects: that is, they must either extend over long enough periods or encompass spatial variations to simulate the transitions.

Finally, the scope for rural electrification, and its impact on rural development, modernization, productivity, and living conditions, are not sufficiently well understood, and should be researched further (Munasinghe 1986).

Thus, the models that researchers bring to the study of rural fuel consumption from the mother disciplines of economics, anthropology, and agricultural science need to be integrated and tested if more meaningful theories are to emerge.

Urban Households

The energy consumption of urban households is easier to analyze in a number of ways. First, urban households purchase energy. They are too concentrated spatially to be able to obtain cooking fuel from a local biomass base, and must buy it from outside. Second, they are significant consumers of energy for lighting and appliances. In both ways, they are more akin to those in industrial countries; insofar as they are, models developed in those countries to analyze domestic energy demand can be applied to them with less danger of misapplication.

The urban concentration of fuel demand requires the transportation of large quantities from outside. This means oil or coal in countries that produce them or can import them, but in many countries that are too poor, remote, or short of foreign exchange, it means firewood and charcoal. The consumption of both leads to expanding circles of treeless zones around the cities. Whereas wood is replaced by agricultural and animal residues in rural areas that run out of it, the low energy density and consequently high transport costs of these substitutes make them noncompetitive with wood in towns even at high firewood prices. Where they are competitive, the low cost of woodstoves compared to stoves using gas or kerosene may still lead poor consumers to use wood (cf., Reddy and Reddy 1983; Alam et al. 1985).

The rising firewood prices have led to firewood plantations in some regions. There are cities, however, especially in arid parts of Africa, where commercial tree farming has made little progress despite high firewood costs. The reasons are unclear; but two factors are indicative. First, arid Africa is also the region with high imports of food or food shortages or both. In theory, a commercial farmer who is supplying a city would grow food, fuel, or any other crop that would pay most. The reason why this choice on the farm does not raise urban fuel supplies may be that the cities have outgrown their agricultural supply base. As we showed earlier in the section on demand-based policies, arid and subequatorial Africa has the lowest levels of agricultural productivity per worker in the world; its agriculture is thus capable of supporting the least number of people off the farm. Its capacity to do so was further reduced by the shift to commercial crops in the 1950s and 1960s when the demand for them in industrial countries was strong. The cities grew up around export industries; the exports paid for imported food among other things. As the slowdown of growth in industrial countries slackened the demand for exports, reduction of export dependence and creation of a domestic market as well as resource base became necessary before growth could be resumed. Thus, the crisis is a general economic one, and not simply a fuel crisis. Second, arid tropics are an area where trees grow with difficulty; their natural vegetation is annual grasses and shrubs. Once the inherited stocks of trees are destroyed, their replacement is difficult and costly. Some of the countries of West Asia and North Africa also share this problem but are lucky to have oil, which has become their primary domestic fuel.

Thus, in respect of urban as of rural households, a narrow formulation in terms of fuel consumption can lead to wrong conclusions, and it would be useful to place fuel use in a broader economic and resource context.

Policy

Above, we distinguished between three types of domestic consumers — those who collected fuel, those who produced it, and those who purchased it. It was also pointed out that those who collected fuel did not necessarily collect all other subsistence goods. From the viewpoint of policy, it makes more sense to distinguish people on the basis of whether they collect, produce, or buy food — i.e., to distinguish between nomadic people, sedentary rural populations, and urban consumers.

It is virtually impossible to make effective policies for nomadic people. The only measures that are easy to enforce are those that restrict, regulate, or influence their migrations. Measures to settle nomads in permanent villages, or to keep human populations out of reserved forests, for instance, are not uncommon. Such measures are not taken to deal primarily with energy problems, and are largely irrelevant to them. However, restrictions on the movement of firewood — and indeed, all kinds of wood — can be an important aspect of a policy to control deforestation.

It is easier to formulate policies for settled and especially for agricultural populations. Agricultural taxation has been one of the mainstays of public finance in many developing countries. Even in agricultural economies that are not monetized, it is possible to have taxes or subsidies in kind. However, taxes or subsidies to influence the production or consumption of fuels or to stimulate interfuel substitution in rural areas are not common, apart from subsidies to rural electrification.

Fiscal measures to influence urban demand for fuels, on the other hand, are very common. However, they are not focused on households as such but on the fuels they buy or on fuel-using devices. For that reason, they are discussed in the next chapter.

Chapter 5 Energy Conservation

Three general approaches to energy conservation may be distinguished: process improvement, investment in energy saving, and improvement in the efficiency of energy-using equipment. The last approach is particularly appropriate to developing countries. The designs of equipment under production can be improved; but more importantly, stocks of equipment under use can be studied, and their operation can be improved to raise energy efficiency. Opportunities in respect of certain common types of equipment are illustrated in this chapter.

The application of hydraulic and variable-frequency drives can greatly improve the energy efficiency of motors. To be economical, hydraulic drive must be applied to entire plants and be accompanied by redesign of machines. Variable-frequency drives need the application of microelectronics to be effective.

The size and importance of vehicle industries in industrial countries has led to intensive research on internal combustion engines; a large number of innovative designs are under design or development. The use of two-wheeled vehicles is increasing in developing countries, and a number of them have achieved large enough production to justify research into improving the engines for two wheelers.

Research on Brayton cycle engines in industrial countries is focused on vehicular uses. The developing countries that manufacture gas turbines may find broader investigation of these engines promising.

Research on conventional boilers is likely to concentrate on improving their heat rate by incorporating on-line monitoring systems and diagnostic tools. Among fluidized bed boilers, circulating boilers offer the best prospects. The large inventories of boilers make them particularly appropriate for diagnostic studies and for working out replacement programs.

The diffusion of improved solid fuel cookstoves has suffered because both solid fuel shortage and the inefficiency of traditional stoves in developing countries have been overgeneralized; the need to study the potential markets for improved stoves has consequently been neglected. Research is necessary to identify areas with high perceived fuel costs and the value placed by consumers on various stove improvements, including improved fuel efficiency.

The prevalent approach to industrial energy conservation was discussed under industry-level policies earlier. However, possibilities of energy saving are not confined to industry. It is worthwhile exploring more general approaches to it, of which three may be distingushed.

Process improvement Scientific study of energy-using processes can lead to significant energy savings. Industry-specific studies of this kind are not uncommon (cf., Moles 1984). However, fundamental studies of energy-using processes applicable to a broad range of industries are rare. Research on combustion problems is probably the most widespread owing to the use of the process in diverse industrial operations (Smoot and Hill 1983), but even in this intensively explored field, the gap between theory and practice is wide (Weinberg 1975). The promotion and application of process research requires two things: first, a strong fundamental research capability in independent research institutions, and second, strong ties between the institutions and industry. It is possible for the government to promote both through financial and other incentives.

Investment in energy saving Such investment can range from incremental investment in insulation and waste heat recovery to investment in major new plants using energy-saving technologies. Techniques for incremental energy saving are fairly standardized and well known and do not call for much research. Their application will be encouraged, however, by state action in surveying opportunities in various industries, as well as by subsidies to energy-saving materials and equipment. Saving energy in new plants, however, is a part of industrial innovation, and will require the building of industrial research capability.

Efficiency improvement in user equipment This is a relatively new approach of considerable promise in developing countries. The manufacture of energy production equipment is still strongly localized in industrial countries. This is true of coal mining equipment, oil production equipment, and power plant, and may come to be true of solar and wind equipment also. This pattern of specialization will continue for some time at least. However, many types of user equipment are being used in large numbers in developing countries, and quite a few — such as motors, engines, and batteries — are being produced in the larger developing countries. Hence, a strategy of concentrating on user equipment could lead to significant energy saving, but would deal differently with existing and with new equipment. Existing equipment can be surveyed to identify the major ways of saving energy, both by improving operational practices and by retrofitting, for example, replacement of valves and better insulation. Once the principal measures for saving energy are identified, they can be promoted by persuasive means, such as information dissemination, and coercive means, such as the setting of minimum performance standards. The scope for the latter is greater in respect of new equipment. In addition, however, research can be promoted to design new equipment for greater energy efficiency. The directions of such research are important from the policy-maker's point of view, and are indicated below for some important types of equipment.

Motors

Motors are the prime device used to convert electricity into motive power, and are widely used for this purpose in all sectors except road and marine transport, where the portability and high energy content of liquid fuels make internal combustion engines the predominant prime mover. In stationary uses, the low cost, high energy efficiency, and wide range of sizes of motors give them an edge over internal combustion engines. In 1984, motors were estimated to account for 67% of all electricity consumed and 35% of the primary energy used in the USA (Baldwin 1986). Although comparable figures are not available for developing countries, electricity consumption in motors would be at least as significant in the countries where a large proportion of the electricity is used by industry; in addition, electricity is extensively used for irrigation pumping in a number of Asian countries.

The energy efficiency of operations involving motors is a product of two factors: the efficiency of the motor itself, and the proportion of the work done by the motor that is actually used. Although the technology of motors is mature, with the advent of computer-aided design in the 1970s, the efficiency implications of design changes could be modeled instead of having to be established from prototypes; hence, technical improvements were speeded up. Innovations such as large-diameter copper conductors and new magnetic materials also contributed to increasing efficiency (Baldwin 1986). Even then, the maximum potential energy savings that would result if the current stock of motors were replaced by energy-efficient models was estimated to be 2.4% in 1977 for the USA (United States Department of Energy 1980). The difference between the efficiency of the motors in stock and best-practice models is probably greater for developing countries and needs to be surveyed in situ. However, the general observation for industrial countries, that energy losses are much greater between the motor and the work done than within the motor itself, is likely to be valid for developing countries also.

The energy losses in motor-driven work arise from the fact that the speed of a motor is fixed by the number of poles in it and the frequency of the electricity applied to it. In uses where variable speed is required, speed regulators such as gears, valves, and throttles are used, and it is in these that most of the losses occur (Ladomatos et al. 1978). Three approaches to the reduction of these losses are available.

Direct-current motors The speed of a DC motor can be varied by simple voltage regulation; the necessary voltage regulator can be quite cheap. However, DC motors are bulky, expensive, and not always appropriate in industry. The commonest motor is the AC squirrel-cage induction motor — cheap, simple, and reliable. No simple way of regulating its speed is available as is with a DC motor (Ben Daniel and David 1979).

Conversion to hydraulic drive A variable range of speed and torque can also be obtained from hydraulic motors. This flexibility can be used to eliminate gearboxes on machine tools and to make the tools simpler and cheaper. The savings would be appreciable in a plant using a large number of machine tools, provided the entire plant was centrally supplied with hydraulic power. In a computer simulation of such a conversion, it was found that the energy efficiency of the plant would be raised from 54 to 68% (Ladomatos et al. 1979).

Variable-frequency drives These drives generally embody two devices in tandem or in combination: a rectifier to convert AC to DC current, and an inverter to provide adjustable three-phase voltages to the motor. They were pioneered in the synthetic fibre industry where the extrusion of fibre requires precise and synchronized motor speed drives. Multimotor drives are extensively used in the synthetic fibre industry. Variable-frequency drives have spread to other industries only slowly owing to high costs and lack of perceived need. In recent years, however, the development of solid-state devices with large power handling capacity has led to their rapid adoption in the USA; they are likely to spread to developing countries owing to their considerable economic advantages (Baldwin 1986).

Of the three approaches, the last two are promising for developing countries. Conversion to hydraulics is worth considering only for entire plants, and only certain plants (e.g., machine tool plants) would be appropriate for it. However, opportunities for system applications of hydraulics are worth seeking in developing countries. The potential impact of variable-frequency drives is broader, but their development requires the application of microelectronics. For a country aiming for strength in the latter, design and development of variable-frequency drives would be an important step toward energy conservation.

Internal Combustion Engines

An engine is primarily a machine for converting any of the different forms of energy into mechanical power and motion. Engines that convert heat energy into mechanical power and motion are called heat engines. Heat engines are classified as internal combustion engines (ICEs) or external combustion engines (ECEs) depending on whether the source of heat is inside or outside the engine. If the source is outside, then heat exchangers need to be used between the source and the sink of heat.

R&D activity in ICEs today seems to be directed primarily to the following three areas: minimizing pollutant emission; maximizing engine efficiency; and maximizing engine tolerance to fuel types and exercising greater control over the combustion process (Maly 1983). A distinguishing characteristic of these post-energy-crisis research priorities is that they aim for total optimization unlike the earlier research on ICEs that was aimed at improving isolated subsystems; for instance, ignition control, turbocharging, knock control, etc.

Potentially the most promising area of research in ICEs is that of programed combustion. In improving the overall combustion efficiency, efforts need to be directed toward decoupling the optimum conditions for ignition from those of flame propagation; this can be achieved by programing combustion in such a way that in-cylinder flow and turbulence are optimized. Two methods of doing so are to use purely electrical control or staged ignition. Attempts to control combustion have led to the development of the following ICE designs.

- *Naturally aspirated divided-chamber diesel engines* for light duty vehicles (most light duty vehicle engines are of this type now).
- *Stratified charge divided-chamber Otto engines* (these have found only limited applications).
- *Rotary uniform charge Otto engines.* Early engines had serious problems with poor combustion chamber sealing, high hydrocarbon emissions, and excessive engine misfiring under idling conditions, leading to poor drivability and lower fuel economy. They have been installed only in Mazda cars.
- *Turbocharging* for both gasoline and diesel engines. Turbocharging has shown better results in terms of fuel economy with diesel engines than with gasoline engines, but in both cases it offers advantages in terms of lower carbon and hydrocarbon emissions than the naturally aspirated versions. Nitrogen oxides emissions, however, are higher (Dowdy 1983).

Advanced engines that have not been implemented on any production vehicle as yet and are still in research stages include the following.

- *Open-chamber stratified charge Otto engines.* The two major R&D programs in this area are: the Texaco controlled combustion system, which not only aims at using lean air–fuel mixtures but also has the ability to use a variety of fuels as it is relatively insensitive to fuel properties; and the Ford programed combustion engine, which permits higher power output but makes the engine more sensitive to fuel properties (e.g., octane number).

Another R&D approach in this area is referred to as the Mitsubishi combustion process, but little information is available on it.

- *Rotary open-chamber stratified charge Otto engines* that try to overcome the limitations of their nonstratified counterparts by increasing the fuel economy and reducing hydrocarbon emissions.
- *Open-chamber diesel engines* that attempt to improve combustion through enhanced air–fuel mixing and are classified by the magnitude of the swirl they develop in the combustion chamber (Cole et al. 1983).
- *Adiabatic diesel engines* that attempt to reduce the heat losses in the engine block and recover the heat from the exhaust gases through the use of turbocompounding or a Rankine bottoming cycle or both. Even though these systems make the design of the engine more complicated, they result in 25% less specific fuel consumption than a large conventional turbocharged diesel engine. At present, the research into adiabatic diesel engines is being sponsored by the U.S. Army Tank–Automotive Research and Development Command (Dowdy 1983).

Research on ICEs continues to be centred in the vehicle industries of industrial countries, and engine improvement has been an important component of comparative advantage in the international vehicle market in recent years. It is a promising area of research for developing countries with their own vehicle industries. At the same time, the pattern of personal vehicle ownership in some developing countries is diverging, and two-wheeled vehicles are becoming increasingly important. Improvement of their engines and development of lightweight, energy-saving models would be appropriate subjects for research in those countries.

External Combustion Engines

The primary advantage of ECEs is that they can use a much wider variety of fuels than ICEs because the combustion chamber is separated from the moving parts of the engine. ECEs are basically two types: Rankine cycle engines, and Stirling engines. Rankine cycle engines can operate on any fluid that would undergo a phase change at a suitable temperature. They can be further subdivided into steam engines and organic Rankine cycle engines. The latter use an organic fluid (normally Freon) as an alternative to water in the Rankine cycle.

The maximum working temperature of Freon-based organic Rankine cycle engines is about 150°C owing to the low boiling point of Freon. This low temperature reduces the maximum attainable efficiency (Carnot efficiency); for organic Rankine cycle engines of this kind, the best efficiency obtainable is about 10% (Hurst 1984). While the maximum attainable efficiency in Rankine cycle engines is limited by the temperature of the heat source and the heat sink, moving up to this efficiency essentially depends on achieving the best heat economies possible.

The basic principle of Stirling engines is that the pressure of air, or any gas, will increase if it is heated and decrease if it is cooled. The cylinder of a Stirling engine contains a certain amount of gas. In the early engines, this gas was air but modern engines are more likely to use hydrogen or helium. The working gas contained in the engine is alternately heated and cooled. In each cycle, work is extracted from the gas in the form of the movement of a piston.

There are primarily two major directions of research in Stirling engines: free-piston Stirling engines, and Stirling engines for automobiles (Beale 1981; Dowdy 1983). Free-piston Stirling engines have the advantage that they they are mechanically simple to construct and do away with critical seals needed otherwise to prevent the leakage of the working gas. They can be used as water pumps, cooling machines, and as alternators to generate electricity. However, these engines have as yet remained only as demonstration units and research tools.

The Philips rhombic Stirling engine is currently the favourite for automotive applications. However, this high-pressure crank-type engine has difficult sealing problems that have to be solved to avoid gas leakage and lubricant contamination of their heat exchangers.

Brayton Cycle Engines

Although the steam engine was the first to be developed, its bulk and inefficiency provided the impetus for exploring other engine principles. One such major engine principle was demonstrated in the 1870s in the Brayton cycle engine that used compressed air instead of steam to provide motive power. The nearly simultaneous development of Otto and diesel engines (both ICEs) with greater power output per unit weight than the Brayton cycle engine made them the obvious choice as prime movers for vehicles. However, nearly half a century later, with the development of better metals and greater knowledge of aerodynamics, Brayton cycle engines made a comeback but in a different form. Instead of pistons, they used rotary compressors and expanders (i.e., "turbines"), and such was their advantage in terms of power output per unit weight that they became the dominant prime movers for large-scale air transport.

Gas turbines are engines that work on the Brayton cycle principle, i.e., compression of a working fluid from ambient pressure to elevated pressure; addition of heat to the working fluid at a constant elevated pressure; and expansion of the working fluid back to ambient pressure with the extraction of useful work. Like Stirling engines, Brayton cycle engines are continuous combustion engines but they can be either ICEs or ECEs — although the latter versions of the Brayton cycle engines have not been tried on any significant scale compared with the former.

Gas turbines are the most well developed of the Brayton cycle engines. For automotive applications, two major types of gas turbines are being developed: single-shaft gas turbine, and free-turbine gas turbine. Whereas the former requires the use of continuously variable transmission, the latter can use conventional automotive transmission. Given the high inlet temperatures in gas turbines, one of the most important areas of R&D activity is that of materials — particularly ceramic materials for rotors and other structural elements (Dowdy 1983).

At present, external combustion or indirect firing Brayton cycle engines are in the early stages of development. The advantages of indirect firing are that the engine becomes less sensitive to the fuel quality and a number of low-grade fuels can be used (Rosa n.d.). Research on Brayton cycle engines in industrial countries remains focused on vehicular uses; but research with a broader focus may yield significant results, especially for those developing countries that manufacture gas turbines.

Boilers

Boilers, both in industry and in power generation, account for a substantial consumption of energy. In the industrial sector, the share of boilers in energy consumption is determined by the importance of key steam-raising sectors; for instance, chemicals, engineering, food, and paper. For OECD countries, for example, it has been estimated that boilers, on an average, account for about 40% of the total industrial consumption of energy (International Energy Agency 1982a). It would seem, therefore, that boilers are one of the most important areas for conservation of energy in both developing and industrial countries. In the immediate future, replacing oil with coal in boilers is likely to be an important area of concern for the countries where coal is cheap.

Conventional Boilers

There are basically three types of conventional boilers — sectional boilers, firetube or shell boilers, and watertube boilers. Sectional boilers are used in residential central heating, whereas the other two types are used in industry.

Because the strength required to resist lateral bursting in firetube or shell boilers is directly proportional to the product of pressure and diameter of the shell, there are severe limits to the pressure that can be generated in these boilers. Normally, pressures of 1.7–3.1 MPa can be catered for, but for larger boilers with evaporation rates above 18 t/hour, watertube boilers are used.

Firetube and watertube boilers may either be custom-made or package boilers. In the world's industrial boiler market, package boilers are the largest single sector and represent 75% of the total order value. Their evaporation rating is usually between 14 and 45 t/hour and they use oil or gas as fuel (Dryden 1982).

In both firetube and watertube boilers, coal and oil present problems of excess air control in combustion. In the case of pulverized coal, the limits to minimizing the amount of excess air are set by the conflicting demands of, first, the need to keep the combustion temperature below the fusion temperature of ash; second, the need to avoid deposition of partially burned coal on wall tubes, which would cause corrosion by combustion in pockets of reducing atmosphere; and, third, the need to avoid condensation of exit gases and acid corrosion of gas passes. In the case of oil, too little oxygen would present slack emission problems, and too much of it would mean unacceptable corrosion rates. In the case of heavier fuel oils, as of coal, there is a lower limit on exit-gas temperature and, hence, an upper limit on efficiency.

Conventional firetube and watertube boilers also have problems with low-rank coal. Even though boilers can be designed for specific qualities of the coal being used, low-rank coals present operating problems by their high variability with respect to moisture, sulfur, and ash sodium concentration that create problems of maintaining unit capacity; fireside ash fouling of the boiler heat transfer surfaces; and difficulty in controlling sulfur dioxide and nitrogen oxides (Goblirsch and Talty 1980). There is little in conventional boiler design or operation that can help sulfur dioxide control; it must be dealt with either before or after burning. Emissions of nitrogen oxides can be significantly influenced by boiler design and operating conditions, but the process of generation of nitrogen oxides during coal combustion remains a little explored area.

Given these limitations, the major objective of research in the area of conventional boilers, especially those being used in power plants, is likely to be improving the heat rate. The two probable trends in this area are likely to be the introduction of on-line performance-monitoring systems at more plants to pinpoint deteriorating components and areas of efficiency loss; and the use of on-line diagnostic tools to anticipate failures, schedule outages, order spare parts, and provide labour in an optimal manner (Yeager 1984).

Fluidized Bed Boilers

Fluidized bed boilers were designed to overcome a number of problems associated with conventional boilers. In these boilers, the fuel is burnt on a bed of turbulent air. This improves combustion efficiency; and if limestone or dolomite is added to the fuel mixture, sulfur can be removed. The temperature of combustion is also relatively lower in fluidized bed combustion. Although research on fluidized bed combustion began as early as 1944, until the early 1970s it was being conducted in a climate of dwindling interest in coal. It gathered pace after the oil crisis (Patterson and Griffin 1978).

Fluidized bed boilers have four basic advantages over conventional boilers: different fuels can be burnt in the same combustion unit; desulfurization of flue gases requires little technological effort; emissions of nitrogen oxides are lower because combustion takes place at lower temperatures; and high heat release and heat transfer coefficients can drastically reduce boiler size, weight, and cost (University of Oklahoma 1975; Howard 1979; Poersch and Zabeschek 1980). The implication is that fluidized bed boilers can be built as factory-assembled, packaged units, shipped to sites and arrayed as required. If this happens, there could be a considerable reduction in the construction times and costs of new power plants. However, standard product lines of fluidized bed boilers have not been developed as yet.

Fluidized bed boilers can be of two types — atmospheric boilers and pressurized boilers. The latter combine a gas turbine and a steam turbine cycle, and increase the overall efficiency of the system by approximately 5% (Müller et al. 1982).

Poor combustion efficiency and high particulate emissions arising from short residence time of the fuel in bed, poor lateral mixing and high elutriation of fine particles of carbon sorbent or bed, and difficulties in removal of ash and heavy combustibles have led to R&D on circulating bed fluidized bed boilers. Liquid fuel can also be used in these boilers without an atomizer (Tata Energy Research Institute 1983). It is these boilers that have a greater chance of commercialization in the future than conventional fluidized bed boilers.

Retrofitting Existing Boilers

One of the major problems encountered in retrofitting existing boilers to coal or biomass fuels is derating capacity. Also, existing boilers that use oil and gas often cannot easily be retrofitted to direct coal or biomass combustion because large new combustion chambers would be required for direct firing. However, charcoal–oil slurry can be burnt with only small modifications in existing equipment (Meta Systems Inc. 1982). Conversion to coal firing is easier than changing over to biomass firing. In the latter case, an alternative could be to utilize low or medium heating value gas obtained from gasifiers.

In retrofitting oil- and gas-fired boilers to coal or introducing new coal-fired boilers, the economics is site-specific. The most favourable case may be that of a greenfield site where expenditure on a new boiler must be incurred and where there are no constraints imposed by a layout of an existing site. The next most favourable case could be an existing site where an oil or gas boiler needs replacement because it has reached the end of its life. And lastly, there could be cases where economics is sufficiently favourable to take an oil or gas boiler out of service early and replace it with coal (International Energy Agency 1982a).

However, efficient retrofitting can be done only if countrywise boiler stock records are created, listing characteristics such as the number of boilers and installations, pressure specification of the steam required, capacity distribution of the boilers, age distribution, utilization and hence the fuel requirement, type of fuel currently used, and previous conversion of fuel usage. Only on the basis of this information can the economics of retrofitting to coal in each country or regions within it be worked out. An inventory of national boiler stocks would therefore be the first step in any research in this field.

Solid-fuel Stoves

The empirically observed low efficiency of cooking with traditional solid-fuel stoves suggests the possibility of saving fuel by raising efficiency. The decline in stands of wood and the use of crop and animal residues as fuel in developing countries suggest a need to save fuel. Numerous experiments have been made to design cheap, efficient stoves that would turn this need into demand (cf., De Lepeleire et al. 1981).

Although some of the improved models have had considerable local success, their overall diffusion has been perceived to be limited compared to the number of researchers engaged in research, the number of models developed, and the ostensible stress on practical results in cookstove projects. Three major explanations have been offered.

