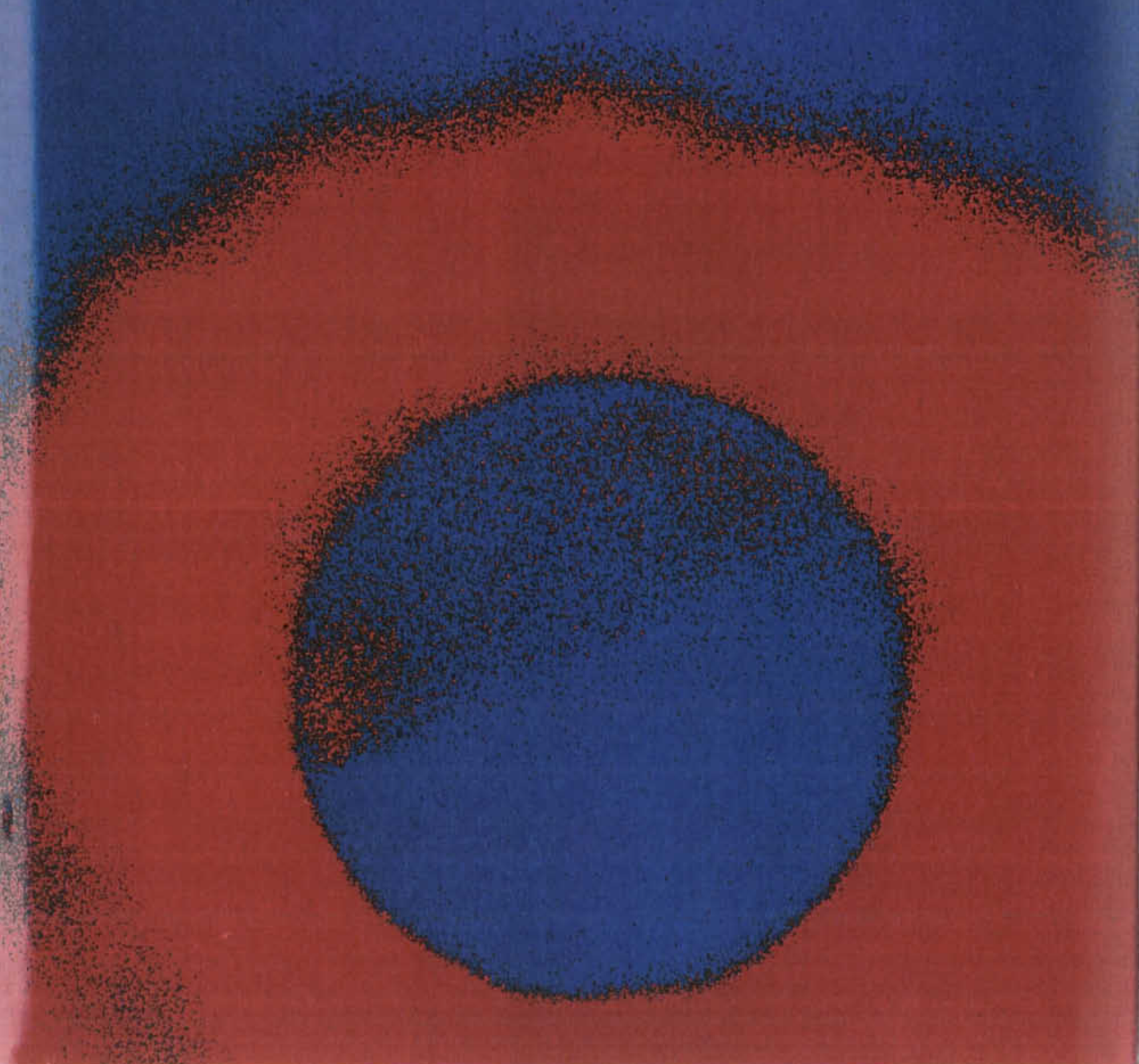
ENERGY IN A FINITE WORLD

Paths to a Sustainable Future

Report by the Energy Systems Program Group
of the International Institute for Applied Systems Analysis
Wolf Häfele, Program Leader

Written by Jeanne Anderer with
Alan McDonald and Nebojsa Nakicenovic



ENERGY IN A FINITE WORLD
Paths to a Sustainable Future

ENERGY IN A FINITE WORLD

Paths to a Sustainable Future

Report by the
Energy Systems Program Group
of the International Institute
for Applied Systems Analysis

Wolf Häfele, Program Leader

Written by
Jeanne Anderer
with
Alan McDonald
and
Nebojsa Nakicenovic

BALLINGER PUBLISHING COMPANY
Cambridge, Massachusetts
A Subsidiary of Harper & Row, Publishers, Inc.

International Standard Book Number: 0-88410-641-1

Library of Congress Catalog Card Number: 80-20057

Printed in the United States of America

Library of Congress Cataloging in Publication Data
Main entry under title:

Energy in a finite world.

Includes index.
CONTENTS: v. 1. Summary and analysis.—v. 2. Technical report.
1. Power resources. 2. Energy policy. I. Häfele, Wolf. II. International Institute for Applied Systems Analysis. Energy Systems Program Group.
TJ163.2.E478 333.79 80-20057
ISBN 0-88410-641-1 (v. 1)
ISBN 0-84410-642-X (v. 2)

MEMBERS OF THE IIASA ENERGY SYSTEMS PROGRAM

Below is a listing of the members of the Energy Systems Program, including name, nationality, period of service with the program, and, where applicable, institute of origin.

Wolf Häfele (Program Leader). FRG. July 1973–present*. Nuclear Research Center, Karlsruhe, FRG.

Abdelmonem A. Afifi. USA. July 1976–September 1977. School of Public Health, University of California, Los Angeles, California, USA.

Malcolm Agnew. UK. August 1976–April 1979. University of Münster, Münster, FRG.

Jeanne Anderer. USA. June 1979–present*.

Piero-Maria Armenante. Italy. May–December 1978. University of Rome, Rome, Italy.

Alexander S. Astakhov. USSR. February–June 1978. Institute of Management of the National Economy, Moscow, USSR.

Rudolph Avenhaus. FRG. July 1973–August 1975. Nuclear Research Center, Karlsruhe, FRG.

Maria Bacher-Helm. Austria. September 1973–present*.

Anthony Baker. UK. Intermittently. National Coal Board, Harrow Middlesex, UK.

Todor Balabanov. Bulgaria. September 1977–present*. Institute for Unconventional Energy Sources, Bulgarian Academy of Sciences, Sofia, Bulgaria.

Paul S. Basile. USA. June 1977–November 1979. Sloan School of Management, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA.

*As of 31 December 1979.

Jean-Michel Beaujean. France. January 1976–January 1979. Institute of Technology of the University of Paris V, National Institute of Nuclear Sciences and Technology, Paris, France.

Klaus Becker. FRG. August–September 1978. DIN, German Nuclear Standards Committee, Berlin, FRG.

Charles Bell. USA. November 1975–January 1978. Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA.

Lev Belyaev. USSR. October 1975–December 1976. Siberian Power Institute, USSR Academy of Sciences, Irkutsk, USSR.

Anne Binkley. USA. March 1978–present*.

Manfred Breitenecker. Austria. October 1976–December 1978. Institute for Theoretical Physics, University of Vienna, Vienna, Austria.

Beverly Broadfoot. New Zealand. Intermittently.

Natalia Burova. USSR. July–December 1976. Computing Center, USSR Academy of Sciences, Moscow, USSR.

Richard Caputo. USA. May 1979–present*. Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA.

Martin Cellerier. France. April 1977–December 1978. French Petroleum Institute, Reuil-Rueil-Malmaison, France.

Bernard Chaix. France. February–July 1976. French Petroleum Institute, Rueil-Malmaison, France.

Verne Chant. Canada. January–December 1978. Bureau of Management Consulting, Department of Supply and Services, Ottawa, Canada.

Jean-Pierre Charpentier. France. November 1973–August 1975. Commission for Atomic Energy, Paris, France.

Sergei Chernavsky. USSR. September–October 1979. Working Consultative Group on Long-term Energy Forecasting, Presidium of the USSR Academy of Sciences, Moscow, USSR.

Karl Cohen. USA. Intermittently. General Electric, San Jose, California, USA.

Christina Derstroff. Austria. February 1976–present*.

Claire Doblin. USA. January 1975–present*.

Nickolai Dranishnikov. USSR. June–September 1979. Committee for Systems Analysis, USSR Academy of Sciences, Moscow, USSR.

John T. Eddington. USA. September 1978–present*. Gulf Oil Corporation, Pittsburgh, Pennsylvania, USA.

Richard Eden. UK. June–July 1974. Cavendish Laboratory, University of Cambridge, Cambridge, UK.

Ward Edwards. USA. June 1977 and January 1978. Social Science Research Institute, University of Southern California, Los Angeles, California, USA.

Francois Emard-Katsonis. France. May–December 1978. National Center of Scientific and Technical Research (CNRS), Paris, France.

Dieter Faude. FRG. Intermittently. Nuclear Research Center, Karlsruhe, FRG.

George C. Ferrell. USA. February–August 1977. Operations Research Center, University of California, Berkeley, California, USA.

Franz Fleck. FRG. December 1976–December 1978. University of Karlsruhe, Karlsruhe, FRG.

*As of 31 December 1979.

Hermann Flohn. FRG. Intermittently. Institute for Meteorology, University of Bonn, Bonn, FRG.

Helmut Frey. Austria. Intermittently.

Barbara Gilbert. USA. June 1976–April 1977.

Dominique Gourmelon. France. Intermittently. French Association for the Development of Systems Analysis (AFDAS), Paris, France.

Michel Grenon. France. January 1974–December 1978. International Energy Consultant.

Jacques Gros. USA. July 1974–June 1976. Harvard University, Cambridge, Massachusetts, USA.

Gabriela Grosse. FRG. September 1975–May 1979.

Arnulf Grübler. Austria. October 1976–December 1978. Technical University, Vienna, Austria.

Hans-Richard Grümm. Austria. November 1974–November 1977 and February 1978–December 1978. Institute for Theoretical Physics, University of Vienna, Vienna, Austria.

Willi Hätscher. GDR. June–July 1975. Institute for Energetics, Leipzig, GDR.

Günter Hildebrandt. FRG. Intermittently. United Association of German Hard Coal Mines, Essen, FRG.

Frank Hoffmann. FRG. Intermittently. United Association of German Hard Coal Mines, Essen, FRG.

John P. Holdren. USA. Intermittently. Energy and Resources Program, University of California, Berkeley, USA.

Alois Hölzl. Austria. January 1978–present*. Technical University, Vienna, Austria.

Eckhard Höpfinger. FRG. April 1977–March 1978. Institute for Economics and Operations Research, University of Karlsruhe, Karlsruhe, FRG.

Fredy Jäger. FRG. March 1976–January 1978. Institute for Nuclear Technology, University of Stuttgart, Stuttgart, FRG.

Martina Jöstl-Segalla. USA. Intermittently.

Günter Kessler. FRG. Intermittently. Nuclear Research Center, Karlsruhe, FRG.

Nathan Keyfitz. USA. Intermittently. Center for Population Studies, Harvard University, Cambridge, Massachusetts, USA.

Arshad M. Khan. Pakistan. January 1978–present*. Pakistan Institute of Nuclear Science and Technology, Rawalpindi, Pakistan.

Kenneth Klitz. USA. February 1977–June 1978. IBM Corporation, Boulder, Colorado, USA.

Yuri Kononov. USSR. December 1975–March 1979. Siberian Power Institute, USSR Academy of Sciences, Irkutsk, USSR.

Troos Koopmans. USA. February–December 1974.

Wolfgang Korzen. Austria. April 1976–present*. Technical University, Vienna, Austria.

Nikolai Kourochkin. USSR. October 1973–September 1974. Institute for World Economy and International Relations, USSR Academy of Sciences, Moscow, USSR.

Janet Kovacs. USA. Intermittently.

Renate Kreisl. Austria. March 1974–July 1977.

Gerhard Krömer. Austria. February 1975–present*. Technical University, Vienna, Austria.

Ruth Kuhn. FRG. Intermittently. Nuclear Research Center, Karlsruhe, FRG.

*As of 31 December 1979.

Gerald L. Kulcinski. USA. Intermittently. University of Wisconsin, Nuclear Engineering Department, Madison, Wisconsin, USA.

Vivien Landauer. UK. July 1973–December 1978.

Bruno Lapillonne. France. September 1975–January 1978. Institute of Energy Economics and Law, National Center of Scientific Research (CNRS), Grenoble, France.

Didier Launay. France. April 1979–present*. Institute of Energy Economics and Law, National Center of Scientific Research (CNRS), Grenoble, France.

Barbara Lewis. USA. Intermittently.

Mary Lindenthal. UK. April 1978–present*.

Nilo Lindgren. USA. September 1979–present*. Consultant, Electric Power Research Institute, Palo Alto, California, USA.

Joanne Linnerooth. USA. September 1974–August 1978. University of Maryland, Department of Economics, College Park, Maryland, USA.

Amory B. Lovins. USA. January–February 1977. Friends of the Earth, London, UK.

Alexej A. Makarov. USSR. Intermittently. Siberian Power Institute, USSR Academy of Sciences, Irkutsk, USSR.

Alan S. Manne. USA. September 1973–June 1974. Stanford University, Palo Alto, California, USA.

Cesare Marchetti. Italy. January 1974–present*. Retired from EURATOM, Ispra, Varese, Italy.

Dagmar Maurer. Austria. February 1976–December 1978. Institute of Psychology, University of Vienna, Vienna, Austria.

John Mayo. USA. June–September 1979. Washington University, Department of Economics, St. Louis, Missouri, USA.

Patricia Mayo. USA. August–September 1979.

Alan McDonald. USA. October 1979–present*. John F. Kennedy School of Government, Harvard University, Cambridge, Massachusetts, USA.

Peter E. McGrath. USA. Intermittently. Sandia Laboratories, Albuquerque, New Mexico, USA.

Dennis L. Meadows. USA. January–March 1977. Dartmouth College, Hanover, New Hampshire. USA.

Jean-Michel Merzeau. France. Intermittently. French Association for the Development of Systems Analysis (AFDAS), Paris, France.

Michael Messenger. USA. November 1979–present*. Lawrence Berkeley Laboratory, University of California, Berkeley, California, USA.

Sabine Messner. Austria. May 1979–present*. Technical University, Vienna, Austria.

Dorothy Mich-Weiss. USA. April 1977–May 1978.

Joachim Mietzner. FRG. Intermittently. Energy Consultant, FRG.

Morton Müller. Norway. January–June 1977. Institute for Advanced Business Studies, CESA, Jouy-en-Josas, France.

Tomas Müller. FRG. January 1977–December 1978, University of Karlsruhe, Karlsruhe, FRG.

Allan H. Murphy. USA. September 1974–May 1975. National Center for Atmospheric Research, Boulder, Colorado, USA.

Nebojsa Nakicenovic. Yugoslavia. August 1973–present*. Princeton University, Princeton, New Jersey, USA.

*As of 31 December 1979.

Friedrich Niehaus. FRG. May 1975–present*. Nuclear Research Center, Jülich, FRG.

William Nordhaus. USA. August 1974–July 1975. Yale University, Department of Economics, New Haven, Connecticut, USA.

Morris Norman. USA. February 1976–May 1977. Econometrics International, Santa Barbara, California, USA.

William Orchard-Hays. USA. May 1976–December 1978. National Bureau of Economic Research, Cambridge, Massachusetts, USA.

Richard Ormerod. UK. Intermittently. National Coal Board, Harrow, Middlesex, UK.

Harry Otway. USA. March 1978–February 1979. International Atomic Energy Agency, Vienna, Austria.

Philip D. Pahner. USA. July 1975–December 1976. Free-lance Psychiatrist, USA.

Helene Pankl. Austria. July 1979–present*.

Alexander Papin. USSR. March 1978–present*. Siberian Power Institute, USSR Academy of Sciences, Irkutsk, USSR.

Jyoti K. Parikh. India. May 1976–September 1978. Department of Atomic Energy, Bombay, India.

Richard Patzak. Austria. September 1973–September 1975. Institute of Low Temperature Physics, University of Vienna, Vienna, Austria.

Peter Penczynski. FRG. July 1976–September 1977. The Siemens Company, Erlangen, FRG.

Alfred Perry. USA. April–July 1978. Institute for Energy Analysis, Oak Ridge Associated Universities, Oak Ridge, Tennessee, USA.

Vaclav Peterka. Czechoslovakia. May 1976–April 1977. Institute of Information Theory and Automation, Prague, Czechoslovakia.

Hannes Porias. Austria. August 1975–present*.

Juan di Primio. Argentina. May 1979–present*. Nuclear Research Center, Karlsruhe, FRG.

Thomas J. Ratchford. USA. June–August 1976. Committee of Science and Technology, U.S. House of Representatives, Washington, D.C., USA.

Claus Riedel. GDR. September 1976–August 1977. Technical University, Karl-Marx-Stadt, GDR.

Lieselotte Roggenland. Austria. September, 1973–present*.

Hans-Holger Rogner. FRG. September 1975–present*. University of Karlsruhe, Karlsruhe, FRG.

Michael Sadnicki. UK. Intermittently. National Coal Board, Harrow, Middlesex, UK.

Leonard Sagan. USA. August 1976–July 1977. Department of Environmental Medicine, Palo Alto Medical Clinic, Palo Alto, California, USA.

Wolfgang Sassin. FRG. July 1975–present*. Nuclear Research Center, Karlsruhe, FRG.

Diethard Schade. FRG. September 1974–April 1975.

Ralf E. Schaefer, FRG. September 1977–February 1978. University of Mannheim, Mannheim, FRG.

Michael Schikorr. FRG. Intermittently. Nuclear Research Center, Karlsruhe, FRG.

Leo Schrattenholzer. Austria. November 1973–present*. Technical University, Vienna, Austria.

Richard Seidl. Austria. February–November 1976. Shell Austria, Vienna, Austria.

Peter P. Sint. Austria. October 1974–June 1976. Institute of Socioeconomic Development, Austrian Academy of Sciences, Vienna, Austria.

*As of 31 December 1979.

Yuri Sinyak. USSR. September–October 1979. Working Consultative Group on Long-term Energy Forecasting, Presidium of the USSR Academy of Sciences, Moscow, USSR.

Malcolm Slesser. UK. September–October 1976. University of Strathclyde, Glasgow, Scotland.

Suzanne Smarr. USA. October 1975–May 1976.

Bernard Spinrad. USA. September 1978–August 1979. Oregon State University, Department of Nuclear Engineering, Corvallis, Oregon, USA.

Irene Straub. Austria. October 1976–April 1978.

Manfred Strubegger. Austria. May 1979–present*. Technical University, Vienna, Austria.

William T. Struble. USA. September–October 1978. MIT Press, Cambridge, Massachusetts, USA.

Atsuyuki Suzuki. Japan. April 1974–July 1975. Nuclear Engineering Laboratory, University of Tokyo, Tokyo, Japan.

Elisabeth Swaton. Austria. March 1976–February 1977. Institute of Psychology, University of Vienna, Vienna, Austria.

Ingrid Teply-Baubinder. Austria. October 1976–present*.

Jean U. Thoma. Switzerland. Intermittently. Energy Consultant, Switzerland.

Plamen Tsvetanov. Bulgaria. August 1974–December 1976. Institute of Power Design and Research, Ministry of Energy, Sofia, Bulgaria.

Albina Tsvetanova. Bulgaria. April 1975–December 1976. Institute of Power Design and Research, Ministry of Energy, Sofia, Bulgaria.

Dagmar Tutzschky. FRG. August 1976–September 1979.

Tadashi Uratani. Japan. March 1977–December 1978. Tokyo Institute of Technology, Department of Social Engineering, Tokyo, Japan.

Helga Velimirovic. Switzerland. October 1974–January 1976. Free-lance Anthropologist/Consultant.

Hans Voigt. FRG. October 1977–October 1978. The Siemens Company, Erlangen, FRG.

Alfred Voss, July 1976–August 1977. Nuclear Research Center, Jülich, FRG.

Judith Wagstrom. USA. Intermittently.

Jerome M. Weingart. USA. September 1974–December 1975. Center for Government Education Relations, Washington, D.C., USA.

Willy Weisz. Austria. January 1976–present*. Computing Center, University of Vienna, Vienna, Austria.

Norbert Weyss. Austria. June 1974–June 1975. Consultant, Retired from Brown, Boveri and Cie, Mannheim, FRG.

Jill Williams. UK. August 1976–August 1978. Climate Research Unit, University of East Anglia, Norwich, UK.

Anne Wimmer. France. March 1974–February 1978.

Detlof von Winterfeldt. FRG. November 1975–June 1978. Social Sciences Research Institute, University of Southern California, Los Angeles, California, USA.

Mudaham T. Zen. Indonesia. October 1976. State Ministry for Research, Jakarta, Indonesia.

Igor N. Zimin. USSR. October 1974–December 1978. Computing Center, USSR Academy of Sciences, Moscow, USSR.

*As of 31 December 1979.

FOREWORD

In June 1973 the first scientist arrived at the International Institute for Applied Systems Analysis (IIASA). He came, just nine months after the signing of IIASA's charter, to work on the Institute's first major study—the Energy Project. In the years since, more than 140 other scientists have come from over nineteen countries to participate in what has become IIASA's Energy Systems Program. Under the leadership of Professor Wolf Häfele, they have carried out a truly comprehensive analysis of the world's energy future.

This book reports their findings. It is also a "first"—the first complete report of a major IIASA program. As such, it carries a dual responsibility. On the one hand, it provides a clear, thorough, and objective presentation of the results of a large, multifaceted study. On the other hand, it demonstrates to a wide and interested audience the nature of the contribution that IIASA can make to a better understanding of major international issues.

Although analysis strives to be objective, it cannot avoid completely the imprint of personality or the influence of individual and group experience. Consequently this study, like all others, reflects the character and background of its authors. Good analysis, however, tries to make these influences and assumptions explicit, so that the user of the analysis can be aware of and compensate for them. Professor Häfele and his team have taken special care in this report to state carefully the assumptions they have made and to distinguish their "visions" from their calculations.

The Institute, for its part, has provided the environment in which this major international and interdisciplinary study could be carried out. And it has established the procedures for scientific review of the report by an international group of experts on energy. But the findings and conclusions of the study are those of the Energy Systems Program under the leadership of Professor Wolf Häfele and should not necessarily be ascribed to the Institute, its Council, or its National Member Organizations.

The global energy problem is so complex that no single study can hope for complete acceptance. This analysis instead aspires to contribute to the continuing debate and discussion by providing a globally comprehensive framework and a long-term perspective. Inevitably, there will be those who disagree with some of its assumptions, methods, or conclusions. They are challenged to trace the consequences of their alternative views within the same constraints that everything add up across and over time. The discipline of quantification and the necessity of coherence are prerequisites for serious energy analysis.

The global energy problem is so difficult that no nation acting alone can solve it. Yet for the necessary international cooperation to succeed, there must be a base of shared understanding of the nature of the problem and its possible solutions. The IIASA Energy Systems Program has aspired to contribute to the development of that understanding. It has done so both through its own research and through the creation of an international network of collaborating energy institutions and specialists who share its perspective and approach. Thus, this book is just one—very important—dimension of the results of the Energy Program. As it is disseminated and read, we hope that it will help to enlarge the network of those who have a common understanding of the global energy problem and, thereby, will help to establish the basis for wise, successful, and equitable international collaboration in its solution.

When the first IIASA scientist began working on energy seven years ago, the Institute's aspirations were high, but its prospects for success were uncertain. This book demonstrates, we believe, that the Institute's international and interdisciplinary analysis can contribute to a better understanding and resolution of major problems of international importance.

Jermen Gvishiani
Chairman of the IIASA Council

Roger E. Levien
Director of IIASA

PREFACE

This volume summarizes the findings of the study of the global energy system by the Energy Systems Program, Phase 1, of the International Institute for Applied Systems Analysis (IIASA). In the companion volume (Volume 2), *Energy in a Finite World: A Global Systems Analysis,* the study findings are reported on in great detail, with all the necessary references and qualifications that are typical of a comprehensive scientific work.

Of course, a summary volume does provide the reader with a more easily understood and condensed accounting, but not without cost. Those interested in a fuller explanation of certain reasonings or in more information about a subject that is only touched upon here are referred to Volume 2 and to the sixty research reports published by IIASA that underlie this energy study.

The goal of the IIASA Energy Systems Program was to understand and to conceptualize by qualitative and quantitative means the global long-range aspects of the energy problem—not to advance the state of the art of a particular discipline (although we would be pleased if this were to happen). We have tried to look at each of the different aspects of the energy problem in a new way—to view them as an integral part of an overall pattern. We therefore suggest that the reader consider this book as a picture or a pattern and not concentrate solely on individual chapters or subjects.

Our aim throughout the study has been to be objective. However, in summing up, we recognized the need to take a position and to express the views we actually hold. Thus, the assessments and implications of our study for energy policy cannot be defended merely on an objective scientific basis: They are either evident or not.

IIASA is a small research institution, and the group studying the energy problem was relatively small. We therefore did not judge it useful to compete with the energy research of larger national and regional study groups. Our intent was to complement their work by providing a long-range, global view of the problems facing civilization. In particular, we aimed for complementarity with the Workshop on Alternative Energy Strategies (WAES). Similarly, our thinking was stimulated by the World Energy Conferences of Detroit (1974) and of Istanbul (1977) and by our contacts with major groups in the energy field such as those of the Academy of Sciences of the Soviet Union and of the European Community.

IIASA, as a nongovernmental institution, is fortunate to receive the cooperation and support of its seventeen National Member Organizations, which span both East and West, and the Energy Systems Program has benefited greatly from the diverse political, social, and economic points of view on the energy problems in these countries. But for a truly global perspective, one must also consider the dynamics of the developing countries, and we are grateful for the cooperation received from numerous institutions, groups, and individuals from these countries. We especially wish to acknowledge the support of the United Nations Environment Programme (UNEP) in Nairobi, which helped us to strengthen our rapport with the developing world.

We would not have been able to complete the research reported on here without the help and support of many institutions, groups, and individuals. In the list below we gratefully acknowledge the help received from these bodies by means of contracts and cooperative agreements. It would give a false impression, however, if this list were considered exhaustive. It is simply impossible to include all here.

UNEP awarded us a major contract on "The Comparison of Energy Options: A Methodological Study," which covered a major portion of our work. Thus, to some extent, UNEP could be considered a co-sponsor of this phase of the Energy Systems Program. UNEP also awarded us a contract on "A Systems Study of Energy and Climate," which permitted us to examine the possible climatic impacts of energy technologies.

The Meteorological Office, Bracknell, United Kingdom, cooperated very closely with us in our study of man's impact on the climate system. Specifically, they provided us with their Global Circulation Model, which served as the basis of the numerical experiments carried out with the abovementioned UNEP support. We are also grateful to the Meteorological Office for providing us with experimental output.

The Nuclear Research Center (Kernforschungszentrum), Karlsruhe, FRG, provided us with large amounts of inexpensive computer time for executing the numerical experiments supported by UNEP and the Meteorological Office.

For our research on the impacts of solar energy production on the meso-

scale climate, we received the cooperation of the Stanford Research Institute, Palo Alto, California.

The National Center for Atmospheric Research, Boulder, Colorado, lent their cooperative assistance to the above-mentioned climate studies supported by UNEP.

The International Atomic Energy Agency (IAEA), Vienna, Austria, formed a joint team with IIASA to study risks. This team made important contributions to IIASA's work in this field.

The Volkswagen Foundation (Stiftung Volkswagenwerk), Hanover, FRG, awarded us a contract for studying "Procedures for the Setting of Standards," which complemented the work of the joint IIASA-IAEA risk team. The Volkswagen Foundation also gave us a contract for studying "The Mechanisms of Market Penetration," which very much expedited our work in this area.

The Federal Ministry of Research and Technology (Bundesministerium für Forschung und Technologie), Bonn, FRG, awarded us a major contract for a "Systems Study on the Possibilities of Intensified Use of Solar Energy in the Federal Republic of Germany (FRG)." Through this assistance we were able to broaden our knowledge of developments in the field of solar power.

The Austrian National Bank (Österreichische Nationalbank), Vienna, Austria, awarded us a contract for studying "Capital and Currency Demand as a Constraint for Future Technological Strategies for Meeting Demand." Their support helped us in the development of the IIASA set of mathematical energy models.

The Siberian Power Institute of the Siberian Department of the USSR Academy of Sciences, Irkutsk, cooperated closely with us, in particular by giving us the early version of a computer program that, after adaptation at IIASA, became the economic IMPACT model.

The USSR Academy of Sciences, through the Kurchatov and the High Temperature Institutes in Moscow, participated in our study of "Fusion and Fast Breeder Reactors."

The Electric Power Research Institute, Palo Alto, California, contributed to our study of "Fusion and Fast Breeder Reactors."

The Institute of Energy Economics and Law (Institut Economique et Juridique de l'Energie), Grenoble, France, cooperated with us, in particular by providing us with a computer program that, after adaptation at IIASA, became the MEDEE-2 model.

Shell Austria, through the Technical University of Vienna, contributed a grant in support of our WELMM studies.

We also wish to acknowledge here the close cooperation of the National Coal Board, United Kingdom; of the United Association of German Hard Coal Mines (Gesamtverband des Deutschen Steinkohlenbergbaus) and the Hard Coal Mining Association (Steinkohlenbergbauverein), FRG; and of the institutions in Poland, the USSR, and the United States that helped us with our assessment of the coal option.

Additionally, we were greatly assisted in our work by the following institutions and industrial firms: The Institute of National Planning, Cairo, Egypt; Siemens, Erlangen, FRG; Kraftwerk Union, Erlangen, FRG; Shell, London, United Kingdom; General Electric, New York; The Organization of Arab Petroleum Exporting Countries, Kuwait; Gulf Corporation, Pittsburgh, Pennsylvania; Electricité de France, Paris; Institut Francais du Pétrole, Paris; Bureau de Recherches Géologiques et Minières, Orleans, France; Charbonnages de France, Paris; Centre National de la Recherche Scientifique, Paris; and Institut für Kernenergetik und Energiesysteme der Universität Stuttgart, FRG.

The IIASA Energy Systems Program was carried out by a closely cooperating multinational team. In addition to scientists from both East and West, we were assisted by scientists from the developing countries who shared with us their first-hand knowledge of energy problems in their countries. The members of the Energy Systems Program over the study period are listed at the beginning of this book. Each member who was with us at Laxenburg for more than a month is included, with the average period of service being between one and two years.

Our team was also multidisciplinary: Economists, physicists, engineers, geologists, mathematicians, psychologists, a psychiatrist, and an ethnologist gave us their different views of the energy problem, thus making it impossible for us to hold an extreme, one-sided view.

The scientific authorship of the various contributions is diffuse and has been explained to the extent possible in the second volume. These contributors cannot be held responsible for ideas that have been synthesized into the overall pattern presented here. The final responsibility rests with the Program Leader.

Naturally, the condensation of voluminous material into summary form is a difficult task and we gratefully acknowledge the assistance of Robert Gerwin, author of *World Energy Perspective: Analysis to the Year 2030, According to the IIASA Study,* Energy in a Finite World, presented by the Max-Planck-Gesellschaft, and published by the Deutsche Verlags-Anstalt, Stuttgart, FRG. Specifically, we were guided in structuring our material contained in this volume by this German-language report of the IIASA study.

We hope that this book will contribute to a better understanding of and among people and also of nature, which makes it possible for us to live on the earth. We mean this book to contribute to keeping the peace.

Wolf Häfele
Program Leader
Energy Systems Program
IIASA

CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 THE ENERGY PROBLEM: NO EASY FIX

Energy specialists no longer have to acquaint the public with the existence of an energy problem. The symptoms of our increasing dependence on dwindling fuel resources have emerged sometimes slowly and gently, sometimes suddenly and painfully. We are all aware of the forms in which we have experienced them in our own lives, and we are becoming increasingly aware of the ways in which they affect others. Our appreciation of the connections between energy problems and difficulties falling under other headings—social, political, environmental, economic, institutional—has also grown. With this understanding it has become clear that the label applied in 1973, "The Energy Crisis," is inaccurate, or at least misleading. The difficulties associated with supplying and using energy spread throughout society and are not temporary; they will continue, and we must learn to deal with them.

Yet most people, whether in their day-to-day living or in their professional lives, have been obliged to deal with their energy difficulties within a limited perspective. They have not had a broad picture of the energy situation, one that encompasses the likely future patterns of global demand and supply, the actual magnitude of fossil resources, the possible efficacy of energy-saving measures, the likelihood of the global trading of energy, or the prospect of ameliorative institutional changes.

To be sure, until the oil shock of 1973 there had been no urgency to think in such long-range and global terms. Institutional and national planning for future activities, some of which might even be strongly energy dependent, simply went on in the absence of such facts and foresight. But subsequent events have pushed to the fore the recognition that sharp oil price increases were merely the trigger and that the world faces not a temporary "crisis," but a pervasive, chronic "energy problem."

The change in perception goes further: It recognizes that the world is tightly interconnected and explains why the development of appropriate energy policies is such a difficult process. While the energy problem transcends national borders, policy analyses have tended to follow suit only selectively. Other nations are scrutinized only when they might prove to be suppliers of energy; as for their problems, those are their own business. But such provincialism can only lead to dangerously misguided national policies. To underestimate the difficulties of others, to fail to appreciate the differences between developing and developed countries, and to neglect the repercussions that one nation's actions can have on another, only inspire policies that increasingly will strain the world's resources and institutions. And the more these are strained, the more painful and difficult will prove any attempts to overcome the energy problem.

Is finding a solution to the oil problem a way of solving the energy problem, or does it go deeper than that? To answer this question, it is imperative first to understand the many sided character of energy, described in the accompanying boxed material and in Figure 1-1, and to appreciate the factors that have shaped today's energy problems.

Today's high gear economies run largely on fossil fuels—coal, natural gas, and especially oil. In 1975, roughly 70 percent of the world's primary energy came from oil and natural gas, and roughly 20 percent of this oil was crude from the Persian Gulf. There are many reasons why energy infrastructures are built around oil. Oil is a clean, versatile, and relatively easy to use fuel that until recently was in constant supply at relatively low prices. And because of its liquid properties, oil can be easily transported over long distances and stored conveniently. Oil not only serves the purposes of industrialization, but, even in developing rural areas, a barrel of oil can fairly easily be brought in, stored, and used for cooking and heating.

If the energy problem had arisen in a fairly static world, it might have been possible to solve it, in time, by reducing the amount of energy used and by gradually substituting new energy sources for oil. But we live in a dynamic world—a world in which populations are growing rapidly, in which the work force is increasing, and in which aspirations for amenities are growing. If the living standards of the industrialized world are at the very least to be maintained, and if the peoples of the developing world are to achieve reasonable standards of living in time, there will have to be economic development and, in the case of the least developed countries, rapid economic growth. But development requires energy—lots of it. Specifically, the need for liquid fuels is high in nations at early stages of industrialization. So, to meet the needs of a rapidly expanding world population undergoing economic development is likely to require a considerable increase in the amount of energy used, especially liquid fuels, as well as the substitution of nondepletable energy sources for those now in use. The question is not whether, but when.

Then too, the earth has come to be seen as a finite system sensitive to

THE CHARACTER OF ENERGY

When people talk about energy, it is not always clear what kinds of energy they are talking about, and this adds to the problem. Therefore, in order to understand the physical energy system, it is important to distinguish between energy at various stages of conversion and use. Figure 1-1 is helpful for understanding this point.

Primary energy is the energy recovered from nature—water flowing over a dam, coal freshly mined, oil, natural gas, natural uranium. Only rarely can primary energy be used to supply *final energy*—energy used to supply the consumer with energy services. One of the few forms of primary energy that can be used as final energy is natural gas, which is why it is a fuel of preference whenever it is available.

For the most part, primary energy is converted into *secondary energy*. This is defined as an energy form that can be used over a broad spectrum of applications: Electricity and gasoline are the major examples. Less convenient (which is why they are declining in their market shares) forms of secondary energy include charcoal, sorted and graded coal, and cut and split fuelwood. In order to apply energy without making undue demands on the consumer, it must be converted into a form that may be readily transported, distributed and used in a variety of devices. The trend has been toward grids, for obvious reasons—specifically toward electricity, gas, and district heating grids. For convenience of storage, portability, and transportability, the trend has also been to liquid fuels, of which gasoline and diesel oil are the best examples.

Primary energy is converted into secondary energy in several different ways. For example, central power plants produce electricity and, sometimes district heat. Refineries convert petroleum to more convenient liquid fuels—gasoline, jet fuel, diesel oil, and naphtha. Sometimes the conversion plant is the end point of a system, as with nuclear fission energy (for which chemical conversion, isotopic enrichment, and fuel fabrication all precede the power plant); sometimes, as with a hydroelectric or a wind generator, it is a simple machine. But regardless, there are *conversion losses* in going from primary to secondary energy and *transmission losses* in getting that energy to the consumer. It is wrong to think of these losses as waste. They represent a trade-off of efficiencies: The use of energy to transform and transmit energy permits the end user to apply it efficiently for his purposes.

These final steps are the conversion of secondary energy into *final energy*—the energy in a motor, a stove, a computer, or a lightbulb—and of final energy into *useful energy*—the energy actually stored in a product or used for a service. It is important to realize that in providing the service—say, a well-lit room—energy is not merely a stored entity, but even more an input for the efficient use of other resources, of labor, of capital, and especially of skill.

Figure 1-1. Energy conversion and use.

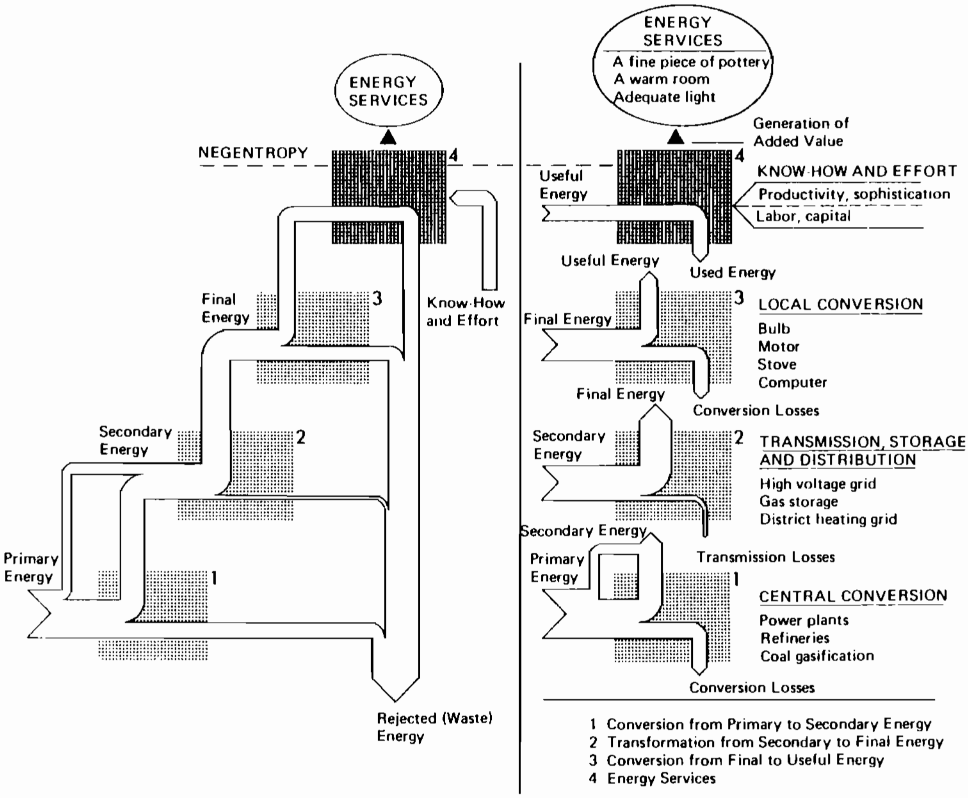


Table 1-1. Estimated global primary energy supply, 1975.