- The new designs are based on "intuition rather than perceptive engineering analysis backed by reliable data" and consequently do not perform significantly or consistently better than traditional stoves (Prasad 1983). In other words, better science is needed to design distinctly better stoves.
- Fuel consumption is less a function of stove design than of the availability and cost of fuel (Foley and Moss 1983). There is considerable scope for saving fuel even with traditional stoves if the fuel supply situation calls for it. The efficiency of a traditional stove is within the cook's control to some extent, and its range of variation is so great that improved stoves would have to exceed the achievable efficiency of traditional ones significantly and consistently if they are to find general acceptance.
- The shortcomings lie in the downstream manufacture rather than in prototype design. The manufactured models are nonstandard, fragile, short lived, expensive and, for one or more of these reasons, uncompetitive with traditional models (Manibog 1984).

Although these factors have probably contributed to the lack of success of stove projects in various places, it is not possible to assess their relative incidence or importance. In fact, one of the most frequent shortcomings of research on stoves is that it does not embody field testing or evaluation; without either, an ex-post judgment on the research is bound to be qualitative and imprecise.

However, a study of the available assessments suggests that both solid-fuel shortage and the inefficiency of traditional stoves have been overgeneralized. Shortages of biomass fuels — or more accurately, their high perceived costs, whether in terms of labour for collection, production costs, opportunity costs, or price — are strictly local, and we have no reliable data on how widespread they are in developing countries. The inefficiency of traditional stoves is partly due to the mismatch between the characteristics of solid fuels and the requirements of cooking, and partly arises from the cook's optimization of parameters other than fuel efficiency.

In its simplest form, cooking can be looked upon as a series of heat transfer operations with varying heat input requirements. The reason for the high energy efficiency of cooking with gas or kerosene is that both permit precise control of heat output; this is also why they are the preferred fuels of cooks everywhere.

The way in which heat output is controlled in fluid-fuel stoves is through the control of fuel supply — by means of a valve in a gas stove, and by the regulation of wick length in a kerosene stove. The valve or the wickholder effectively separates the combustion zone from the fuel tank. This separation cannot be achieved in the case of solid fuel. The combustion zone is part of the fuel, and every fuel has a characteristic time pattern of heat supply. For instance, in a fuel with high moisture content the water is first vaporized; heat supply during this phase is low. As the water is driven out, heat supply increases. Fuels with a high surface-to-volume ratio like straw, dungcake, or paper burn and begin to supply heat rapidly; fuels with a low ratio, e.g., hard coal, burn slowly.

Cooks learn or work out ways of making the recalcitrant solid fuels yield their required heat demand pattern. First, they mix slow-burning and fast-burning fuels: for instance, they start the fire with a quick-starting fuel like straw, and use thick logs when they want a slow fire. Second, they withdraw fuel from the combustion zone; sticks and logs are particularly easy to pull out or push in. Third, they quench the fire when they do not need it or when they want to reduce heat supply. Finally, they use different cooking devices — a fast-burning water heater with a chimney for bath water, a small iron charcoal-burning stove for small but quick jobs like making tea, a massive earthen stove for long cooking jobs, etc. All these are time-saving devices; those will be used that the cook can afford with the given income and fuel supply. Where the fuels available do not permit a broad range of variation in heat output, the type of cooking is adapted to the fuels. For instance, in an area where only fast-burning fuels like straw and dung are available, the cook will make foods that can be cooked quickly; in households that are short of fuels, hot baths will be uncommon, and so on.

Thus, the inefficiency of fuel use in cooking arises from the fact that the pattern of heat release from various solid fuels can only imperfectly be controlled and matched with the pattern of heat demand. The degree of mismatch will vary from one cooking operation to another, and so will fuel efficiency. In addition, the cook adopts practices such as withdrawing fuel from the fire or quenching which improve the correlation between the time patterns of heat supply and demand, but in doing so reduce fuel efficiency. Where fuel is scarce, cooks indulge less in such convenient but fuel-wasting practices; they also adapt the cooking operations to the fuel scarcity. Thus, fuel efficiency partly reflects the behavioural response of cooks to fuel scarcity or abundance. However, this response may be slower than the rate at which regional fuel scarcity develops; in that case, there will be real distress.

If this interpretation is correct, it is necessary first to identify the areas in developing countries with high perceived fuel costs. (Values given later in Table 11 suggest that per capita supply of combustible biomass is low in a belt stretching from West Africa to East Asia.) Within the fuel-scarce regions, towns are known to be suffering from particularly high fuel costs. Location of such fuel-short areas is the first step toward finding potential markets for improved stoves. Within such areas, some classes of consumers are likely to be more sensitive to fuel scarcity. For instance, commercial cooking establishments are likely to be more aware of the impact of fuel costs on their viability — although fuel may account for a smaller share of their costs than of household costs.

Even after doing this, it would not always be correct to assume that fuel efficiency is a matter of prime concern to cooks. Rather, it is advisable to investigate what features they value most in a stove. Some, such as the controllability of heat output and time-saving, are universal. Others are likely to be site-specific at least to some extent. For instance, smokelessness would be valued in close, confined spaces; radiation of heat would be an inconvenience in hot climates. A stove that meets a number of consumers' requirements has a better chance of acceptance than one that gives an improved performance in only one respect.

Finally, the key to the control of heat output as well as to fuel efficiency lies in regulation of the fuel–air ratio. Adjustment of the fuel–air ratio plays a critical role in the efficient running of industrial furnaces. Fuel-efficient stoves were developed in industrial countries over a century ago; their essential features were a closed firebox and controllable entry of air. Although the design of neither modern furnaces nor old ovens may be appropriate for cookstoves in developing countries, advances in this field are also to be expected from the manipulation of the fuel–air ratio.

Chapter 6 Liquid Fuels

The energy-related problems of developing countries arise from the dependence of the development process on the supply of inanimate energy. They were serious before the oil crisis, and will remain so after the fall in oil prices. However, the developing countries as a group are highly oil dependent, and most of them rely on the international market for oil. Hence, global oil and energy futures are of great interest to them. These futures are inherently uncertain, but reducing their uncertainty through research is important.

The uncertainty partly relates to the ultimate reserves of oil, whose basis has been challenged by the theory of nonbiogenic origin of gas and oil. Whether this theory is right or wrong, the intensity and quality of past exploration in most developing countries have been low, and there is scope for further exploration. Here, exploration contracts between developing countries and oil companies require a complex combination of legal and economic expertise and have to be devised for local circumstances. Exploration activity in developing countries has been low even after the oil crisis; most of it has been concentrated in countries with proven prospects, and undertaken by national oil companies. Thus, developing countries may be underexplored because their oil prospects are considered too small or risky by multinational oil companies. In that case, research into alternative institutional structures for exploration is called for.

Equally uncertain are the international oil markets and prices. While some of this uncertainty is irreducible, it is still important for a country to better understand how the oil market works and oil prices behave.

Should oil begin to run out, methanol from gas will be the prime successor either as vehicular fuel or as an input for gas-based gasoline. Research into its commercialization would be undertaken in industrial countries. The making of methanol from wood would prove feasible only where foreign exchange is scarce and wood is cheap.

Ethanol has been commercialized in Brazil and Zimbabwe; there are few developing countries with equally favourable prospects. Although ethanol production is an established process, its economics can be improved by research aimed at reducing feedstock costs, increasing capacity utilization, and improving fermentation efficiency.

The rapid increase in oil prices in 1973/74 triggered global fears of the exhaustion of oil in a few decades and of unpredictable disruptions in its supply at any time. It led to a search for ways of saving and replacing oil and to a burst of research to the same end. Conversely, the decline of oil prices since 1982 has led to a decline in energy research and in funds available for it. In developing countries the decline is probably even greater, for they have also been seriously affected by the stagnation in the world economy.

In the Group's view, energy-related problems of developing countries were serious even before the oil crisis, and continue to be so even after the recent fall in oil prices. For they arise not simply from oil dependence, but from the dependence of the development process on the supply of inanimate energy. The difference between industrial and developing countries arises from the energy implications of growth in either. Having reached high levels of income, energy consumption, and technological capacity, industrial countries could maintain rates of growth similar to those in the past few decades, and still manage to constrain the growth of energy consumption to a low and manageable rate. Developing countries would face a much more difficult task in doing so, as their rates of growth and their rates of increase of productivity must be higher and their growth would entail a shift toward more energy-intensive activities. For these reasons, it is essential to build the technological capacity of developing countries to deal with energy-related problems.

Developing countries as a group are extremely oil-dependent. If China and India, both major coal producers, are excluded, 61% of the commercial energy consumed by the rest in 1980 was provided by oil (World Bank 1983a). Oil-dependent countries need to have an oil policy, and must make assumptions for policies that require research.

National oil policies must be formed within the global energy context. The uncertainties in the global energy futures far exceed the predictable in the present state of knowledge. Specifically,

- The possibility of global warming is discussed in "The Greenhouse Effect" in chapter 12. If the likelihood of this event became more definitely established, and if reduction of global carbonaceous fuel consumption were found to be the only way to prevent its disturbing impact, the world would have to shift in a few decades to alternative fuels, of which nuclear electricity and hydrogen are the only ones that can be produced in quantities that would meet even the present demand in industrial countries.
- More is known about the risks of nuclear power, although what we know may be significantly influenced by future accidents — or their absence. If the risks come to be globally regarded as unacceptable, the only major sources the world could turn to are solar energy and hydrogen (Bockris and Veziroglu 1985). The investment costs of exploiting them are likely to be so high that an extreme conservationist strategy would become economically more attractive (Goldemberg et al. 1985).
- If global warming comes to be viewed as less likely or more manageable, and nuclear power is regarded as unduly risky, there would be an argument for continued reliance on fossil fuels until they become too costly or their environmental impact becomes intolerable. Even before they do, the obvious impact of acid rain and its connection with large-scale fossil fuel combustion supports a conservationist strategy, at least in the regions where such combustion is concentrated.

The views of the Group's members range across the spectrum of the above possibilities. However, they all agree that in the present state of knowledge a variety of views of the future can be reasonably held. Reducing the uncertainties is in the interests of the entire world, and developing countries would be well advised not just to keep a watching brief but also to participate in research directed toward it. Meanwhile, however, developing countries would be justified in assuming that oil would or should retain its importance for decades to come.

Oil

While the importance of oil to developing countries is incontestable, it is difficult to measure its degree. In Table 7, we list the developing countries for which the burden of energy imports was the heaviest. There can be some debate on how to measure the burden. It would be simplest to relate energy imports to merchandise exports. For some countries, however, invisible receipts have become important in recent years: receipts from tourism in the case of some, remittances from emigrants for others. For other countries, invisible payments — principally interest payments — have created difficulties even when the balance of trade was favourable. Hence, we have related energy imports to merchandise exports as well as to all major receipts on the current account.

Some oil exporters faced the obverse problem of excessive dependence on oil. The rise in the value of oil exports leads to the appreciation of the domestic currency, the decline of domestic industry, and the growing specialization of the country's activity base. The danger is greater when the reserve–production ratio is low and oil is expected to run out in the near future: in those circumstances, it is difficult to restructure the economy fast enough to ensure that there is no fall in per capita income when oil runs out. To identify such countries, we give the export dependence on oil and the reserve–production ratio of those developing countries that rely heavily on oil exports (Table 8).

Figures have not been published after 1981, but the fall in oil prices has substantially changed the picture. The ratio of oil imports to exports of the countries in Table 8 has declined; at the same time, some have sunk further into debt, while the terms of trade of others have been worsened by exchange rate depreciation and a fall in export prices. Nevertheless, the countries in Tables 7 and 8 are the ones whose oil dependence poses long-term problems and calls for long-term solutions.

Solutions to the problems arising from oil dependence can be sought at different levels of generality. All countries can tackle them by means of macroeconomic policy. They can also look for solutions through energy demand management and conservation (chapters 4 and 5). They can explore the economic validity of producing oil substitutes, which are discussed in this and the next chapter. Finally, they can look for oil within their own frontiers and produce it. Those countries that produce or import it can refine it.

World Oil Reserves

The most careful and authoritative estimates of world oil reserves show them even now to be only large enough to last a few decades. The more meticulous authors have frankly characterized them as "subjective," and subject to a wide margin of errors: for instance, while the mean estimate of remaining reserves made by Masters (1983) for the 1983 World Energy Conference was 182 Gt, the probability was stated to be 95% that they might be 149 Gt, and 5% that they might be 306 Gt. They also believed that the high estimates would require new discoveries of fields like those of Saudi Arabia, which they considered unlikely. However, the estimates are sensitive to new discoveries, especially those of supergiant and giant fields, for experts take the known fields as their starting point and proceed to more uncertain reserves.

Conventional petroleum geologists take as a basic premise that almost all

Table 7. Energy imports as a proportion of exports and foreign exchange receipts (US $ million), 1981.[a]

Country	Energy imports [1]	Merchandise exports [2]	Exchange receipts[b] [3]	Energy imports as % of Exchange receipts [1/3]	Energy imports as % of Exports [1/2]
Brazil	12049.4	23276.0	10340.0	116.5	51.8
Guatemala	749.2	1299.0	974.9	81.5	61.1
Côte d'Ivoire	543.1	2734.0	819.6	66.3	19.9
Turkey	3903.5	4703.0	5937.0	65.7	83.0
Kenya	720.7	1072.0	1161.1	62.1	67.2
Trinidad and Tobago	1192.0	2531.0	2030.7	58.7	47.1
India	6531.8	8437.0	11450.0	57.0	77.4
Morocco	1121.0	2283.0	2001.0	56.0	49.1
Nicaragua	216.9	500.0	408.3	53.1	43.4
Jamaica	496.7	974.0	959.9	51.7	51.0
Uruguay	534.6	1229.7	1130.7	47.3	43.5
Thailand	2974.7	6902.0	6362.0	46.8	43.1
Philippines	2574.9	5722.0	5653.0	45.5	45.0
Dominican Republic	475.2	1188.0	1045.8	45.4	40.0
Liberia	127.4	529.0	291.0	43.8	24.1
Ethiopia	164.6	374.0	379.7	43.3	44.0
Korea, Republic	7864.0	20671.0	19653.0	40.0	38.0
Sri Lanka	466.2	1062.5	1250.8	37.3	43.9
Tanzania	283.0	688.3	760.0	37.2	41.1
El Salvador	213.8	768.0	648.0	33.0	26.8
Pakistan	1497.6	2730.0	4737.0	31.6	54.9
Costa Rica	203.3	1003.0	681.9	29.8	20.3
Sudan	289.5	792.7	1002.4	28.9	36.5
Colombia	797.5	3219.0	2868.0	27.8	24.8
Chile[c]	963.6	4705.0	3498.0	27.5	20.5
Jordan	739.3	733.2	2776.1	26.6	100.8
Tunisia	684.8	2102.0	2685.0	25.5	32.6

Source: Compiled from World Bank (1982b, 1983b, 1984) and International Monetary Fund (1984).

[a] Only countries for which energy imports as a percentage of foreign exchange receipts was greater than 25%.

[b] Foreign exchange receipts were calculated by totaling merchandise exports, other goods and services (net credits), and unrequited transfers (private and official).

[c] 1980 figures.

underground hydrocarbons were formed from biomass and marine animals that became buried underground. Recently, Gold (1985) has resuscitated the contrary view, which he traces back to Mendeleev (1877), that most of the hydrocarbons are abiogenic in origin. According to him, methane is generated deep underground and migrates toward the surface. Some is converted into carbon dioxide and escapes into the atmosphere, but a good deal must be trapped below the surface, including some that has been converted into oil. The biological markers that characterize oil and gas formations are not peculiar to them, and are found in nonpetroliferous rocks as well. Gold finds support for this theory in the fact that methane of clearly nonbiological origin is common in the atmospheres of Jupiter, Saturn, Uranus, and Neptune, and tarlike substances can also be inferred on asteroids. If the theory is right, much larger quantities of gas, but also of oil, await discovery than conventional geologists would expect.

Further, the undiscovered hydrocarbons would not be where conventional geologists expect them, but near plate boundaries, and deeper. Because they have not been looked for there, the volume of direct evidence to support Gold's theory is small. Much more will have to accumulate before it can be used in oil exploration. However, its implications for developing countries, especially those that are short of

Table 8. Export dependence on oil, 1981, and reserve–production ratio, 1982, in major oil-exporting countries.

Country	1981 Exports (US $ million) Petroleum and products [1]	1981 Exports (US $ million) All commodities [2]	Energy exports as % of total merchandise exports [3 = 1/2]	Estimated proved reserves of oil on 1.1.1983 (million b[a]) [4]	Estimated oil production 1982 (million b/day) [5]	Reserve–production ratio (years) [4/5 × 365 days]
Libya	15513	15571	99.6	21500	1.127	52.3
Iraq[b]	10914	11064	98.6	41000	.914	122.9
Saudi Arabia	116222	119916	96.9	162400	6.484	68.6
Iran[c]	250555	25943	96.6	55308	1.896	79.9
Nigeria[d]	15563	16405	94.9	16750	1.324	34.7
United Arab Emirates[b]	8585	9078	94.6	n.a.	n.a.	n.a.
Oman	4420	4696	94.1	1730	.328	22.8
Venezuela	16265	17518	92.8	21500	1.826	32.3
Algeria[e]	14313	15624	91.6	9440	.750	34.5
Qatar	4920	5389	91.3	3425	.340	27.6
Trinidad and Tobago[e]	3378	3761	89.8	580	.182	8.7
Congo[e]	856	955	89.6	1550	.087	48.8
Gabon	1925	2189	87.9	460	.130	9.7
Kuwait	13178	16300	80.8	64230	.675	260.7
Syria[e]	1662	2108	78.9	15210	.175	23.8
Mexico	13910	19379	71.8	48300	2.734	48.4
Indonesia	14393	22260	64.7	9550	1.341	19.5
Egypt	2082	3232	64.4	3325	.667	13.7
Brunei	2413	4022	60.0	1	.155	21.9
Ecuador[d]	1178	2104	56.0	1400	.215	17.8
Tunisia	1352	2504	54.0	1860	.106	48.1

Source: McCaslin (1983), United Nations (1984).
[a] 1 barrel (b) = 159 L.
[b] 1978 figures.
[c] 1977 figures.
[d] 1979 figures.
[e] 1980 figures.

oil, are portentous; it is in their interest to help in and promote research that would test the validity of the theory.

Even if the theory were wrong, there are large areas in developing countries that are potentially oil-bearing according to conventional geology. The probability of finding oil there depends, not on global reserves remaining to be found, but on the past intensity and quality of exploration, which are low in a number of developing countries (Halbouty 1983; Parra 1983). Where such areas exist, exploration is called for irrespective of global pessimism on remaining reserves.

Exploration and Development

Exploration and production were relatively mature technologies in the 1960s. The advent of offshore drilling and deep drilling, whose competitiveness was greatly increased by the rise in oil prices, has turned exploration and production technologies into rapidly changing frontier technologies. With this acceleration of technological change, there has been a change in the technology market. Earlier, oil companies, especially the major ones, had better mastery of technology than others outside the oil industry. In the last 15 years, the oil technology market has tended to divide into a number of specialist technology markets, each dominated by a few firms (Surrey and Chesshire 1984).

The major multinational oil producers are no longer the prime owners or controllers of technology. However, they still possess field experience that is important in interpreting and dealing with site-specific geological conditions; and they have competence in packaging technologies from specialist companies as required for particular exploration or development jobs.

In the 1960s, the major oil companies supplied oil to the market economies from a small number of prolific fields. Owing to the low cost of production from those fields, it was difficult for newcomers to compete with them; the oil market was therefore oligopolistic and stable. However, the leases of oil companies in North Africa and West Asia were nationalized in the early 1970s; the major oil companies were converted from owners into marketers of oil. They therefore became more interested in exploring new areas. The appropriation of their profits by the oil-producing countries reduced the competitive strength of the majors and made it easier for newcomers to enter. Thus, there developed a market in exploration and production contracts in the 1970s. The norm was for a country to lease out blocks for exploration. Both the attraction of bids and the drawing up of contracts became skilled operations. The expertise they require has been available from professional consultants or through technical assistance programs of the United Nations agencies. This has also been an area of some good studies (e.g., Hossain 1979; Van Meurs 1981). Exploration contracts require a complex combination of law and economics, and oil contracts have much in common with other resource contracts. Research will continue to be needed in this area for the application of principles to new situations and for systematization of experience.

However, it is not clear that developing countries need only to devise the right terms of contract, for oil companies require a combination of low political risk and high economic returns that few developing countries can offer (Parra 1983). Of the major expansions of oil production since 1973, two — in the North Sea and Prudhoe Bay — have been in industrial countries, and one in Mexico, which is contiguous to the USA. It is particularly difficult for those developing countries, which because of large domestic markets or small discoveries are unlikely to become substantial exporters, to attract oil companies.

Statistics from the data base developed by IED Consulting and EDPRA Consulting are revealing (Table 9). Between 1973 and 1981, concessions in producing developing countries remained roughly constant, while those in nonproducing developing countries fell drastically. Seismic work nearly doubled in producing countries and declined in nonproducing countries. Of the 678 exploratory wells drilled in developing countries, only 40 were in nonproducing developing countries. Thus, exploration activity is highly concentrated in countries where prospects have already been proved and have resulted in production. Most of the exploration activity in producing countries is not by multinational oil companies at all; over 70% is by national oil companies of Argentina, Brazil, and India (Foster 1985).

This underexploration of developing countries may be due to a lack of the right type of agreement. Generally, where the prospects of oil discovery are high, international oil companies are prepared to take all risks in return for a share of the eventually discovered oil. However, the prospects of discovery may not be good enough, an oil-importing country may not be prepared to let part of the discovered oil be exported, the country may be poorly located for access to the oil market, or an oil company may perceive political risk. The terms of compensation have to vary to reflect these conditions. A great variety of contracts is prevalent. However, research to relate situations and the optimum contracts for them may facilitate further exploration in developing countries.

It is also possible, however, that small or politically "risky" oil prospects in developing countries are underexplored for lack of companies that would package and sell the required services. The framework for filling this institutional gap exists in the Caracas Programme of Action (Dorado 1985), and a number of constructive ideas have been generated by Ross (1984) in his paper written for the Group. We consider this a highly promising area for research and action.

Oil Markets and Prices

When oil prices rose in the early 1970s, the rise was readily associated with the low estimates of the reserve–production ratio. The decline in oil production in the 1970s was predicted by Hubbert (1962) 10 years earlier on the basis of the theory that the production of minerals followed a logistic curve; this theory suggested that marginal production costs must rise progressively after peak production was reached, and that prices would follow them. In fact, as subsequent events have demonstrated, the factors that influence price are more complex.

First, the notion that oil production is determined by supply, and demand adjusts itself to it, can no longer hold. Demand has proved to be price-elastic, and while a good deal of its price-sensitivity is accounted for by interfuel substitution that is reversible, there is an important element of increase in utilization efficiency that would be irreversible. Thus, Odell's (1984) view that, if prices continue to be high, oil would cease to be used before it is exhausted is no longer so fanciful.

Second, oil prices have not, perhaps never, been based on marginal costs; since 1973 at any rate, OPEC (Organization of Petroleum Exporting Countries) has had an influence on prices that has had nothing to do with costs. More recently, the decline in prices can be traced back to the rise in the non-OPEC share of the international oil market, the consequent decline in OPEC's influence, and finally Saudi Arabia's abandonment of its policy of restraining its own output to prop up

Table 9. Indicators of exploration activity in oil-importing developing countries, selected years, 1973–83.

		Producing	Nonproducing	Total
Contractual holdings of prospecting rights (million km^2)	1973	1.58	5.92	7.50
	1980	1.57	2.55	4.12
	1981	1.53	2.87	4.40
Seismic work (1000 line-km)	1973	125.1	86.6	211.7
	1980	237.9	60.4	298.3
Exploratory wells drilled (number)	1983	638[a]	40	678[a]

Source: Derived from Foster (1985).
[a] Data exclude India and are probably incomplete for some other countries.

the price. On the demand side, there are large buyers whose influence may be less evident but no less real.

Finally, even if prices were determined by marginal costs, they would show a continuous rise only if all the reserves were known and the cheapest reserves were exploited first. This is far from true. New finds of low-cost reserves are always possible, as in Mexico in the last decade. Further, it is inherent to the exploitation of oil reserves that new reserves should continue to be found at virtually no additional cost for some years after a field goes into production. For production is started once exploration has established the minimum necessary reserves, and information continuously gathered in the course of production leads eventually to the establishment of total recoverable reserves, which are almost invariably higher than those initially confirmed. Even if all reserves and the cost of exploiting them were known, some countries would exploit their own high-cost reserves for reasons of security or balance of payments.

Thus, the structure of the international oil market is complex and changing. It is important for any developing country that is importing or exporting oil to form an idea of how oil prices would behave and, for this purpose, to obtain and improve its understanding of the working of the oil market.

Alcohols

Among liquid substitutes of oil products, two alcohols, methanol and ethanol, are the most likely candidates. Their energy density is appreciably lower than that of oil-based fuels — 19.9 GJ/t for methanol and 26.8 GJ/t for ethanol as against 44 GJ/t for gasoline and 43 GJ/t for diesel oil. Hence, larger quantities of them would be required to drive the same distance, and the same volume in the storage tank of a vehicle would give lower mileage. However, their high octane number implies that they can be used as straight fuels in engines with higher compression ratios, and can achieve higher fuel efficiency than their energy content would suggest; pure ethanol is thus expected to achieve 20% higher efficiency in a high-compression engine than its energy content implies (World Bank 1980b). Both are highly soluble in water and therefore difficult to separate from it. Whereas some water can be tolerated in them if they are used alone, they must be anhydrous if blended in gasoline.