Type	*Level (TWyr/yr)*
Commercial Energy	
Oil	3.8
Of which oil from Middle East and North Africa	(1.6)
Natural gas	1.5
Other	2.9
Total Commercial Energy	8.2
Noncommercial Energy (e.g., fuelwood, agricultural waste)	0.6
Total Energy	8.8

Sources: Commercial primary energy supply estimates are based on data from United Nations (1978). Estimates of noncommercial energy supply are taken from Parikh (1978).

human activity. People are becoming more aware of the possible long-term harmful effects of their activities on the environment and it is no longer automatically possible to substitute new resources and technologies for those in short supply or whose use has become uneconomic. Indeed, the deployment of nuclear energy or of coal in place of oil is constrained by such concerns. It seems as though the whole range of human activities must be taken into account in the development of new energy strategies.

Another possible way of grasping today's energy problem is to assess the amount of primary energy being consumed around the world. As Table 1-1 shows, in 1975 the world consumed primary commercial energy at a rate of 8.2 terawatt-years per year (TWyr/yr) and noncommercial energy (e.g., animal and farm wastes) at a rate of 0.6 TWyr/yr.

The fact that it has been necessary to use terms like "terawatt" gives some indication of the increase in worldwide energy consumption. One terawatt-year per year is a big unit; it equals roughly one billion tons of coal per year or 14 million barrels of oil per day, which is more than the oil production rate considered currently possible for Saudi Arabia. Definitions of the units that can be used for describing energy supply and consumption are given in the accompanying boxed material.

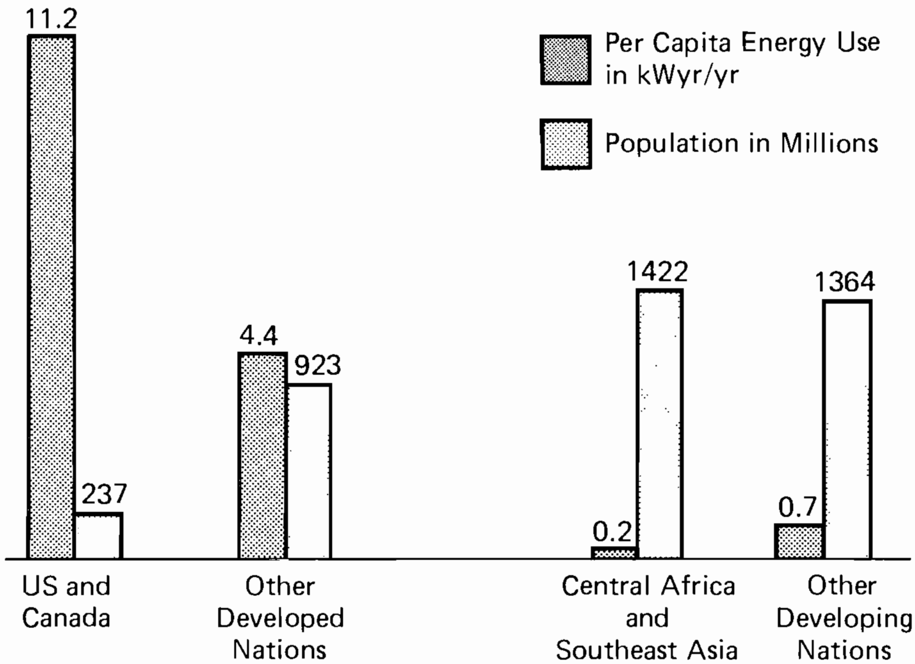
ENERGY UNITS

There are two fundamental types of energy units, those that describe *amounts* of energy, and those that describe *rates* at which energy is supplied, converted, transported, or used. In the first category, amounts, are units such as barrels of oil equivalent (boe), tons of coal equivalent (tce), or kilowatt-hours of electricity (kWh(e)). In the second category, rates, are million barrels of oil per day (mbd), tons of coal equivalent per year (tce/yr), and kilowatt-hours of electricity per year (kWh(e)/yr).

The unit most commonly used in this book for *amounts* of energy is the terawatt-year (TWyr). One terawatt-year (1 TWyr) is equal to 1,000,000,000,000 watt-years (which can also be written as 10^{12} Wyr). It is therefore also equal to 1,000,000,000 kilowatt-years (10^9 kWyr) or 1,000,000 megawatt-years (10^6 MWyr) or 1,000 gigawatt-years (10^3 GWyr).

The unit most commonly used here for *rates* of energy supply, conversion, transportation, and use is the terawatt-year per year (TWyr/yr). The unit, terawatt (TW), which is sometimes used in place of terawatt-year per year (TWyr/yr), is in this book reserved for the description of the *capacities* of various energy conversion facilities. Thus the capacity of an electricity generating station might be listed as 1,000 MW(e) (= 0.001 TW(e)). Since energy conversion facilities seldom operate at their installed capacity all year long, their ratings in TW or GW or MW will differ from the actual rate at which they convert energy, as expressed in TWyr/yr or GWyr/yr or MWyr/yr.

Figure 1-2. Distribution of world population and energy use in 1975.[a]



[a]Consumption figures exclude 0.21 TWyr/yr in bunkers.

The problem can be seen to be even more complex when viewed through the lens of per capita energy use worldwide. Figure 1-2 shows how the 8.2 TWyr/yr of primary energy supply in 1975 was divided over the globe. The United States and Canada, with 6 percent of the world's population, used energy at the rate of 11.2 kWyr/yr per capita—more than five times the worldwide average of 2 kWyr/yr per capita. In contrast, energy was used in Central Africa and Southeast Asia, which account for 36 percent of global population, at a rate of only 0.2 kWyr/yr per capita—one tenth of the worldwide average. About 60 percent of the world's population exists with less than half of the average 2 kWyr/yr per capita.

These statistics illustrate once again the variety of forms that the immediate energy problem can take. Conservation potentials differ throughout the world, energy requirements for development differ, and the global pattern of energy use is but one dimension of a broader set of disparities and tensions that exist between the developed and the developing countries.

These issues are just the surface of what we today call the energy problem. While the world's communities work to solve their immediate energy problems, they must simultaneously set in place strategies for the future. This means that the peoples and nations of the world will have to work together toward these two goals.

Specifically, in the short term, growing energy demands must be satisfied in ways that would allow differing rates of economic development and that promote the welfare of a rapidly growing global population. The world will have to respond to the potentially explosive aspects of this growth and attempt to maintain a degree of geopolitical stability. Both human and natural resources of the globe will be stretched in this enterprise.

At the same time, looking to the long term, the nations of the world must build sustainable, equitable, and resilient energy systems that satisfy the needs of the global population in the next century and beyond. By sustainable, we mean systems that do not simply consume or burn energy resources but also invest these resources in order to generate additional ones. By equitable, we mean that all peoples have their fair share of these common global resources. And by resilient, we mean systems that can respond vigorously and flexibly to a wide range of unanticipated global energy needs and difficulties.

Can these goals be met? The pragmatic question of any global energy study is to determine whether there are realistic strategies for satisfying such challenging goals.

For the most part, today's debates about energy policy in the world legislatures, parliaments, central committees, special energy groups, and in advanced scientific research groups focus on relatively short-term adjustments. This is natural, for much higher oil prices (and therefore higher energy prices) have created emergencies in the industrial economies that have subsequently reverberated throughout the world community. But there is good reason to believe that the most appropriate perspective in which to make choices about energy strategies emerges only if we look sufficiently far into the future and only if we add up the situations of all parts of the world.

Considering the tremendous scope of energy markets in a world steadily growing and progressing, it is essential to address possible adjustments at all levels—national, continental, and global. For example, the flow of oil from the Persian Gulf must be studied as a wide ranging system, feeding an expansive global market; likewise, the enormous coal basins of the United States, the Soviet Union, and China must be analyzed for their potential role in a global coal supply system.

The transition from the present fossil era to an era based on inexhaustible energy sources will not be straightforward. We cannot even be sure it is possible. At the very least, it will require that national energy policies, corporate energy policies, and personal energy behavior be conceived with as clear an understanding of their relationship to the global energy problem as possible. For better or worse, we cannot isolate ourselves.

The purpose of this book is to contribute to that understanding. We do not pretend to have definitive answers to the questions of when and how the fossil era will decline in the years to come. Nor can we recommend detailed energy strategies for all the nations of the world. But the analytic results presented here, and the insights that can be derived from them, illuminate features of the way in which our world operates that are far from selfevident, even in retrospect. To communicate these findings clearly is our objective here. Only then can they become useful to those who must deal with the energy problem daily—to all of us.

REFERENCES

Parikh, J.K. 1978. Energy Use for Subsistence and Prospects for Development. *Energy* 3:631-637.

United Nations. 1978. *World Energy Supplies 1972-1976.* New York.

2 THE IIASA APPROACH

Our purpose in the last chapter was not to belabor the obvious, but to recall and illustrate the familiar—that there is associated with the rubric "the energy problem" a wide variety of dimensions, perspectives, repercussions, and interests. These inspire a comparable diversity of approaches, each with its particular focus and concomitant strengths and weaknesses. Thus, it is important before launching into the details of our analysis that we state clearly the major characteristics of our approach; specifically,

- The boundaries defining our area of inquiry;
- The way in which we categorized and sequenced the material within those boundaries; and
- The analytic tools we used.

A WORLDWIDE, LONG-TERM PROBLEM

A Global Analysis

The international dimensions of the energy problem are clear—often painfully clear: Domestic politics of nuclear development in the developed countries can limit the hopes of those developing countries poor in technology; the internal politics of Iran and Iraq can have severe repercussions on economies worldwide; and the frustration and bitter words generated by long lines at gas stations can reappear on a grander scale when allies find themselves competing for the same barrel of oil. Thus, any informed energy policy—personal, corporate, or national—must rest on as clear an understanding of these intercontinental realities as possible. In the past this has not always been the case. For example, there have been many national analyses, most of which have implicitly or explicitly concluded that any excess of energy demand over energy supply would be met by imports. If every nation goes through a similar exercise (and practically every one does), there arises the question of whether one given barrel of imported oil has been, at least analytically, appropriated by several different parties.

For our study we therefore chose to extend our geographical boundaries to include the entire globe. This is not to say that we tried to predict international politics; that is a risky business at best and one that we leave to those more expert in the field than we. However, underlying the politics are realities of a more physical nature—resource limitations, technological limitations, and population growth. We were qualified to analyze these, and IIASA, as an East-West institute, was particularly qualified to provide a globally comprehensive analysis.

To analyze energy supply and demand for every country in the world individually would have been impossible, yet to ignore international differences in resources and consumption patterns is to neglect the causes of international competition and dependence. As a compromise between these conflicting considerations of theory and pragmatism we grouped the countries of the world into seven regions, chosen on the basis of national energy resources and economic structure and not necessarily on the basis of geographic proximity. Figure 2-1 shows this grouping, and Appendix A lists the countries in each region. Briefly the regions can be characterized as follows:

Region I (North America) has developed, market economies and is rich in resources.

Region II (the Soviet Union and Eastern Europe) has developed, centrally planned economies and is rich in resources.

Region III (Western Europe, Australia, Israel, Japan, New Zealand, and South Africa) has developed, market economies, but is relatively poorer in resources than the other developed economies.

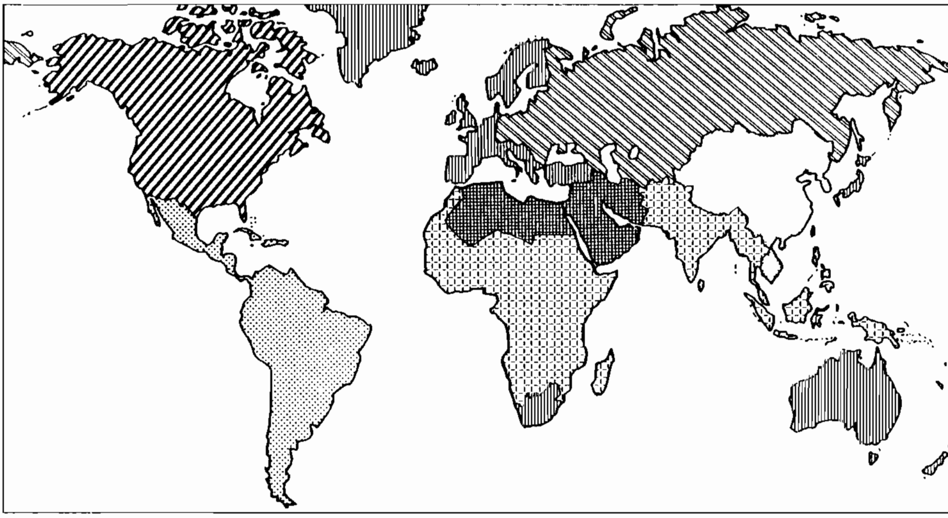
Region IV (Latin America) is a developing region with market economies and many resources.

Region V (South and Southeast Asia, as well as sub-Sahara Africa excluding South Africa) is also a developing region with mostly market economies, but with relatively few resources except in a few instances (e.g., Nigeria and Indonesia).

The countries of the Middle East and Northern Africa (region VI) are a special case with their economies in transition and their rich oil and gas resources.

Finally, region VII (China and other Asian countries with centrally planned economies) is a developing region with only modest resources.

Figure 2-1. The IIASA world regions.



Region I	(NA) North America
Region II	(SU/EE) Soviet Union and Eastern Europe
Region III	(WE/JANZ) Western Europe, Japan, Australia, New Zealand, S. Africa, and Israel
Region IV	(LA) Latin America
Region V	(Af/SEA) Africa (except Northern Africa and S. Africa), South and Southeast Asia
Region VI	(ME/NAf) Middle East and Northern Africa
Region VII	(C/CPA) China and Centrally Planned Asian Economies

1980-2030: Half a Century

If the 1970s have vividly reminded us that the energy problem is inherently worldwide, they have further taught us that its nature is long term. How we exploit or conserve the resources available to us today, how vigorously we develop new technologies, and how carefully we contain their potential for environmental damage all determine the range of opportunities left to future generations. Looking at it from the reverse perspective, if we wish to guarantee that in the future, and particularly in those parts of the world that are so poor today, there will exist the opportunity to meet certain aspirations, we are restricted in the range of actions allowed today.

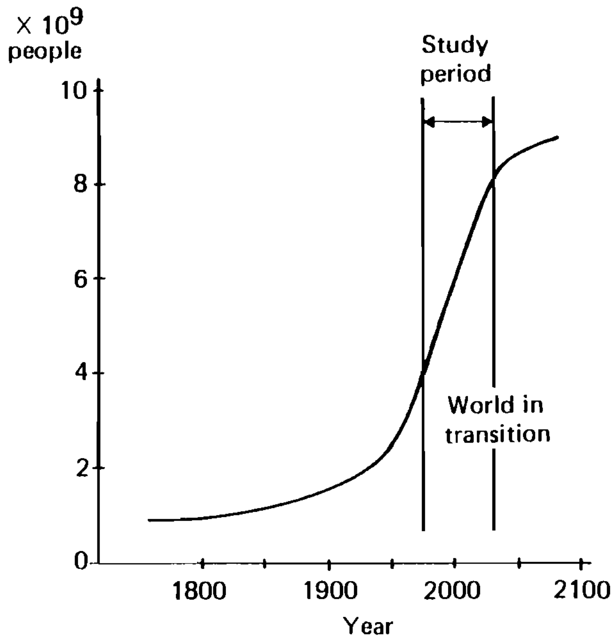
The period studied in the work reported here covers the next fifty years, from 1980 to 2030. That such an extended period could be considered was due to the unusual opportunity offered by an international institute like IIASA, which is insulated from many of the short-term pressures that prevent corporate strategists or national administrators from concentrating as much on the year 2020 as on the year 1985. But more importantly, we chose to look at the next fifty years because of what we expected to find there—specifically, the possibility of a transition from a global energy system based on consuming depletable fossil fuels to a sustainable system based on nondepletable fuels. Such a transition must occur sometime, and for the following four reasons—technological inertia, social inertia, market inertia, and population growth—we expected that the coming fifty years would provide an opportunity, though of course with no assurance that that opportunity would be exploited.

Technological Inertia. The study of certain technologies, from wood stoves to nuclear power plants, is a necessary part of a study of the energy problem. Understanding how various technologies might be used, improved, and substituted for one another is critical. While the methods described in Chapter 7 explore these relationships in detail, it is still possible at the very beginning of our study to make some general observations. Specifically, while some technologies, such as hydroelectric projects and residential buildings, have lifetimes longer than fifty years and while others, such as automobiles, have shorter lifetimes, many of the key technologies in the current energy system, such as oil refineries and electricity-generating plants, have lifetimes on the order of twenty-five to thirty years. Thus, a period of fifty years corresponds to two generations for such technologies and is therefore not so short to rule out the possibility of major technological transitions during the study period.

Social Inertia. Even more critical than the energy technologies are the people who use energy. While people are more adaptable than machinery, they nonetheless have their own forms of stubbornness. Because fifty years also encompass two human generations, the study period should allow time for major social transitions, whether manifested in individual lifestyles or in international relations.

Market Inertia. The development of a technology, whether a small-scale solar water heater or a new coal liquefaction process, and the successful penetration of that technology into the energy market, are two different processes. From a global perspective, the substitution of one energy technology for another cannot occur overnight: It takes time—judging from history, quite a bit of time. In the case of the fuelwood crisis in Europe over a century ago, it took about fifty years for the contribution of coal to rise from 20 to 50 percent of the primary energy market. In the United States it has been shown that fifty to sixty years are needed for a new energy source to increase its share of the primary energy market from 3 to 50 per-

Figure 2-2. World population. Projections to 2030 based on data from Keyfitz (1977).



cent.[a] These figures only reinforce the need to look as far as fifty years into the future, in order to allow not only for technological improvements, but also for technologies already developed to penetrate the market.

Population Growth. A fundamental driving force behind the energy problem is population growth, and as indicated in Figure 2-2, the period 1980 to 2030 coincides with what is anticipated to be the steepest increase ever in global population. By 2030 the population will have doubled from four billion in 1975 to some eight billion, and although it will continue to grow thereafter, the rate of growth is expected to diminish steadily. The energy problem with which the world is confronted during these next fifty years is therefore unique, and any analysis based on a period of less than fifty years would run a risk of underestimating the pressures that will be placed on energy supplies due solely to population increases.

For these reasons, then, fifty years were thought to be sufficient to represent accurately the severity of the energy problem facing the world, and at the same time to allow for the possibility of a transition to a sustainable global energy system. However, as will be discussed in Chapter 8, that transition turned out to be elusive. Within those fifty years and within the scope

[a]Data and calculations supporting these numbers are discussed more fully in Chapter 7. An even more complete treatment is provided in Marchetti and Nakicenovic (1979).

of our analysis, we found only the possibility for a less sweeping transition, one that would precede the transition we had expected. This preliminary transition is perhaps best characterized as one from clean conventional fossil fuels, such as natural gas and oil, to dirtier unconventional fossil fuels, such as heavy crudes, tar sands, and oil shales. But so straightforward a characterization can be deceptive, as will become clear in Chapter 8. Quite simply, time proved to be the major constraint, the most limited resource.

FINDING A PATH THROUGH THE ANALYTIC MAZE

The last section described the geographical and temporal boundaries of our study; it covers the whole world and extends over the fifty years from 1980 to 2030. The next question is, Within those boundaries, where to start?

It is a truism that everything affects everything else. More particular to our case are the observations that the evolution of energy demand depends on the supply options available, while the availability of different supply options is itself influenced by the level of energy demand. Moreover, both depend on environmental constraints, safety constraints, resource constraints, and the like. Where one chooses to start to impose order among all this need not be critical: What is more important is that once a starting point has been chosen, the analysis should proceed systematically and consistently. It is the purpose of this section to describe where we began, how we proceeded from there, and how we eventually brought together the lessons we learned along the way.

Supply

We began by looking at supply options and in our study borrowed the four categories most often used in discussions of supply—fossil fuels, nuclear power, centralized high technology solar power, and decentralized solar power and other renewables.