Despite these limitations, they would be serious candidates for substitution as vehicular fuels if oil became significantly more expensive. The reason is that, being liquids, they are cheaper to handle and transport than solid or gaseous fuels. Petroleum fuels have dominated road transport despite the fact that natural gas was much cheaper per unit energy in North America; part of the reason is that the delivery system was built for liquid fuels and fed into a large stock of oil-driven vehicles. It was impossible for gas to break into the market because the entry costs were high. If oil were to become more expensive, it would be easier for alcohols to take over part of the market than for gaseous fuels.

Methanol is already in use in the manufacture of high-octane gasoline additives. Both methanol and ethanol improve the octane rating of gasoline if added in small quantities (about 5–15%), and are preferable to lead additives or alternative refining processes for this purpose. This is the best use of alcohols in vehicular fuels, and is economically justified even now in broad circumstances. They can be used in higher proportion (15–20%) as extenders to blend with gasoline without engine modification. In this use, what matters is whether their costs are lower than those of gasoline; foreign exchange shortage may justify their shadow pricing in local conditions. If they are found cheaper or economically justifiable, the designing of engines to use them without blending would also be justified as long as the demand was large enough.

Methanol

Methanol has long been in use as a solvent and an intermediate for acetic acid and other chemicals, and continues to be a bulk chemical. It is mainly produced from naphtha or natural gas. Its producibility from natural gas is what makes it a prime candidate for gasoline substitution. For if industrial countries need a substitute, it will be required in large quantities, and a biomass-based substitute cannot be produced in sufficiently large volumes without devoting vast areas of agricultural land to its production (Smil 1983). Such substitutes will appeal to countries with a large arable area per capita, and may become more valid as the efficiency of use of liquid fuels rises. For industrial countries as a group, however, methanol from natural gas would remain of considerable interest.

The interest in methanol has increased with the development of a process by the Mobil Oil Corporation to make gasoline from methanol. The process is relatively simple and has low energy costs. It has been used in a 14500-barrel/day gasoline plant based on natural gas in New Zealand. Experiments have also been made with a somewhat more efficient fluidized-bed process in Europe and the USA (World Bank 1982a).

The currently dominant process of synthetic gas conversion is a high-pressure, high-temperature process. Its capital costs are high, and economies of scale are significant up to single-train capacities of 2000–2500 t/day or 0.6–0.75 Mt/year (Humphreys 1977). Thus, a country would have to consume 3–4 Mt/year of gasoline to consider producing methanol for blending. If the methanol were to be used undiluted in specially designed engines, a country would have to import methanol-driven cars and hence await their commercialization elsewhere — or manufacture and commercialize them. Either way, only a country with a large domestic demand for gasoline can take initiative in methanol substitution. This limits the possibilities to perhaps half a dozen of the larger developing countries (or combinations of smaller countries).

Methanol can also be produced by gasification of wood, and was in fact so produced till the advent of cheaper hydrocarbon feedstocks. This technology is being modernized (Reed 1981; Egnéus and Ellegärd 1985). It is also possible that advances in enzymatic hydrolysis will improve the performance of wood as a feedstock for ethanol, which is a better automotive fuel (Ostrovski et al. 1985; Saida et al. 1985). However, collection of wood from large enough areas to support a methanol plant is costly, and wood has valuable alternative uses as timber and in paper industries. Thus, although experimentation in wood-based methanol continues, it seems unlikely that it will compete internationally with gas-based methanol. Closer, site-specific investigation of process options would be necessary before major investments in research on methanol from wood can be recommended; they are likely to prove feasible only where the shadow price of foreign exchange is high.

Ethanol

There are few developing countries yet that have natural gas but have not found oil, and fewer among them whose balance of payments is so difficult that they must consider methanol as a gasoline substitute. Except for those few, ethanol has better prospects than methanol. There is an established process for its manufacture from biomass; it is a fermentation process in which economies of scale taper off at a much lower level than in the case of methanol. There do not seem to be pronounced economies of scale above the level of 240000 L/day (≈200 t/day) that is normal for new distilleries in Brazil. The process is based on the one for rum manufacture, which has been used and is well understood in many developing countries (Rolz et al. 1983). Whereas rum and ethanol manufacture are confined to cane-growing countries, fermentation of other feedstocks is carried on in many developing countries, and sugar-rich crops appropriate for ethanol manufacture — principally maize, sweet sorghum, and cassava — can be grown under many agrarian conditions. Among countries that are short of arable land, feedstocks for ethanol must compete with other crops. Where these happen to be food crops and the country places a high value on food security, allocation of land for ethanol feedstocks — and indeed, many nonfood crops, including wood for fuel, timber, and paper — would be disfavoured. Under such conditions the production of nonfood crops is contingent on an increase in the total biomass productivity of the land.

The economics of ethanol as a vehicular fuel seems to be favourable in Brazil, where it was initially commercialized under subsidy, as well as in Zimbabwe (Goldemberg et al. 1984; Kahane 1985; Wenman 1985). Elsewhere, there are less favourable indications (cf., Koide et al. 1982). However, a production base exists for ethanol in Brazil; it is also being produced in other countries for use in beverages and chemicals. Hence, there is considerable scope for process experimentation, for which a number of promising directions are indicated. Below are the major ones.

Reduction of feedstock costs Because feedstock is the single major item of cost, a reduction in its cost would improve the economics of alcohol significantly. A major component is the cost of feedstock transport; it can be reduced by increasing cane yields, on which research is being concentrated in Brazil.

Increasing plant capacity utilization Sugarcane is a seasonal crop that can feed a plant six months in the year at best; the more the season is extended, the lower the sugar recovery, and the greater the danger of disease and fire. A number of ways of improving capacity utilization have been proposed. One is the chipping and drying of cane for use throughout the year, as in the EX-FERM process (Jenkins et al. 1982). Another is concentration and storage of cane juice. A third is a combination of cane and sorghum as feedstocks (Instituto de Pesquisas Tecnológicas 1981).

Process improvements Advances in fermentation chemistry are leading to ideas for more efficient fermenters involving cell immobilization (Tokuyama 1984) and packed bed reactors (de Cabrera et al. 1982).

Chapter 7 Gaseous Fuels

The low energy density of fuel gases makes them costly to store and transport. When they are produced from bulky biomass, they must be exploited on a small scale for local markets. Natural gas requires large investment, however, and to justify it, it is necessary to find a large market in advance and to lay down a distribution network.

The prospects of discovery of natural gas are better than those of oil; hence, exploration holds attraction for developing countries. Once it is found, its exploitation requires a synthesis of considerable research in a number of fields before investment can be undertaken, i.e., research into reservoir management, the market, technology, finance, and contractual arrangements. Large, concentrated markets must be found for gas first; once found, its uses can be extended to vehicles and residences. For use in vehicles, however, it is probably better to convert it to a liquid fuel such as methanol or gasoline.

Although millions of biogas plants have been constructed and many are observed to malfunction, systematic, diagnostic studies of their operation are few. Biogas development has been closely linked with stabled animals; its connection with agrarian systems needs to be better understood if biogas is to be diffused further. The directions of research on biogas technology are promising, i.e., cell immobilization and two-stage processes.

Producer gas was produced from coal in large installations in the 19th century, and the process survived in some industrial countries until the 1960s. However, recent interest in developing countries has focused on small biomass-based gasifiers, which present different problems. Producer gas is extremely sensitive to competition, and its costs depend greatly on the cost of wood or charcoal used to produce it; research on reducing their cost would improve the prospects of producer gas. Research on gasifier design is voluminous; it needs to be disseminated and applied to local conditions. Where gasifiers have been commercialized, diagnostic research on their defects would lead to better designs, and to organization of their manufacture so as to minimize defects. One of the main objects of research on design should be to reduce the skill requirements in gasifier operation.

Hydrogen can be made by steam reformation of hydrocarbon gas or oil and also by electrolysis of water. However it is produced, it is unlikely to be able to compete with fossil fuels as long as they are cheap. However, if fossil fuels are banned for environmental reasons, hydrogen may become viable in some markets. Two promising ones are energy storage in power plants to meet peak loads, and long-range vehicles on road and sea. However, these uses are remote at least until acid rain and global warming cause much greater alarm than now. Until then, hydrogen may be relevant to countries with good hydroelectric sites, difficult balances of payments, and poor coal and oil reserves.

Gaseous fuels have a low energy density per unit volume. It can be increased by compressing or cooling them, but at a cost. Consequently, their storage, handling, and transport costs are high in relation to their value. It is economic to consume them as they are produced, and close to where they are produced. This advantage of local markets and small scales is reinforced when fuel gases are produced from biomass such as wood and animal residues, which have high transport costs per unit value; such gases are thus particularly suited for small and decentralized applications. However, a large scale is often unavoidable in natural gas production because of the investment required; then it is necessary to develop a large enough market for it, and to invest in the necessary transport and distribution network.

Natural Gas

In the previous chapter, we referred to the theory that hydrocarbons are formed deep in the earth and migrate toward the surface through fissures in the crust. This theory would have a far greater impact on our view of the ultimate availability of natural gas than of oil, for most of the hydrocarbons thus formed would be methane, whose reserves would be enormously larger than present estimates suggest. It would also affect our expectations about the location of those reserves: they would lie at greater depths than the gas deposits that have hitherto been extensively surveyed. If such large deposits existed deep underground, the capital costs of exploiting them would be higher; but gas supplies could last much longer in the future. The key to proving the existence of such possible resources lies in geophysics and geochemistry. Whether developing countries participate in the research needed or not, they have a considerable interest in watching its progress.

The deep-earth-gas theory is not consistent with conventional petroleum geology, which attributes the origin of oil and gas to buried plants and organisms (North 1982). However, the possibility of gas originating in magmatic rocks is accepted in petroleum geology. The conditions of gas formation are also known to be broader: whereas all organic matter can generate gas when buried long enough and at sufficient depth, the ability to generate oil varies among different types of organic matter (Tissot and Welte 1984). Thus, gas can be found in larger quantities and across a greater variety of geological formations than oil. Hence, developing countries have a better chance of finding gas than oil on average — although the chances would, of course, vary across geological formations.

Once reserves are discovered, a decision must be taken on whether, when, and at what rate to exploit them. This decision often requires considerable information and analysis, for the economics of gas exploitation is generally less favourable and more uncertain than that of oil. The reason is that most developing countries have built an oil distribution network; even though it may not be extensive, it provides a basic market. When gas is discovered, its distribution network has to be built up; it is more capital-intensive than for oil both because gas storage, handling, and transport facilities are more expensive and because the energy density of gas is low. If pipelines are laid for gas, a large enough market for the gas must be identified at its receiving end to absorb the output. The market can be expanded by extending the network to new users, but to reduce capital costs of transportation it is necessary initially to identify a small number of large users. Once the pipelines are laid, gas supply is tied to purchasers for a long time; and if investment in gas production is to yield a reasonable return in that time, the basis for the determination of the price to be paid by the purchasers has to be laid down in advance. Finally, gas generally has close substitutes in many uses, and its economics is sensitive to their relative prices. Thus, the high capital requirements, capital intensity, the small number of buyers, and the presence of substitutes combine to make advance planning extremely important in the gas industry; and the plans generate research requirements. The requirements fall into five interconnected areas.

Depletion and reservoir management This involves a combination of the national resource policy with the technical aspects of the reservoir management.

The market Information would be required about the potential major buyers, the quantities they can buy, and the price they can pay. The price would in turn depend on the prices of substitutes available to the buyers. The uncertainty of these factors makes it no less necessary to make the best possible estimates (Julius 1985).

Production scale and costs Gas, like electricity, requires detailed technical planning. It involves greater complexity owing to uncertainties introduced by geology and the markets.

Investment and finance Almost always, a financial package has to be worked out owing to the large investments involved. Because the availability of finance will depend on the return on investment and its reliability, market analysis and project planning will be important inputs into financial decisions (De Vallée 1985).

Economic–legal arrangements As sellers, buyers, and financiers get locked into long-term relationships in gas projects, the formulation of contracts among them is complex, requires coordination, and offers scope for ingenuity (Colitti 1985).

Thus, gas exploitation involves a synthesis of considerable research inputs before investment is undertaken. Much of it is indispensable, and its quality may make a great difference to the viability of gas projects, which are generally risky and sensitive to competition. Once gas begins to be produced and used, its extension to new uses and users is easier; hence, the quality of research is particularly important in the initial period of exploitation in which many developing countries find themselves.

The substitution of gas for oil in vehicular and residential uses is of potential interest to countries with gas that find it difficult to import enough oil, but gas is not easily applied to these uses. Propane and butane, whose boiling points are high, are bottled and put to small-scale uses such as car or cooking fuels. However, their proportion in natural gas is low; the most important constituent is methane, whose boiling point is so low that it is not economic to liquefy it except for large-scale tanker transport to distant destinations.

Short of liquefying methane, the best that can be done is to compress it. If it is compressed at 16.55 MPa (which would require strong and heavy containers), it would give a vehicle one-third the range of oil. Compressed natural-gas use in vehicles thus requires more filling stations than oil, and a correspondingly dense network of pipelines. For domestic use, natural gas does not need to be — indeed must not be — compressed so much, but would need an even more extensive network. Thus, vehicular and residential uses require considerable investment in distribution, which adds to the cost of gas. Exploitation of gas in new areas would seldom be justified if it were primarily for these uses, especially in developing countries where low incomes restrict demand. Once gas production and distribution are established, however, extension of gas usage to vehicles and residences in cities may become economical.

The investment in distribution would be considerably less if gas were converted to a liquid fuel, i.e., to methanol or gasoline from methanol, discussed in the previous chapter. For countries intending to put gas to a vehicular use, this is a more promising route.

Biogas

Biogasification is an extremely versatile process to convert low-grade biomass into a low-calorie fuel. It has been the subject of considerable experimentation in developing countires (Brown and Tata 1984). It is also one of the widely adopted renewable energy technologies in developing countries (apart from hydroelectricity and biomass fuels). Although the number of biogas plants in the world can be counted in millions, little research has been done on their operation. There are scattered observations about the proportion of nonfunctioning plants, more common observations of gas leakage, and a general impression of considerable variation in gas productivity of plants. Statistical diagnostics of existing plants would yield more reliable information on the shortcomings of their operation, and lead to improvements in their management.

Biogasification has been adopted on a mass scale only in China and India. In both countries, there appears to be considerable geographical concentration in areas where there are a large number of stabled animals — pigs in China and cattle in India. Apparently, a large livestock population, as found in other parts of India, North Africa, and West Asia, is not enough; stabling plays a role. This is partly due to the extreme labour intensity of collecting the dung of grazed animals. More importantly, however, grazed animals spend so much energy in grazing that their dung output for the same fodder input is much lower than that of stabled animals. If this is so, the wider spread of biogas would have to await a change in animal husbandry practices. This connection between biogas and agrarian systems calls for research.

The link of biogas with stabling suggests that it may be a particularly appropriate by-product for dairying enterprises. Biogas plants have been set up in dairying enterprises in industrial countries and in India; the constraint there appears to be demand for biogas. The possibilities of generating biogas in dairying enterprises of developing countries need to be investigated, especially because they would be able to exploit the economies of scale of biogasifiers.

Apart from collection costs, the major costs are the capital costs of the digester, and research has sought to reduce them in two ways: by reducing the construction or fabrication costs (cf., Stuckey 1983), by design optimization (cf., Subramanian et al. 1980), and by accelerating the throughput of substrates and increasing gas output (Advisory Committee on Technology Innovation 1977). Attempts to reduce fabrication costs are common in developing countries; they mostly involve changes in design or in materials. In industrial countries, on the other hand, the biogas output is of secondary importance, and biogasification is generally used to biodegrade farm and industrial effluents to render them innocuous. Hence, the accent has been on maximizing throughput of substrate and accelerating the reactions (Klass 1982).

Recent research has made significant progress in identifying the microorganisms involved in biogasification, their role, and the conditions of their growth; and in understanding the processes involved in biogasification. It suggests two possible routes by which biogas productivity could be increased.

- Cell immobilization techniques make it possible to observe and accelerate microorganic activity, to grow microorganisms outside, and to introduce them into digesters.
- The initial stage of hydrolysis does not require anaerobic conditions and can be carried out in ambient conditions. This points toward a two-stage process in which acidogenesis is carried out in one reactor and the substrate is then transferred to a second reactor for anaerobic methanogenesis. Two-stage experiments have hitherto been made on a substrate with a very low solids content; it is yet to be established whether the process works equally well with the type of substrate normally used in developing countries, which has a higher solids content. It also remains to be established whether a two-stage process would raise productivity sufficiently to justify investment in an additional reactor.

Thus, advances in the anaerobic gasification technology seem to be particularly promising in two directions: cell immobilization and two-stage gasification.

Producer Gas

Producer gas is a low-calorie mixture of carbon monoxide and methane with noncombustible gases (mainly nitrogen and carbon dioxide); when produced from biomass, it also contains a significant amount of hydrogen. It is readily produced when a carbonaceous fuel is burnt with insufficient oxygen. Kaupp and Goss (1984) trace its knowledge back to 1669 and the first patent to 1788. It was produced on a large scale from coal and used for street lighting as well as residential lighting and cooking in industrial countries in the 19th century. In the late 19th century, a number of inventions were made to design small producer gas units for decentralized and mobile uses. The Otto engine was originally invented to apply producer gas to shaft power uses. Producer gas applications also spread to developing countries, especially to the colonies of Britain and France. From the 1870s onward, however, it lost one market after another. In lighting, it was replaced by electricity, and in small engines, by oil. In residential use, it failed to gain new markets once cheap kerosene became available, but continued in domestic uses in coal-rich countries where the distribution pipelines had already been laid. In this use also, natural gas replaced it in the USA from the 1930s onward, and in western Europe in the 1960s. Now, its only large-scale use is in the form of coke-oven and blast-furnace gas in steel plants.

Its substitutability for other fuels and the simplicity of its production technology have attracted interest to producer gas whenever competing fuels became scarce or expensive. During World War II, the countries that were hit hard by the Allied blockade — especially France, Germany, Japan, and Sweden — converted road vehicles on a large scale (National Research Council 1983b). After the oil price increases of 1973, a large number of small producers sprang up in Brazil; they supplied charcoal-burning gasifiers for vehicles, pumps, generators, etc. after 1978. In the Philippines, a government corporation began to sell gasifiers for pumps, boats, and vehicles (Scharmer et al. 1984).

Experience suggests that producer gas is extremely sensitive to competition. Investment in research on it therefore requires the identification of promising and relatively secure markets.

It can never be as cheap as its own feedstocks (except where it is an unavoidable by-product, as in coke ovens and blast furnaces), and hence cannot compete with them where they can be used directly. The two instances where they cannot be so used are direct applications where they would contaminate the product (for instance, in ceramics and glass making), and in internal combustion engines. In these uses, the competitiveness of producer gas depends — but only partly — on costs, which consist principally of fuel, equipment, and labour. There are two possible major classes of fuel — coal and lignite, or wood, charcoal, and biomass.

Producer gas would always be in the wings for coal-rich countries, to be considered if oil becomes scarce or expensive. After oil prices rose in 1973, R&D was directed in the Federal Republic of Germany and the USA toward the possible use of producer gas as a feedstock for methanol, a substitute for gasoline (Scharmer et al. 1984). Coal and lignite were the primary fuels, but in the search for markets for the process in developing countries, other fuels were also tried out — for instance, wood, peat, and bagasse (cf., Baudequin et al. 1984; Bellin et al. 1985). In this use, producer gas competes with natural gas, and methanol with other liquid fuels from coal and gas. In view of the favourable global long-run supply prospects of natural gas, this line of research would be worth considering only in coal-rich countries that expect to have serious and persistent balance-of-payments problems. Its relevance to small or portable gasifiers running on biomass, which have been the subject of research in and for developing countries, is limited.

Biomass fuels are different in that their local costs vary enormously. They are particularly low where biomass arises as a by-product, for instance, in rice mills, saw mills, and sugar mills; here, a market may be found for its captive use for shaft power, although whether it is competitive or not in that use will depend on the availability and cost of electricity. Elsewhere, its potential would depend on the availability of a cheap, standardized fuel — generally, wood or charcoal. Although wood is the principal fuel in many developing countries and charcoal is important in some, they would have to become available at lower costs and in larger quantities before producer gas becomes viable. In these countries, therefore, research on biomass, and especially wood production, would have priority.

Equipment costs also can vary greatly; and insofar as small-scale engineering is labour-intensive, they can be lower in developing countries. One of the reasons for the spread of producer gas in Brazil is the existence of engineering capacity, which has led to the proliferation of manufacturers. Where this capacity exists, costs would also depend on the volume of production and on its distribution across models. Thus, in countries where indigenous production gets established, standardization of models can help to reduce costs, and to make them more reliable. At that stage, diagnostic research on the gasifiers in use and related research on gasifier design would be indicated. The volume of research on design that was done in industrial countries in the heyday of producer gas is considerable (Kaupp and Goss 1984). There has also been much research in the last 12 years (Mahin 1984). The sharing of all this accumulated experience would save resources. Research on design requires application engineering and adaptation to local uses, fuels, and scales rather than innovation. After designs are standardized, the product would also need to be standardized. The production systems have to be organized to minimize manufacturing defects — which is itself a subject for research.

Labour costs of gasifier operation are not necessarily high; in the case of owner-operated vehicles, they are only notional. However, gasifiers can malfunction in a number of ways. Some of them are tedious, others serious or even dangerous (Foley and Barnard 1982). Good design can reduce their susceptibility to trouble. However, even the best-designed gasifiers require that operators tend to them frequently and regularly, and that they do and not do certain things. Operator training and skill make a considerable difference; and even where labour is cheap, skill and care may not be. Thus, deskilling would have to be a major objective of research on design.

Hydrogen

The knowledge of hydrogen gas is traced back to Paracelsus, who obtained it by reacting iron with sulfuric acid, and established its combustibility (Aureille 1984). In the modern world, hydrogen is an important chemical intermediate used to make ammonia for nitrogen fertilizers, in hydro treatment of mineral oil, and in the manufacture of methanol.

It attracted widespread interest after the rise in oil prices in the early 1970s for a number of reasons. First, it can be readily used as an engine fuel, and can thus replace oil products in vehicles without extensive re-equipment. Second, it can be made from water, whose available stocks are enormous. Third, its combustion yields water, its potential raw material; it can thus be infinitely recycled. Finally, its combustion is nonpolluting and can thus avoid the environmental ill-effects of fossil-fuel combustion. Its combustion in air would generate nitrogen oxides, but not those of sulfur; nor would it generate carbon dioxide, whose effects on global temperature are a source of concern.

The fact that hydrogen is being produced in bulk for chemical uses makes it easily available for experimentation. Its advantage over fossil fuels in respect of environmental effects makes it interesting to the electrical power industry, and its potential as an engine fuel makes it attractive to the transport equipment industry when it is concerned with rising costs of oil products. In addition, hydrogen has been used as a reactant in alkaline fuel cell power plants on board U.S. and French spaceships (Doniat and Rouget 1984; Srinivasan 1984). Thus, the interest of potential users with large resources for R&D has made hydrogen energy one of the most active areas of energy research in the past decade. It has evoked interest in Brazil, China, and India among developing countries (Campos 1984; Li et al. 1984; Nema et al. 1984; Mattos 1985).

However, there is broad agreement among students of the question that hydrogen will be uncompetitive with substitute fuels for some decades at least. The cheapest way to produce hydrogen at present is by steam reformation of hydrocarbons; the ones commonly used are natural gas (methane and propane), refinery gases, and naphtha. Hydrogen produced by this process will be inevitably more expensive than the hydrocarbons from which it is made. Thus, it cannot compete with petroleum liquid fuels now and, when these become expensive, hydrogen from steam reforming will not be able to compete with natural gas, which can be used as easily as hydrogen in engines, and is cheaper to transport since methane, its major component, has three times the energy of gaseous hydrogen per unit volume (Gelin and Petit 1980; Fein 1982, 1985). Hydrogen is cheaper than electricity in the USA even now, but cannot capture any of the markets for electricity owing to lower end-use efficiency and greater difficulty of transporting it (Gaines and Wolsky 1984).

Thus, hydrogen is unlikely to emerge as a competitive fuel as long as oil or gas is the dominant energy form — except perhaps in small, special markets like steelmaking. When the cost of oil and gas increases, they are likely to be replaced by coal, from which a number of liquid and gaseous fuels (including hydrogen) can be made. Among them, synthetic oil and methanol would be more convenient as transport fuels. Being liquid fuels with higher energy density, they would be cheaper to store and transport; and such cost calculations as have been made suggest that they would be cheaper too.

Thus, hydrogen may not emerge as a competitive fuel until coal extraction costs rise considerably — which, in view of the large world reserves of coal, may be some centuries away. However, hydrogen's competitiveness would improve much earlier if definite signs of environmental deterioration led industrial countries to restrain fossil-fuel consumption. As we discuss in chapter 12 below, there is considerable controversy on whether and when this will happen; there is also considerable variation in opinions about how much environmental deterioration is tolerable. However, if and when public opinion turns against fossil fuels as strongly as it did against nuclear power in some industrial countries in the 1970s, the prospects of hydrogen as an alternative fuel will improve.

When that happens, hydrogen would not be produced from fossil fuels even if the costs of production were low, for hydrogen production by that means would be as environmentally undesirable as any other combustive use of fossil fuels. It would thus have to be produced from water; and all processes for doing this require large amounts of energy (Bockris et al. 1985; Ohta et al. 1985). Hence, to be competitive, hydrogen would need an abundant and cheap source of energy. Three have been suggested: nuclear power, off-peak electricity, and solar energy.

Nuclear power can, in theory, be produced in abundance, especially if breeder power reactors are commercialized. It has the advantage that, in addition to electricity, such reactors produce considerable waste heat that can be used to increase the energy efficiency of electrolysis. If coal-based power generation is phased down for environmental reasons and nuclear generation is not, nuclear power would clearly be the prime potential source of hydrogen.