Fossil Fuels (Including Coal, Oil, and Gas). A consideration of fossil fuels usually starts with estimates of reserves and resources. Our study is no exception. Where it differs from most studies is in its concentration on unconventional resources, on deep offshore oil, on oil available only with tertiary recovery methods, on tar sands and oil shales—in short, on fossil resources that are much more expensive in terms of money, environmental impacts, and possible social effects than we are used to. Because we are looking fifty years into the future, our investigation of fossil fuels also considers both conversion technologies available today or in the forseeable future and technologies that are only in the early stages of conception or research.

Nuclear Power (Including Fission, Fusion, and Hybrid Schemes). Our consideration of nuclear power also begins with resource estimates and examines technological developments—existing, probable, and possible. However, there is an additional dimension not present in the case of the fossil fuels. This arises because of the variety of nuclear processes that can contribute to a power production system. These range from those of existing light water reactors (LWRs), through those of breeder reactors and converter reactors, to possible fusion schemes. How the different types of reactors might be arranged to complement and supplement each other turns out to be critical for assessing the world's nuclear resources.

Centralized, High Technology Solar Power. Estimating the amount of sunlight falling on the earth is much easier than estimating the amount of fossil and nuclear fuels beneath the ground. Even estimating the land that might be available for centralized solar power stations is an easier task. But to estimate what part of that sunlight might ultimately be converted into the forms of energy we need is extremely difficult, partly because of our relative lack of experience with the technologies in question and partly because of the intermittent nature of the solar resource. To complete the examination of solar energy, we devote much of Chapter 5 to describing how hydrogen, in particular, could be used as a secondary energy carrier that would complement electricity, in order to better match the supply characteristics of solar energy to demand patterns. And, by considering hydrogen as an inherent part of a solar energy system, we are able to suggest ways to exploit the solar potential that go beyond the usual schemes based on the traditional engineering hardware of mirrors, boilers, photovoltaic cells, wires, pipes, and valves.

Decentralized, But Not Necessarily Low Technology, Solar Power in Conjunction with Other Renewables. The definition of solar energy is often extended to include energy derived from biomass, hydropower, the wind, and ocean temperature gradients, currents, and waves. No matter how these sources are labeled, an examination of their potential is critical for assessing the earth's energy resources. In this book they are considered in Chapter 6 in conjunction with geothermal energy, tidal energy, and decentralized uses of direct solar insolation. Each of these sources represents a continuous flow of energy, in one form or another, through the environment. The questions that must therefore be examined include: What portion of these flows might we be technically capable of diverting for our immediate use, and what would be the effects on the environmental system from different levels of diversion. As with the other resource categories already discussed, the examination of these renewable sources leads from considerations of resource magnitudes, to conversion technologies, to the characteristics of an energy system consistent both with the special attributes of these sources and with the energy demand patterns that might evolve over the next fifty years.

In our initial look at each of the four resource categories, we aimed to explore the full technical potential of each under the most optimistic of assumptions. Problems of environmental impacts, safety questions, or mismatches between supply and demand patterns were presumed essentially solvable; promising technological developments were presumed to reach timely fruition and to be readily implemented. The only limits that we imposed in each case were those due to direct fuel resource limitations and those associated with the time required to build up or expand any given technology on the global scale.

The intent of stretching our thinking to the technological limits for each supply possibility was twofold. First, it revealed the technical characteristics of each supply option that would ultimately determine its attractiveness in competition with the others. Second, it focused attention on the side effects that would accompany aggressive development of any of the options on an unprecedented global scale. That we chose to look at only one option at a time is not to imply that we believe the globe's energy future must be exclusively solar or exclusively nuclear or exclusively anything else. As will become clear in Chapter 8, our synthesis of the considerations of supply and demand, and particularly of those factors constraining supply, revealed the feasibility of scenarios that rely on a mix of the various sources, at least for the next fifty years.

Constraints

The exploration of the different supply options also revealed the sorts of resource constraints, environmental constraints, and possibly institutional constraints that become vividly important when considering supplying energy for a global population expected to double in the next half century.

Chapter 7, which describes the study of these constraints, is divided into four sections. The first considers the limits on the rate at which one energy technology or source can replace another in the worldwide primary energy market. This subject was already mentioned as one of the considerations that originally led us to choose a time period of fifty years. Essentially, the lesson that emerged from the study of the theory and data of market penetration confirmed our intuition—that time is a scarce resource. But beyond this, Chapter 7 provides the numbers that allowed us to be more quantitatively precise when we eventually brought together supply, demand, and constraints as reported in Chapter 8.

The second section of Chapter 7 addresses the climatic effects that might accompany the large-scale deployment of any of the four categories of energy resources—fossil, nuclear, hard solar, and soft solar plus other renewables. Three classes of such effects are considered:

- Carbon dioxide released by the burning of fossil fuels can increase the amount of heat absorbed by the atmosphere. This is commonly referred to as the greenhouse effect, a phenomenon that could theoretically lead to a significant increase in global temperatures. Other gases, as well as particulates generated by fuel combustion, can also alter the atmosphere's tendency to reflect, transmit, or absorb different types of radiation.

- Essentially, all energy that is used is ultimately degraded to waste heat, which is dissipated in water and air and transported to the upper atmosphere, where it eventually leaves the earth as infrared radiation. The rate at which waste heat is released differs from technology to technology, but none escapes the problem entirely. The question, then, is whether the waste heat associated with providing energy for a growing global population might lead to climate changes that are globally, or even locally, severe.
- In addition to their atmospheric impacts, energy conversion technologies can also affect important characteristics of the earth's surface. These range from possible changes in the radiation properties of large land areas to changes that could more directly alter major wind and water currents within the global climate system. An example of the former might be the effects of large arrays of solar photovoltaic cells, while alterations in wind and water currents might arise from the extensive use of windmills or from the large-scale exploitation of temperature differentials in the oceans. Again, local effects might be of concern, even if global impacts proved negligible.

The third category of constraints discussed in Chapter 7 includes resource limitations other than direct fuel limitations and environmental factors other than those dealt with under climate considerations. Specifically, the discussion is divided into five parts addressing the following resources—water, indirect energy requirements, land, materials, and manpower. Our goal in examining constraints was not to define acceptable levels of environmental impacts or manpower utilization. Rather, the investigation was intended to reveal potential dangers and to clarify the relation between the different constraints and supply possibilities.

The fourth section of Chapter 7 deals primarily with health and safety risks, both public and occupational. Again, the object was not to determine "acceptable" levels of risk, but rather to identify what such a determination might involve. The discussion is divided into three parts—risk estimation, risk evaluation, and risk management:

- Risk estimation refers to the identification and quantification of risks associated with constructing and operating different energy technologies. The objective is initially to describe the magnitude of the risks, their frequency, and any other characteristics that are felt to be important. Only after this has been done can one address the more explosive questions of whether certain risks are acceptable given their associated benefits or which risks should be avoided more than others. Still, risk estimation is hardly a trivial task, and much controversy remains concerning the impacts of various energy technologies on health and safety.

- Risk evaluation is the term we use to describe analytic methods for comparing risks with one another and with different sorts of benefits. It is at this stage that one goes beyond numerical estimates and tries to incorporate individual and social values and perceptions. Evaluation is even more controversial than estimation, and it would be presumptuous to suggest that we have resolved that controversy in this book. What we have done is describe the methods that were developed by us and by others, and explore how they can be used and the sort of results they might produce. How these results might influence social policies belongs to the topic of risk management.
- Risk management refers to the organizational and political aspects of the environmental management of energy systems. It deals with the pragmatic problems that arise when competing groups, which most likely disagree on both the estimation and the evaluation of risks, actually try to negotiate and implement an energy strategy. Here, analytic techniques and insights are even less developed than in the cases of risk estimation and evaluation. We therefore limit the discussion to describing work done at IIASA in an effort to better understand the dynamics of negotiating environmental standards, since the setting of such standards appears to be a popular technique for managing both health and environmental risks.

The investigation of the different constraints, from those associated with market penetration to those of health and safety, parallels in spirit the earlier explorations of different supply options. The intent was to go as far as available analytic tools would take us—and a little farther. We did not limit ourselves to considering only technologies used today, but tried to imagine how these might be modified and expanded in the next fifty years to meet the energy demands of a rapidly growing world population. While in many cases the insights gained were only qualitative, others could be described numerically and could therefore be incorporated directly in the quantitative analysis of demand and supply about to be described.

Demand, Conservation, and Two Scenarios

We now turn our attention to that aspect of the energy problem that underlies the need to look at supply possibilities in the first place—energy demand.

To analyze future energy demand is to deal in assumptions—a lot of them. This necessitates, first, that the assumptions be reasonable (which is not necessarily the same thing as conservative); second, that they be consistent with one another; and third, that they be stated explicitly. We therefore had to make assumptions about the four major factors determining energy demands:

1. Population growth in the different regions of the world and at different times during the period analyzed;

2. Economic growth, again for different regions and at different times;
3. Technological progress in the processes and machines involved in energy conversion; and
4. Structural changes within national or regional economies.

These last two categories encompass the many aspects of energy conservation. The third includes both improvements in machines (e.g., a better insulated, more efficient refrigerator) and improvements in the way machines are used (e.g., locating refrigerators and furnaces so that the former is not wasting energy trying to cool down the latter while the latter is, in turn, trying to heat up the former). The fourth category, while not restricted to structural changes involving conservation, includes energy savings resulting from economic shifts away from energy-intensive manufacturing industries to more labor-intensive service industries. It also includes the reverse sort of shift—from, perhaps, labor-intensive farming in a developing country to activities consuming more energy.

The assumptions made range from those concerning near-term energy demand in economies where data are voluminous, if not always directly useful, to such things as the appropriate room temperatures in India in 2010, where available data prove less helpful. The object in each instance is, first, to make the best use of available data, analytic techniques, and collective human wisdom to produce reasonable numerical values and, second, to organize the resulting numbers systematically. Our basic method for meeting these objectives involved the writing of two quantitative scenarios. These two benchmark scenarios are labeled "High" and "Low," the former referring to a situation in which the demand for energy is relatively high, the latter to one in which demand is relatively low. These, as well as three variations arising from them—a worldwide nuclear moratorium case, an enhanced nuclear development case, and a very low energy demand case—will be discussed in detail in Chapter 8, but it is worthwhile to outline here their most important features.

In writing scenarios we were in no sense attempting to make predictions. Rather, we viewed scenario writing as a way to organize our thinking about available information; specifically, we insisted rigorously on two criteria—internal consistency and global comprehensiveness. We started by assuming, first, the pattern of global population increase for the next fifty years and, second, the pattern of global economic growth. The population assumptions were shown in Figure 2-2 and will be described in their disaggregated form in Chapter 8. For economic growth patterns, we considered two different sets of assumptions, and it is the difference between the two that defined the two distinct scenarios already alluded to.

Table 2-1 shows the regional growth rates associated with the two scenarios. The growth rates of Table 2-1 do not represent initial assumptions that remained unchanged throughout the subsequent analysis. Rather, we began with two sets of such growth rates, but continually reexamined and modified them as we proceeded through the calculation of energy demand associated with economic growth; the supply technologies needed to meet

Table 2-1. Historical and projected growth rates of GDP, by region, High and Low scenarios (%/yr).

A. High Scenario

Region	*Historical* 1950–1960	1960–1975	*Scenario Projection* 1975–1985	1985–2000	2000–2015	2015–2030
I (NA)	3.3	3.4	4.3	3.3	2.4	2.0
II (SU/EE)	10.4	6.5	5.0	4.0	3.5	3.5
III (WE/JANZ)	5.0	5.2	4.3	3.4	2.5	2.0
IV (LA)	5.0	6.1	6.2	4.9	3.7	3.3
V (Af/SEA)	3.9	5.5	5.8	4.8	3.8	3.4
VI (ME/NAf)	7.0	9.8	7.2	5.9	4.2	3.8
VII (C/CPA)	8.0	6.1	5.0	4.0	3.5	3.0
World	5.0	5.0	4.7	3.8	3.0	2.7

B. Low Scenario

Region	*Historical* 1950–1960	1960–1975	*Scenario Projection* 1975–1985	1985–2000	2000–2015	2015–2030
I (NA)	3.3	3.4	3.1	2.0	1.1	1.0
II (SU/EE)	10.4	6.5	4.5	3.5	2.5	2.0
III (WE/JANZ)	5.0	5.2	3.2	2.1	1.5	1.2
IV (LA)	5.0	6.1	4.7	3.6	3.0	3.0
V (Af/SEA)	3.9	5.5	4.8	3.6	2.8	2.4
VI (ME/NAf)	7.0	9.8	5.6	4.6	2.7	2.1
VII (C/CPA)	8.0	6.1	3.3	3.0	2.5	2.0
World	5.0	5.0	3.6	2.7	1.9	1.7

Note: Historical and projected values of GDP in constant (1975) U.S. dollars are given in Chant (1980).

that demand; and the pressure on the economy in general, and economic growth rates in particular, arising from the provision of such supply technologies. Thus, the numbers shown here are the result of an iterative procedure (discussed in Chapter 8) that insured internal consistency within each of the scenarios.

Several observations on the numbers in Table 2-1 are in order. First, they reflect something of a conservative bias on our part in that they decline consistently over time. Second, they incorporate a recognition that the developing countries will be limited in their economic growth potential to one or two percentage points above that of the developed countries.[b] More

[b]The fact that economic growth rates in the developing countries are in some way tied to growth rates in the developed countries is intuitively appealing. It would be unrealistic to assume high growth rates in the former while assuming low or zero growth rates in the OECD countries. For further discussion of the relationships see Hicks et al. (1976).

specifically, for the next several decades, the developing countries will still be tied to the economies of the rest of the world through trade and other relations.

After population growth and economic growth, the third and fourth determinants of energy demand listed earlier were technological progress and structural changes within economies. Since it is more difficult to specify in a single figure or table the basic features of the many distinct input assumptions falling within these two groups,[c] we summarize some of the scenario results that suggest the extensive degree to which shifts to less energy-intensive technologies, processes, and activities were incorporated in the scenarios. This is done in Figure 2-3 where the historical energy intensiveness of the different regional economies is shown in conjunction with the energy intensiveness indicated by the two scenarios for the years 1985, 2000, 2015, and 2030. As will be discussed in Chapter 8, energy intensiveness is expected to drop consistently throughout the study period in the developed regions, while it is expected to peak in the developing regions over the next fifty years.

The scenarios began with the quantification of demand assumptions, but were extended well beyond purely demand considerations. Rather, their principal function was to provide for the detailed quantitative synthesis and balancing of demand and supply. The mechanics of carrying out that synthesis and the numerical results obtained for the seven world regions form the material of Chapter 8. The scenario results incorporate the technical supply characteristics explored in Chapters 3 through 6, though the supply potentials considered available within the context of the scenarios were limited to what would be feasible within the next fifty years. To the extent that they could be reliably quantified, the constraints discussed in Chapter 7 were also incorporated in the scenario calculations. One type of constraint not included explicitly is that dealing with the environment. While some of the global environmental implications were considered directly in designing the two scenarios,[d] to have gone beyond that to suggest actual upper limits to be enforced would have been dangerously presumptuous. The purpose of the scenarios was to detail the engineering and economic consequences that might follow from two different sets of reasonable assumptions, and not to predict how political and social controversies will be resolved.

Interpreting Results

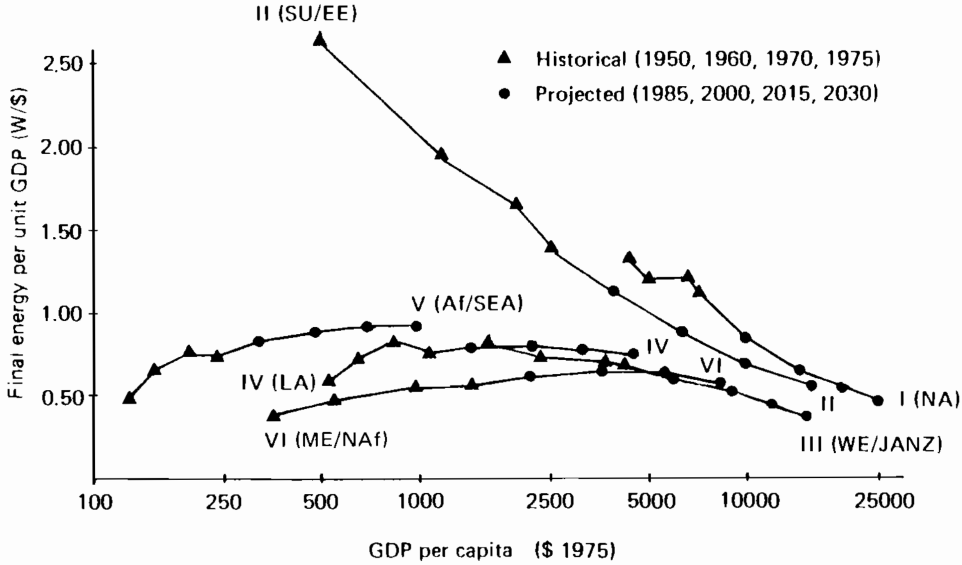
The quantitative results of the two scenarios, and the three variations arising from them, are voluminous. They represent the synthesis of a tremendous amount of data, analysis, and insight and present a globally complete pic-

[c]The demographic assumptions, the sectoral assumptions, and assumptions about energy intensiveness, technological adaptations, use patterns, and the like are detailed in Chapter 16 of Volume 2, where the numbers are summarized in Tables 16-1 through 16-24.

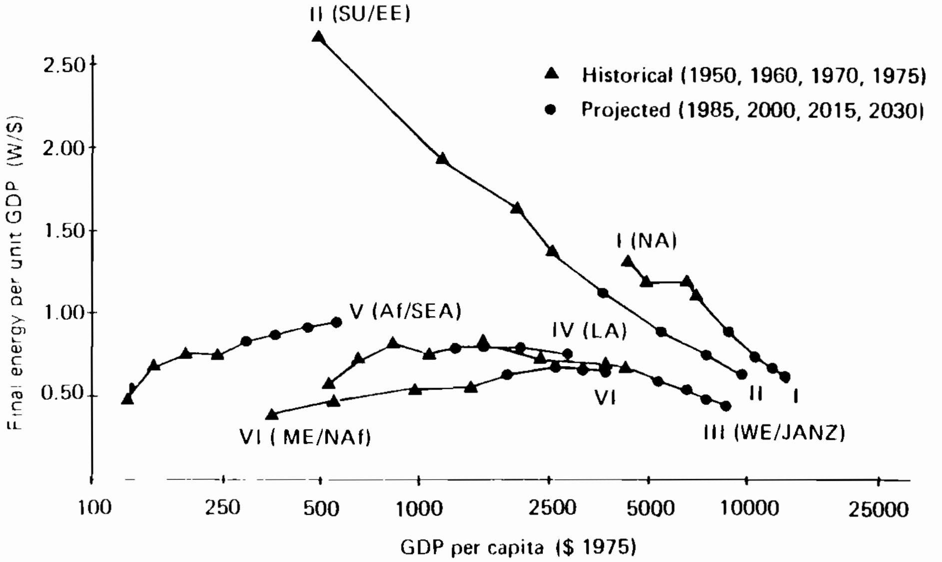
[d]In Chapter 8 the changes in atmospheric carbon dioxide that are associated with the two scenarios are discussed. Requirements for land and water are covered in Chapter 9 of Volume 2.

Figure 2-3. Energy intensiveness in six world regions.

A. High Scenario



B. Low Scenario



ture. Although they can in no sense define a unique set of conclusions, they are suggestive, and in Chapter 9 we elaborate and defend the important implications they suggest to us.

Here, we summarize the picture we see emerging from all the laborious analysis as one of a world endowed with the necessary physical resources to support a population of eight billion people in 2030. Moreover, this appears possible without exhausting our depletable energy resources and without shifting completely to sustainable energy sources. Still, such a shift must come eventually, and while the scenarios indicate that we can buy perhaps another fifty years using mainly fossil fuels (albeit unconventional ones), they also indicate that the buildup of a sustainable global energy system is a more time-consuming process than had been expected.

Paths to a Sustainable Future

While fifty years proved too short a time to allow the transition to a sustainable global energy system, the analysis of the two scenarios provided insights on some of the features of such a system. In the final chapter of this book we bring together the relevant bits and pieces that emerged and arrange them such that they are suggestive.