If either nuclear or hydroelectric power is used to make hydrogen, the question of its uses would become important. Basically, two have been proposed.

Hydrogen as an energy carrier It may be produced in off-peak hours. It may also be generated in regions with surplus power and transported by pipeline to power plants where there is excess demand for power. Electricity generated from hydrogen will inevitably be more expensive than the electricity that produced it, both because of conversion losses and production costs; whether it is still economical or not would depend on the difference in the cost of off-peak and peak power. Technoeconomic research on this question, though sparse, suggests the following: building excess capacity in reservoir and hydroelectric generation capacity is likely to be cheaper than hydrogen production; hydrogen makes better sense where it can be used directly; if excess generator capacity turns out to be more expensive or is ruled out, hydrogen storage is likely to be cheaper than alternative storage techniques; and hydrogen storage is better for long-term energy storage, for instance, from one season to another (for short-term storage, in the range of a day to a week, batteries or pumped storage may be cheaper) (Carpetis 1984; Fein 1985). However, there are a large number of alternatives and parameters in such calculations, and site-specific research is necessary to test the viability of hydrogen storage.

Hydrogen transport may be cheaper than the transport of energy-equivalent electricity, but its actual economics will depend a great deal on the distances involved and on whether hydrogen has a direct use at the destination. The cost of alternative fuels at the destination will determine the competitiveness of transporting hydrogen as well as electricity. Here, as with storage, only site-specific investigations can determine the viability of hydrogen transport. Clearly, however, the first countries for such investigations are those that have abundant hydropower resources in remote locations, for example, Brazil, Canada, and China.

Hydrogen as a transport fuel If electricity and electricity-based hydrogen come to be the major energy sources, it is likely that hydrogen, though more expensive than electricity in terms of delivered energy, will nevertheless command a significant part of the market for transport energy. The reason is that if transport in personal vehicles, as numerous as they are now in industrial, and indeed in many developing countries, continues into the electricity–hydrogen age, electricity will not be conveyed to them by means of transmission lines, as in electric trains; it must be stored in batteries on board the vehicle. Batteries are heavy and impose a penalty on energy consumption. It can be reduced, though not eliminated, by more frequent charging of vehicles. In a city with a well-developed transmission network, this would pose no problem; it would be enough to have a large number of power outlets where vehicles are usually parked. Charging of batteries takes time, however, so there will be an upper limit on the proportion of time a vehicle can be driven, and on how long it can be driven without charging. In uses where such limits are unacceptable, hydrogen will be the only admissible fuel. Among vehicles where such limits cannot be placed are buses, trucks for interurban transport, ships, and aircraft. Thus, the market for transport (other than rail transport) would be divided, relatively small and short-haul vehicles being powered by electricity, and large and long-haul vehicles being powered by hydrogen.

Research on hydrogen energy is an area of considerable activity and extreme volatility; it is not possible at this stage to narrow down the lines of research to a promising few. If, as stated earlier, it will be at least a few decades before hydrogen finds a significant market as a fuel, there is no urgency about hydrogen research. It may have greater relevance to the small number of countries with favourable hydroelectric sites, poor fossil fuel reserves, and difficult balances of payments. However, the attractiveness of hydrogen is closely related to the negative externalities of fossil fuels. If research on the greenhouse effect and on acid rain led to a more serious and urgent view of the threat they pose, the promise of hydrogen as a nonpolluting fuel would also correspondingly improve.

Chapter 8 Solid Fuels

Internal combustion engines, which power most vehicles in the world, run on lighter fractions of oil; the demand for these arising from transport largely determines the production of oil. The remaining heavier fractions consist chiefly of fuel oil, which competes with coal. The demand for coal in industrial countries is thus limited by oil output and, more remotely, by the use of oil products in transport. The rise in the price of oil has curbed transport demand for it and expanded the market for coal which, however, is still sensitive to oil, and will remain so for the foreseeable future.

Most of the coal output of developing countries comes from China and India. Other developing countries would benefit from more intensive exploration. Where coal is being produced, improvements arise from the adaptation of technology to local conditions; hence, coal producers need to become informed buyers of equipment first and then do adaptive innovation.

The underground coal industries of China and India are labour intensive. Their conversion to mechanized longwall technology has raised site-specific problems that call for user learning, interaction with machinery manufacturers, and learning from each other. The new technology requires new management structures, conversion to which can be helped by research. Coal slurry transport and coal preparation offer well-defined research problems.

Charcoal is extensively put to domestic use in urban areas in developing countries. This use is sustainable in the long run only if wood is produced in plantations, which would compete with other agricultural uses. If they are to compete successfully and still produce cheap wood for charcoal, the productivity of land would have to increase. Thus, sustained commercial production of charcoal requires research to raise land yields on a broad front. For sedentary charcoal making, beehive kilns are best; they call for diffusion and technological improvement.

Where urban areas use wood instead of charcoal, the fuel shortage can be relieved similarly by raising the productivity of land and thus making room for forestry near towns. However, it can also be relieved by diversifying the fuel base and by discovering and breeding new species of trees and shrubs for fuel supply.

Solid fuels were the major source of energy until the turn of the century. Biomass was the main source until the industrial revolution. Then, demand for energy grew so much and became so geographically concentrated that biomass could not supply it, and mineral coal gained in use. In the 20th century, oil gained over solid fuels for three reasons. First, unlike coal, which had to be mined, oil was brought to the surface by subterranean pressure. Thus, under the favourable initial conditions under which it was found, it was cheaper. Second, it had a higher energy density. In terms of weight, it had almost 1.5 times the energy density of the best coal; in terms of volume, it was even better. Hence, its transport costs were lower.

Finally, it was well suited for use in internal combustion engines. As a result, it became the main means of motive power, especially in vehicles. Only part of the oil can be refined into products that can be used in engines; this proportion can be increased only by highly capital-intensive methods. Thus, the products that could not be used in engines — the residual fuel oils — were used directly as fuel and competed with solid fuels.

With the rise in the price of oil, innovation in industrial countries concentrated on reducing the oil demand for prime movers. This considerably slowed down the growth of demand for gasoline and diesel oil and, hence, the growth of supply of its joint product, fuel oil, and led to the growth of demand for coal as a heating fuel. It is likely that this process will continue worldwide. The demand for engine fuels will determine the supply of fuel oil, which will be priced to find a market. Fuel oil price will determine the maximum price of coal, and the output of coal will be what can be produced at that price.

The prospects of developing countries that wish to enter the international market for coal will be governed by this international mechanism (Wilson 1977; Greene and Gallagher 1980; Long 1982; Gordon 1984). Those countries that are using their coal domestically may price it above international levels if they are under balance-of-payments pressure, and increase its domestic use. (This applies as well to countries with good prospects for firewood production.)

It is unlikely, however, that solid fuels will find a significant use as engine fuel even in those countries. They can be so used only by conversion into producer gas. On the prospects of producer gas from biomass we have commented in chapter 7. Coal gasification faces similar problems if done on a small scale. Besides, in small-scale uses, producer gas would compete with electricity. Electricity is generally cheaper than even diesel power once transmission facilities are in place. Thus, our assessment of the prospects of small-scale producer gas does not change if mineral coal is considered as the fuel instead of biomass.

On a large scale, coal-based producer gas has two potential markets: domestic and commercial use, and power generation. It would find a domestic or commercial use in urban areas near coalfields. However, most of them are being served by soft coke (for instance, in north China and eastern India). Where coking coal is available, it is unlikely that producer gas can compete with it. In power generation, the currently used steam turbines do not face potential competition from producer gas. Thus, while the technology of coal-based producer gas is well established and can be further improved, its application will depend on what markets can be found for it.

An exception may be producer gas from underground coal gasification. In principle, this technology has tremendous scope. Millions of tons of coal that have been discovered in the course of exploration for oil are too deep to mine at competitive costs at present; even at much higher energy prices, they would be difficult or impossible to mine.

Underground gasification is the only possible use for them in the near future. Considerable experimentation is going on in industrial countries. The results, however, are most unpredictable (Schilling et al. 1981). We have not been able to make a dependable assessment of it.

Another technology we have left out of judgment is magnetohydrodynamics (MHD). In principle, MHD can increase the efficiency of power generation considerably. Unlike underground gasification, it is known to work. However, the operational MHD plants — all of them small ones — are in the Soviet Union, and what we have been able to discover secondhand does not justify a confident assessment.

Coal

More than 85% of the coal production, reserves, and resources of the developing world are concentrated in China and India (Table 10). However, there is reason to believe that this reflects the lack of exploration for coal in other countries rather than the lack of resources (Subba Rao 1981). Coal began to yield to oil some decades before serious development efforts began in many developing countries; there was thus little incentive for exploration for coal. Many developing countries do not even now have the infrastructure for the exploitation of coal, which is a relatively bulky, low-value, transport-intensive fuel. Although small mines are economic where coal is on the surface or not too deep, exploitation of underground coal requires a minimum scale that the potential demand in a single developing country may not justify. Thus, coal is underexplored in many developing countries. Where geological conditions are favourable, exploration for it would be a promising area of research (Fettweis 1984).

The coal industries of industrial countries, which were the prime source of energy till the advent of oil, steadily lost ground to oil after World War II and were weakened by competition. In their years of decline, their rate of investment was low. Most of the innovations came from equipment manufacturers, but mining enterprises contributed by defining the site-specific conditions for which the equipment was required. The equipment markets were and are largely national, and some crucial innovations are site-specific and not necessarily transferable to developing countries without adaptation. Hence, coal-producing developing countries need to acquire informed buyer competence in the first place, and capacity for adaptive innovation in the second. These are the areas in which research and the buildup of research competence need to be concentrated (Surrey and Chesshire 1984).

Mining Technology

Coal, iron ore, and bauxite are the three most important bulk minerals of the world. All were initially discovered near the surface. Surface reserves of iron ore and bauxite are so large that nearly all their mining is above ground; they are served by a large surface quarrying equipment industry. This industry has continuously innovated and scaled up its products to give higher throughputs and lower costs. There is considerable interflow of innovation between hardrock mining and coal mining, but scaling up of equipment — for instance, excavators, draglines, and trucks — has progressed further in coal and lignite industries. Rapid technical progress in it has given an edge to surface mining of coal over underground mining. In all countries where both are available, surface coal has gained ground over underground coal; underground coal has come increasingly to be exploited with open cast techniques after overburden removal.

However, the old coal-producing countries, the Federal Republic of Germany, France, and U.K., have no significant surface deposits of coal, although the F.R.G. is a producer of open pit lignite. Faced with competition from oil and U.S. coal, the underground coal mining industries of the three countries developed longwall

Table 10. Population, coal production, reserves, and resources of developing countries.

Country	Population 1978 (million)	Coal production 1980 (million tce)[a]	Reserves: Subbituminous coal and lignite 1983 (million t)	Reserves: Subbituminous coal and lignite 1983 (million tce) [1]	Reserves: Bituminous coal 1983 (million tce) [2]	Reserves: Total 1983 (million tce) [1 + 2]	Total coal resources 1983 (million tce)
Africa							
Algeria	18.24	<0.01	0	0	43	43	0
Botswana	0.71	0.31	0	0	3500	3500	107000
Central African Republic	2.61	0	4	1	0	1	1
Egypt	38.74	<0.01	0	0	13	13	25
Ethiopia	28.98	0	0	0	0	0	0
Madagascar	8.52	0	0	0	0	0	1025
Malawi	3.53	<0.01	0	0	12	12	25
Mali	6.04	0	0	0	0	0	1
Morocco	18.25	0.72	0	0	45	45	149
Mozambique	9.68	0.38	0	0	240	240	395
Niger	6.84	0	0	0	0	0	5
Nigeria	66.63	0.19	169	132	0	132	1065
Swaziland	0.50	0.15	0	0	1820	1820	5020
Tanzania	16.09	<0.01	0	0	200	200	1804
Zaire	26.38	0.08	0	0	600	600	600
Zambia	5.35	0.78	0	0	24	24	130
Zimbabwe	6.74	3.65	0	0	734	734	8108
Latin America							
Argentina	26.06	0.39	130	101	0	101	2878
Brazil	112.24	4.09	13000	8190	0	8190	14490
Chile	10.66	1.14	1150	897	27	924	291
Colombia	25.05	3.34	25	19	1010	1029	9788
Ecuador	7.56	0	18	10	0	10	3
Haiti	4.75	0	0	0	0	0	13
Honduras	2.83	0	0	0	0	0	16
Mexico	64.59	6.61	496	357	1295	1652	4317
Peru	16.36	0	0	0	0	0	884
Venezuela	12.74	0.05	34	27	275	302	11965

(continued)

Table 10 concluded.

Country	Population 1978 (million)	Coal production 1980 (million tce)[a]	Reserves: Subbituminous coal and lignite 1983 (million t)	Reserves: Subbituminous coal and lignite 1983 (million tce) [1]	Reserves: Bituminous coal 1983 (million tce) [2]	Reserves: Total 1983 (million tce) [1 + 2]	Total coal resources 1983 (million tce)
Asia (excluding China and India)							
Afghanistan	26.06	0.18	0	0	66	66	512
Bangladesh	80.56	<0.01	0	0	0	0	1054
Burma	31.51	0.01	0	0	2	2	152
Indonesia	143.28	0.19	0	0	0	0	6591
Iran	34.27	1.00	0	0	193	193	385
Korea, Democratic People's Republic	16.65	16.65	300	234	300	534	6650
Korea, Republic	36.44	18.00	0	0	192	192	1500
Malaysia	12.6	0	0	0	0	0	430
Mongolia	1.53	1.32	0	0	0	0	15960
Pakistan	75.28	1.04	102	80	0	80	355
Philippines	45.03	0.22	82	64	0	64	133
Taiwan, China	16.93	2.24	100	106	100	206	453
Thailand	44.16	0.21	471	228	0	228	680
Turkey	42.13	9.16	1728	518	186	704	2470
Vietnam	47.87	4.10	0	0	0	0	1004
Yemen, Arab Republic	7.08	0	0	0	0	0	≪1
New Caledonia, France	0.14	0	0	0	2	2	12
Total	**1202.49**	**113.12**	**17809**	**10964**	**10879**	**21843**	**208339**
China	**865.49**	**618.00**	**0**	**0**	**99000**	**99000**	**1539365**
India	**625.82**	**102.37**	**1581**	**1407**	**0**	**1407**	**115014**
Developing countries	**2693.80**	**833.49**	**19390**	**12371**	**109879**	**122250**	**1862718**
Other countries	**1118.33**	**2121.22**	**382980**	**206969**	**383045**	**590014**	**6466386**
World	**3812.32**	**2954.71**	**402370**	**219340**	**492924**	**712264**	**8329104**

Source: Fettweis (1984).
[a] 1 tonne coal-equivalent (tce) = 7 Gcal = 29.3 GJ.

mining techniques to increase productivity and reduce capital costs (Peng and Chiang 1984). In the USA, with its more abundant and shallower reserves, machines were developed for room-and-pillar mining (Meyers 1983).

China and India have the largest and oldest coal mining industries among developing countries. Both employ relatively labour-intensive techniques; and because overburden removal by manual means is too expensive, both have traditionally had predominantly underground mining. However, the throughput of labour-intensive mines is low. Consequently, labour-intensive techniques require a larger number of mines, with their requisite fixed investment in shafts and haulages per unit of output; and because shaft and gallery construction are time-consuming, the rate at which output can be raised is constrained. Hence, both countries have been turning toward surface mining. The same need to achieve rapid and large output increases has also forced both countries to seek to mechanize their underground mines.

However, both China and India have large underground coal mining industries that need to be mechanized to reduce capital costs and maintain a rapid growth of output. Our preference for labour-intensive techniques in general must be abandoned in the case of the underground coal industry, for the industry is known to be extremely hazardous and unhealthy for workers in industrial countries (cf., Ramsay 1979; Clifford and Mead 1984). It is undoubtedly even more so in developing countries.

Both China and India have imported longwall technology and machinery and are in the process of indigenizing them. However, their coal is at shallower depths than in Europe, and India also has thick and multiple seams. Roof support during extraction and caving after it raise problems under these conditions. Powered supports developed in Europe are not always effective, and roof collapse after extraction is uneven (Mathur 1980; Sarkar 1980; British Mining Consultants Ltd 1983a, b; Sarkar et al. 1983). These problems are site specific, and require user learning that comes through the development of technological competence in the users and close interaction between them and the equipment manufacturers. There is also scope for learning from experience — especially from the mutual experience of China and India. One of the major difficulties in user learning is that longwall mining requires different organizational and management structures; these also must be transferred and adapted, not just the technologies.

Other developing countries that have begun to mine coal more recently, such as Colombia, invariably employ mechanized surface mining techniques. At high levels of mechanization, both above and below ground, capacity utilization has a decisive influence on the economics of the industry. This has two important aspects. One is equipment maintenance, generally an area of weakness in developing countries; a high level of competence in maintenance can form the basis of interaction between the mining enterprise and the equipment manufacturer, and lead to innovation. The second and related aspect is operator and management training. Labour-intensive mining employs large numbers of unskilled workers and tends to have rather simple, authoritarian management structures. Mechanized mining, on the other hand, requires better trained workers with mechanical experience and aptitude, and works better if they are given more initiative. The necessary change in the style of management does not come easily to old-established mining enterprises, but is nevertheless essential for new technologies to be effective. Interpretation of experience through research can, in these circumstances, mediate between old managements and new technologies.

Coal Transportation

Transportation is generally more mechanized than mining, but here also the mechanization of mining requires the raising of the throughput of haulages, handling facilities, and transport equipment (Surrey and Chesshire 1984). It thus generates the same types of maintenance and training requirements as mine mechanization.

Often, coal from a mine is exclusively dedicated to use in a single power plant or other user, and generates a large volume of transport in a single direction with no return loads. When a common carrier, e.g., railways, is used for coal transport, this type of traffic leads to low fleet utilization and makes traffic scheduling difficult. Railway traffic studies are of great importance where bottlenecks are being faced or are in the offing, but other modes of transport must also be explored. In particular, coal slurry transport is feasible, presents technical problems that are soluble, and can be commercialized with an input of research. The water requirements of coal slurry are large and must be met at the minehead; the coal must be dewatered at the destination and the water disposed of without causing pollution. The design of the pipeline system would also be different from that of gas or oil pipelines: the pumping stations would have to be spaced more closely, and the conditions of keeping coal in suspension would need to be established. Nevertheless, these problems pose a manageable research assignment (Grainger and Gibson 1981).

Coal Preparation

All coal contains noncombustible mineral matter — ash — in varying proportions. Ash reduces the energy density of coal; in addition, it reduces the output of coal-burning equipment such as furnaces, boilers, and blast furnaces. For these uses, it is often economic to reduce the proportion of ash in coal even at some cost if this reduces the downstream costs. Coal preparation, as the reduction of ash content is generally known, can be done in four ways. Manual techniques are useful only for low throughputs and are not always reliable. Magnetic techniques can be used with ferrous impurities, principally fragments of mining equipment. Mechanical techniques can be employed for large outputs and are the most extensive ones used in conjunction with water in coal washeries. None of the three is quite effective where the carbonic and mineral elements are strongly bonded. Where they are, flotation is the most effective. In India as well as China, washeries employ flotation agents in water, but a number of new techniques have been tried or suggested: for instance, bulk oil flotation, selective flocculation, electrostatic separation, and ionization processes for sulfur removal. Thus, coal preparation offers opportunities for fruitful research in the form of a well-defined problem and a range of possible solutions (Zimmerman 1982).

Charcoal

Charcoal has an extremely high proportion of carbon, and was the only reducing agent and fuel used in ironmaking before the industrial revolution. The growing demand for iron led to deforestation in the U.K., and the search for an alternative to charcoal led to mineral coal in the 18th century. The use of charcoal in iron smelting has been revived in Argentina and Brazil; in Brazil, it is used to produce about 10 Mt of steel/year. It holds considerable promise for countries with a large biomass potential. Elsewhere, the enormous quantities involved as well as the larger blast furnaces permitted by the use of coke will ensure the use of mineral coal. As coking coal gets scarcer, noncoking coal will be increasingly used to make sponge iron.

Charcoal powder also has a high surface-to-volume ratio, and was used as active carbon in chemical reactions before the advent of petroleum coke. Petroleum coke is a by-product of oil refining and will be priced to sell whatever is produced; hence, charcoal is unlikely to compete with it. However, if a slowdown in the total demand for oil leads to a shortage of petroleum coke, charcoal will undoubtedly be a serious alternative.

Charcoal continues to be used in large quantities as domestic fuel in some developing countries, especially in the cities of Southeast Asia and Africa. Here and elsewhere, it faces competition from liquefied petroleum gas (LPG), kerosene, and electricity. These fuels enter the upper-income markets first because of their convenience, and are increasingly adopted at lower-income levels as their relative prices fall or incomes rise. Some developing countries, however, cannot afford to import oil-based domestic fuels. In those that refine their own, an imbalance between the demand pattern and the refinery output pattern leads to a shortfall in kerosene. The distribution channels for kerosene become increasingly weak and unreliable as one travels away from the ports and centres of production. Thus, national or local market segments remain for charcoal, and they expand or contract as the supply of oil-based fuels varies. Kerosene has a refinery cut that is similar to diesel oil, and a country that wishes to minimize oil imports except for essential and irreplaceable requirements may well consider import substitution of kerosene with charcoal. Thus, charcoal making survives in many developing countries as an industry, and can grow under global or national pressures to reduce oil imports.

A high proportion of energy in wood is lost in making charcoal. However, much of this energy would be lost in any combustion process to vaporize and drive out the moisture as well as to char and separate the noncombustible mineral elements. If these inevitable losses are excluded, the energy loss in charcoal making is not large. This is an instance where it would be wrong to think in terms of the quantity of energy without considering its quality and economics. Charcoal is preferred to wood as an urban fuel owing to its lower emissions, higher flame temperature, and greater controllability.

Thus, the use of charcoal as a viable urban cooking and heating fuel can be expanded and developed; however, it must be on the basis of technologies and management systems that lead to a low-priced, reliable, and sustainable supply. The present predatory and energy-inefficient methods, whereby existing forests are cut down and burnt in pit kilns, are unsustainable beyond a low threshold level of exploitation. More efficient pit kilns would improve their economics, but not the long-term output or viability of the forests.

If charcoal is to be supplied to cities on a sustainable basis, it must come from plantations that are regularly cut and replanted. Although energy plantations have generally been promoted on land that is unfit for agriculture, the availability of such land varies considerably from region to region. It is fairly clear that energy forestry (as distinct from agroforestry) is not generally competitive with agriculture anywhere, whether in developing or in industrial countries. It is not because food is more "essential" than fuel; whether it is or not depends on how much food is produced in relation to need. It is because fuel (as distinct from pulpwood) fetches too low a price relative to other agricultural products. Agriculture produces a great many products for urban markets besides food, and meets a certain proportion of the fuel requirements of rural populations. It could equally meet urban fuel demand if agricultural productivity were high enough to leave a surplus of land and labour above subsistence, and if the relative price of fuelwood was high enough to make its production remunerative. Where further import-based urbanization and industrialization are no longer possible, growing quantities of both food and fuel would have to be supplied by rural to urban areas if the growth of the latter is to continue.

A charcoal industry for towns would require sustainable plantations, in the first place; these are discussed in the next section. Second, it would require technological choices to be made. Charcoal-making technologies have been extensively researched and discussed (Food and Agriculture Organization 1983; Karch and Boutette 1983; Caceres 1985). There will undoubtedly be site-specific factors in actual technological choices. In the present context, however, a certain direction is indicated.

If charcoal making is to be a sustained, sedentary industry, kilns also can be sedentary; there is no special advantage in pit kilns or portable kilns. Pit kilns are the common type in Africa where a certain choice is faced between improving them and building or manufacturing more efficient kilns. As pit kilns will probably continue to be used, it is obviously desirable to improve them. Whether charcoal makers actually adopt improvements, however, will depend on the economic return and the costs of improvement. As the return is largely in the form of more highly carbonized, better charcoal, more thorough carbonization would actually reduce the weight of the charcoal and would be unwelcome to the charcoal maker unless the market is sensitive to quality. On the other hand, there is a significant cost in the form of greater skill and labour in the construction of the kiln. Thus, the prospects of diffusion for improvements in pit kilns are unclear. Because their technology is user-sensitive, and must be diffused to large numbers of users, their average practice will be much below best practice.

The choice would, then, fall between the brick kiln and the retort. The retort would be the right choice if there was a local demand for tars, resins, and other wood chemicals; if not, the brick kiln. In Brazil, beehive kilns are used to make charcoal for ironmaking. Beehive kilns are a fuel-efficient design with a history of at least 150 years behind them. They are also used in brickmaking and soft-coke making. Their technology deserves to be widely diffused, and possible improvements deserve a closer look.

Biomass

Plants have been characterized as versatile solar collectors (Coombs et al. 1983). The variety of their species, uses, and growth conditions makes it difficult to deal with them all together. Yet, the fact that they can replace one another to a varying extent in production and consumption makes it necessary to deal with all biomass together.

The quality of biomass as fuel is important to the user, and depends on four major factors.

Moisture Water in biomass is evaporated and escapes when biomass is burnt; this process makes the heat of evaporation unavailable. The energy thus absorbed is 2.4 kJ/g of water. As a result, as moisture content increases from 0 to 50% (wet basis), the available energy of wood falls from 18.7 to 8.2 kJ/g.[1]

Volatiles Wood contains tarry and resinous substances; their proportion varies between species. Their energy content is higher than that of dry wood, but they are smoky and corrosive. Incompletely burnt volatile fractions can accumulate in user equipment, e.g., gasifiers and engines, with serious effects.