There are two components to the discussion in Chapter 10. The first concerns the technical possibilities, as they are discerned from this vantage point in history, for exploiting resources with essentially unlimited potential. More specifically, these are solar technologies, nuclear fusion, and nuclear fission technologies involving breeder reactors. The material covered here is that from the more exploratory and futuristic sections of Chapters 4 and 5 on the nuclear and solar supply options. The second aspect of the discussion in Chapter 10 concerns the relationship between the technical characteristics of all the supply options (Chapters 3 through 6) and the important features of energy demand as examined in the scenarios of Chapter 8. For example, existing solar and nuclear technologies provide energy in the form of either heat or electricity, but a persistent part of energy demand will continue to be for liquid fuels—for transportation and chemical feedstocks. How to modify the supply technologies so that they provide energy in forms better suited to demand patterns will therefore be a critical feature of any energy system based on solar or nuclear technologies.

Any attempt to discuss the world's energy future as far away as fifty years and beyond, as is done in Chapter 10, requires careful qualification. The "path" sketched in that chapter, along with the short cuts and alternate routes and destinations that it suggests, is not offered as "the solution to the energy problem." In retrospect from fifty years hence, what we outline here may serve as a vivid reminder of our limited, transitory, prejudiced perspective of the possibilities available to us. Nonetheless, it does describe what we have seen, while taking a long, hard look at the future. It is certainly not all that might await us over our temporal horizons, but it is a part of it.

THE ANALYTIC TOOLS: THEIR STRENGTHS AND WEAKNESSES

The focus of our study was principally on the natural science aspects of the energy problem, and our methods were primarily those of engineering and economics. But to have restricted our scope and our techniques in this way is not to assert that those aspects of the energy problem not properly addressed by this approach are unimportant or specious. Rather, it is to address that part of the problem where we feel particularly equipped to make a contribution. Quite simply, IIASA is an international institute that seeks to provide a service to its national member organizations, and in this case that service takes the form of clarifying a factual basis upon which certain political issues might be settled.

Still, to limit our focus is to incorporate certain implicit assumptions, and it is the purpose of this section to make those explicit.

- The future is assumed to be relatively free of surprises. We are neither confronted with catastrophic wars nor rescued by technological panaceas. The world's economic and physical regularities that are the subject of modern economics and engineering are assumed not to be unrecognizably transformed.
- The future is assumed to be blessed with a degree of international cooperation that can only be described as optimistic, though by no means impossible. What the results suggest is not what will be done or what should be done, but what could be done with the world's endowments of energy resources, manpower, capital resources, and know-how if we succeed in translating our increasing understanding of international dependencies into increasingly effective patterns of international cooperation. In particular, a functioning world trade in oil, gas, and coal, allowing for the flow of resources from the resource-rich to the resource-poor, is assumed.
- The constraints included explicitly in the analysis described in Chapter 8 were restricted to those that are technical (e.g., the efficiencies of electricity generating plants), physical (e.g., the heating value of different deposits of coal), or structural (e.g., limitations on the rate at which one energy source can be substituted for another in the global energy market). To some extent these include well-established concerns that could be described as basically political or social. But there is a much larger class of sociopolitical constraints that is left out of the analysis; these must be kept in mind by anyone drawing conclusions from the numerical results.
- The analysis of competitive economics is carried out throughout in terms of constant 1975 U.S. dollars. Thus the monetary aspects of the energy problem, particularly those associated with inflation, are essentially neglected.

Two more assumptions have to be added here, although they were touched upon earlier and are, in fact, more explicit than implicit.

- A unifying characteristic of the demand and supply assumptions incorporated in the scenarios is that they reflect a future in which strong energy conservation programs in the industrialized countries would be pursued in conjunction with aggressive exploration for additional energy resources.
- In both scenarios, economic growth rates are assumed to be moderate, declining over time, and consistently greater in the developing countries than in the developed countries.

The accompanying boxed material presents the various aspects of the energy problem (as we perceive them), catalogued under ten different headings. Of these ten, our analysis addressed only the first seven. The final three, though touched upon throughout the text, were not given the sort of detailed treatment we afforded the others.

This categorization is one we found useful, and we refer to it here in an effort to better communicate to the reader what we sought to accomplish at IIASA. The analysis described in this book cannot hope to cover every dimension of the global energy problem. But it does examine a large and important piece of that problem—and provides as thorough and as careful a treatment of it as we believe has been done to date.

The energy problem cannot be broken down into individual elements requiring solution; rather, it is the whole pattern of the energy system that constitutes the problem. It is from this basis that the following elements must be considered:

- Absolute size of energy demand.
- Rate of annual increase of energy demand.
- Allocation of global resources to countries—features of world energy trade.
- Buildup rates of technical supply facilities.
- Innovation rates.
- Absolute size of resources.
- Absolute size of environmental and ecological impacts.
- Management of environmental and ecological impacts.
- Societal and political acceptance of technical and economic changes.
- Relationship between energy problems and policies and more general social problems.

REFERENCES

Chant, V.G. 1980. *Two Global Scenarios: Evolution of Energy Use and the Economy to 2030.* Laxenburg, Austria: International Institute for Applied Systems Analysis (forthcoming research report).

Hicks, N.L. et al. 1976. A model of trade and growth for the developing world. *Eur. Econ. Rev.* 7:239.

Keyfitz, N. 1977. *Population of the World and Its Regions, 1975–2050.* WP-77-7. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Marchetti, C., and N. Nakicenovic. 1979. *The Dynamics of Energy Systems and the Logistic Substitution Model.* RR-79-13. Laxenburg, Austria: International Institute for Applied Systems Analysis.

3 FOSSIL RESOURCES: FROM CLEAN TO DIRTY BUT STILL INDISPENSABLE

For centuries people satisfied their energy needs principally by local fuelwood. But with the advent of the Industrial Revolution in the Western world in the early nineteenth century, local forest reserves in many countries were gradually depleted. And because there was no adequate transportation system to balance supply and demand, people encountered their first energy crisis.

Fortunately, coal was able to fill the supply gap. Although coal use dates back some 2000 years, it took the pending energy crisis to foster the development of a coal industry. The growth of cities and of the railway system, as well as the transition from an agricultural to an industrial society, combined to make coal the preferred primary energy fuel, a position it held from around 1840 to 1920. Because of its high energy density, coal offered consumers many benefits that were not possible with fuelwood. Coal yields more energy than an equal amount of fuelwood. Then too, coal could be more easily stored and transported, features that were essential to well-functioning industrial societies.

However, during the 1920s coal began a gradual decline on the primary energy market, and by 1975 it contributed only 28 percent to world energy supply.

Why, after such a convincing development in favor of coal, did it stagnate and eventually decline in the primary energy market? How was it possible for oil, and to some extent for gas, to encroach upon coal's position in the energy supply infrastructure—a supply system that evolved on the basis of coal? In Chapter 7, when we take up the subject of how energy sources can replace each other in the energy market, we will examine the market penetration process, which is illustrated in Figure 7-1 for primary energy.

Here we note briefly that coal's replacement by oil and natural gas was not simply a matter of price, nor was it stimulated by a shortage of coal resources. Coal as a commodity was displaced not so much by these two sources as by secondary energy carriers. During the eighty years of coal's reign, urban lifestyles were evolving, and consumers increasingly sought more convenient forms of secondary energy such as town gas, electricity, heating oil, and hot water. Grid systems were gradually built up in cities to supply both electricity for lighting purposes and gas for heating and cooking, and consumers learned to rely on centralized supplies of environmentally clean, quality energy. The utility industries turned to oil and gas as their mainstays, generally for the very reasons that once made coal the preferred fuel over fuelwood. Oil and natural gas have higher energy contents and are easier to transport and handle. High degrees of storability and transportability also mean a minimum of required infrastructure. Then too, both fuels are environmentally cleaner to burn than coal.

Oil was especially attractive, as it could be moved inexpensively around the globe. Furthermore, the development of the oil-based automotive and airplane industries and of modern agricultural technologies strengthened the demand for secondary liquid fuels—or, more precisely, for oil.

Yet despite coal's historical decline on energy markets, there is renewed interest in this black solid, spurred by several factors—most notably, the oil crisis of 1973-1974, coal's advantageous resource position in relation to dwindling supplies of other fossil fuels, and the political debates constraining the full-scale deployment of nuclear power.

CAN COAL MAKE A COMEBACK?

Our study of the global energy supply options revealed that the transition to a nonfossil energy system would not occur by 2030 and that fossil fuels would still be needed during the interim period. Moreover, there would be no abatement to the demand for secondary liquid fuels. Is coal a possible solution?

We are convinced that a return to coal as a major energy source is not only necessary but also inevitable, both for the coal-rich nations and for the rest of the world. But this time around coal use will have to be managed differently for several reasons. Coal should not be used as the major source of primary energy for meeting world demand for large amounts of energy over the next fifty years, since this would not only deplete its resource base within one hundred years but also create severe environmental and human health hazards. This is not to say that coal as a primary solid fuel should not continue to be used restrictively for certain traditional purposes—say, for steel production.

But, over the near term, perhaps the next ten or twenty years, coal must be used in such a way as to permit an orderly buildup of the coal industry and particularly of the coal supply industry to a level that will allow it to become a major source of secondary liquid fuels. Coal must become "new coal"—that is, it will have to be adapted to suit the specific features of secondary energy requirements which in today's terms means liquid fuels. Thus to be used strategically during the period of dwindling fossil resources, new coal must serve as the raw input for the production of synthetic liquid and gaseous fuels, so-called synfuels and syngas. Used in this way, coal would serve as a bridge to a future energy world built around nondepletable energy sources.

How Soon Can We Expect New Coal?

As we explain in Chapter 7, the market penetration of new coal will take time, even with public and private support. There are many technological, environmental, and economic problems to be resolved for the mining, processing, and transporting of very large amounts of coal. Then too, sociopolitical factors will work either for or against the revival of the coal industry.

Our study of new coal's prospects in the Federal Republic of Germany, for example, revealed that some ten years would be needed before it could contribute significantly to meeting secondary energy requirements. A similar study of coal's future in the United Kingdom showed a somewhat longer lead time—about ten to fifteen years—which can be attributed to this country's prodigious oil and gas resources from the North Sea.

While we see certain difficulties for new coal, they are not insurmountable. But before we consider these, we first examine whether one can confidently assume that there is enough coal to support the development of a new coal industry.

Is Coal Really A Giant Resource?

First, it is worthwhile to distinguish between reserves and resources, as explained briefly in the accompanying boxed material.

Coal reserves are large. The economically recoverable coal reserves worldwide are estimated to be 600 billion tons of coal equivalent (tce), or, equivalently, about 600 TWyr, which is almost seventy times the amount of all primary energy fuels used globally in 1975. Coal resources are even more impressive, estimated at some 10,000 billion tce or about 10,000 TWyr (World Energy Conference 1977). Although for technical reasons it will probably not be possible to use all these resources, we estimate that between 2400 and 3700 TWyr could eventually be reached (Astakhov 1980).

The data in Table 3-1 indicate the unequal distribution of coal resources around the globe, with China, the United States, and the Soviet Union own-

Reserves and resources are different. *Reserves* are those deposits that are known and measured and that can be produced at economic costs. Beyond that are *resources*—deposits that are known fairly well, shading out into those that are known only generally, and continuing into those that exist only as estimates of what we might find if we look harder. In the cost dimension, resources are marginally economic, shading out into those that can be produced only at higher and higher prices. Resources may be transferred into reserves through discovery and measurement, through improvements in production technologies that decrease production costs, and through economic changes that increase the price of the product and thus the cost that is considered acceptable in extracting the product.

ing some 88 percent of the total. Japan, for example, has only 0.1 percent, while only two developing countries—Botswana and India—have noticeable coal resources, with some 1 and 0.6 percent of world totals.

The fewer resources a country has, generally the harder it works at improving its reserve base. As Table 3-2 shows, region IV has only 0.3 percent of the world's coal resources; region V, 1.9 percent; and region VI, with its

Table 3-1. World distribution of coal resources (in 10^9 tce).

Greater than 10^{12} tce (1000 × 10^9 tce)		*Between 10^{11} and 10^{12} tce (100 and 1000 × 10^9 tce)*		*Between 10^{10} and 10^{11} tce (10 and 100 × 10^9 tce)*		*Between 10^9 and 10^{10} tce (1 and 10 × 10^9 tce)*	
USSR	4860	Australia	262	India	57.0	GDR[a]	9.4
United States	2570	FRG	247	South Africa	57.0	Japan	8.5
China	1438	UK	163	Czechoslovakia	17.5	Columbia	8.3
		Poland	126	Yugoslavia[a]	10.9	Rhodesia	7.1
		Canada	115	Brazil	10.0	Mexico	5.5
		Botswana	100			Swaziland	5.0
						Chile	4.6
						Indonesia[a]	3.7
						Hungary[a]	3.5
						Turkey	3.3
						Netherlands	2.9
						France	2.3
						Spain	2.3
						North Korea	2.0
						Romania	1.8
						Bangla Desh	1.6
						Venezuela	1.6
						Peru	1.0

[a]Mostly lignite.

Source: Based on data from World Energy Conference (1978a).

Table 3-2. Coal resources and reserves for the seven IIASA regions (in 10^9 tce).

Region	Coal Resources			Coal Reserves		
	Hard Coal	*Brown Coal*	*Total*	*Hard Coal*	*Brown Coal*	*Total*
I (NA)	1286	1400	2686	122	65	187
II (SU/EE)	4127	892	5019	107	41	148
III (WE/JANZ)	683	80	763	117	29	146
IV (LA)	25	9.3	34.3	4.9	5.9	10.8
V (Af/SEA)	179	4.9	184	43	1.9	44.9
VI (ME/NAf)	0.4		0.4	0.2		0.2
VII (C/CPA)	1427	13.4	1440	99	n.a.[b]	99
Total[a]	7727.4	2399.6	~10,127	493.10	142.8	635.9

[a]Regional figures do not sum to totals because of rounding.
[b]Data not available.
Source: Based on data from World Energy Conference (1978a).

rich oil and gas deposits, has no known coal resources. Coal reserve figures for these regions are slightly higher—1.7, 7.1, and 0.1 percent, respectively. Relatively energy-poor region III has 23.3 percent of global coal reserves but only 7.5 percent of resources, suggesting an already intensive search for coal. These figures could serve to explain why countries rich in coal reserves—for example, the Soviet Union—have not felt compelled to look intensively for new coal deposits.

Indeed, coal experts are almost unanimous in predicting large additions to the resource figures. Unlike oil, coal resources have not been of large interest, owing generally to the comfortable reserve picture that has allowed the industry to keep up with demand. Likewise, many see a large potential for finding coal deposits in the vast land areas of Africa and South East Asia (region V) because of the minimal exploration that has thus far gone on there. For a developing country with, say, an annual energy consumption of 1 tce per capita, even a small discovery of 50 to 500 tce per capita could be important. Further, the potential for new discoveries exists even in known coal districts, as the Selby example illustrates: A new coal field of some 600 million tons of clean, dirt-free coal was discovered in 1972 in the Yorkshire coal region of Selby in the United Kingdom, which had previously been explored unsuccessfully.

Still, the earth's favorable coal deposits have been largely exploited by today's technologies. Surface coal mines in the western part of the United States, for example, now operate at a 10 to 20 million ton per year level. Surface mines near Garsdorf in the Federal Republic of Germany are exploiting brown coal deposits at a record rate of 50 million tons annually, and a few miles from there, in Hambach, brown coal extraction at an annual rate of 100 million tons is planned by the 1990s. The Siberian mines in the Soviet Union are expected to reach an annual level of 50 to 100 million tons within a short time.

We look to technological progress to enhance the coal industry. New tools and techniques, such as seismic exploration adapted from the oil industry, are enhancing possibilities for successful coal exploration, especially in many developing countries where coal occurrences are known to exist and where manpower is abundant and inexpensive. Although pollution problems cannot be ignored, they are not judged to be as pressing in these countries as they are in the developed ones, and there is time to develop control techniques.

But surface mining—so-called strip mining—can only buy time. If the coal industry is to survive globally for a long time, it will have to go to incredible depths to reach the big veins. Technologically there are many possibilities, from robotization to chemical and bacterial leaching. Of these possibilities, only underground gasification has been used thus far, mainly in the Soviet Union, although it is currently being explored also in Belgium, France, the Federal Republic of Germany, Poland, and the United States. The success of this method would make it possible to reach levels of 1000 or 1200 meters, which are generally not included in reserve estimates, and would thus improve the process of transferring resources to reserves as well as adding new resources.

There is yet another problem facing the coal industry that technology could resolve. For coal, as with oil, as the best sources are explored, users must accept poorer grades and must work harder to extract and process them into quality energy. The coal industry in Bulgaria, for example, is now extracting brown coals with a low energy content of only 1400 kilocalories per kilogram (kcal per kg) and plans to go to even lower grades of 900 kcal per kg. The many technological and environmental problems associated with such endeavors can perhaps be understood best when we consider that good quality brown coals in the Federal Republic of Germany yield some 3000 kcal per kg and the hard coals in the western part of the United States yield some 7000 kcal per kg.

Converting Coal Into New Coal

Since the demand for secondary fuels, particularly for liquids, drives today's energy problem, we considered how coal could be used in the production of synthetic fuels. We focused on those coal conversion technologies that would be technologically mature over the near term and that would allow new coal to be used in conjunction with, or to substitute for, primary energies such as nuclear power, oil, and natural gas in meeting secondary demands. By emphasizing a strategic role for coal in synthetic fuel production, we do not wish to minimize the importance of other coal-based technologies, such as the fluidized bed process for producing industrial heat and electricity. Still, it is the need for liquid and gaseous fuels that is of utmost concern and therefore deserving of the most immediate attention.

Coal Gasification and Liquefaction. The problems of converting coal into a gas or a liquid are not technically insurmountable. Both gasification and liquefaction are known technologies, although their use up to now has been

In *autothermal* coal gasification and liquefaction schemes, both the process heat and the required hydrogen are produced by burning coal, in addition to the amount of coal needed for the chemical carbon content of the synfuels. A large amount of energy is lost in the conversion process, and the resulting gas or liquid contains about half of the energy content of the original coal.

For the *allothermal* process the process heat and the required hydrogen are supplied exogenously, preferably by means of heat from a nuclear reactor such as the high temperature reactor (HTR) or in more futuristic schemes by means of hydrogen gas from a solar plant. The synfuels thus produced have a higher energy content than the original coal. While in both processes the combustion of coal releases carbon dioxide into the atmosphere, the allothermal process requires less coal (by a factor of 3 to 4) and accordingly releases a smaller amount of carbon dioxide than the autothermal method.

Allothermal gasification processes are still in the development stage. However, the adoption of such methods will probably be influenced as much by strategies for deploying nuclear and solar energy as by considerations of the efficient use of coal.

on a smaller scale than what is being considered here for coal. Currently, autothermal processing is the preferred method, but there are many who argue for the rapid development and deployment of allothermal processing. The distinction between the autothermal and allothermal methods of coal gasification and liquefaction is explained briefly in the accompanying boxed material.

There are a number of known gasification processes, the most technically advanced being the Koppers-Totzek, the Winkler method, and the Lurgi method. Additionally, new processes are being developed for burning coal in steel converters that would not only reduce the amount of pollutants but also permit the use of low-grade coal for producing high-quality energy. In the Federal Republic of Germany, for example, some $350 million has been invested in research projects in this direction.

The raw gas generated can be converted to produce liquid fuels such as methanol. Although the energy content per volume of methanol is lower than that of gasoline, it can substitute for gasoline or be used in combination to supply the transport sector. In South Africa, for example, an advanced Fischer-Tropsch process is being used to liquefy some 10 million tons of coal annually.

A Global Coal Trade

In 1977, the World Energy Conference (1978a) estimated the existing international coal market as 7.7 percent of the total global coal production in 1975 and prognosticated a meager 8.6 percent for world trade in 2020. But interest in coal has been growing to such an extent that at the 1980 World Energy Conference it was suggested that total global coal production would probably increase 20 percent by the year 2000, assuming that steps to develop the industry are taken very soon. It seems certain that a global trading system for coal will evolve, but we refrained from dealing with this issue explicitly. There are several major studies on this subject, among them the World Coal Study (WOCOL) organized by Carroll Wilson of the Massachusetts Institute of Technology (WOCOL, 1980).

OIL: THE KING OF THE FOSSILS—BUT FOR HOW LONG?

Oil is the commercial fuel to which the world has become accustomed, around which major infrastructures have adjusted, and on which highly mobile lifestyles are based. In short, liquid fuels are indispensable in today's world—and for good reasons. Oil is high quality energy and surpasses all other fossil fuels in the ease with which it can be transported and stored.

It was only after the first oil shock of 1973 that people began to question the future role of oil in energy systems. Until then, it was easy to ignore predictions about oil supplies running out. New discoveries were being made often, supporting the view that oil would somehow always be an available commodity.

Disagreement among experts as to the amount of oil has clouded an already murky situation. Over the past thirty-five years there have been at least twenty-five estimates of what are termed variously as recoverable global resources, but comparatively speaking, there are only about a half a dozen independent estimates. Among the major assessments, made in 1977, was that of a group led by Pierre Desprairies (1977) of the Institut Francais du Pétrol, conducted under the sponsorship of the World Energy Conference. Our judgments of what is realistically possible for oil are indebted to Desprairies' work.

The thirty experts participating in the Desprairies study made estimates of ultimately recoverable conventional oil resources ranging from a low of 173 billion tons to a high of 950 billion tons, with the mean value being 257 billion tons. Estimates were also made of the cost (1976 U.S. dollars) of extracting the oil: of the 257 billion tons of oil, 36 percent would be recovered at a cost of less than \$5 per barrel, 26 percent at between \$5 and \$12 per barrel, and 38 percent at \$12 or more up to the limit of \$20. To put these numbers in perspective, more than 50 percent of the world's conventional oil was extracted in 1976 at a cost of less than \$2 per barrel. It is interesting to note that in 1977, when Desprairies' study was underway, from the estimated total of 257 billion tons of oil only 88 billion tons of oil had actually been discovered.

We estimate conventional oil resources to be some 300 billion tons (or equivalently 430 TWyr) and to include oil in deep offshore and polar regions, which Desprairies' group could not include because of the constraint that production costs (excluding taxes and profits) not exceed $20 per barrel (1976 U.S. dollars) by the year 2000. Then too, our time horizon is wider—that is, 2030, as opposed to 2020 in Desprairies' study.

A look at the regional distribution of conventional oil resources and of proven reserves as given in Table 3-3 shows that region VI possesses some 42.4 percent of global resources, followed by region II with 18.2 percent, and region I with 10.9 percent. The industrialized countries of region III, which rely heavily on oil supplies, have only 6.2 percent of total global resources.

How realistic is our estimate of 300 billion tons of conventional oil? Can we expect discoveries of a new "Middle East"—say, off the coast of China or in Antarctica? Although the possibility cannot be excluded, the chances are generally thought to be small. Still, recent discoveries in Mexico provide arguments for the optimists.

Then too, progress in exploration and drilling might serve to revise our estimate upward. The large differences in the drilling densities between the developing and developed regions do point to a possible "drilling gap." Curiously, the two regions that have been drilled the least are oil-rich region VI (but with surprising success) and the vast land area of developing region V, indicating the need for care in addressing world oil perspectives. Enhanced recovery might also result in much more oil than our 300 billion ton estimate. This is particularly the case for heavy oils for which improved heat-processing methods could increase the rate of recovery from 5 to 40 percent. Even a minor increase in the rate of recovery—say, from 40 to 41 percent for 300 billion tons—would add 7.5 billion tons (or 10 TWyr) to our estimate. For perspective, such additions would result in conventional oil resources that are only slightly more than the amount of primary energy (8.2 TWyr/yr) that the world consumed in 1975.

Table 3-3. Oil resources, reserves, and drilling densities for the seven IIASA regions.

Region	*Resources*[a] *(10^6 tons)*	*Reserves*[b] *(10^6 tons)*	*Prospective Areas*[c] *(× 1000 km^2)*	*Total Number of Wells*[c] *(end of 1975)*	*Drilling Density (total wells/ 1000 km^2)*[c]
I (NA)	28,000	4857	12,928	> 2,575,000	202.75
II (SU/EE)	46,730	10,670	9797	542,325	55.36
III (WE/JANZ)	16,020	4021	11,030	34,737	3.15
IV (LA)	23,000	5521	12,444	103,359	8.31
V (Af/SEA)	21,150	6176	17,729	28,281	1.60
VI (ME/NAf)	109,100	54,363	8212	12,501	1.52
VII (C/CPA)	12,730	2736	2831	8500	3.00
Total	257,230	88,344	~75,000	> 3,300,000	44.00

[a]Based on data from Desprairies (1977).
[b]Based on data from International Petroleum Encyclopedia (1978).
[c]Based on data from Grossling (1976).

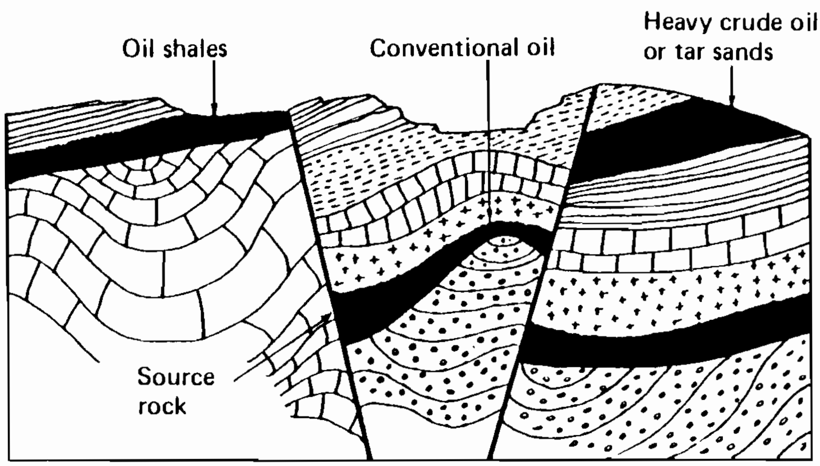
Still, there are experts who argue that 300 billion tons of conventional oil is too high an estimate, since it assumes a continuation of present discovery rates which they consider unrealistic in light of the discovery of most of the giant and super-giant fields. Also, many doubt the feasibility of worldwide increases in recovery rates up to 40 percent and believe that eventually the high extraction and production costs for conventional oil will make alternative energy sources more attractive. Then too, a deteriorating political climate in the oil-producing regions may ultimately force the international oil companies out of the oil business. No matter what opinion one may hold about the worth of these companies, they do have the know-how and the capital to support the search for less accessible, more expensive oil deposits.

Oil from Unconventional Sources

Meanwhile, as prices of conventional oil rise and supplies become threatened, the production of unconventional oil has begun in earnest. Unconventional oil—that is, heavy crude oil, tar sands, and oil shales—are found in the earth's layers where geological changes were either insufficient to produce petroleum or where later disturbances have led to changes in existing oil deposits.

Figure 3-1 illustrates the basis of recent theories of oil formation in the earth's crust that are guiding today's oil explorations. The burial of organic matter led eventually to the formation of kerogen—that is, to oil shale formation—which is significantly more abundant than coal. Had the kerogen remained near the surface, it would have constituted the oil shale deposits that are currently known. But generally organic layers were buried under

Figure 3-1. Continuity of oil resources.



additional layers of sediment—that is, they crossed the so-called petroleum window—and kerogen was transformed into oil (and eventually into gas if burial was even deeper). Often, the fluid oil migrated to anticlinal or stratigraphic traps, forming today's deposits. But if this oil were to be forced back up to the surface by geological means, the chemical processes would convert it into tar sands or heavy oil deposits.

Exploration of these unconventional oil resources is at an early stage, but the quantities appear vast—about 300 billion tons. In some respects, worldwide distribution of unconventional oil resembles that for coal, with a broad geographical distribution dominated by a few giants. Interestingly, the supergiant deposits of unconventional oil belong to the "oil ring" of the ancient continent of the Pangea, which, before it drifted apart some 180 million years ago, included known deposits in Alaska, Texas, Mexico, North Africa, the Middle East, and western Siberia.

The estimated 300 billion tons of heavy oil and tar sands are divided as follows: Orinoco in Venezuela, with 100 billion tons; Athabasca in Canada, with 86 billion tons; Olenek in the Soviet Union, with 86 billion tons; and Cold Lake in Canada, with 23 billion tons. Another 27 billion tons are spread out among eight large fields—two in Canada, five in the United States, and one in Madagascar.

The reserve base is also impressive, although only 5 to 10 percent of these unconventional oils can be extracted by surface mining techniques with their high recovery rates. The rest will call for in situ technologies that have lower rates of recovery, about 35 to 50 percent less than what is possible with either surface mining or retorting methods.

Thus, these figures are only rough estimates that will probably benefit greatly from technological progress in extraction and recovery. Recently progress has been made in the recovery of heavy oil and tar sands, particularly in Canada, Venezuela, and the United States. The Syncrude Plant, owned by Syncrude Canada Limited, began operation in 1978 with today's maximum level for both surface mining and surface processing of 6.25 million tons of oil per year, and government incentives in Canada are leading to other plants of this type. Likewise, several pilot processes for in situ recovery are being developed in Canada to extend this maximum recovery figure.

Estimates of oil shale resources are even larger—420 billion tons, of which 5 to 10 percent is considered recoverable by present methods. Two-thirds of these resources are located in North America. While the extraction of these deposits is uneconomic by today's terms—that is, it exceeds the $12 to $15 per barrel cost category—the Synfuel Program set up in the United States in the late 1970s for producing synthetic fuels is expected to lower costs.

It is very difficult to predict exactly when these unconventional fuels could enter the market at a noticeable level. But the findings of the Desprairies' group, as well as those of our quantitative analysis described in Chapter 8, point to a progressive phasing in of unconventional oils globally sometime around the 1990s.

Oil Trade

Clearly, region VI will continue to play a major role in the international oil trade. We will consider the implications of oil production ceilings on oil trade later in Chapter 9.

GAS: AN EMERGING GIANT

It was not long ago that those searching for oil were disappointed if drilling operations resulted only in discoveries of "useless" gas deposits. To be sure, interest in natural gas is a recent phenomenon.

The natural gas industry itself is relatively young. In the United States, for example, it began after the Second World War and only developed in Western Europe in the early 1970s, with the discovery of gas fields in Italy, France, and especially in the Netherlands. Development has been impressive, so much so that natural gas now holds the energy share in Western Europe that postwar energy forecasters projected for nuclear energy—some 15 percent. Yet less than 8 percent of the estimated global resources have been consumed, with a good part of this being burned away wastefully in the major gas-producing region of northern Africa and the Persian Gulf because there have been no means for transporting the gas to distant markets such as those in Western Europe.

Conventional gas resources are large, with some 280 trillion m^3 (or 330 TWyr) remaining to be produced worldwide as of 1976 (WEC 1978b). Comparatively speaking, this is the same resource level as for conventional oil resources; only the recovery rate of gas is higher—about 80 to 90 percent. And there is no slackening in the rate of finding giant deep gas deposits as a result of advanced exploration technologies. While worldwide gas consumption is expected to increase over the next decades, production could most likely grow even faster, reaching 3.7 to 4 trillion m^3 per year (or 4.3 to 4.7 TWyr/yr) between 2000 and 2030. From a resource standpoint, this level could be maintained for several decades.

As Table 3-4 shows, distribution of conventional gas resources, like that of the other fossils, is uneven. Region VI has some 34 percent, followed by region II with 25 percent, and by region I with 18 percent. Region III is again in a weak supply position, with only 6.7 percent.

We need to say a few words about unconventional gas resources in order to present an accurate picture of global gas resources. Unconventional gas includes gas in geopressure zones, gas in tight formations such as sandstone, Devonian shales, methane from coal fields, landfill gas, and gas hydrates. Because of the ample supply of conventional and cheap natural gas, there has not been much interest in knowing how much more is available or in making use of what we know about unconventional resources. Yet most experts agree that these unconventionals are probably very appreciable, each perhaps equivalent to or even one order of magnitude greater than conven-

Table 3-4. Estimates of ultimate gas resources remaining to be discovered and world gas reserves for the seven IIASA regions (in $10^9 m^3$).

Region	*Reserves (as of 1 January 1977)*[a]	*Resources Still to be Discovered*[b]
I (NA)	7763	43,500
II (SU/EE)	22,654	59,000
III (WE/JANZ)	5061	14,500
IV (LA)	2695	15,000
V (Af/SEA)	3560	12,000
VI (ME/NAf)	21,157	78,000
VII (C/CPA)	594	10,000
Total[c]	63,484	232,000

[a]Based on data from World Oil (1978).
[b]Based on data from World Energy Conference (1978b).
[c]The two values do not add up to the ultimate value of 280 trillion m^3 given above because of differences of dates and of origins of the data.

tional gas resources. But we need to know more about them before we can make reliable global estimates.

The United States is pioneering in data collection and the development of technologies for exploiting these unconventional gas resources. The data in Table 3-5 indicate a large unconventional gas resources base in the United States. Coal bed degasification techniques are being tried, and gas in Devonian shale and in tight formations is being produced on a small scale that is expected to reach higher levels once the technology of fracturing has been mastered. In 1979, for example, a pilot well was drilled in Texas to assess gas in geopressure zones and to see how much of the estimated volume could be recovered. It was concluded that obtaining even as little as 5 percent would bring recoverable unconventional gas reserves in the range of 4 to 70 trillion m^3—which is roughly the same order of magnitude as global conventional gas resources. And this is from only one form of unconventional gas. Thus, from a resource perspective, the future of gas as a global fuel looks very promising.

Table 3-5. Estimated additional gas resources, United States.

Source	*Estimated Volume in Place (10^9 m^3)*
Coal bed degasification	8630–23,100
Devonian shale	14,470–17,260
Tight formations	17,260
Geopressured gas	85,000–1,444,400

Source: Based on data from World Energy Conference (1978b).

Transporting Gas

Global gas trade has been minimal up to now, and unless the problems of transporting gas over long distances and of getting it from wellhead to consumers are solved, international trade will not expand. Gas is moved primarily by pipelines, but many countries and particularly Western European countries are facing limitations on regional gas trade through land pipelines. The technological possibilities for extending the transportability of gas include large diameter or high pressure pipelines, such as those planned for moving gas from Tunisia to Western Europe.

Many experts see liquefied natural gas (LNG) as a way out of the gas transportation problem. As is the case with coal, the liquefaction process itself is not in principle challenging. But for gas, the main problems are those of scale, of transporting gas economically, which means covering both the costs of the special cryotankers that handle liquid gas at very low temperatures and the capital investments for building up the necessary processing facilities. There are high energy losses at both stages of converting the gas—from gas to liquid and back into gas. What concerns many people and what is challenging research efforts is the safety of the LNG technology.

Another alternative for making natural gas a global fuel is to liquefy it on site, converting it into the liquid methanol that could then be transported more easily by pipeline. The Soviet Union has made arrangements to pipe its Siberian gas, as a liquid, to Western Europe.

CONCLUDING REMARKS

Fossil resources will continue to be indispensable to the world's energy system until we have a sustainable system built around nondepletable energy sources. Thus, from now until some fifty years hence there will be a slow but continuous change from the heavy reliance on relatively cheap and easy oil and natural gas to an extended period of using fossil fuels that cost more to extract and process and that have potentially larger and larger environmental impacts. We call these "dirty" fuels.

The resource base of fossil fuels in indeed large, but only if one includes these dirty, unconventional fuels. There is no imminent danger of running out of coal, oil, and natural gas. Ultimately, conventional oil fields could deliver perhaps 400 TWyr of energy; unconventional oil (heavy oil and tar sands), possibly another 400 TWyr; shale oil, 60 TWyr (on the assumption that environmental problems will be difficult and will restrict greater yields); natural gas, 350 TWyr; and coal, 2400 TWyr. About half of the conventional oil and natural gas resources are recoverable inexpensively. The rest comes from a variety of sources that are associated with higher production costs: poorer fields that require drilling more holes and capitalizing drilling and land costs against smaller product yields; production from continental shelves, deeper basins, and polar regions; and secondary and tertiary extraction. All these activities, moreover, imply larger environmental impacts.

Eventually, we envisage a time when people will choose not to use fossil fuels because of the availability of cheaper and easier alternatives. That the transition from the use of fossil fuels is inevitable is indisputable.

REFERENCES

Astakhov, A. 1980. *Some Estimates of Global Effective Coal Resources.* Research Report. Laxenburg, Austria: International Institute for Applied Systems Analysis (research report in preparation).

Desprairies, P. 1977. *Report on Oil Resources, 1985-2020. Executive Summary.* Tenth World Energy Conference. London: Conservation Commission.

Grossling, B.F. 1976. (London) *The Financial Times, Window on Oil: A Survey of World Petroleum Sources.* June 5, 1976.

International Petroleum Encylopedia. 1978. Tulsa, Oklahoma: Petroleum Publishing Company.

World Coal Study. 1980. *Coal-Bridge to the Future.* Cambridge, Massachusetts: Ballinger Publishing Company.

World Energy Conference.

1978a. *World Energy Resources 1985-2020. Coal Resources, An Appraisal of World Coal Resources and Their Future Availability.* Guildford, United Kingdom: I.P.C. Press.

1978b. *World Energy Resources 1985-2020. Oil and Gas Resources. Worldwide Petroleum Supply Limits. The Future of World Natural Gas Supply.* Guildford, United Kingdom, I.P.C. Press.

World Oil. 1978. Thirty-Third International Outlook Issue. 187(3).

4 NUCLEAR ENERGY: REALIZING THE POTENTIAL

Nuclear energy could supply very large amounts of energy for millennia on a sustainable basis. Even within the fifty year time horizon of our study, nuclear power could contribute decisively to meeting global energy needs. The question of whether or not this potential will be used is not so much a technical question as a social and political one. The forces that have restricted nuclear energy's growth to a level far below the rate once predicted by its supporters are those that have mobilized around questions in which subjective estimates and value judgments must play a large part—questions of the balance between individual and societal safety and other social and individual needs. We did not try to resolve these questions in our study, although we addressed them. These remain decisions that go beyond simple analysis and are influenced by national goals, values, and institutions. We confined our examination of nuclear energy to an exploration of what its potential would be if most of the crucial questions holding back its development were resolved. Through this exploration we hope to clarify the global stakes involved in the difficult and critical choices that face individual nations.

The promise of nuclear energy lies in the high energy intensity of nuclear fuels as a primary energy source: One gram of fissionable material yields about three million times more energy than 1 gram of carbon from coal, oil, or natural gas. In the temporal dimension, this means that when properly used, nuclear fuels remain available almost indefinitely. The world's current resource of uranium, if used in "breeder" rather than "burner" reactors, should last thousands of years. In the spatial dimension, this means that nuclear fuel can be easily stored and transported over distances as great as 10,000 kilometers (km). Uranium is a truly global fuel that can be inexpensively shipped to any place on earth.

But the great potential of nuclear primary energy has been restricted thus far by its almost exclusive use as a source of one form of secondary energy—electricity. This is generated by conventional turbine technology from steam produced by nuclear reactor heat. Uranium is simply a direct replacement for coal or oil. Today's nuclear reactors are designed to produce steam, are sized and sited to conform to the requirements of electrical power grids, are designed for maintenance at schedules convenient for electrical demand schedules, and are required to be chemically compatible with the steam to be produced. They are thereby tied closely in space and time to the demands of population concentrations—cities and urban agglomerations. And they are limited to the portion of final energy demand that is served by electricity—currently about 11 percent.

In 1975 nuclear energy provided only 1.5 percent of total commercial primary energy worldwide. But nuclear energy could also be used to produce space heat (as is planned in the Soviet Union), process heat, and, most importantly, the external energy input for allothermal gasification and liquefaction of coal and for the electrolytic or thermochemical production of hydrogen from water. The resultant coal-based synthetic fuels, or hydrogen, could in the longer term be used to satisfy needs that cannot be fulfilled by electricity. Indeed, we anticipate a future in which "electronic" (electricity) and "protonic" (hydrogen) energy carriers become the only necessary secondary energy forms. Nuclear energy would then, in principle, be able to satisfy all of the energy requirements of a global society on an inexhaustible basis. And because hydrogen (and synfuels) production is not tied to the immediate demands of population (since they are storable and transportable), the nuclear energy system could be relieved, at least in part, of its close tie in space and time to the needs of cities and urban agglomerations.