Noncombustible materials These, known as ash, do not burn, but absorb heat in combustion (to lose it later). They will thus reduce the energy density of biomass. Though not high in wood, they can be significant in straw and dung.

Surface-to-volume ratio Although it does not affect the energy density of biomass, a higher ratio is related to a greater speed of burning. In cooking, which is in essence a heat exchange, a higher rate of heat production can lead to greater heat losses, lower heat transfer efficiency, and higher fuel requirements. In general, the larger and thicker a piece of wood (or charcoal), the more slowly it will burn. Crop residues are generally thinner and have high surface-to-volume ratios; so also has dung.

Quality becomes important when users have a choice; and in urban areas, people with high enough incomes can command the choice. Where they cannot get or afford premium cooking fuels such as kerosene or gas, they choose charcoal, which leads among the preferred locally produced fuels, and roundwood, which follows it. Both involve the destruction of trees. Rural inhabitants use fuels that are abundant and near at hand, and tend to minimize labour inputs to fuel collection and preparation. On their own, they generally follow less destructive fuel collection practices. Where available, they also prefer high-quality fuels (wood) to low-quality fuels (crop residues and dung), and waste the latter if the former is available. There are considerable inequalities in access to fuel and, consequently, in the labour costs of fuel; the landless and women bear the brunt of inequalities (Desai 1985; Howes 1985).

There is also a regional dimension to biomass fuel supply, as indicated by the estimates of Hughart (1979) (Table 11). The figures are highly approximate projections to 1990, and not reliable enough for close intercountry comparisons. Also, organic resources include more than what local populations would normally view as potential fuels. The figures are good enough, however, to indicate that the area most short of biofuels is the arid landmass stretching across West Asia and North Africa; higher, but still low, biomass availability extends at its extremities, eastwards into South, East and Southeast Asia, and southward down East Africa.

The rural energy crisis has attracted considerable research as well as policy action prodded by the Food and Agriculture Organization (1983). The above observations suggest that there are two sources of potential crisis, and they are by no means only rural. There is the urban energy crisis: treeless zones expand around cities that depend primarily on woodfuel, and fuel gets increasingly expensive. In addition, however, biomass productivity of land is low in arid areas, which puts pressure on the supply of all useful biomass, and not just fuel. The solutions for the two must also be looked for in different directions.

If fuelwood costs in cities that depend on them are to be reduced and stabilized, wood needs to be supplied to them from standing plantations. Thus, forestry needs to be integrated into the land use systems around those cities. It can be combined

[1] K. Openshaw, 1984. Personal communication based on Bialy (1979).

Table 11. Estimated organic resources, 1990 (GJ/capita per year).

	Sustainable forest yield	Dung[a]	Crop residues	Total
Algeria	3	3 SC	1	7
Egypt	0	1 CH	6	7
Iraq	1	5 CS	2	8
Bangladesh	2	4 CS	4	10
Ethiopia	3	6 SH	3	12
Kenya	1	7 CS	4	12
Ghana	8	2 CS	2	12
Nigeria	8	3 CS	2	13
Pakistan	1	6 CS	7	14
Morocco	6	5 CS	5	16
India	6	5 CS	6	17
Sri Lanka	11	2 CS	4	17
Korea, Republic	9	1 CP	7	17
Vietnam	12	1 CP	6	19
Afghanistan	6	8 CS	7	21
Philippines	12	3 CP	7	22
China	11	3 CP	8	22
South Africa	2	8 CS	13	23
Nepal	15	11 CS	6	32
Thailand	22	3 CP	9	34
Iran	22	6 SC	7	35
Korea, Democratic People's Republic	24	1 CP	13	38
Mexico	39	9 CH	9	57
Tanzania	54	11 CS	3	68
Indonesia	63	1 CS	6	70
Chile	71	7 CS	4	82
Burma	82	4 CP	6	92
Malaysia	114	2 CP	7	123
Sudan	148	18 CS	5	171
Argentina	104	45 CS	33	182
Colombia	180	16 CH	4	200
Venezuela	211	11 CH	4	226
Brazil	229	15 CP	9	253
Peru	245	7 CS	2	254

Source: Hughart (1979).

[a] Primary sources indicated by letter codes: C = cattle, buffalo, camel; S = sheep, goats; H = horses, mules, asses; P = pigs.

with more efficient stoves to make better use of the wood; and more efficient kilns where charcoal is used. Thus, where the energy crisis is urban in origin, research needs to concentrate on all three: agroforestry, efficient stoves, and efficient charcoal kilns.

Where, however, fuel shortage arises from low biomass output, the solution must be sought in two different directions: increasing the biomass output, and diversifying the fuel base. Here, research on general biomass productivity, and not just that of biomass fuels, is important; increase in the land yields of any crop potentially frees land for other crops (Hall 1984). Further, people in arid areas already use a broad variety of biomass fuels: woody stems from food crops, combustible residues from commercial trees, woody shrubs, weeds, and dung. Research should seek to exploit this diversity, to develop or introduce crops that improve the quantity and quality of fuels and make them available in enviromentally less destructive ways. A broader investigation of locally appropriate species is required. Trials on species have to be done over long periods and on a large enough scale to be fruitful. Hence, a substantial minimum investment in research and a long-term commitment must be made (cf., Du Toit et al. 1984). More detailed surveys of the composition of fuel supplies in different parts of the arid regions would also yield valuable comparative information.

Chapter 9 Other Thermal Sources

As heat is easily dissipated, local sources like geothermal or solar heat are best used locally without much investment in heat storage or transport.

Most geothermal discoveries have been a byproduct of oil exploration, but much more geothermal energy is probably available in young igneous systems where no one looks for oil; it would justify exploration. Most of the discovered hot water resources would have too low a temperature for direct conversion to electricity, and could only be used for process heat. However, developing countries should follow developments in binary cycle plants and hot dryrock technology.

Virtually all costs in exploiting heat from sunshine consist of equipment costs, and owing to small-scale exploitation, large numbers of devices are required. Most research is concentrated on their design, but their wide diffusion requires the development of mass production technologies that would yield cheap, reliable devices.

Because sunshine is available only part of the time, solar devices must be oversized or underused. Their costs go up rapidly with the temperature they achieve. Hence, to be economic, solar thermal devices must be used as fuel savers working together with nonsolar devices: for instance, water heaters, cookers, and crop dryers. Matching nonsolar devices with market identification is crucial to success.

A nonenergy product, when hot, can act as a carrier and a source of energy; many energy-using processes generate heat as a by-product that can be used further. The opportunities of recovering by-product heat are numerous in industry. Because heat is readily transferred from hotter to colder objects, it is rapidly dissipated if anything hotter than ambient atmosphere is exposed to the air. The only way of preventing its dissipation is to enclose it in media that are poor conductors of energy: thus, insulation is the other important means of heat conservation in industry. However, because heat is easily dissipated, and its value is seldom high enough to justify storage or transport, it is usually used where and when it is available. Here, we discuss two forms of heat: geothermal and solar thermal energy.

Geothermal Energy

The heat stored in the upper 3 km of the earth's crust under land areas is estimated to be 10^{14} times as much as the total energy in fossil fuel and nuclear resources (Rowley 1982). The obstacles to its exploitation relate to its cost and quality (Fridleifsson 1984).

To bring the subterranean heat to the earth's surface, a medium is necessary;

the only practical medium proved to date is water. A great deal of water is stored underground; to retain heat, however, it should not be in contact with water on the surface — the water should be trapped underground. At the same time, to be brought to the ground, a permeable path for it is essential. These are the special conditions for subterranean water to be exploitable. In addition, the cost of exploiting it will depend on its depth, temperature, pressure, chemical composition, and the difficulty of drilling for it.

The first step in exploiting geothermal energy is the establishment, delineation, and estimation of the resources; this requires on-site exploration. Many geopressured fields have been discovered in the course of oil exploration. However, the occurrence of steam or hot water fields does not generally coincide with that of hydrocarbons. Hydrocarbons have been looked for in or near sedimentary systems; geothermal systems that hold water over 200°C are more likely to be found in young igneous systems. Such high-temperature steam can be used directly to generate electricity; used in a multiflash unit, it would be particularly economic. However, steam pressure declines as a geothermal field ages, and the number of flashes for which it can be used will also decrease.

The occurrence of geothermal resources is much greater for water at lower temperatures whose use for electricity generation is not economic. Such hot water can be used for district heating; indeed, it is being so used in Tianjin and Paris. It can also be used in greenhouses and for fish culture in cold areas. Where there are concentrations of industries using large quantities of steam or process heat (e.g., for drying), the use of hot geothermal water would save energy. However, the chemical content of geothermal water can pose problems of corrosion and the waste water may need to be reinjected after heat extraction to prevent environmental pollution.

Exploration for geothermal resources is worthwhile in countries with favourable geology. For countries with large, low-grade geothermal resources, following, and perhaps participating in, research on binary cycle plants would be well advised. Hot dryrock technology is in too early a stage of research for firm indications of its prospects to emerge. However, experiments by the European Community and the USA are certainly worth observing.

Solar Thermal Energy

The higher the temperature required, the more solar radiation has to be concentrated. Thus, high-temperature applications require large reflectors spread over extensive areas coordinated with tracking mechanisms. Capital costs are much lower in devices that do not require concentration or tracking, and which, therefore, operate at low temperatures. These are essentially devices that achieve moderately higher-than-ambient temperatures by trapping solar energy: for instance, water heaters, dryers, cookers, and stills. Because they do not concentrate radiation, economies of scale are exhausted at a relatively modest size; they are, therefore, largely for use in households and small industry. However, this does not mean that there are necessarily no economies of scale in their manufacture. Possibilities of economies of scale depend on design and engineering. Hitherto, most of the research on these devices has been done by researchers interested in making and testing prototypes. Most have not given thought to the problems of production; those who have, tended to assume that production would be on order or in small batches. If, however, any of these devices are to be adopted in developing countries on a large scale, as much thought would have to go into their production technology as into product design.

Variations in sunshine hours and intensity of radiation imply that these devices would either have to be oversized and underutilized, or used in conjunction with devices using conventional fuels, or both. Their economics is thus determined by savings in alternative fuels, and not by savings in capital expenditure on other devices.

They are all medium-temperature devices operating at temperatures between 60°C and 150°C. Among them, devices operating at high temperatures are less economic because they require more expensive materials and work under more severe operating conditions. Hence, the economically workable devices are likely to be ones operating at relatively low temperatures (Collins 1985). Where they are used in conjunction with conventional devices, therefore, the latter are likely to act as boosters.

Water Heaters

Solar water heaters are common in Australia, Israel and Japan. They are manufactured by firms that are small by the standards of those countries and by no means large by developing-country standards. However, the firms are basically assemblers that buy in components. In all three countries there are seasons when insolation is high but ambient temperatures are low enough for hot water to be preferred. Applications in developing countries will be appropriate where climatic conditions are similar — in temperate or subtropical regions as well as dry, hilly areas. However, their economics will depend critically on the relative price of electricity or oil where these are available. Water heaters are a mature product, and their research requirements are modest. If installed in large, multi-unit residences, however, they can pose problems of interfacing with plumbing systems (Isaza 1984).

Cookers

Concentrating cookers are unlikely to find large markets in developing countries. They are expensive and, hence, appropriate at relatively high incomes, and they are more inconvenient to operate than high-income families would tolerate.

Flat-plate cookers are limited in the variety of cooking operations to boiling, steaming, and baking. They are slow, and do not necessarily cook at a time when food is required. Their effectiveness varies from season to season. On the other hand, they are relatively cheap, and could get cheaper if they were properly engineered and commercially produced. They also require no attention when cooking. They can best be used as an ancillary device, and must economically justify themselves in terms of the fuel saved on the main device. They thus probably have greater appeal for households that have another main device that uses an expensive fuel — which may be kerosene, LPG, or charcoal. It is unpromising to promote solar cookers as a poor person's device — at least in low-income countries — and market identification and development for scale production are necessary for their success.

Stills

As long as the solar still is designed as a simple heat trap, there are no economies of size; and the communities that demand desalinated water have large requirements. Hence, despite decades of experiments with solar stills, most of the desalination is done in large-scale fossil-fueled plants in countries that are rich in oil. Solar stills are unlikely to become large-scale suppliers of fresh water. However, small models should be supported as a health-promoting device for drinking water in areas that have polluted water or endemic water-borne diseases.

Pumps

The capital costs of solar thermodynamic pumps should come down considerably if they are to compete with photovoltaic systems even at current costs. The development work necessary to make pumps competitive is likely to be expensive. Given the present and prospective funding levels, research in this area is likely to have modest success (McNelis and Fraenkel 1984).

Crop Dryers

Drying is a thermal process; apart from all fuels and electricity, it can use solar heat as well. There have been extensive experiments with solar dryers in developing countries. The constraints on their application are twofold. First, it is possible to dry many products by just spreading them out in sunshine, without incurring the capital expenditure on dryers. Where such ambient drying is feasible, the only justification for dryers would be in the effect they have on the quality of the product; for instance, they may keep out dust, prevent birds or insects from attacking the product, or prevent contamination by foreign organisms. There are few applications where these marginal improvements can make a decisive difference: for instance, dirt added in the open can be washed, birds and insects can be kept out in other ways, and except in some medical uses, contamination is not a serious drawback (solar dryers have been devised for sterilization of medical equipment, but they are required to reach higher temperatures, and are therefore more costly).

Second, the temperatures that can be reached in simple solar dryers limit their throughput, and make them inappropriate where the volume of throughput has to be large or where the drying has to be done rapidly. Ordinarily, the investment required in a solar dryer can be afforded only by a producer with relatively substantial means, and the output may well be so large that a diesel or electric dryer is cheaper than a battery of solar dryers. Also, artificial drying is generally resorted to when ambient drying is impossible: for instance, when multiple cropping requires a crop to be harvested before it is dry on the ground, or when the weather in the postharvest season is too rainy or cold to allow outdoor drying.

It seems to us that where solar dryers have a market, they will invariably have competition from fuel-using or electric dryers. Apart from being slow, the present solar dryers also require manual handling of products, whereas diesel or electric dryers can easily incorporate a motor to move the grain in and out. Hence, the economics of solar dryers is precarious (Bruggink 1984). There seems to be greater scope for hybrid dryers, however, in which air used in diesel or electric dryers is preheated with solar heat.

Chapter 10 Electricity

Versatile in its uses as well as in its sources, electricity is a prized source of energy for use in industry and in the family, and shows a rapid rise in demand as development proceeds.

Power utilities in developing countries are often national in scope and owned by the government. Political interference in management results in poor organizational structures; institutional reforms and a workable relationship with the government remain the highest priority, and organizational innovation is an important area of research. Next to organization, investment policy and pricing policy are interrelated areas where research has a major role to play. Remedial diagnostics of plants in operation are potentially very useful.

Crystalline silicon photovoltaic cells have been commercialized, and have shown a rapid decline in costs. However, research potential is greater at present in thin film cells, especially in amorphous silicon cells. At least until they reach the stage of commercialization, research on them in developing countries is promising.

For a developing country that considers wind power generation, identification of sites is the first step. The number of sites will decide the market for generators, on the basis of which designs and process of manufacture would be chosen. Problems for research would also arise in adapting the generators to the transmission network.

Electricity can be produced from a large number of primary energy sources, and is equally versatile in its uses. It has become the major source of stationary shaft power in industry because of its convenience, efficiency, and low cost relative to other prime movers using oil or coal. It is also responsible for great improvements in the quality of life, both as an illuminant and as the energy source for domestic appliances. Consequently, its share of energy consumption in developing countries has shown a steady rise (Brooks 1984).

Electricity is produced in all developing countries, and improvements in its production and management are of interest to all of them. It offers some of the most promising avenues of research.

Power Sector Organization, Management, and Policy

The electricity sector in most developing countries has developed rapidly, especially since the 1950s. Because it is one of the most capital-intensive sectors of the economy, potentially capable of generating significant revenues, and also dependent on relatively modern technology, electricity has tended to attract greater foreign involvement throughout the Third World. Typically, power supply was originally available only in the main cities, and was produced by isolated thermal or hydro plants of relatively modest size. These plants were often associated with large industrial users and foreign companies. As more developing countries received independence after World War II, and consumer demand began to grow, it became advantageous to develop interconnected grids — at the regional and national levels — as well as larger generating stations, to realize economies of scale in planning and operations, greater reliability, improvements in coordination and efficiency, and other benefits. At the same time, socioeconomic and political pressures compelled many governments to take over private power producers (both local and foreign), and to centralize the supply of electricity.

The principal objective of electricity supply is to meet the load. A modern power company is expected to perform the following technical functions efficiently in order to provide satisfactory services to its customers: demand forecasting (short, medium, and long run); long-run, least-cost investment planning to meet the future demand at an acceptable quality of supply (generation, transmission, and distribution systems); optimal operation and maintenance of the power system (including system security, losses, etc.); and price setting.

A successful power utility — as, indeed, all public enterprises — should have:

- Clearcut general, national-level policy guidelines provided by the government, but without involvement in daily activities;
- A relatively independent Board of Directors that will interpret the national guidelines, provide more specific policy directives, and generally protect the management from undue interference;
- A competent and well-motivated management, with a high degree of continuity;
- The authority to recruit good staff, and retain them by offering competitive salaries and other incentives, as well as to dismiss incompetent staff;
- A high degree of financial viability and independence, including the ability to set tariffs that will raise sufficient revenues, help meet social-subsidy objectives, ensure economic efficiency, and so on;
- Primary responsibility for the procurement of goods and services; and
- A separate, unbiased, and fair regulatory environment that focuses on policy concerns (e.g., investment and pricing issues) rather than on minor aspects that can lead to undue interference and delays in decision-making.

In actual practice, few if any of these requirements are satisfied in all but a handful of developing countries. Typically, political pressure to keep tariffs low will lead to inadequate financing, underinvestment, and poor upkeep of the power system. Quality of supply could deteriorate while outages and losses mount, imposing further burdens on the utility as well as the consumers. Interference with management decisions on staff, procurement, and even daily operational matters, as well as frequent replacement of senior managers, may undermine both competence and morale. Concurrently, rising consumer demand and expectations, fueled by political rhetoric (especially regarding rural electrification), will further exacerbate the situation.

The problem of institutional reform is complicated by the need to maintain continuity, and not to subject the often fragile fabric of a developing country's power sector to violent changes, with unforeseen consequences. Structural shifts should be more of a transition type that take the existing institutional framework and sociopolitical and economic constraints into account, and build on past experience.

The conditions that determine whether electricity supply in a given country exhibits natural monopoly characteristics should be carefully studied in relation to the multistage aspects of the power system (generation, transmission and distribution). Economies of vertical integration and coordination, within and between stages, should also be examined. Generally, the overall philosophy underlying the macroeconomy (e.g., centrally planned, mixed, capitalist), the existing degree of reliance on market mechanisms, and the degree of access to capital markets by autonomous institutions are equally important factors to consider in making decisions concerning the institutional framework and sector policy.

The principal area for reform is likely to be distribution. The spinning-off of the distribution function from bulk supply is usually a relatively uncomplicated step in the right direction. In large power markets, some competition at the generation level could also be encouraged — starting possibly from industrial cogeneration. The legal and contractual problems are likely to be more formidable than the technical ones.

Organizational reforms will generally not result in significant benefits without the efficient pricing of electricity, although areas of implementation such as metering, billing, and revenue collection may improve performance. Therefore, the promotion of tariff policy reforms should continue to be pursued irrespective of the policy on power sector reorganization (Munasinghe and Warford 1982; Collier 1984).

The experience of other countries should be monitored. Further country-specific case studies should be carried out. Developments in other related sectors, e.g., telecommunications and natural gas, are also relevant.

Further applied research is required to determine to what extent it is possible to adapt utility organization to the new technological conditions. We think that the organizational innovation in the power industry and related economic issues form one of the most promising areas of research in developing countries.

Optimizing Investment Planning, Pricing, and Operations

The two principal policy decisions to be taken by power utilities relate to investments in and the pricing of electricity; therefore, both areas are prime candidates for further research. In most developing countries where the government is the main supplier of electricity services, it can intervene directly in the sector. Successful policy analysis and formulation requires the following items. First, the national and corporate policy objectives must be clearly defined. Second, the policy models must explicitly define and quantify the most important technical–economic relationships within the electricity sector and interactions with the outside world. Third, other social and political constraints that are difficult to quantify must be systematically accounted for. Finally, the results should be readily translatable into straightforward policy options and the methodology should be practical and applicable even when data are poor.

From the engineering–economic viewpoint, the basic objective of analysis is to determine a set of policies that will maximize the net benefits of electricity consumption to society as a whole. This also corresponds to the most efficient use of scarce economic resources and maximization of output or GDP based on a national economic viewpoint. There are several other important objectives, for example, meeting the basic energy needs of poor consumers, establishing independence from foreign sources of funds, raising financial resources for future investments, etc., that will also influence both pricing and investment policy.

In investment policy, the principle of maximizing net benefits may be used to optimize overall planning, reliability, and losses. Often the maximization-of-net-benefits criterion may be reduced to the simpler rule of minimizing total costs such as for least-cost investment planning. In recent times, sophisticated system planning models and techniques have been developed, based on the criterion of minimizing the cost of supplying a given long-range demand forecast at some acceptable reliability level (or quality of supply) (Munasinghe 1979). The optimal size, mix, and timing of new capacity additions are treated in this way, and related models also provide for optimal (least cost) operation of the system (Turvey and Anderson 1977).

Currently, a new approach involving the minimization of total costs, which includes both supply costs and shortage costs (costs incurred by consumers due to unreliable supply), is being explored. Methods of measuring shortage costs in developing countries need to be further researched.

In pricing policy, basic economic principles require that prices reflect the marginal costs of supply, thus ensuring that economic efficiency criteria are satisfied. However, these marginal costs must be systematically adjusted to yield a practical tariff structure that meets other national policy objectives such as supplying the basic electricity needs of poor consumers, ensuring financial viability, price stability, and so on.

The worldwide scarcity of energy resources and the increasing costs of energy supply have highlighted the importance of energy conservation and elimination of waste by both producers and users of energy. Power system loss reduction is one of the principal ways for achieving this in the electricity power sector (Munasinghe and Scott 1982).

In the process of delivering electricity to consumers, losses are incurred at the generation, transmission, and distribution stages of a power system. Generation losses may be reduced by improving the efficiency of plant and reducing station use; for instance, by using new technologies such as combined-cycle thermal plants, replacing old boilers, and generally uprating old thermal generation facilities, using higher efficiency designs in new hydro installations, replacing older turbines, etc. Leaving generation aside (where acceptable norms for losses vary according to the mix of plant), recent work indicates that average energy losses in the power delivery system, i.e., in transmission and distribution, should normally be below 10% of gross generation, while economically optimal loss levels may be as low as 5%. The corresponding losses in many developing-country networks approach 20%, even after allowing for substantial amounts of theft.

The basic principle involved is minimization of overall supply costs, defined as the sum of system costs and value of system losses. Modest investments in system rehabilitation can often yield a more than commensurate reduction in losses. In other words, reducing losses is often far more cost-effective than building further supply facilities to feed those losses.

An important area for improving operations concerns plant availability, which is observed to be low in many developed countries (Khatib 1983). The principal causes are:

- *Poor system configuration* Lack of an integrated grid may make it impossible to stabilize the system; or the proportion of large plants in a system may be too high given the spinning reserve.

- *Unbalanced investment* Inadequate quantities of spare parts may be carried; or there may not be enough reserve capacity in the auxiliary, control, and protection systems.
- *Operational constraints* The fuel may be inconsistent with the plant, or there may be a shortage of expert personnel.
- *Plant derating* Mishandling may lead to a fall in plant capacity.

Remedial diagnostics of specific plants and systems are of considerable potential utility.

The power systems of developing countries are considerably smaller than those of developed countries, and typically take smaller plants. Such small power equipment is not a major product of the large plant manufacturers but is produced on demand by them. However, there is a steady demand for them, and if they were standardized at ratings in the range of 25–250 MW, serial production would lead to economies of scale and incremental innovation. This type of production would be more feasible if it were the joint program of a number of developing countries.

In general, the developing countries do not have a comparative advantage in R&D on hardware relating to sophisticated generation, transmission, and distribution equipment. Large countries such as Brazil, China, and India may have the resources and internal markets to support such efforts on a workable scale. Cooperation among developing countries and joint ventures with foreign companies are other options.

Solar Photovoltaic Systems

The solar energy potential of developing countries, most of which are tropical or subtropical, has long been recognized. It is of particular interest to the arid countries of West Asia and North Africa, which receive intense solar radiation for a large part of the year (Kettani 1982). Despite the fact that interest in solar energy goes back almost 30 years (United Nations Educational, Scientific and Cultural Organization 1956), the practical consequences are yet modest. The prospects are different for solar photovoltaic (pv) systems on the one hand and solar thermal applications on the other; the latter are therefore discussed separately in the next section.

Absence of pronounced economies of scale makes pv systems attractive for stand-alone uses in locations away from grids. However, because the capital costs per watt are still high, the technology is better suited to low-voltage uses. Radio, television, and telecommunications are the obvious ones, but lighting is also attractive. All these uses require storage; however, the costs of battery storage are avoided if the power is fed into the grid. In countries with high diurnal peak demand (for instance, where cooling and refrigeration are important and where residential and commercial demand dominates the load curve), grid-connected systems would make sense.

Both stand-alone and grid-connected systems require power conditioning equipment, whose cost will be relatively more important in smaller systems. In stand-alone systems, the equipment varies with the type of application; for instance, AC loads would require a voltage controller and a self-commutated inverter. Grid-connected systems require simpler and cheaper inverters along with harmonic filters to suppress the injection of electrical noise into the grid.

Current Photovoltaic Systems

The current pv systems, based on monocrystalline and polycrystalline silicon, involve four stages of manufacture (Backus 1984a, b; Luque 1984).