This far-ranging potential of nuclear energy cannot be fully realized during the fifty year time span of our study, although it does play a role in the longer term vision of a sustainable energy society sketched in Chapter 10. But what could be obtained in the next decades? And on the assumption, perhaps unrealistic, that political and social inhibitions would be relaxed in coming decades, what is the maximum technologically and economically reasonable development path for nuclear energy over these decades? The answer to this question would tell us not only what we might obtain, but also what we might forego if the inhibitions remain in effect.

Thus, in this chapter we shall ask: What facilities and institutional capacities would be needed to support a large-scale deployment of nuclear energy? At what rates would they have to be built up? What would the resource requirements be? We begin our inquiry by looking at the present status of the nuclear power industry.

THE PRESENT STATUS OF NUCLEAR POWER

Nuclear fission power is not in its infancy. The light water reactor (LWR), a class of reactors that includes both the pressurized water reactor (PWR) and the boiling water reactor (BWR), is the workhorse of nuclear fission power. Besides LWRs, there are other types of burners in use commercially such as the Canadian CANDU heavy water reactor (HWR), the British advanced gas-cooled reactor (AGR), and the Soviet Voronezh reactor (VR).

These reactors are designed to use one neutron out of the two or three available fission neutrons. This one neutron maintains the chain reaction. The fissile atoms[a] are "burned," thus providing energy. Fueling these reactors by natural uranium or by enriched uranium[b] means that essentially only fissile uranium (^{235}U) can be burned, leaving more than 99 percent of the natural uranium unused. Burner reactors are therefore inefficient users of natural uranium resources.

Apart from burner reactors, there is a second type of reactor—so-called breeders that are under advanced development, such as the liquid metal fast breeder reactor (LMFBR). Thus far, worldwide, there are four LMFBRs in operation and five additional ones planned, of which two are being constructed.

Breeder reactors are designed to use more than two of the available fission neutrons. One neutron maintains the chain reaction, the other converts the fertile atoms (^{238}U and thorium 232 (^{232}Th)) into fissile atoms (plutonium 239 (^{239}Pu) and ^{233}U, respectively). The converted fertile atom replaces the fissile atom whose fission provided the energy initially. In effect, the fissile atom is not burned, but is replaced by a new fissile atom; instead, the fertile atom is burned. The fissile atoms serve no longer as fuel, but as "catalysts" for converting fertile atoms into fuel—or, in other words, they "breed."

There is a third class of reactors designed to approach but not achieve the situation of breeding. These are advanced converters or near breeders. Examples are the heavy water reactor (HWR), the high temperature reactor (HTR), and specially designed advanced LWRs. These advanced converters "burn" fissile atoms, but their share of fertile atoms that are converted and ultimately burned is larger than that of burner reactors.

Table 4-1 reflects the status of fission reactors worldwide, showing that by the end of 1980, some 300 nuclear power stations were operating with a total installed capacity of some 180 GW(e). By 1993, when the reactors presently under construction or on order would also be in operation, total installed capacity is expected to be some 390 GW(e).

[a]Fissile atoms are those that can be used to fuel a reactor; the most important ones are uranium-235 (^{235}U), uranium-233 (^{233}U), and plutonium-239 (^{239}Pu). But only ^{235}U occurs in nature—natural uranium contains only 0.7 percent ^{235}U, and 99.3 percent fertile atoms ^{238}U.

[b]Enriched uranium means that a part of the 0.7 percent ^{235}U is separated from some of the natural uranium and added to natural uranium fuel in order to increase the ^{235}U concentration in the fuel to 2 to 3 percent.

Table 4-1. Nuclear power plants worldwide[a]

Year[b]	No. Installed Plants	Total Installed Capacity Per Year (GW(e))	Installed Capacity: Average Size MW(e)	Cumulative No.	Cumulative GW(e)	Annual Growth Rate (%)
			132.93	41	5.443	
1966	6	1.719	286.50	47	7.162	31.6
1967	5	1.217	243.40	52	8.379	17.0
1968	7	2.165	309.29	59	10.544	25.8
1969	11	3.384	307.64	70	13.928	32.1
1970	6	3.099	516.50	76	17.027	22.3
1971	10	5.755	575.50	86	22.782	33.8
1972	22	11.412	518.73	108	34.194	50.1
1973	15	8.541	569.40	123	42.735	25.0
1974	20	14.544	727.20	143	57.279	34.0
1975	19	14.464	761.26	162	71.743	25.3
1976	14	9.913	708.07	176	81.656	13.8
1977	19	15.160	797.89	195	96.816	18.6
1978	17	14.647	861.59	212	111.463	15.1
1979	44	35.580	808.64	256	147.043	31.9
1980	40	33.013	825.33	296	180.056	22.5
1981	39	34.938	895.85	335	214.994	19.4
1982	36	32.701	908.36	371	247.695	15.2
1983	32	31.974	999.19	403	279.669	12.9
1984	31	30.823	994.29	434	310.492	11.0
1985	23	24.902	1,082.70	457	335.394	8.0
1986	14	15.409	1,100.64	471	350.803	4.6
1987	9	9.536	1,059.56	480	360.339	2.7
1988	11	11.997	1,090.64	491	372.336	3.3
1989	6	7.190	1,198.33	497	379.526	1.9
1990	4	4.226	1,056.50	501	383.752	1.1
1991	4	4.880	1,220.00	505	388.632	1.3
1992	0	0	0	505	388.632	0
1993	2	2.530	1,265.00	507	391.162	0.7

[a]Plants either operable, under construction, or on order (30 MW(e) and over) as of 31 December 1978. Additional 12 power plants with a total of 10,487 MW(e) are not included here since the expected date of commercial operation is not known.

[b]Actual or expected date of operation.

Source: Based on data in *Nuclear News* (1979).

Besides fission, there is fusion. The fusion D-T (deuterium-tritium) reactor is also a breeder. Deuterium and tritium are made to fuse in a sophisticated plasma configuration or in a rapidly heated pellet. The neutrons released in fusion are used to make more of the tritium, which is needed as a fusion fuel. Since tritium does not occur in sufficient quantities in nature, it must be converted from lithium which, together with deuterium, acts as a fuel. Lithium is therefore comparable to depleted natural uranium (i.e., fertile ^{238}U) and tritium to fissile material.

Fusion reactors have not yet reached the stage of scientific feasibility, but this will undoubtedly be reached within a few years. Thereafter it will be technological feasibility that must be achieved, and that includes both the successful mastering of materials development and mature, reliable engineering. This will take time. Only after the final stage of commercial feasibility has been reached can fusion reactors be deployed at a scale that is significant with respect to global energy demand—that is, at a terawatt and not a gigawatt level. Therefore, we do not consider the contribution from fusion reactors to be significant before 2030.

In the broader context of nuclear energy strategies, both the fission and the fusion breeder have similar features. In both cases the resource potential is roughly 300,000 TWyr so that for all practical purposes each of the breeders permits an unlimited supply of energy and is essentially decoupled from the resource problem.

In the more distant future, the fusion reactor could be designed to allow fusion of deuterium with deuterium. Such a futuristic D-D reactor would enhance the fusion potential resource by a factor of 1000.

Finally, in addition to pure fission and pure fusion breeders there are the related possibilities of hybrid fusion-fission breeders and accelerator breeders, either of which would also achieve a net production of fissile material, and would be essentially resource decoupled. However, like fusion reactors, accelerator breeders are technically not yet feasible today.

Operating nuclear reactors need a nuclear fuel cycle to serve them. The *front end* of the fuel cycle includes all steps for producing the reactor fuel elements. This comprises the mining of uranium, its processing into yellowcake, its conversion into the gas uranium hexafluoride, in most cases the enrichment of fissile ^{235}U atoms and the conversion of this material into uranium dioxide, and finally fuel fabrication. After the fuel elements are irradiated, or burned in a reactor, they enter the *back end* of the fuel cycle. The back end of the fuel cycle comprises intermediate fuel element storage, chemical reprocessing for recovering the fuel materials (uranium and plutonium) from the spent fuel, intermediate waste deposit, waste solidification, and final waste disposal.

In sum, the front end steps of the fuel cycle, including enrichment and fuel fabrication, are in hand, and we assume that additional capacity could be built as needed. But for the back end of the nuclear fuel cycle, time is needed to develop the facilities required industrially, if reprocessing and waste disposal are not to become urgent problems. The challenges of developing the back end of the fuel cycle are not purely of an engineering nature. Technically, reprocessing is in a stage of development similar to that of enrichment, and the question is not whether reprocessing plants can be built but whether they will be built. Currently, the nuclear civilian industry worldwide has only one reprocessing facility at its disposal, the French plant at La Hague, with scheduled additions being limited to the further expansion of the La Hague plant and to the completion of a rebuilt facility at Windscale in the United Kingdom. A similar situation exists for waste disposal: There seem to be no insurmountable technical problems of solidifying wastes into chemically stable forms and of disposing of them permanently, but political opposition has delayed the execution of specific projects in many countries. The back end of the fuel cycle is therefore in hand only in the technical sense, but is well behind the schedule necessary for nuclear power to play an increasing role in the decades ahead.

URANIUM RESOURCES

The magnitude of high grade natural uranium resources in the United States and throughout the world is subject to ongoing debate. This quantity is important, because, as we shall see, knowledge of how much uranium is available is useful for estimating both the worldwide potential of nuclear fission energy in the absence of breeder reactors and, as a corollary, the rate at which breeder reactors can be introduced in order to create a practically unlimited supply of energy.

The availability of economically recoverable uranium resources, plus known and speculative resources (rather than the total potential availability of natural uranium) is relevant for planning nuclear industry projects over the near term. The findings of the joint study by the OECD-NEA/IAEA (1978) give a figure of orientation for the world (excluding Eastern Europe, the Soviet Union, and China) of 4.3 million tons of natural uranium, at prices below $130 per kilogram. The International Nuclear Fuel Cycle Evaluation (INFCE 1979) published a revised estimate of 4.8 million tons at less than $130 per kg. It is these figures that are generally being referred to by those stating that the world has enough natural uranium to fuel the nuclear power plants both in operation or under construction.

But for exploring the real potential of nuclear fission energy, we regard these figures as only a beginning rather than a conclusion. Our interest is in the total uranium resources that would be available globally over the long term. Unfortunately, after almost half a century of careful exploration, we still do not know the ultimate amount or price of natural uranium available globally. Still, assumptions must be made, and we therefore estimated global uranium resources at 24.5 million tons. We will explain briefly how we arrived at this estimate, acknowledging that we relied on current knowledge of the nature of uranium deposits, which is at best only qualitative.

The United States, with the largest uranium reserves, has one of the smaller finding rates—that is, the amount of discovered reserves compared to the amount of drilling for uranium (OECD-NEA/IAEA 1977). A.M. Perry (1979), among others, draws the reasonable conclusion that this does not mean that the United States is unusually poorly endowed, but that it has been relatively well explored. In the absence of any better assumption, and because both the land area of the United States and the diversity of geological provinces are large, we have regarded the country as a representative sample of the world.

The uranium resource base of the United States has been estimated at some 1.7 million tons (OECD-NEA/IAEA 1977). The country's land area is 9.4 million km^2, which translates to some 0.18 tons of available uranium per km^2. Extrapolating this, we arrived at a a global figure of 24.5 million

Table 4-2. Adjusted uranium resource estimates

IIASA World Regions	*Area (10^6 km^2)*	*OECD-NEA/IAEA Estimate (10^6 tons)[a]*	*IIASA Estimate (10^6 tons)*
I (North America)	21.5	2.53	3.87
II (Soviet Union and E. Europe)	23.5	–	4.23
III (W. Europe, Japan, Australia, N. Zealand, S. Africa, Israel)	15.5	1.26	2.79
IV (Latin America)	20.6	0.08	3.71
V (Africa except N. Africa and S. Africa, South and Southeast Asia)	33.6	0.33	6.05
VI (Middle East and N. Africa)	9.8	0.08	1.76
VII (China and Centrally Planned Asian Economies)	11.5	–	2.07
World	136	4.29 (14.2–26.4)[b]	24.48

[a] Excluding regions II and VII.
[b] Including the speculative resources given in *OECD-NEA/IAEA* (1977).

tons. Table 4-2 compares these uranium estimates for the seven IIASA world regions and the values given in the OECD-NEA/IAEA report.

Again, the actual amount of ultimately recoverable uranium resources is debatable. Some may argue that it is impossible to get 24.5 million tons or that even more than this amount is possible. Against this background, we now explore the potential of nuclear fission, using the extrapolated 24.5 million tons of uranium resources as a reference number. Given this figure and in view of the uncertainties associated with its derivation, the following discussion will be based on a range of 15 to 30 million tons of uranium resources.

EXPLORING THE POTENTIAL

The answers to the questions of whether we will run out of uranium resources and of how long the available natural uranium can be made to last depend both on how fast nuclear fission is introduced in the future and on the extent to which it is called upon to supply global energy. In Chapter 8, where we describe our two global supply and demand scenarios for the year 2030, we address the specific issue of how much nuclear power can contribute realistically over the next fifty years in light of real world constraints. Here, our intention is to explore upper limits and to consider the full potential of nuclear energy, assuming that political and social constraints are resolvable.

Nuclear power is different, not only from fossil power, but even from the solar option. Fossil fuels are sooner or later depletable; solar and nuclear are not. Unlike solar, the current status of the nuclear industry offers an infrastructure that would allow for the deployment of nuclear energy on a massive scale during the next fifty years. The present status of nuclear power is therefore our starting point for considering feasible rates for introducing nuclear power.

On this basis then we explicitly defined an accelerated program of nuclear energy supply that by the year 2030 would allow nuclear energy to contribute 17 TWyr/yr of thermal power.[c] This is a hypothetical trajectory of the nuclear potential and not a prediction that would allow us to draw unassailable conclusions from this exercise.

To achieve this trajectory, the installed generating capacity of nuclear energy would have to be about 1.6 TW(e) by 2000, leading to 10 TW(e) by 2030. We arrived at this figure by considering many factors too complex to detail here. Simply stated, our figure is based on our historical market penetration analysis (see Chapter 7) and on our judgments about maximum capabilities of the nuclear industry worldwide over the near term.

The nuclear industry worldwide, if called upon to do so, could supply an additional 150 GW(e) of installed capacity annually by the end of the period 1995-2000. This would amount to a 50 percent expansion of supply capabilities over the next 15 years. The annual additions implied in our trajectory exceed neither the postulated installed capacity of 150 GW(e) per year by 2000 nor the market penetration rates for oil and natural gas observed in the past, although the rate of additions is still below that historically observed for nuclear energy. The annual additions to installed electrical capacity envisaged for the period 2000-2030 average less than twice those postulated for the year 2000. From the information on our 17 TWyr/yr nuclear trajectory given in Table 4-3, we can observe that the high levels of installed capacity could be achieved only if there is a prompt upsurge now in orders for new nuclear plants, that would bring installed electrical capacity to some 500 to 600 GW(e) by 1990. Let us recall that the added capacity of the reactors currently under construction and on order would lead to a total installed capacity of some 390 GW(e) by 1993.

In Table 4-3 we compare our trajectory with a "low" estimate of the International Atomic Energy Agency and with figures from the World Energy Conference (1978). Our figures are consistent with other sources that are optimistic about nuclear energy. Nevertheless, our trajectory is a pure construct, whose purpose is simply to provide a framework for considering reactor strategies and uranium requirements under conditions of high demand for nuclear power.

From this basis, we observed that if the world continues to rely on current designs of LWRs with their once-through fuel cycle,[d] by the year 2030 even our expanded estimate of uranium resources (of 24.5 million tons) would be

[c]17 TWyr/yr correspond to 10 TW(e) installed electrical capacity assuming, first, that by 2030 most reactors would show advanced thermal performance with some 40 percent efficiency of heat to electricity conversion and, second, that the capacity factor for the whole nuclear system is about two thirds.

[d]A once-through fuel cycle is one in which the fuel is only partially burned and then totally discarded.

Table 4-3. Trajectories for potential nuclear power installations worldwide (in GW(e))

	Year					
	1980	*1990*	*2000*	*2010*	*2020*	*2030*
IIASA high-nuclear reference trajectory[a]	160	580	1630	3640	7030	10,000
Annual addition[b]	24	64	154	305	359	252
Annual growth rate (%)[c]	15	11	9	8	4	1
Nuclear capacity, INFCE hign	188	698	1654			
Nuclear capacity, INFCE low	167	531	1082			
Nuclear capacity, IAEA high	207	909	2227			
Nuclear capacity, IAEA low	162	558	1403			
Nuclear capacity, WEC	152[d]	521[d]	1543		5033	

[a]Equivalent electrical capacity, not necessarily for distribution on electrical grids.
[b]Includes replacement after 30 years of service.
[c]Net growth rate, after deduction of replacements.
[d]Interpolated by IIASA.
Sources: Data for the *IAEA* figures are from *Lane et al.* (1977); *WEC* (1978); and *INFCE* (1979).

used up. A simple calculation serves to illustrate this point: Currently about 130 tons of natural uranium are needed annually to fuel 1 GW(e) of installed LWR capacity, implying that for 10 TW(e) of installed capacity in 2030 about 1.3 million tons of uranium would be required in that one year alone. Clearly, action must be taken before 2030—and preferably earlier—if our nuclear trajectory is to be more than an episode of resource consumption and depletion.

Basically, there are three ways of continuing the nuclear option according to our trajectory: (1) to exploit more dilute sources of uranium than are currently used, (2) to rely on more efficient advanced reactors and fuel cycles, or (3) to adopt a strategy for providing practically unlimited amounts of energy by means of breeder reactors. We looked into all three of these alternatives and report on our findings in turn.

Mining Yellow Coal

Our figure of orientation—24.5 million tons of natural uranium—is an extrapolation of the amount of relatively *high grade* uranium that might ultimately be found—that is, ores with a uranium concentration of 2000 parts per million (ppm) (0.2 percent) down to perhaps 500 ppm. There has been very little discovery of intermediate concentrations (between 300 to 500 ppm) of uranium, but it is known that the quantity of uranium with average concentrations of about 70 ppm, and especially of shales containing uranium concentrations of between 30 to 300 ppm, is vast. Unfortunately, the problems of recovery are at least as forbidding as the quantity is attractive. The foreward cost would surge from some $130 per kg of uranium to at least several hundred dollars per kg of recovered uranium. The switch from 2000 ppm uranium to 70 ppm uranium would have more than just price implications. The requisite mining operation would be very large, as the following example best illustrates.

Earlier we observed that 1 gram of fissionable material (in this case ^{235}U) yields three million times more energy than 1 gram of carbon. But mining dilute uranium resources of about 70 ppm concentration would imply that 1 gram of mined material would yield about the same amount of energy as 1 gram of carbon. One gram of 70 ppm uranium ore contains 7×10^{-5} grams of natural uranium. Recall, too, that natural uranium contains 0.7 percent fissionable atoms (^{235}U) and 99.3 percent fertile atoms (^{238}U). But not all of the 0.7 percent can actually be used in a reactor because of losses in the enrichment plant tails[e] and because of incomplete burning in the reactors—some 0.5 percent (5×10^{-3}) is actually used. Multiplying all of these factors—$3 \times 10^6 \cdot 7 \times 10^{-5} \cdot 5 \times 10^{-3} \cong 1$—we observe that the use of 70 ppm grade ores in LWRs with once-through cycles would mean a return to a scale of operation equivalent to mining coal or, as we refer to it, to mining "yellow coal."

We also examined the environmental implications of relying on LWRs of current design, and refer here to the concept of WELMM (Water, Energy, Land, Materials, and Manpower) requirements discussed later in Chapter 7. Table 4-4 illustrates some results for an installed generating capacity of 1 GW(e) over a 30-year lifespan for two types of LWR operations—one using 2000 ppm ores and the other 70 ppm ores. The results of a third type of operation considered—coal mining—are also given for comparison.