Production of silicon Here, efforts to reduce costs have involved a reduction in the purity of silicon. However, a reduction in purity has a trade-off in the form of deterioration in cell efficiency, thus the opportunities of cost reduction are limited.

Sheet manufacture Recent developments, i.e., single-crystal continuous sheets and polycrystalline silicon wafers, also reduce cost as well as efficiency.

Cell manufacture Here, the technology is not changing much; it has perhaps been frozen as a result of the automation of operations.

Panel manufacture Efforts are being made to increase cell output by using concentrators. This would limit pv cells to the use of direct sunlight, and require trackers. Trackers introduce economies of scale in operation, and raise the minimum economic size of generation plant to 3 MW.

There has been a rapid fall in the cost of pv modules: from US $50/peak-W in 1973 to US $6 in 1984. However, recent years have also witnessed a price war between the subsidiaries of oil companies and other manufacturers. When the war ends, cell prices may well rise. In any case, major cost-reducing innovations are unlikely to occur in conventional pv cell manufacture.

Developments in Prospect

Thin film cells are uncompetitive at present, but offer greater hope of innovations; they are also easier to make. Their efficiency is low at present, as is their stability outdoors. Of the two kinds of thin film cells, compound semiconductor cells and amorphous silicon cells, the latter hold great interest.

Compared to crystalline cells, amorphous silicon cells have better optical absorption and better photoconducting properties for the solar spectrum. They also use less silicon. At present, they are mainly used in watches and calculators. They can, however, be deposited on any noncrystalline substance. Thus, in Japan they have been deposited on polymer films, stainless steel substrates, and ceramic substrates; Sanyo is in the process of depositing them on roofing tiles. Their efficiency is reported to be about 10% in commercial applications (Hamakawa 1985).

The ease of making thin film cells has led to the proliferation of research on them in developing countries. When the technology reaches the commercialization stage, it will require different skills; but until then, it suffers from no handicaps. Thus, research on thin film cell technology appears particularly promising for developing countries; it would be helped even more by the creation of communication networks among researchers in developing countries.

Solar Thermal Electricity

Solar radiation is very diffuse; as Tabor (1981) pointed out,

> if we take the world average solar radiation at about 200 W/m^2 (continuous) or 17 MJ/m^2 per day, we would require some 260 m^2 of collector to replace one barrel of oil a day, if a collector were 100 percent efficient: in practice, the efficiencies are very much lower so that considerably larger areas are needed.

In fact, the Solar One 10-MW central-receiver power plant used 1818 heliostats of 39 m^2 each, achieved 13% average efficiency, produced 71 MWh/day in a location where insolation was 950–990 W/m^2 and when an average day had 10–11 hours of sunshine, and cost US \$13/W_e (Weingart 1984). In places with lower insolation or fewer sunshine hours, the capital costs would be still higher. Undoubtedly, the technology will improve and costs decline as new prototypes are built. At present, however, this is a submarginal technology, and its future is speculative. Thus, we do not see any justification for research on it in developing countries at the moment.

Wind Generation

Wind generators may stand alone or be grid connected. Stand-alone generators have a potential market in developing countries in areas that the grid cannot reach. They require batteries. Battery sizing to achieve reliability at a low cost would be important, and would require site-specific calculations.

Grid-connected generators do not need batteries; they can also exploit economies of scale, since their output is not limited by local demand. Hence, their capital costs are lower (Piepers 1985).

Most of the development in wind generators has been toward grid-connected machines in the USA. Besides the good wind regime in parts of the USA, there are three reasons for this: tax incentives or direct government purchase assistance to encourage the purchasers of grid-connected machines; government instructions to utilities to use avoided cost pricing to purchase electricity; and a wind generator with grid connection is a more marketable and profitable proposition for manufacturers in the USA because almost all the potential consumers of electricity are already grid connected (Merriam 1984).

A majority of the grid-connected machines are horizontal axis machines and their technology is fairly well proven. Although vertical axis machines, such as Savonius and Darrieus, have been developed, they have yet to reach a point where they prove to be as reliable and efficient as horizontal axis devices (Kristoferson et al. 1984). A major problem with vertical axis machines is that they cannot be furled and need other methods of speed control.

The major operational problem in grid-connected wind generators is power control to maintain the stability of the connected power systems. Power limit operation from horizontal axis wind generators is achieved through pitch control, whereas in vertical axis wind generators, some form of spoilers or aerodynamic braking is used (Quraeshi et al. 1984). The need for voltage and reactive power control has direct consequences for the choice of generator. The trend in commercial machines, at present, seems to be fixed pitch with overspeed control and an induction generator, and variable pitch with a synchronous generator (Sexon et al. 1981).

Although there have been attempts at using wind generators in tandem with diesel generators in some industrial countries, problems can occur when the diesel generator is called on to change its output frequently as wind energy availability fluctuates. As well as decreasing the oil-saving potential of the wind generator, this may lead to more frequent overhauls of the diesel generator. A consequence in both cases would be increased costs (Kristoferson et al. 1984). A way around this problem would be to interpolate battery storage, which would ease the strain on the diesel engine but would add to costs.

A wind generation program will require detailed site-specific research to determine whether the wind regime is appropriate for generation: the windspeeds should be neither too low for generation nor so high as to require unduly strong and expensive structures. Thus, the number of sites for wind generators is likely to be limited; it will determine the maximum extent of the market for them, within which they could be installed where they are found economical. If a developing country gets this far, it will need to standardize a design for production. It would be well advised to choose the largest size that can be economically produced, in view of the fact that the power output of a windmill varies in proportion to the square of its wingspan. The major problems of technical research it will encounter are likely to be on the generation–transmission interface.

Chapter 11 Motive Power Sources

Much of the demand for energy is in the form of motive power, but only wind, flowing water, and animate sources directly supply it in that form. Wind power was paramount in shipping and extensively used in grain milling, but is now unimportant. Water power used to provide energy to industry but now only generates electricity. Animate energy, however, continues to be important in developing countries, although to a varying degree. Improvement in the conditions and quality of work is a crucial part of development. It entails reduction in physical drudgery, thus research into human energy is a vital area of energy research.

Windpumps have been getting lighter and easier to assemble and operate, but their design remains empirical; it can be improved by more precise observation of their performance. Another area of research lies in matching rotors with pumps.

Human energy has been measured in three ways: in terms of workers, labour time, and calories. The first two are approximations. Actual measurements in terms of calories have not yielded a robust theory because variations in the calorie expenditure involved in work have not been systematically studied. More accurate measurement and theoretical innovation should go hand-in-hand in this field.

While motive power accounts for a high proportion of energy consumed in industry, agriculture, and transport, only three primary sources directly supply energy in that form: wind, flowing water, and animate sources. Wind power was paramount in shipping until the advent of the steamship, and was used extensively for grain milling in parts of Europe and China. Now, however, it is of small importance, and is unlikely to become a major source of energy. Water power was important as a source of industrial energy in many locations before the advent of prime movers; now, it is used only to produce electricity.

Animate power was the major source of motive power before the industrial revolution. Since then, inanimate sources have both replaced it and supplemented it in industrial countries. The quantities used in industrial countries now are small compared with those from inanimate sources; and most human workers are engaged in nonphysical work.

In developing countries also, supply from inanimate sources has been growing, and it outweighs supply from animate sources in many. However, the proportion of animate to inanimate energy varies considerably from sector to sector; animate energy remains important in agriculture and small-scale transport. Certainly, a high proportion of the working population earns its living by physical labour. Because development consists as much of a change in the quality of work as of a rise in the standard of living, human energy and its use are one of the most important areas of energy research.

Wind Energy

Windmills have no direct use, but are invariably used with an energy convertor such as a generator or a pump. To minimize costs, servo-matching of the wind regime, the windmill, and the convertor is necessary. This is a site-specific task of some mathematical complexity. At the same time, the windmills and the convertors need to be produced on a certain minimum scale to bring down costs. Hence, integrated planning of windmill systems can pay considerable dividends.

While stronger winds mean more power to be harvested, they also require stronger windmill structures; hence, capital costs go up with the maximum windspeed, and if windspeeds are too high, windmills become too costly to be economical. Even if they are feasible, it is necessary to prevent them from being damaged by high winds. This is done by changing the orientation of the rotor to the wind or the pitch of the blades. If done manually, it involves constant human supervision and consequent labour costs; if done by servomechanisms, it raises capital costs. Exposure to elements and stress on moving parts also implies frequent maintenance. Thus, the capital costs of windmills can be high, and the running costs are by no means negligible.

We have discussed wind generators in chapter 10; here, we shall confine ourselves to windpumps. Windpumps differ from wind generators in their design parameters. The weight of the pump's piston has to be lifted before the pump can start. Hence, water-lifting windmills require a higher starting torque, which varies inversely with the tip-speed ratio. The power output of wind generators, on the other hand, varies directly with the tip-speed ratio. Hence, windmill designs that give a low tip-speed ratio and high ratio of blade area to swept area (solidity) are used for windpumps: for instance, multipropellor horizontal-shaft designs or Savonius rotors.

Among windpumps, there are two distinct end-use categories — water supply windpumps and irrigation windpumps. Water supply windpumps need to be reliable, to run unattended for most of the time, and to require the minimum of maintenance. Thus, they tend to be expensive in relation to their power output. They are industrially manufactured with steel components and have automatic protection devices to prevent overspeeding in storms (McNelis and Fraenkel 1984). Traditional multiblade farm windpumps fall into this category of end use; they tend to be heavy, material-intensive, and complicated to assemble but they are robust and reliable. Their modern counterparts tend to be lighter because they use construction tubes instead of rolled sections. Their modular subassemblies result in structural simplicity and are easier to manufacture. They can also be used for higher wind-speed regimes with electric drives (Intermediate Technology Power Ltd 1983).

Irrigation windpumps are used only seasonally, and it is less important to have a machine that can be left unattended than one that is low cost. Thus, irrigation windpumps tend to be of indigenous or local designs that are often improvised or built by farmers using local materials to achieve low-cost mechanization. Most of these "self-built" machines are made of wood or basic steel structural components and use cloth or wooden sails. Their efficiency is typically half that of water supply windpumps, and they may need relatively frequent oiling and adjustment. A number of attempts have been made to improve them by applying scientific principles to local materials and designs (cf., Stanley 1977; Govinda Raju and Narasimha 1980).

While the old designs tend to be more reliable, they are heavy, expensive to ship, and complicated to assemble. On the other hand, however, the newer designs do not have a proven field performance record in terms of either efficiency or life span. Attempts at transferring the technology of low-cost irrigation windpumps from one region to another have tended to fail. A possible reason is a mismatch between wind regimes, irrigation requirements, and pump capacity. Another important reason could be not viewing the low cost of a windpump as a direct function of the cost of raw materials and labour. Thus, there would be interregional variations in the cost of a windpump.

Technically, there are two areas of research that may prove to be fruitful in the long run. Through a lack of science combined with a lack of measuring equipment, windpump design in the past was largely empirical. Designs have thus tended to be suboptimal. Through comparatively minor modifications, the performance of some machines could be significantly improved.

A second area of research lies in matching rotors with pumps wherever reciprocating pumps are being used. There are two mismatches between rotors and pumps. The first mismatch results from the fact that power available from a rotor is proportional to the cube of the wind speed while the power requirement of the pump varies only linearly with its speed. The second mismatch arises from the cyclic torque requirement of piston pumps in which starting torque in the first stroke is three times the average torque required. While the first mismatch requires research on pumps where the speed better matches the power available, the second mismatch requires research on methods of reducing the starting torque.

Although wind electric pumps are potentially more efficient than wind mechanical systems, their track record so far has been quite limited. They, however, offer the advantage of higher heads, can be located away from the water sources at better wind locations, and can also be used for charging batteries.

Human Energy

Human energy is perhaps the most important aspect of energy in developing countries; certainly, if it is excluded, the significance of energy studies would greatly diminish. It is also an area, however, in which research has been least useful in terms of understanding or policy. The difficulty arises in the measurement of human energy itself.

In economics, the concept that comes nearest to human energy is the number of workers. The potential number of workers is termed labour, the number that is actually working is termed employment, and the number of workers who are not employed is called unemployment. In the 1930s, when a large proportion of the workers was unemployed in industrial countries, an explanation of unemployment was offered by Keynes (1936). In developing countries, the problem often arises, not from the complete unemployment of people who are willing to work, but from occasional or partial unemployment. This phenomenon was termed disguised unemployment by Robinson (1947). A number of conceptual variations were observed and explanations offered (Turnham and Jaeger 1970; Todaro 1981). However, empirical estimates in terms of the number of workers remained too approximate in terms of intensity of work to be of use in energy research.

An improvement in the concept is constituted by measurements of time utilization; it permits a closer study of the phenomenon of work. Much evidence on time utilization is collected in the course of anthropological studies (Carlstein et al. 1978a, b, c). Recently, this evidence has been used by Carlstein (1983) to refine the concept of carrying capacity. It has been used as a proxy for work loads within families (Tinker 1984). Time utilization has also become a subject of interest to sociologists (cf., Szalai et al. 1972) and economists (cf., Winston 1982). However, time utilization studies imply that the energy expended per unit of time is constant, which is manifestly not the case.

Differences in energy intensity of physical activity have been known to physiologists for a long time; one of the most systematic efforts to quantify them was made by Passmore and Durnin (1955). Since then, numerous estimates of energy expenditure per unit of time have been made in a large variety of circumstances, and have been used to calculate energy balances for human beings (e.g., Thomas 1973).

The idea that the cost of work in terms of food could vary was put forward by Leibenstein (1957). He assumed that the efficiency with which a worker converted food into physical work is low when he is severely undernourished, increases as the standard of nutrition improves, then falls, and reaches a point when an increase in his food intake will not raise his work output. This relationship, known as the work-efficiency mechanism, has been used extensively in economic theory (Bliss and Stern 1978). However, it had no basis in physiology until Sukhatme and Margen (1982) argued that there were systematic variations in human energy efficiency in physical activity. More recently, Borrini and Margen (1984), in a paper written for us, have given considerable evidence of variations in human energy efficiency, and have questioned the validity of mechanical models of human energy balance. Their views are strongly contested by other physiologists (cf., Rand and Scrimshaw 1984).

We observe that the entire subject of the physiology of human energy is one of considerable theorizing without accurate enough measurement to test the theories, of voluminous empirical work without testing theories, and of generalizations based on averages without consideration of variation around the means. In the circumstances, it may be that more accurate measurements of the human metabolism reacting to variations in work, nutrition, and ambience may lead to more definite hypotheses. At any rate, it seems clear that investment in further empirical work in this area without greater clarity in theory can only lead to waste.

Meanwhile, the role of human energy in production systems remains central to development problems. We cannot emphasize enough the importance of research in this area, but feel that theoretical innovation is necessary for a more thorough understanding of how human energy is used or underutilized in socioeconomic activities.

Chapter 12 Environmental Effects

Although environmental effects of energy production and use are pervasive, such effects are not exclusive to energy, and their study is not closely related to energy research. Thus, the report deals with only three issues closely related to energy: deforestation and desertification, the greenhouse effect, and acid rain.

The logical chain between firewood consumption, deforestation, and desertification is weak and partly misconceived. The use of firewood does not necessarily or frequently lead to deforestation. Deforestation may cause concern on scientific, aesthetic, or economic grounds; in each case, the best remedy is not necessarily reforestation — that needs to be worked out in each specific circumstance. Desertification is due to the removal of vegetation cover, which seldom consists of forests in desert-prone arid areas. Here again, a number of remedies are available, of which afforestation is by no means the best. This field calls for better research.

The evidence for a progressive rise in carbon dioxide concentration in the atmosphere is irrefutable, and its connection with fossil fuel burning is fairly clear although other factors are also important. Projections using this relationship suggest that carbon dioxide concentration would double between now and the middle of the 21st century. There is considerable uncertainty, however, about how much this doubling would raise global temperatures, and what would be the effects of warming. The mechanism of climatic change is poorly understood, and a better understanding of it is as important for developing as for industrial countries.

Most rain is slightly acid. Its acidity is believed to be due to nitrogen oxides. Although they are formed by combustion and breakup of natural fertilizers, most of the world's emissions come from natural decay of biomass. Rain can be acidified by sulfur dioxide and hydrogen sulfide also, which can be emitted by the burning of sulfurous fuels and by volcanic eruptions. Precipitation in North America and Western Europe has become so acid in recent years as to kill certain flora and fauna; it has been linked with the burning of sulfurous fuels. However, the chemistry of acid rain has two obscure areas: the nitrogen oxides – volatile organic compounds cycle, and the role of hydroxyl and hydroperoxyl radicals. Understanding these has a strong bearing on the best way of dealing with the problem. Abatement also requires research on coal preparation, furnace geometry, combustion efficiency, and flue gas treatment. This research may be relevant to developing countries that consume fossil and biomass fuels on a large scale.

Most major energy production and consumption activities have environmental effects, and the effects of some are pervasive. For instance, coal mining and utilization can have widespread effects underground, on the ground, and in the air (Fig. 1). A number of the environmental effects are deleterious ones and a cause for concern. They should clearly be addressed and taken into account in planning energy investments.

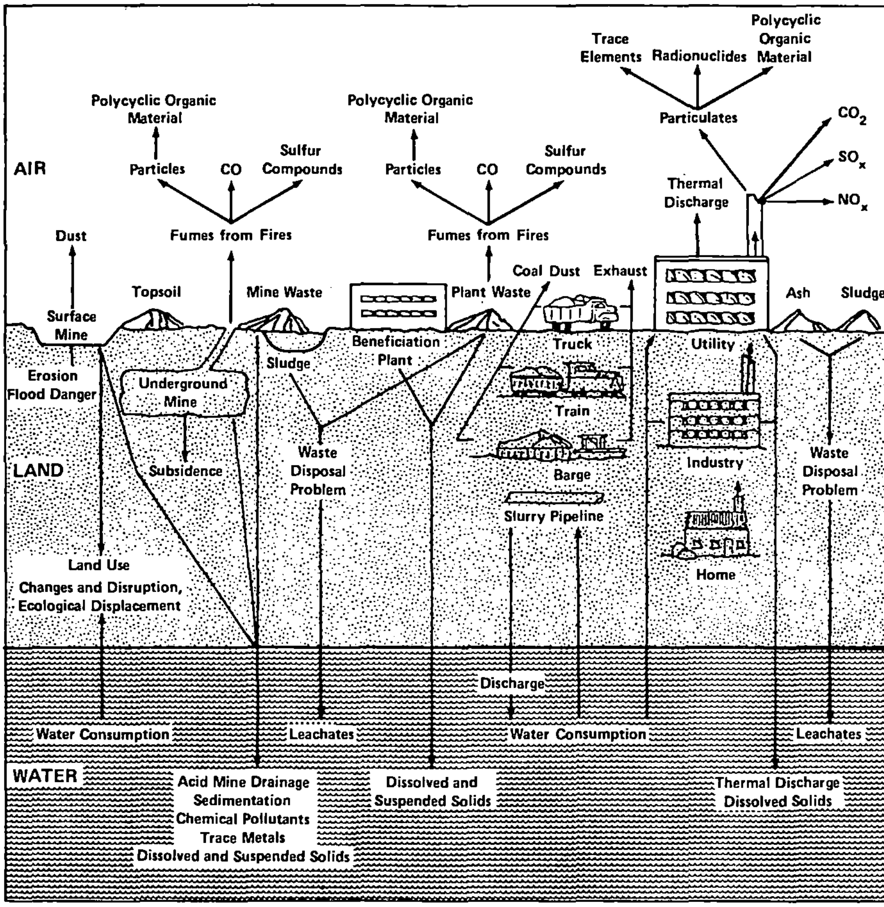

Fig. 1. Environmental disturbances from coal-related activities (Source: United States of America 1979).

Throughout this report, the Group was faced with the problem of defining boundaries; this problem was particularly acute in regard to environmental issues because a number of the major environmental effects are related, not to energy activities as such, but to types of resource exploitation and processing. In formulating policy on environmental issues, also, it would be a mistake to relate them only to energy. Environmental effects arise from a whole range of growth-related phenomena such as population increase, a rise in incomes, and extension of agriculture, industry, mining, and transport; these are the phenomena to which environmental policies must be related. Nor is environmental research closely related to energy research. There is a good deal of distance between the people, the techniques, and the issues on the two sides. Thus, doing justice to environmental research would have required a different range of expertise. For these reasons, the Group decided to confine itself to energy research in the narrow sense.

However, there are three environmental issues that are closely related to energy and deserve serious interest from developing countries in the opinion of the Group: deforestation and desertification, the greenhouse effect, and acid rain. These are reviewed below.

Deforestation and Desertification

The logical chain from domestic firewood combustion through deforestation to desertification, although never fully argued through in literature, has taken such hold on popular imagination that it needs to be seriously addressed.

Firewood Consumption

The available estimates of firewood consumed simply do not serve as a basis to judge the nature and seriousness of the problem. Smil (1983:81–83) gives estimates ranging from 1.3 to (his own) 3.2 billion m^3/year, and conversion factors ranging from 0.15 to 0.8 t/m^3. The uncertainties extend in three directions. First, per capita fuel consumption varies enormously. Second, its composition varies not only from place to place and family to family, but for the same family over the seasons, in response to fuel supply and need. Finally, much of what we know comes from energy consumption surveys, most of which do not give information on the origin of the fuel — whether it came from trees or crops; if from trees, whether harvested or obtained by destroying trees; and whether it was the main product or the by-product of another activity such as timber production. It is quite important to distinguish between fuel coming from natural annual biomass accretions and other biomass fuel.

Deforestation

Deforestation is a strictly regional problem, and is to be encountered in two types of situations: where land is being cleared for agriculture, as in Brazil and Indonesia (both of which are exporting wood to industrial countries); and where strong demand in nearby urban centres uses up wood for two main purposes (i.e., construction and combustion), for instance, in Nepal, parts of China, and parts of Africa. This effect of strong urban and industrial demand leading to deforestation is not unknown in industrial countries: it occurred around the Mediterranean in Roman times, in the U.K. and Europe as early as the 18th century, in the USA in the 19th century, and is going on even now in Canada and the Soviet Union. It may cause concern on a number of grounds: scientific (e.g., the destruction of tropical forest species), aesthetic (e.g., the ugliness of deforested landscapes), or economic (e.g., erosion may cause flooding or reduce land productivity; destruction of forests may deprive forest-dependent populations of livelihood; deforestation may lead to desertification). It is important to discuss deforestation in a regional context, however, because the reasons for deforestation, the reasons for concern, and the remedies will be different in each region. If this is done, it will be found only seldom that the remedy for deforestation is reforestation; for, as with desertification, cheaper and more effective solutions can be found to specific problems created by deforestation.

Desertification

As far as it has occurred, desertification is not the creation of new deserts in what were vegetation-rich areas in recent history, but an extension of what have been deserts for a few thousand years. The connection between climate and deserts is palpable; and the connection between climatic change in the last 4000–6000 years and desertification is also fairly well established (Kellogg and Schneider 1977). However, whereas desertification has been local and incremental, climatic change has been global; the climate all over the world is dryer and cooler than 4000–6000 years ago. Long-term evidence does not support the thesis that desertification caused climatic change.

Two mechanisms have been suggested through which removal of vegetation cover leads through a reduction of rainfall to desertification (Le Houérou 1977:20).

> Where vegetation in an arid zone is not degraded, there is always a diffuse ground cover of at least 20 to 40% of perennial species such as shrubs, undershrubs, and perennial grasses. This is enough to protect the soil surface from erosion; or, more precisely, wind erosion in these conditions is compensated by sand deposited behind the obstacles that perennial plants constitute.
>
> Where the distance between two perennial species is equal to or longer than five times their height, deflation is no longer compensated by sand deposition and erosion increases up to the point where the whole land surface is covered by pebbles or stones after removal of all movable material. The sand that drifted away accumulates in barkhans, reboubs, nebkas, sand veils, and the like. This sand drift takes place over rather short distances, seldom surpassing a few hundred meters and then up to no more than a few kilometers. The final result is that soil layers, which used to be superposed as sandy or loamy deposits over rock outcrops or limecrusts, become juxtaposed as a result of wind erosion. Permanent plant life then becomes impossible, for the lack of water reserves in the shallow soil of the reg prevents seedlings from surviving the first prolonged drought period. In shifting sand, perennial species, too, cannot get established. Just as soon as the seedlings have emerged, they are uprooted and blown away.

Here, what is referred to is vegetation; the natural vegetation of arid regions is shrubs and perennial grasses, and not trees.

The second cause that has been suggested is an increase in albedo and a reduction in vegetative debris through overgrazing. An increase in albedo reduces the warming of land and the formation of convective plumes that bring rain (Charney et al. 1975). Rain formation is facilitated by the presence of ice-forming nuclei in the clouds. Among the sources of such nuclei are microflora and bacteria from decayed leaf litter, whose production would vary with the ground vegetation (Schnell and Vali 1976; Vali et al. 1976). Thus, it may well be that a reduction of vegetation cover tends to reduce rainfall owing to lower production of ice-forming nuclei (Kellogg and Schneider 1977).

Among the remedial measures, students of desertification place afforestation quite low. It can have no significant effect on the regional climate, and would require subsequent management and organization (Le Houérou 1977). A remarkably large number of remedial schemes have been proposed for the Sahara (Glantz 1977). Of them, one is proven: Egypt and Pakistan are standing evidence of the efficacy of irrigation in desert areas. Another — cloud seeding — has been often tried but not evaluated. More speculative and exciting schemes have included asphalt belts (spraying a large area with asphalt to reduce albedo); seeding clouds with carbon dust to absorb solar radiation, to heat up the surrounding air, and to increase evaporation from the oceans; and flooding the Sahara by means of a canal from the Mediterranean. On a social scale, a number of alternatives have been suggested including control of overgrazing (Kellogg and Schneider 1977), concentration of development in a few better-endowed areas, and urbanization and industrialization (Ware 1977).

The problems of the desert areas have been brought to the fore by the Sahelian famine. We are sure that the solutions are not clear; but we are also sure that singling out bivariate relationships such as that between deforestation and desertification is a misspecification of a complex of relationships, and if used as a basis for policy, can lead to much waste of resources. More meticulous, comprehensive, and multivariate study of the relationships is required.

The Greenhouse Effect

Carbon dioxide resides mainly in the lower atmosphere. It is an efficient absorber of infrared radiant energy that is reflected back from the earth. Hence, it is expected that a rise in carbon dioxide concentration in the atmosphere would lead to an increased retention of radiant energy that would otherwise have escaped into the stratosphere, and would therefore be associated with a rise in global temperatures.

Since carbon dioxide concentration in the atmosphere began being monitored at the Mauna Loa Laboratory in Hawaii in 1958, there has been a distinct increase from about 315 ppmv (parts per million by volume) in 1958 to 339 ppmv in 1981 (Bergman 1983). Although there are strong seasonal variations of 5–7 ppmv every year, the upward trend emerges clearly. Although direct measurements are not available before 1958, carbon dioxide concentration can be indirectly measured on the basis of the composition of vegetation as well as of oxygen isotopes in geological strata. Indirect measurements suggest that carbon dioxide concentration was 265–290 ppmv in 1860 (Rotty 1983). Thus, there is evidence of a progressive rise of carbon dioxide concentration over the last century and especially in the last few decades.

Carbon dioxide is released into the atmosphere when any carbonaceous fuel — coal, oil, gas, synthetic fuels, or biomass fuels — is burned. For every 100 quads (105 EJ) of energy released, natural gas produces 1.45 Gt of carbon in the carbon dioxide released, oil 2 Gt, coal 2.5 Gt, and synthetic fuels perhaps 50% more per unit of useful energy in the final product; the carbon dioxide produced is 3.67 times the carbon released in terms of weight. From these and other figures, it is estimated that carbon dioxide emissions from fossil fuels were 150 Gt between 1860 and 1975; in that period, the rise in carbon dioxide in the atmosphere was 95–148 Gt. Thus, the carbon dioxide released by combustion of major fuels in 1860–1975 appears to have significantly exceeded the increment in carbon dioxide in the atmosphere (Woodwell 1974). Other factors have thus been at work that have reduced the carbon dioxide concentration in the atmosphere. However, combustion of fuels has been the most important single factor behind the rise in carbon dioxide concentration, and continues to be so.

General atmospheric circulation models have been used to predict the impact of carbon dioxide concentration on temperature. They suggest that a doubling of carbon dioxide concentration from the recent level of 335 ppmv would raise global temperature by 3 $\pm$ 1.5°C (National Research Council 1983a). Such a rise in temperature would cause significant changes in the precipitation patterns, including lower rainfall in some of the temperate regions that are major food producers in today's world. It may cause some of the Antarctic ice sheet to melt, raise the sea level and lead to the inundation of extensive coastal areas. It is these prospective changes, however uncertain they may be, that have given prominence and urgency to research on the greenhouse effect.

Global Projections

Although projections only spell out the future implications of existing or assumed tendencies, in recent years, they have been used to study the implications of realized or impending discontinuities. All the discontinuities that have formed the starting point of recent global energy models have been in the nature of catastrophes. Thus, the models have a strong element of firefighting: explicitly or implicitly, they are normative models, and each of them emphasizes a few instrumental variables.

The first major model, that of the Workshop on Alternative Energy Strategies (WAES), took the prospect of oil exhaustion as its starting point. It conceived of the ensuing problem as essentially changing the fuel mix. According to Wilson (1977), it could be solved if

> nearly all fossil fuels were removed from use in electric power plants, to reduce processing losses; synthetic crude oil is made from available coal supplies, in order to meet essential demands for liquid fuels; and industrial and domestic sectors use significantly more coal and less electricity than currently and preferred plans.

In other words, the WAES advocated a shift from oil to coal and nuclear power. The International Institute for Applied Systems Analysis (IIASA) envisaged an even faster decline of oil consumption, and hence a faster shift to other fuels. It was also sceptical of the feasibility of a rapid buildup in nuclear capacity. Hence, it leaned in favour of a larger increase in coal production up to 2000 than WAES did. After 2000, however, physical constraints on coal output led IIASA to advocate more rapid increase in nuclear capacity; its projected energy mix for 2030 was thus not very different from that suggested by WAES for 2000 (Häfele et al. 1981).

The International Energy Agency's (IEA) projections involve a similar shift toward coal and nuclear power by 2000 for OECD countries. They involve a larger shift toward coal and a smaller one toward nuclear than those of WAES; they are thus closer to those of IIASA (International Energy Agency 1982b).

In association with the IEA projections, the Oak Ridge Institute of Energy Analysis made projections of implicit carbon dioxide emissions; however, because the greenhouse effect is expected to become serious later than IEA's terminal date of projections, the projections were extended to 2050. As will be seen from Table 12, the projections of Edmonds and Reilly (1985a) are similar to those of IIASA for 2000. By 2050, however, extrapolation on the same set of assumptions leads to considerably larger energy consumption estimates, and hence to requirements of coal and nuclear energy. Edmonds and Reilly's projections of oil supply look too high if oil depletion curves are to be believed; in which case, their estimates of the growth of coal output and nuclear power also would be too low. On the basis of their model, they concluded that the global carbon dioxide level would double sometime between 2049 and 2067 — 30 years later than previous studies had predicted. However, the only ways, according to them, of significantly postponing the doubling window were slower global economic growth or shift to more carbon dioxide-benign solar and nuclear technologies.

Other Oak Ridge researchers have similarly worked out the carbon dioxide implications of IIASA projections and have come to conclusions that call for a greater sense of urgency (Perry et al. 1982). In their view, it may be necessary to keep the ultimate global carbon dioxide level below 800 ppmv and perhaps below 500 ppmv. If this is to be done, a shift away from the combustion of fuels, and

Table 12. Some recent global energy (EJ) consumption projections for selected years, 2000–50.

Coverage	Total for year 2000	2025	2030	2050	Origin: Oil	Natural gas	Nuclear	Hydro	Coal	Other	Source
WOCA[a]	436				204	61	62	26	75	8	Wilson
	364				161	47	86	19	47	4	(1977)
World	531				186	98	55	26	156	10	Häfele et
	428				150	80	40	26	124	8	al. (1981)
			1122		215	188	255	46	377	41	
			705		158	109	163	46	203	26	
OECD[b]	244				88	35	26	–[c]	73	22[d]	International
	213				67	40	24	–[c]	62	20[d]	Energy Agency
	231				63	43	27	–[c]	78	20[d]	(1982b)
World	485				154	82	40	57[d]	152	–	Edmonds and
		922			183	113	158	118	350	–	Reilly
				1646	301	89	363	119	747	27[e]	(1985a)

[a] "World outside communist areas."
[b] Member countries of the Organisation for Economic Cooperation and Development.
[c] Included in "other."
[d] Includes solar electric.
[e] Includes hydro.

especially of fossil fuels, would have to start within the next few decades, possibly as early as 2010 and probably by 2040. This implies a rise in the use of renewable energy sources, especially of the noncombustive ones. However, their maximum feasible potential in the next century is no more than 250–315 EJ. This means that the total global energy consumption must be subjected to an absolute limit, and that any growth of incomes should be achieved within that limit. In other words, growth should be based on increasing energy efficiency — on energy conservation.

This is the starting point of the study of Goldemberg et al. (1985). Given the fact that fossil fuels are nonrenewable, they must be replaced by renewable energy eventually. Meanwhile, the use of fossil fuels gives rise to a number of undesirable externalities, of which the rise in atmospheric carbon dioxide is only one. The approach of other researchers has been to advocate the continuation of high levels of fossil fuel consumption in the coming decades while technological solutions to the attendant environmental problems are developed. The approach of Goldemberg and his colleagues, on the other hand, is to seek to eliminate those problems themselves, by working toward a supremely energy-efficient world.

Areas of Uncertainty

Of the rise in global temperature to be expected from the increasing carbon dioxide concentration, however, there is no firm evidence to date. Average temperature in the northern hemisphere was noticeably higher (by 0.4–0.5°C) in 1920–1960 than in 1880–1920; since 1960, however, it appears to have come down slightly (by 0.2–0.3°C) (Bergman 1983). However, year-to-year temperature variations are so large that reading of trends or cycles into them is hazardous.

Clearly, there are short-term influences on global temperature that obscure its expected relationship with carbon dioxide concentration. There are also a number of refinements or modifications of this relationship.

First, exchanges with the considerable stocks of carbon on land and in water affect the volume of carbon dioxide through a number of mechanisms other than combustion (Fig. 2). Second, there are feedback mechanisms that introduce lags in the relationship (Hansen et al. 1985). Third, the magnitude of the warming effect of carbon dioxide has been contested by Somerville (Yulsman 1985), who claims that carbon dioxide buildup will make clouds denser and more reflective, and will reduce the quantum of solar energy entering the atmosphere. Finally, a recent study claims that the influence of trace gases, i.e., fluorocarbons, ozone, methane, and nitrogen compounds, may lead to a much (1.5–3.4 times) greater warming than carbon dioxide. If this were the case, the causes of climatic change might be more diverse than fuel combustion alone (Ramanathan et al. 1985). The stocks of various trace gases in the atmosphere are growing at different rates; these growth rates may have important implications for the time pattern of the warming effect. The strategies for reducing their emissions also vary: some are easier to control than others, and than carbon dioxide emissions, whose reduction would require a fall in global combustion of fossil and biomass fuels.

The greenhouse effect is one of the most active fields of research, and it is impossible to sum up the present state of knowledge with any degree of adequacy. While considerable uncertainty attaches to many parts of the complex mechanism of climatic change, the potential implications of climatic change are as serious (although not the same) for developing countries as for industrial countries. Developing countries have an interest in keeping a watching brief on the research as well as in participating in it. This is a field in which there is no alternative to international cooperation in research, and eventually in policy.

Acid Rain

The fact of acid rain admits no doubt any longer, nor its impact on vegetation, fish, roads, buildings, etc. Its mechanism of causation does, but the role of combustion in this mechanism is also fairly firmly established, although its precise degree of significance is not.

Normal rain is slightly acid; the dissolution of atmospheric carbon dioxide in rain water makes its normal pH about 5.60–5.65. This value will vary somewhat from region to region, and can be below 5.6 in regions where the atmosphere lacks alkaline materials (Canada 1981; Harte 1982; Haines et al. 1983).

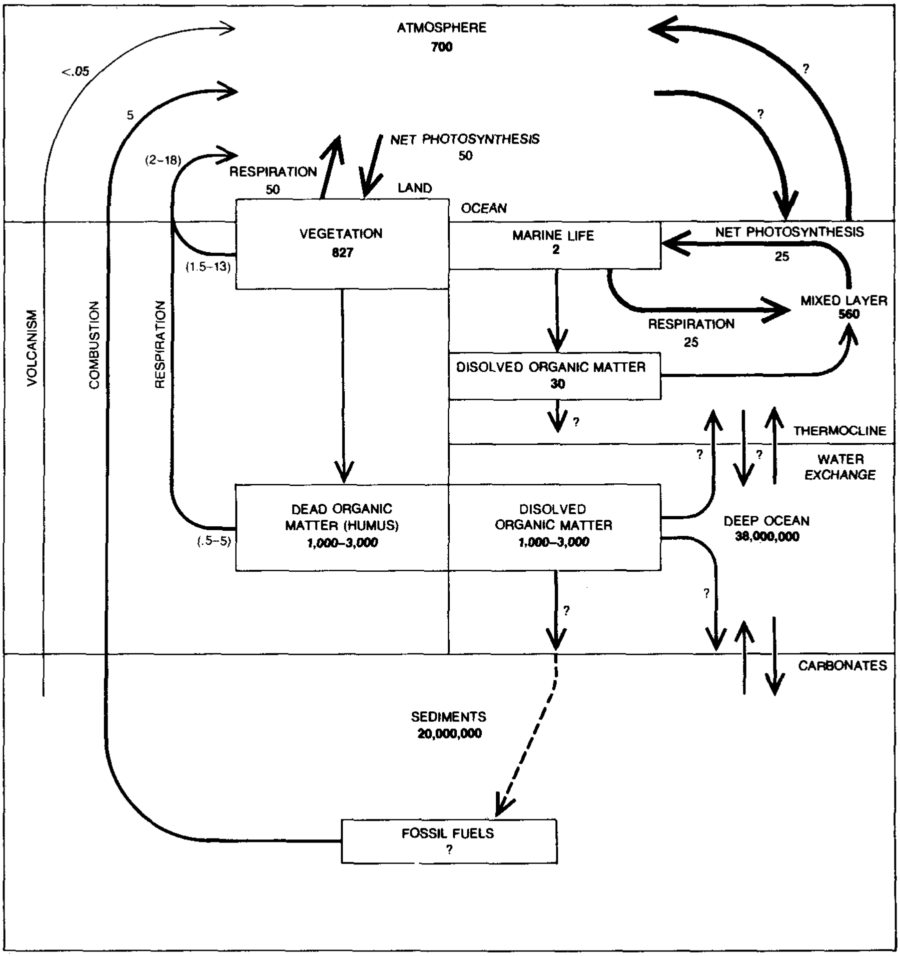

Fig. 2. Global pools and flows of carbon. Pools are expressed in billions of metric tonnes of carbon, flows in billions of metric tons of carbon per year (Source: Woodwell 1974).

However, rain (precipitation — rain and snow — to be precise) has become noticeably more acid in some parts of North America and Western Europe, and its increased acidity shows association with some serious deterioration of flora and fauna: in particular, the destruction of certain species of common forest trees, and the disappearance from the lakes of acid-sensitive fish such as trout and salmon. The hydrogen ions in acid rain are believed to disrupt the mineral element cycle in plants because they displace minerals from leaves and from soils and inhibit their acquisition by plant roots. It is possible that increasing acidity of rain increases the uptake by plants of toxic substances such as cadmium, and the intake of mercury in freshwater fish; however, this latter correlation is not yet fully understood. There is also no direct evidence yet of the effects of acid rain on human beings (Taylor 1980).

The tolerance of vegetation to specific toxicants varies widely among species, and frequently among different varieties of the same species (Taylor 1980). The extent to which acid rain affects ecosystems also depends on the buffering capacity of soils. For instance, where soils and lake water are alkaline, acid rain may have little effect, but elsewhere the same increase may alter the soil balance and convert essential nutrients into forms that cannot be absorbed by plants (Haines et al. 1983).

Acid precipitation is primarily due to the emission into the atmosphere of sulfur dioxide, hydrogen sulfide, and nitrogen oxides, which react with water to form sulfuric and nitric acid. Sulfur dioxide emissions are mainly traced to the combustion of sulfurous fuels and volcanic eruptions; the former emissions are estimated to be more than twice the latter (Table 13). Any high-temperature combustion process leads to the formation of nitrogen oxides by the reaction of atmospheric oxygen and nitrogen; the predominant urban source is transportation activity. Most of the emissions of nitrogen oxides, however, come from the decay of biomass. They can also be formed by the breakup of nitrogenous fertilizers (Chamberlain 1981).

By virtue of their volume, emissions of nitrogen oxides play a critical role in acid rain formation through direct oxidation of nitric acid as well as precursors to the formation of strong oxidants such as hydrogen peroxide and ozone. Emissions of nitrogen oxides exceed sulfur dioxide emissions. Most of the emissions of nitrogen oxides, being from natural causes, are of global distribution, and probably account for the acidity of normal rain. Local adaptations to acidity abound. However, the destructive effects of acid rain have been observed mainly in North America and in Western Europe, and have been correlated with sulfur dioxide emissions.

Research

A crucial research weakness seems to be the understanding of atmospheric chemistry of acid precipitation. Although a number of numerical models exist, the large number of adjustable parameters makes it difficult to say whether the predictive success of a model is a reflection of its accurate chemistry or not. In terms of the degree of understanding of atmospheric reactions, the best understood reactions at present are the homogeneous gas phase reactions, followed in a descending order by aqueous phase reactions ("droplet" chemistry), heterogeneous reactions, and catalytic reactions.

Two broad areas of research that would help in better understanding the chemistry of acid precipitation are understanding the nitrogen oxides–VOC (volatile

Table 13. Worldwide sources of emissions of sulfur dioxide, hydrogen sulfide, and nitrogen oxides.[a]

	Emissions (million t)			Atmospheric concentration	Residence time
	Anthropogenic	Natural	Total	(ppb[b])	(days)
Sulfur dioxide	207	100	307	0.2	4–8
Hydrogen sulfide	–[c]	200	200	0.2	1–2
Nitrogen oxides	48	391	439		
Nitrogen dioxide	–[c]	598	598		
Ammonia	4	1054	1055		
Nitrous oxide	–[c]	536	536		

Source: Chamberlain (1981).
[a] These estimates refer to the early 1970s. The estimates of emissions from natural sources may err by a factor of 2 or more.
[b] Parts per billion.
[c] Small amounts only (<0.5 million).

organic compounds) cycle and its influence on the concentrations of hydroxyl and hydroperoxyl radicals; and understanding the role of these radicals.

The hydroxyl radical is an important gas phase (i.e., outside the cloud and rain) reactant for both sulfur dioxide and nitrogen oxides. It is essential for the formation of hydrogen peroxide — a strong oxidant for sulfur dioxide in cloud and rain droplets. Many chemists believe that the liquid phase oxidation of sulfur dioxide may be the dominant pathway for producing sulfuric acid. Finally, nitrogen dioxide itself is oxidized by the hydroxyl radical to nitric acid (Chamberlain 1981; Shaw 1984).

Understanding the two phenomena mentioned above has direct consequences for the strategies of abatement of acid rain. The main sources of hydrogen oxides are ozone photodissociation and formaldehyde. In both cases, nitrogen oxides are a basic raw material (although formaldehyde formation begins with the presence of hydrocarbon radicals in the atmosphere). Thus, if nitrogen oxides in the atmosphere could be reduced, this would reduce the hydrogen oxides concentrations and might, therefore, lessen both major sources of acidification by diminishing the nitric acid directly and reducing the rate of aqueous oxidation of sulfur dioxide to sulfuric acid. A reduction in the rate of oxidation of sulfur dioxide would have a greater probability of allowing it to be absorbed as a gas on the ground, thus reducing acidified precipitation. Some fraction of ground-absorbed sulfur dioxide would nonetheless be converted to sulfate by oxidants including molecular oxygen.

In effect then, a reduced rate of oxidation of sulfur dioxide in the atmosphere may not do away with all the adverse impacts of acid deposition, but it would alter its geographic distribution and probably also the nature of its effects.

Abatement

The height of stacks has gone from an average of 61 m in 1960 to 183 m in 1981 in North America (Chamberlain 1981). This cannot, however, be seen as part of an abatement strategy. Tall stacks reduce local pollution but greatly increase the chance of pollution at a distance (Postel 1984).

"Liming" of lakes to reduce their acidity must be seen as a strategy that focuses on alleviating damage at the receiving end (in downwind areas) rather than controlling emissions at source (United States of America 1984). It is a temporary palliative at best because decreasing the acidity does not put the leached metals back into the rocks.

Thus, abatement strategies, to be successful in the long run, must focus on emission reduction techniques which, in the case of sulfur dioxide, consist of the following: washing coal; "scrubbing" the flue gases in older power plants; switching to lower-sulfur fuels; and using limestone injection multistage burners (LIMB). The first is not cost-effective at present for lower-sulfur content coals, and LIMB is in early stages of development in the USA and under commercial demonstration in the Federal Republic of Germany (United States of America 1984).

Control of oxides of nitrogen emissions is more difficult than control of sulfur dioxide emissions. Nitrogen oxides can currently be controlled by changing the rates and proportions at which air and fuel are mixed in a combustion process. However, not all utility boilers can be retrofitted with combustion modification equipment. In any case, this would reduce the emissions only by about 25%. For higher levels of control, changes in furnace geometry may be required. Nitrogen oxides can also be removed through flue gas treatment and reduced through LIMB.

If the use of small-scale coal combustion units (e.g., stoves) increases in a particular area, then high nitric acid concentrations are likely to become a major local problem. In such cases, research on coal stove combustion efficiency and nitrogen oxides emission control would be especially important (Harte 1982).

Those developing countries that have high concentrations of fossil fuel and biomass combustion and a large land mass, for example, Brazil, China, and India, have an interest in the study of rainfall acidity and any correlations it shows with vegetation and fauna. If such correlations are found, acid rain abatement may be as relevant to them as to industrial countries.

Chapter 13 Prerequisites

The general conclusions of the report are summarized in the following three chapters.

The efficacy of a research system depends on informed user capability, long-range accumulation of knowledge, informed research direction, and goal-oriented funding.

Informed users are those who can make problems researchable and judge the quality of research. They must be diffused in organizations that use research. Informed users must be trained to do and judge research, and must update their knowledge from time to time.

Knowledge takes time to accumulate. It requires material facilities such as libraries, but it is made usable by researchers through a process of learning and problem-solving. Hence, researchers' careers need to be planned to increase their depth, but also in the longer run to give them versatility.

Informed research direction requires the study of the environment of research, especially of the emerging needs of research users, and its translation into problems that can be solved by researchers and build their capability.

Goal-oriented funding requires long-term investment in programs of potential importance to research users, and the exploitation of that importance through projects.

Having completed our survey of energy research priorities, we shall sum up our conclusions in the next three chapters. This chapter relates to the prerequisites of research, the next chapter to the uses of energy, and the last chapter to energy resources.

Setting energy research priorities is not meaningful without an organizational setup to implement them. It is first necessary to build such a system and, if in place, to improve its working when it malfunctions. What matters is not only its ability to follow research priorities but also its capacity for quality research. The efficacy of the system depends on four major factors: informed user capability, facilities for long-range accumulation of knowledge, informed research direction, and a goal-oriented funding pattern.

Informed User

Informed users are those who can decide what research is necessary to solve specific problems, and who can judge the quality of research. Informed user capability must be diffused among organizations that can use research, principally the government and producers. Research organizations can also act as informed users for organizations, for example, small producers, who do not have the capability; but it is most effective when built into the user organization itself.

The first necessary condition of informed user capability is training. The training may not be as advanced as for research, but is the same kind.

The second condition is the presence of trained persons close to the decision-making centres in user organizations. It is all too easy for technical persons to be absorbed into the routine administrative tasks which would, however, make no contribution to research user capacity. It is important that professionally trained persons be used for the professional task of judging the results of research.

Trained personnel can retain good judgment only if their knowledge is updated from time to time. This could best be achieved by periodic interchange of staff between research and user organizations. Such an exchange would also build informal social ties that are useful in transferring research and technology. If exchanges are not possible, however, it would still be desirable that trained persons in user organizations periodically return to training and research organizations for renewal of their knowledge.

Finally, there may well be elements of knowledge that are better generated in user organizations than in research organizations. In policy-making, for instance, the information that is required for day-to-day decision-making is best stored within the government for immediate use. In producer organizations, the aspects of development — working out processes for new products, commercializing innovations, etc. — are downstream facilities that fall between research and its use, and have to be built by user organizations.

The above preconditions are particularly important in respect of policy research: serious energy problems are inevitably the subject of national policy, and both the volume and quality of research on them will depend on the ability of policymakers to guide as well as use research. This is especially evident in energy demand management, which is relevant only in the context of policy. Sufficient expertise should be available in key positions in the government to translate policy problems into research issues and the results of research into policy solutions, and the government should take a long- and broad-enough view — for instance, in a national planning framework — to be able to use research.

Long-range Knowledge Accumulation

The knowledge and experience that go into solving problems quickly and satisfactorily are accumulated in researchers; but researchers acquire them through a process of learning and problem-solving. Thus, the career pattern of researchers is important — the problems they have tackled, and the facilities they had to tackle them with, will influence the capability. Hence, it is necessary to build research facilities over a long period in research organizations. The facilities may be simple and modest for a subject such as mathematics — although new opportunities have been opened up by computers — or expensive and elaborate for a subject such as nuclear physics. However, the scale and adequacy of facilities built over a long period do affect the accumulated capability of researchers.

However, while the facilities and the use made of them determine the depth of a researcher's experience, the variety of the problems tackled determines breadth and versatility. Research directors should ensure that researchers turn to fields of current utility.

Informed Director

The research director translates the demands of the external environment into problems that can be tackled by researchers, and finds a use for researchers' talents. In this role, she or he must be able to take a long view, and to anticipate the areas that are likely to become important.

He or she must also be aware of the resources of the country that shape the research requirements. The use of local resources invariably throws up site-specific problems, whereas the lack of resources — in countries that cannot import them — generates problems of finding substitutes.

Finally, the informed director must be aware of the external environment — domestic and international — in the relevant fields. The scanning of parallel work is the task of every researcher but, in research direction, it is particularly useful for preventing duplication and waste and accelerating the progress of research.

Finance

Finance can generate useful research only if the above institutional conditions are satisfied; but to some extent finance can shape the institutions. Institutions take time to build, so they require long-range program funding. Once they are established, however, they should be able to respond quickly to emerging problems. This is best achieved by short-term funding.

Expenditure on building institutions and program areas should be regarded as an investment in human and material capital. Although it must not be expected to yield quick results, it must eventually earn a return on the investment in the form of projects; that return indicates the wisdom of the initial decision. Expectations of eventual projects it would generate must be the basis of a decision to invest in research facilities, and to choose among areas in which to build them.

Chapter 14 Uses

National energy systems need to be projected for a period that is at least as long as the gestation lags in energy industries. Such projections must be based on the knowledge of interrelationships among energy industries, and between them and the rest of the socioeconomic system.

A knowledge of structural relationships would help to decide how energy demand can be changed by varying the structure of production and consumption. Similarly, an understanding of consumer behaviour can be used to influence and regulate their energy consumption.

Interfuel substitution is required when the relative scarcity of energy sources changes. The substitution of mechanical for human energy that occurs during development is a principal form of interfuel substitution that generates major policy problems. These problems require broad-based research.

Two types of research aimed at energy conservation hold particular promise in developing countries. One is to make an inventory of each type of energy-using equipment, to diagnose the reasons for energy inefficiency, and to work out ways of reducing it. The second is to use such surveys to work out better designs for new equipment.

"Developing countries" is a generic term that hides many differences. The decision to implement energy research priorities would have to be made at the level of a developing country, or at the even more micro level of a producer or a research organization. Decision-making at these levels would be greatly improved if a long-term perspective of the development of the energy system were available.

The length of the period for which such a projection should be made is the period required for the forward planning of energy industries with long gestation lags. It is particularly long for coal, oil, and gas; between the beginning of exploration and full-scale commercial production, a period of 8–15 years may elapse. For electricity, the period may be shorter, but hydroelectric projects can take a decade to complete, especially where there are geological surprises. In all these industries, it is necessary to gather information, make the best guesses, and minimize uncertainties at least as far into the future as their gestation lags. The lags in renewables are not necessarily short. For instance, forestry projects would take at least 5 years from planting before they show economic return. Thus, a long view is forced upon decision-makers by the gestation lags in energy industries.

Over such long periods, it is impossible to plot the course of energy industries without a firm idea of the interrelationships among themselves and with the rest of the socioeconomic system. Knowledge in three areas is particularly essential: the links between energy consumption and the socioeconomic system; substitution possibilities among energy forms; and possibilities of increasing energy efficiency.

Structural Relationships

Except in home heating, cooking, residential electricity consumption, and passenger transport, energy is not used by final consumers but by producers who use it to produce other goods and services. The relationships that connect the latter with energy consumption — structural relationships — can be explored with the techniques mentioned in chapter 4. Generally more complex techniques give more consistent results, but they also require more data and computation, so a compromise has to be made.

The most promising use of research at the macro level is to reveal how the composition of energy demand can be changed by varying the structure of production and consumption. If useful models to show this link are developed, they can be used to formulate fiscal and other policies that would steer demand away from the scarcer energy resources. The policies can operate either on the consuming sectors, e.g., transport and industry, or on the energy sources, e.g., oil products.

At the micro level, research on how consumers decide what proportion of income to devote to energy needs to be advanced further. Consumers in developing countries present special features. For instance, their income is not always in terms of money but can also be in kind, or in the form of their own labour; and their decisions as consumers are made for the family rather than the individual. These special features call for special analytical tools.

Interfuel Substitution

The form of interfuel substitution that is of greatest concern to developing countries is the substitution of inanimate for animate energy. It is capable of bringing great gains in labour productivity and living standards, but also runs the risk of creating unemployment. Managing this energy transition generates some of the most difficult policy problems in developing countries, especially in agriculture, on which a large proportion of the population depends. Interfuel substitution in agriculture can have macroeconomic implications for employment, balance of payments, and energy resource use; for useful policy conclusions to emerge, all these have to be studied together. Agriculture can produce biomass in many usable forms; if its biomass productivity increases in one crop, area can be diverted to another crop. Thus, research can pursue broader aims than energy use and energy productivity.

Interfuel substitution in transport has attracted considerable research in the past 12 years owing to its dependence on oil. The research has not led to any promising ways of substitution for oil, but has led to increases in energy efficiency in industrial countries. In developing countries, research on town and country planning to minimize transport and on more efficient use of transport facilities may yield more fruitful results in the long run.

Energy Conservation

While a large proportion of the equipment needed to produce and transform energy is produced in industrial countries, developing countries use energy-consuming equipment — boilers, motors, firestoves, etc. — in very large numbers. Ways of saving energy applicable to them could be diffused widely and lead to significant savings. This approach suggests two lines of research.

The first is to make an inventory of existing equipment of each kind, diagnose the reasons for energy inefficiency, and work out improvements in operational practice and retrofits that would lead to better efficiency. These could then be applied to all equipment.

The other way is to work out design improvements on the basis of similar diagnostic surveys, and to introduce them in new equipment. Their impact will depend on how fast the stock of equipment grows and is replaced; it will be small in the short run but can lead to major energy savings in the long run.

Chapter 15 Resources

The criterion of the Group has been to base priorities on the contribution of research to broad decisions of policy and production. From this viewpoint, resources can be broadly classified into two groups: those whose successful exploitation primarily depends on the study and careful identification of the market for them, and those whose cost needs to come down for successful application.

Natural gas generally faces the greatest uncertainty about the market and would benefit most from research on demand. Coal may also be in this position, where there are close competitors, but it can shift more easily between users. Oil has a relatively secure market defined by the distribution network, but can face international competition; hence, the need to study the international market for it. Electricity is least sensitive to market pressures unless there has been overinvestment in it. Small-scale energy sources will generally have small, local markets, but their identification may still require research.

Such sources generally face competition from large-scale sources; hence, research could contribute best by reducing their costs of production. In the case of resources with high capital costs, raising capacity utilization can directly improve viability. For seasonally available resources — e.g., cane-based ethanol — low-cost storage may be the way to raise capacity utilization. Where storage costs are high — e.g., with solar and wind energy — the identification of favourable sites and uses is a good subject of of research. All land-based biomass resources can be made more viable by increasing the productivity of land; research on biomass productivity would benefit biomass fuels by releasing land for them. Reserves of mineral fuels often hold geological surprises; by identifying them and working out solutions to deal with them, research can improve the feasibility of mining projects.

As explained in chapter 1, the Group decided not to go deeply into the production and engineering technologies of the large-scale energy industries — coal, oil, gas, and electricity (thermal, hydro, and nuclear). It also decided to dispense with novelty and potential advances in knowledge as an indicator of priority; rather, it decided to base priorities on the contribution of research to the broad strategic decisions of policy and production. We have thus tried essentially to assess how far research would improve the quality and robustness of major decisions where a mistake could lead to waste of resources. The improvement would be greatest where the market for a resource was uncertain, and ensuring that there would be a large enough market and that the resource can hold its own against competing energy forms would make all the difference to its viability; and where the application of existing or available technologies to new situations is likely to raise serious site-specific problems. Of the numerous instances of both these types given in chapters 6–11, we take up only the most important ones here. The priority areas are identified in terms of the types or clusters of problems.

Market-sensitive Resources

From the viewpoint of the volume and stability of demand, natural gas probably faces the greatest uncertainty and would benefit most from research. Its users have to be identified in advance, and its minimum scale of production is large. The groundwork for working out the scale, the markets, and the terms of contract implies essential research for every gas project.

Coal can face similar problems where it is a relatively new source of energy or where its output is to be significantly expanded. Generally speaking, however, coal is easier to transport and to shift from one user to another. Viability of coal projects is likely to depend more on the cost of production and less on the advance identification of the market.

Because most developing countries have a distribution network for oil, oil is similarly less sensitive to market conditions. However, it will be sensitive to international competition — more so in countries that depend significantly on oil exports or imports. Hence, research is needed on the international oil market and on oil price formation.

Electricity produced by utilities is the least sensitive to the market, especially in countries where demand is growing. This is true of all generating facilities owned by utilities. Although relatively insensitive to the intrusion of competing energy sources, the demand for electricity may, of course, limit growth where there has been overinvestment or where large facilities have led to the buildup of capacity beyond current demand.

Small-scale, decentralized sources of power have relatively small markets and a correspondingly less serious problem of finding a market, although it may still need to be identified. This is true of stoves, solar cookers, photovoltaic devices for consumers, solar dryers, etc.

Even where there is no market constraint, there can be a constraint arising from buyers' preferences. This type of problem is likely to arise in respect of equipment — for instance, fuel-efficient stoves that do not meet the users' expectations in other respects. The problem for research here lies in the adaptation of the design to the market.

Cost-sensitive Resources

Where resources have potentially cheaper substitutes, the problem for research lies in reducing their costs of production. Small-scale, decentralized sources of energy have a relatively small volume of production, and face a less serious problem of finding a market. If they have large-scale competitors, however, their cost of production will determine their viability. This is particularly true of decentralized power-generating facilities — photovoltaic, wind, geothermal, dendrothermal, etc. — when they face competition from grid electricity; but it is also true of other resources such as charcoal, producer gas, and windpumps.

Many new and renewable energy resources are characterized by low — sometimes negligible — running costs and high capital costs. Wherever the capital costs are high, capacity utilization can have a considerable effect on viability. Hence, the development of low-cost energy storage technologies calls for priority.

In the case of energy that is difficult or costly to store — e.g., solar and wind energy — capacity utilization would depend on resource availability, as well as on the time pattern of demand. In such cases, the identification of promising sites and appropriate uses is the most important object of research. However, even in the case of energy sources based on cheap biomass — e.g., producer gas, biogas, and ethanol — reduction in the capital–output ratio can be the major route to viability.

Biomass-based energy resources require land, and their productivity per unit of land has a great effect on their collection costs. Land productivity also becomes important whenever there is a shortage of land; in such situations, an increase in the yields of one crop releases land for other crops. Thus, broader research on biomass productivity would have an indirect benefit for biomass energy resources.

The scale of biomass-based fuels is limited by collection costs. If biomass productivity increased, larger scale may become economic — for example, in the manufacture of ethanol, dendrothermal electricity, and charcoal. Thus, increases in biomass productivity can generate the need for consequent research in expanding downstream processes.

Finally, the exploitation of mineral fuels is often subject to geological surprises and difficulties. Their solution may have to be local and site-specific, and research for them may lead to substantial benefits in terms of returns. This type of situation is common in coal mining.

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Appendix 1: Members of the Energy Research Group

Dr Ashok V. Desai — India
Coordinator, Energy Research Group, Ottawa, Canada

Dr Ashok Desai was associated for many years with the National Council of Applied Economic Research in Delhi and was its Director for some time. He was Professor and Head of the Economics Department of the University of the South Pacific in 1973–76; earlier, he had held teaching positions in Oxford, Bombay, and Delhi universities. He holds a doctorate in economics from the University of Cambridge, and has published one book and many papers. His major work has been in the field of industrial economics, especially the economics of technology transfer.

Professor Djibril Fall — Senegal
Director, Centre d'Études et de Recherches sur les Énergies Renouvelables, and Professor, Université de Dakar, Senegal

Professor Fall received his doctorate in physics from Toulouse University in 1974 and has been Director of CERER since then. Since 1976, he has also been Project coordinator at the Institut de Technologie Nucléaire Appliquée. For 7 years, he was a technical adviser at the Secrétariat d'État à Recherche Scientifique et Technique.

Professor José Goldemberg — Brazil
Rector, University of São Paulo, Brazil

Professor Goldemberg has held positions as Professor of Physics at the University of São Paulo, University of Paris (Orsay), and the University of Toronto. He was Head of the Nuclear Physics Division of the Atomic Energy Institute (1971–72), Head of the Commission on Energy from Biomass of the Ministry of Agriculture, Brazil (1979), and President of the Companhia Energética de São Paulo (1983–86). He is past President of the Brazilian Society of Physics and has published four textbooks and numerous technical papers on nuclear physics and energy.

Mr José Fernando Isaza — Colombia
President, COLDEACEITES, and Consultant, Bogotá, Colombia

Mr Isaza, until recently, was the Colombian Minister of Public Works and Transportation. He has been President of the Colombian national oil company, Ecopetrol (1980–82), as well as that of the National Financial Corporation (1978–80). He has been director of numerous government departments including the energy division of the national planning department. He has taught economics at the Universidad de Los Andes, Bogotá, and has published 1 book and more than 20 papers.

Professor Ali Kettani — Morocco
Director General, Islamic Foundation of Science, Technology and Development, Jeddah, Saudi Arabia

Professor Kettani is at present responsible for cooperation in and promotion of science and technology among the 46 member-states of the Organisation of the Islamic Conference. As professor of electrical engineering in the University of Petroleum and Minerals, Dhahran, Saudi Arabia (1969–82), he developed and directed research in energy, especially in new energy sources with emphasis on solar energy. Professor Kettani has chaired numerous international conferences and is Vice-President of the Coopération Méditerranéenne pour l'Énergie Solaire. He is the author of 8 books and more than 100 technical papers.

Dr. Ho Tak Kim — Republic of Korea
Associate Professor of Agricultural Economics, Seoul National University, Suweon, Republic of Korea

Dr Kim was Vice-President of the Korea Energy Research Institute (1979–81). He is Special Advisor to the Korea Energy Management Corporation and a member of the Energy and Resource Policy Committee of the Korean Ministry of Energy. He has published 14 major reports and articles in the energy field.

Professor Mohan Munasinghe (Chairman) — Sri Lanka
Senior Energy Advisor to the President of Sri Lanka

Professor Munasinghe holds six degrees in physics, engineering, and economics from Cambridge University, the Massachusetts Institute of Technology, and McGill University. He has taught in universities in Sri Lanka, Canada, and the USA, and also trained over 1000 senior energy officials from 65 developing countries. He is Head, Energy Policy Development Unit, World Bank, Washington, DC, USA. He was Chairman, Computer and Information Technology Council of Sri Lanka, and expert-advisor to many international organizations. He is the author of 15 books and over 100 technical papers, and serves on the editorial boards of several international journals.

Dr Fredrick Owino — Kenya
Associate Professor of Forestry, and Dean, Faculty of Forestry and Wildlife Resources, Moi University, Eldoret, Kenya

Dr Owino received his doctorate in forest genetics from North Carolina State University in 1975, and has taught at the University of Nairobi since then. He is a member of the editorial board of the international journal *Forest Ecology and Management* and is a member of the Presidential Permanent Commission on Soil Conservation and Afforestation, Kenya. He has 14 publications to his credit.

Professor Amulya Reddy — India
Chairman, Department of Industrial Management, and Professor, Department of Inorganic and Physical Chemistry, Indian Institute of Science, Bangalore, India

Professor Reddy was the Convenor of the Centre for the Application of Science and Technology to Rural Areas (ASTRA), Indian Institute of Science (1974–83). He has, on a number of occasions, been a Visiting Senior Research Scientist at the Center for Energy and Environmental Studies, Princeton University. He is on the editorial board of two international journals, *Biomass* and *Current Science*, and has served on the Working Group on Energy Policy of the Planning Commission, Government of India (1978–79). He has written over 85 publications.

Eng. Carlos E. Suarez — Argentina
President, Instituto de Economía Energética, Río Negro, Argentina

Mr Suarez is also Vice-President of the Fundación Bariloche, with which the Instituto de Economía Energética is associated. He was Director of Energy Planning in the National Planning Commission in Buenos Aires (1963–67). He is a graduate in chemical engineering of the Universidad de Littoral.

Professor Zhu Yajie — China
Senior Advisor, East China Petroleum Institute, Beijing, China

Professor Zhu is also a member of the Scientific Council Academia Sinica and President of the China Energy Research Society. He was Professor at the Beijing Petroleum Institute (1952–66) and has extensive experience in designing furnaces, ethylene plants, and ammonia plants. He has published four textbooks and numerous papers.

Appendix 2: Authors and Review Papers Commissioned by the Energy Research Group

Integrated energy systems for rural development **Abhat, A.**
Energy conservation in the industrial sector **Anandalingam, G.**

Electricity's effect on rural life in developing nations **Barnes, D.**
Information systems for energy planning and management **Bernardini, O.**
Contribution of renewable energy sources to the solution of energy problems in some countries in Latin America **Best, G.**
The developing world as a market for power plant technology **Bharadwaj, T.**
Energy demand analysis in developing countries **Bhatia, R.**
Energy research programmes in South Asia: a review of past activities and possible research themes **Bhatia, R.**
Energy and agriculture in developing countries **Bhatia, R. and R. Sharma**
Energy research and development programmes in India **Bhushan, B.**
Energy policies and issues in Latin America **Bianchi, A.**
Energy problems and policies in Central America **Bogach, V.S.**
Human energetics **Borrini, G. and S. Margen**
Markets for utility electricity with efficient application **Brooks, D.**
Biomethanation **Brown, N. and P. Tata**

Small- and medium-size hydroelectric power plants **C.I. Power Services Inc.**
Current status and development of solid fuel mining and utilisation technologies in Asia **Chari, K.S.R.**

Le bois de feu, source d'énergie renouvelable menacée **De Lepeleire, G.**
Developing country fuel pricing policies — I: a discussion of issues associated with retail pricing policies **deLucia, R. and M. Lasser**
Developing country fuel pricing policies — II: a discussion of issues associated with wholesale pricing policies **deLucia, R.**
Rural energy utilization in China **Deng Keyun and Wu Changlun**
Atoms for peace, atoms for war, atoms for profit **Desai, N.**
Energy modelling in developing countries **Devezeaux, J.G.**
Energy consumption patterns and their implications for energy planning **Dunkerley, J.**
Problèmes politiques et énergetiques au Brésil **Duquette, M.**

Is there a vicious cycle of low food energy intake and low human work output? **Edmundson, W.**
The international transmission of economic growth, exhaustible resources and long waves: a review paper **Elkan, P.G.**
Health and environmental impacts of energy systems **El-Sayed, H.**
Application of alternative biomass energy technologies in developing countries **Eusuf, M.**
Application of solar energy technologies in developing countries **Eusuf, M.**
Petroleum exploration, development and production **Foster J. and T.C. Foster**

Markets for technology equipment and services **Foster, J. and L. Jackson**
Oil refining, transport and distribution **Foster, J. and R. Tragatsch**
Geothermal energy exploration and utilization **Fridleifsson, I.**

Transportation and energy in developing countries: a survey and discussion of research needs **Geltner, D.**
Recent advances in solar energy utilization in China **Gong Bao, Lu Weide and Tian Xiapong**
Energy policy in developing countries **Gordon, A.**

Sociopolitical issues in rural energy development **Hayes, P.**
Nuclear electric futures **Hayes, P.**
Third World island futures **Hayes, P.**
Human and animal energetics: a review of the role of metabolized energy in traditional agriculture **Hurst, C.**
Human and animal energy in transition: the changing role of metabolized energy in economic development **Hurst, C.**
Energy for small-scale engines: a review of potential energy sources **Hurst, C.**

Oil and gas: exploration and production in developing countries **Ion, D.C.**

Markets for renewable energy technology in developing countries **Jhirad, D.**

Utilization of fuelwood and charcoal in East Africa **Kaale, B.K.**
Energy in West Africa: a literature survey **Kahane, A. and S. Lwakabamba**
Energy transitions and energy-related R&D needs and priority areas in Korea **Kim, H.T.**

An overview of R&D in energy resources, uses and technology **Lamptey, J., M. Moo-Young and H.F. Sullivan**
China's energy economy **Lan Tianfang, Lu Yingzhong and Mao Yushi**
Modèles de demande d'énergie et modèles globaux **Lapillonne, B., P. Criqui and J. Girod**
Industrial energy consumption and conservation in China **Lu Qi and Liu Xueyi**
The development of electric power in China **Lu Qinkan and Fu Zhesun**
The development of nuclear energy in China **Lu Yingzhong**
Photovoltaic technology in developing countries **Luque, A.**

China's transport and its energy use **Mao Yushi and Hu Guangrong**
Energy-related issues in early economic literature **Martinez-Alier, J.**
Science and technology of the renewable energy sources in Mexico **Martinez-Negrete, M.A., F. Cepeda-Flores, J. Cervantes-Servin, O. Masera-Cerutti and O. Miramontes-Vidal**
Solar and wind technologies for developing countries: current status and anticipated developments **McNelis, B. and P. Fraenkel**
Use of wind for electricity generation in developing countries **Merriam, M.**
Status assessment of solar photovoltaic technology **Mintzer, I.**
Alternative fuel — a Brazilian outlook **Moreira, J.**
Issues in natural gas production and utilization **Mortimer, G.**
Energy demand management and conservation **Munasinghe, M.**
A framework for establishing energy research and development (R&D) policies and priorities in a developing country **Munasinghe, M.**

Current state of biomass energy development and conservation technologies **Ng'eny-Mengech, A.**
Comparative evaluation of nuclear power in the developing countries **Obermair, G.**
Energy and development in East Africa **O'Keefe, P.**

Trends in forestry/woodfuel resources and utilization **Owino, F.**
Energy problems and policies in developing countries: an analysis and review **Pachauri, R.K. and R. Pachauri**
Electrothermy in Brazil **Pimentel, O.M.**
Energy, urban transport and the city: a narrative of some recent Brazilian experience and its wider implications **Poole, A.**

Petroleum industry in China **Qin Tongluo**

Geothermal energy in China **Ren Xiang, Yang Qilong and Tang Ninghua**
Petroleum exploration and production in developing countries **Ross, R.J.P.**

Biomass potential and conversion in southwest Asia and northern Africa **Sandhu, G.R.**
Energy use in cities of developing countries **Sathaye, J. and S. Meyers**
Optimizing electrical distribution systems **Scott, W.**
Applications of solar thermal technologies **Selçuk, M.K.**
Electric transmission technology **Shah, K.R.**
Asia's adjustments to the changing energy picture: a summary **Siddayao, C.**
Hydroelectricity: evolution and perspectives **Siqueira, G.**
China's energy advances and limitations **Smil, V.**
Traditional fuels and health: social, economic, and technical links **Smith, K. and J. Ramakrishna**
Energy-intensive materials and the developing countries **Strout, A.**
Technology and market structure in equipment for the energy industries: coal, oil and electricity **Surrey, J. and J. Chesshire**

Recent research in electric power pricing and load management **Tabors, R.**
Technology in the petroleum industry **Tanzer Natural Resource Associates**
Domestic energy supply and demand in southwest Asia and northern Africa **Tasdemiroglu, E.**
The real rural energy crisis: women's time **Tinker, I.**
Biomass technology survey in Japan **Tokuyama, F.**
Alternative transport fuels: supply, consumption and conservation **Trindade, S.**
Energy technologies and policies: options for developing countries **Tsuchiya, H.**
Energy use in industry **Tunnah, B.G.**

Economics of energy and natural resources: review of an expanding field of transdisciplinary research **Umaña-Quesada, A.F.**

Solar thermal central receiver power generation technology: prospects for the developing world **Weingart, J.**
Electric power for industrialization in developing countries **Wereko-Brobby, C.**
Notes on the state of the future of energy research in Latin America **Wionczek, M.**
The coal industry in China **Wu Jing**
Biomass utilization in China **Wu Wen**

Energy policy study in China **Zhu Yajie and Wang Qingyi**
The prospects of hydrogen as an energy resource **Zhu Yajie and Wu Zhenxiao**
How small hydro power is helping China's rural electrification programme **Zhu Xiaozhang, Ding Guangquan and E. Chang**

Appendix 3: Referees of the Energy Research Group's Final Report and Commissioned Papers

Sr J. Ramon Acosta
Prof. M.A. Adelman
Prof. S.M. Alam
Dr A. Tajuddin Ali
Prof. S. Alvarado
Mr M.H. Ang
Dr E. Ardayfio-Schandorf
Dr S. Baldwin
Mr F.E. Banks
Mr B. Baratz
Mr G.H. Barrows
Mr S.B. Baruch
Prof. G.H. Beaton
Mr R.C. Bending
Prof. J. O'M. Bockris
Ms S. Bogach
Sr R. Boix Amat
Dr C. Boonyubol
Prof. D.K. Bose
Mr S.K. Bose
Mr G. Bouchard
Mr H. Broadman
Mr D. Brooks
Mr N.L. Brown
Prof. E. Campero
Dr R. Canales-Ruiz
Dr R.K. Cattell
Eng. M.F. Corrales V.
Mr A. Davenport
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Dr A. de Oliveira
Mr R.J. deLucia
Madam Deng Keyun
Dr R. DiPippo
Mr E. Dommen
Prof. J.A. Duffie
Mr B. Duhamel
Mr J.R. Egan
Dr A.-M. E. El-Bassouoni
Dr P. Elkan
Prof. B.J. Esposito
Dr E. Fein
Mr C. Feinstein
Mr F. Fesharaki
Prof. G.B. Fettweiss
Mr J.L. Fish
Prof. G. Fishelson
Mr W. Floor
Mr G. Foley
Mr I.B. Fridleifsson
Dr J.C. Frost
Dr P.G. Gibbon
Prof. P.V. Gilli
Dr M.L. Gupta
Prof. V. Gupta
Prof. D.O. Hall
Prof. B. Hannon
Dr S.D. Hu
Dr H. Inhaber
Dr M.N. Islam
Dr B.C. Jain
Mr W.E. James
Mr L. Jarass
Mr K.G. Jechoutek
Mr A. Jelich
Prof. G. Kadekodi
Mr A. Kahane
Dr W.K.H. Kinzelbach
Dr L. Kristoferson
Mr G. Leach
Mr A. Leslie
Dr C.T. Leung
Dr C. Lewis
Mr R. Lichtman
Dr J.W. Lund
Mr M.C. Lynch
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Mr K. Newcombe
Dr A. Ng'eny-Mengech
Prof. S.R. Nkonoki
Prof. P.R. Odell
Prof. T. Ohta
Mr A. Oldfield
Mr K. Openshaw
Mr R.M. Ornstein
Mr C. Ostrovski
Mr P.F. Palmedo
Dr J. Parikh
Mr D.J. Passmore
Prof. R. Passmore
Mr J. Pasztor
Prof. A. Pereira
Mr R. Peters
Dr O.M. Pimentel
Sr L. Pinguelli Rosa
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Dr V. Raghuraman
Dr S. Raj
Ms J. Ramakrishna
Prof. R. Ramakumar
Prof. T.V.S. Ramamohan Rao
Prof. K.S. Rao
Mr R.S. Rangi
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