Obviously, in terms of land use, manpower, and materials handling and the related societal and environmental implications, the 70 ppm LWR operation approaches that of coal. Putting aside the problem of carbon dioxide emissions resulting from coal use (see Chapter 7), we find that the 70 ppm LWR operation is, in fact, more difficult. That is, almost all of the material extracted from the ground becomes solid waste, whereas in the case of coal, roughly one-half of the extracted material is overburden.

The data of Table 4-4 were applied to our reference case of 10 TW(e) of installed nuclear capacity. We present some of the results of this exercise in order to indicate the very large scale of operation that would be involved. If this capacity were supported by uranium extracted from shales—that is, from "yellow coal"—an area of 330,000 km^2—comparatively speaking, the land size of Italy—would have to be mined over a period of 30 years. This would call for the use of some 1100 of the largest bucket-wheel excavators that are currently used in open pit mining—a large operation, but not physically impossible.

We also analyzed two possibilities for extracting uranium with even lower concentrations than those of shales—for example, granite rock with a uranium

[e]When ^{235}U is separated from natural uranium, not all 0.7 percent ^{235}U of it can be recovered. The amount left in the depleted natural uranium is what is known as enrichment plant tail losses.

Table 4-4. Requirements for the operation of a 1 GW(e) power plant[a]

	Land 30-Year Total (km^2)	*Mining Personnel (person yr/yr)*[b]	*Material Handling Involved 30-Year Total (10^6 tons)*
LWR (2000-ppm ore)	3	50	45[c]
Coal	10–20	500	321[d]
LWR (70-ppm ore)	33	300	360[d]

[a] Corresponds to an electricity chain producing 6.1 TWh/yr with a 30-year lifespan.
[b] person year = 2000 hours.
[c] Overburden factor: 15 m^3 per ton (averaged).
[d] Overburden factor: 3 m^3 per ton (averaged).

content of about 3 ppm and uranium from the sea with about 0.0015 grams of uranium per cubic meter. Although these resources from the sea are enormous–estimated at about 5 billion tons (Weast 1974)–extracting the 1.3 million tons of natural uranium needed annually to fuel our reference trajectory would call for the processing of some 870,000 km^3 of sea water annually. This is more than twenty times the annual water flow to the sea of all of the world's rivers–an enormous operation that is only conceptually possible.

Thus, in extracting more dilute uranium resources–or, in our terms, mining "yellow coal"–we are faced with the old problems of large-scale mining and the new problems of solid waste, including both residues from rock milling and radioactive wastes.

More Efficient Reactors and Fuel Cycles

The use of advanced converter reactors, together with the recycling of spent fuel after reprocessing, could stretch out the lifetime of natural uranium resources. In sum, given the reprocessing of spent fuel and only the recycling of uranium, the demand for "virgin" uranium could be reduced by about 20 percent. Additionally, the recycling of plutonium from spent fuel (that is, ^{239}Pu, a conversion product of fertile ^{238}U) could reduce this demand another 15 percent. (Such recycling could be achieved with LWRs of current design.) Additional savings would be possible by using fuel cycle designs that include thorium (^{232}Th) and its fissile conversion product, ^{233}U. Then too, more fissile ^{235}U could be extracted from natural uranium by lowering enrichment plant tail losses, although this would require an increase in enrichment capabilities and therefore costs. Nevertheless, by going to enrichment schemes that produce uranium tails more depleted than 0.15 percent ^{235}U, more of the original 0.7 percent ^{235}U content of natural uranium could be separated and made available for use in reactors, which would result in additional savings of up to 15 percent. All in all, it is conceptually possible to run a LWR system, with reprocessing, using ^{239}Pu and ^{233}U and more ^{235}U separative work, which would require about half as much natural uranium as does the existing LWR system.

Here we recall a salient point: The continued use of LWRs of once-through fuel cycle design would use up the world's high grade natural uranium resources during the build up phase of our reference trajectory–or more precisely, some 2.5 million tons of natural uranium would be required by the year 2000, and a total of 24.5 million tons by the year 2030. But, by adopting more efficient reactors and fuel cycles as just described no later than the year 2000, only some 15 million tons of virgin natural uranium would be used by 2030. This is still not far below what might be ultimately available, but perhaps buys us some time.

How much time? We recall two numbers. First, if we consider our expanded estimate of natural uranium, we see that with advanced converters about 9.5 million tons would still be available by 2030. Second, 10 TW(e) of installed capacity by 2030 under the conditions of our reference case would require about 1.3 million tons of natural uranium annually, while with advanced converters the annual requirements would be reduced to 0.65 million tons. In brief, by using advanced converters we would be able to stretch out the life of high grade uranium resources by less than 15 years before we would be forced into mining yellow coal. One can play with the numbers, but the fact remains that burning only fissile atoms makes nuclear power a short affair when viewed in the global context considered here.

The Asymptotic Solution: The Breeder

We have just described how we could stretch the lifetime of the world's high grade natural uranium resources. But *some time* in the twenty-first century, if not by 2030, supply will run out, and there would be basically only two choices–mining yellow coal or breeder reactors.

The use of LWRs with their once-through fuel cycle require about 0.5 percent of the mined natural uranium. The use of LWRs, along with recycling of fissionable material after reprocessing and in conjunction with lower ^{235}U tails, effectively requires about 1 percent, and the use of advanced converters requires at best 5 percent of the uranium mined. But breeders, by relying on a stockpile of fissile atoms as catalysts for burning fertile atoms, could use most of the energy of natural uranium and, with proper design, also thorium. In other words, even if the 24.5 million tons of natural uranium were used by 2030 in LWRs of current design to build up our reference case, some 24.3 million tons of depleted natural uranium (mostly ^{238}U) would still be left over, in addition to the thorium, and could be made available for burning in breeders. This "reserve" translates into 60,000 TWyr of energy and would eliminate any need for further uranium mining.

Thus, the deployment of breeder reactors is essential if nuclear power is to achieve its real potential. When viewed from a sufficiently long-term perspective, this enormous resource saving would justify investment costs for breeder reactors, with their associated fuel cycle, that are higher than those costs associated with cheaper burner reactors. Taking the argument one step further, because breeders utilize natural uranium much better than burners, the very low grade uranium ores of only a few parts per million would become economic if used in breeders, increasing the resource potential of breeders to some 300,000 TWyr, which is equivalent to the potential of fusion reactors.

The transition to the system of using breeder reactors will have to take place gradually over a long period. Indeed, time for building up the system is a major constraint. We therefore examined two possible strategies for moving from present reactor systems consisting of burners and a few breeders to reactor configurations of 10 TW(e) of installed capacity that, because of a sufficient number of breeder reactors, would create no further demands on natural uranium resources. Because of this characteristic we have labeled these "asymptotic strategies"; specifically these are the classical reactor strategy, and the converter-breeder strategy. We will examine the features of each briefly, in turn. Basically both strategies rely on the following principle: Fissile plutonium converted from fertile ^{238}U in burner reactors is not recycled but is used to install the breeders, leading gradually to the buildup of breeders.

It is standard practice to consider a combination of LWRs and breeders that would lead eventually to the elimination of LWRs. Accordingly we call this possibility the classical reactor strategy. In this strategy, about 13.6 million tons of natural uranium would be used by 2030, and by 2040 cumulative demand of some 15 million tons would be reached for the buildup of our reference case, with no additional requirements. Thereafter, the system would be practically self-sufficient, using only the accumulated stockpiles of depleted natural uranium left over from the buildup phase of the system. In this way it would be independent of external sources of fissile materials and, because of a net production of fissile materials, would also be self-multiplying at a rate of a few percent per year.

The disadvantage of the classical reactor strategy is as follows. It would require that prior to the year 2000 breeders be installed quickly to properly complement the less efficient burners. For this to occur there would have to already have been, worldwide, fast breeder programs comparable to that of the French. This has not been the case.

To compensate for this an alternative strategy is needed, which we labeled the converter-breeder strategy. The essence of this strategy is to enhance the efficiency of the burners, effectively making them advanced converters, by fueling them with ^{233}U in place of ^{235}U. The beauty of this scheme is that the fast breeder reactors (FBRs) being introduced can produce the necessary ^{233}U.

For the converter-breeder strategy we assumed improved breeding ratios on the order of 1.3 (through proper design measures that would, for example, increase the share of fuel within the core volume) and good conversion in advanced converters (that would improve current values of 0.55 to 0.9 by 2030). It would then be possible to achieve 10 TW(e) of installed capacity by 2030 by means of 40 percent FBRs and 60 percent advanced converters.

In the converter-breeder system, the converter reactors are fueled initially by enriched natural uranium. The spent fuel is reprocessed, fissile uranium is recycled, and plutonium is used to install FBRs.

Gradually, the capacity of FBRs becomes large enough to convert the thorium to ^{233}U in the radial blankets in sufficient amounts, which is then used in the converters in place of enriched uranium thereby making them advanced converters. The requirements for enriched uranium would therefore be reduced and ultimately eliminated. In sum, cumulative natural uranium requirements would total only about 15 million tons before the state of self-sufficiency is reached. Shortly after 2030, the system would be a net producer of fissile materials in excess of the ^{233}U needed to fuel all of the advanced converters, which would therefore still permit a certain self-multiplication.

THE NUCLEAR FUEL CYCLE AND ITS RELATED FACILITIES

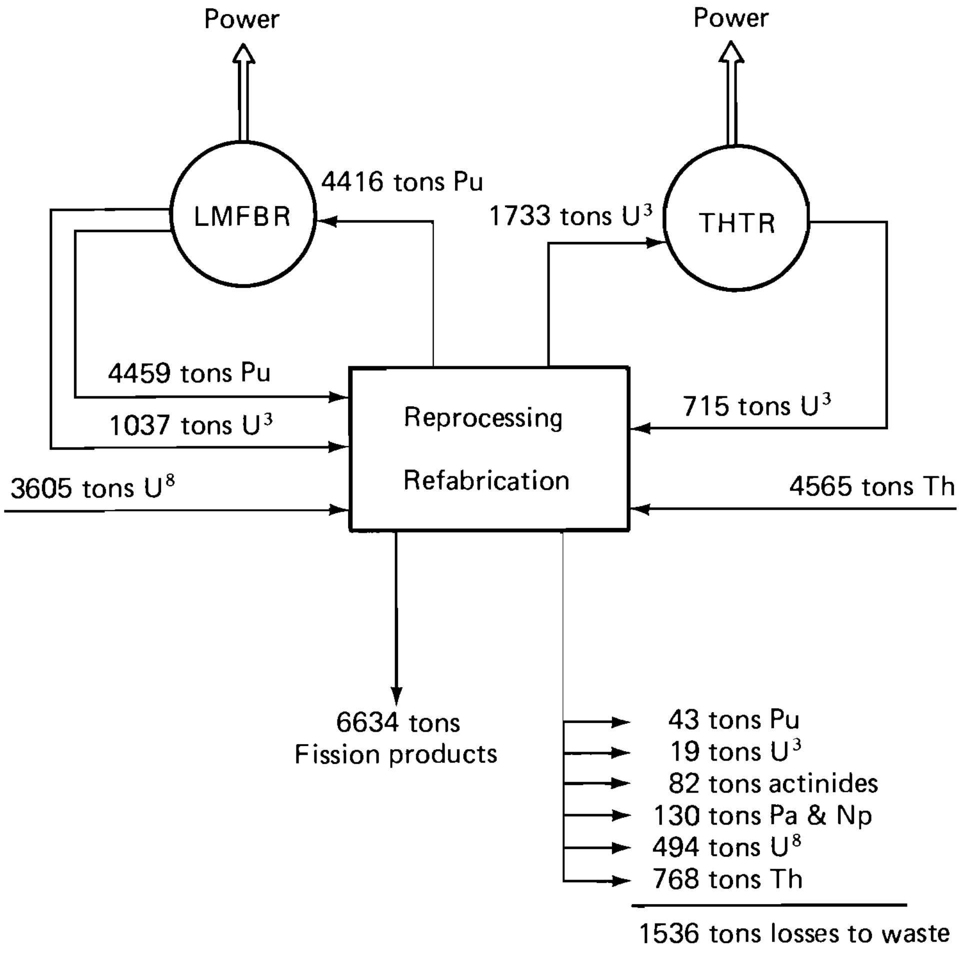
Among the systems questions that have to be considered for 10 TW(e) of installed capacity by 2030 is that of the nuclear fuel cycle—specifically, what is the number of related facilities and how much material is processed by these facilities. To evaluate these features we considered a converter-breeder strategy at the stage of self-sufficiency as just described.

Figure 4-1 illustrates the flow of fissile materials, inputs of fertile uranium (^{238}U) and thorium (^{232}Th), losses, and wastes for a system with an installed capacity of 10 TW(e) in which the converter is assumed to be the thorium-fueled high temperature reactor (HTR) and the breeder is the liquid metal fast breeder reactor (LMFBR).

Altogether, less than 8500 tons per year of both fertile uranium and thorium provide for the generation of 17 TWyr/yr of primary energy. Assuming that about 15 million tons of natural uranium were used to achieve the asymptotic self-sufficiency of this system, the reserves accumulated by 2030 of depleted fertile uranium could fuel the system for some 4500 years. Further, only about 4600 tons of thorium would be needed per year. Again, this is a negligible amount and requires only a minor mining effort. To put this number in perspective, providing 17 TWyr/yr from coal would require an annual input of 18.3 billion tons (four million times more material input).

The annual production of fission products is about 660 tons; in solidified form this is a cube of 20 × 20 × 20 m. The share of discarded heavy elements in waste is about 1500 tons per year. From this amount, some 144 tons per year (or 1.7 percent of total waste) are ^{233}U, ^{239}Pu, and higher actinides, all of which are of potentially long-term concern. In the case of coal, the analogue would be some 60 billion tons of carbon dioxide emis-

Figure 4-1. Annual throughputs and losses (in tons) for a 17 TWyr/yr, FBR-HTR operation. Only closed balances for Pu, U^3, and total (U^8 and thorium) are shown. The 6 ton mass defect associated with 17 TWyr/yr is not accounted for.



sions per year (equivalent to adding each year about 3.5 percent of the current carbon dioxide content of the atmosphere), plus about 1.6 billion tons of ashes and, if only high quality coal is burned, about 0.4 billion tons of sulfur emissions per year. The annual flow of fissile uranium and plutonium in this reactor configuration is about 6200 tons.

The number of nuclear facilities in the fuel cycle capable of handling these fissile products is given in the accompanying boxed material. In view of extremely low maximum permissible concentrations (MPCs), tight confinements are necessary for processing these materials.

Total Number of Nuclear Facilities

A fuel cycle operation of 17 TWyr/yr from an installed generating capacity of 10 TW(e) would require the following nuclear facilities:

- 10,000 nuclear reactors, each of an equivalent of 1 GW(e), or 3000 reactors of 3.3 GW(e) rating each. The present number of electrical power stations, nuclear or nonnuclear, worldwide is of the order of 15,000.
- 94 fuel fabrication plants capable of handling 1500 tons per year.
- 94 chemical reprocessing plants capable of handling 1500 tons per year.
- 650 intermediate (5-year) waste-storage facilities (tanks) of 1000 m^3. Seven such facilities would go with each reprocessing facility.
- 47 final waste storage facilities, one for every two reprocessing plants, for example. The inventory of radioactivity practically saturates after 20 years of input. Each final waste storage facility therefore contains, under equilibrium conditions, the equivalent of 20 years multiplied by 6634 tons per year for the total of the 47 facilities—that is, 2823 tons per facility of stored fresh fission products equivalent.

CONFINEMENT REQUIREMENTS AND SAFETY

Nuclear power by its very nature is connected with radioactivity, and the confinement of radioactivity is a necessary corollary to nuclear energy providing virtually unlimited amounts of electricity and heat. The consideration of confinement measures necessarily begins with the inventory of radioisotopes in reactors and other nuclear facilities. Under normal operating conditions, this inventory can physically leave a facility only at a certain rate. The ratio between the annual flow of a radioactive isotope in question through a given facility and the related annual release of that radioisotope is called the confinement factor (CF). In most cases, the CF is a large number. But the pathways of radioisotopes in the environment once they are released must also be considered. Usually these pathways involve diluting released radioisotopes in water or air before the points of biological impact are reached.

However, the opposite could also be the case. The famous example is the iodine-grass-cowmilk-baby chain, where the concentration of iodine is increased such that the resultant danger could be enhanced by a factor of 700. Finally, the radiobiological concentration levels are important. They relate the ambient concentration to the doses and dose rates that actually cause biological effects. Those dose levels that have acceptably trivial impacts are called maximum permissible concentrations (MPCs). From them, one can infer how large the appropriate CFs have to be.

It is useful to compare the dose rate (B) with the existing natural background dose rate B_0; (for orientation $B_0 \cong 110$ mrem per year). We used this approach to evaluate the design requirements for CFs associated with the large-scale development of the nuclear fuel cycle—in particular, for those relevant to our reference trajectory leading to 10 TW(e) of installed capacity by 2030. Table 4-5 reports the results for the most critical isotope releases, giving the CF required for each isotope and facility to make each contribution to the relative dose rate (B/B_0) below 1 percent. For example, the CFs of reprocessing plants for krypton (^{85}Kr) should be increased to 100, implying an improvement by a factor of 3 to 10 over the next decades. This is within technical reach, but requires further development. Similarly, the CFs associated with the release of most of the other critical isotopes from reprocessing plants into water or air need further improvement. Such improvements appear to be within reach over our planning horizon of 50 years, and we assumed that they would be achieved. In some cases, special sites for nuclear facilities could even lead to some relaxation of confinement requirements.

Radioactive iodine (^{129}I) is a special case since its half-life is some 17 million years. Although releases are small, they are large enough to have an impact. The average iodine content of biomass and water is about 0.3 ppm, so that a CF for radioactive ^{129}I of 100 would lead, after a few decades, to a saturation dose rate (B/B_0) level of 1 percent in the neighborhood of the facilities in question, and this is the maximum limit considered in our study. But even in the neighborhood of the facilities, it should not be a problem, though it requires further study.

Our discussion of confinement measures can only indicate the order of magnitude of the problem involved, though fortunately there is a vast literature on more specific evaluations. We conclude that 17 TWyr/yr of nuclear power appears possible with respect to the necessary confinement measures. These measures are not straightforward, but that is the price that must be paid and that must be compared with alternatives.

Table 4-5. Required confinement factors for making each relative dose rate contribution well below 1%

	Reactors	*Reprocessing*	*Fabrication*
^{85}Kr	Present designs, slightly improved	100	
^{3}H into air	Present designs	100	
^{3}H into water	Present designs	100	
Pu into air		10^9	10^{10}
Pu into water		10^9	10^{10}
Actinides		10^9	10^{10}
^{129}I		$\sim 10^3$	

In evaluating design targets for confinement measures in the previous section, we considered not only normal conditions but also accidental releases. Whereas for normal operating conditions the CFs were limited by the target values for the relative increase in the dose rate (B/B_0), in the case of accidental releases the probability of the release per unit time is the parameter for which target values should be established. Our evaluation on this basis showed both that reactors are not the most critical facilities for the occurrence of accidental releases and that the intermediate and final storage facilities had the smallest target values.

Because any such method deals with expectation values, a large number of small accidents is mathematically equivalent to a small number of large accidents. It is not clear whether such an equivalence accurately reflects how people really view possible nuclear accidents. But these are subjects that are more properly left to Chapter 7, where the various constraints limiting the options are dealt with.

THE USES OF NUCLEAR POWER

Up to now, nuclear power has been employed principally as a source of large-scale, centralized electricity. Yet once breeding is established, the practically infinite resource of nuclear energy will be realized, offering the possibility of more widespread uses. Some, such as propulsion of naval vessels, in particular submarines, and as power sources for remote bases in Greenland and Antarctica, are already in use. Others have been suggested—in space or the deep oceans, for factory ships and floating cities, for district and chemical heat. We reconsider briefly three important specific characteristics of nuclear energy that suggest such smaller applications in the future:

- Nuclear fuel is extremely compact and can therefore be easily stored and transported.
- "Burning" nuclear fuel (the chain reaction) requires no air and consumes nothing that must be supplied by the environment.
- Fission energy is of such high quality that the potential exists for generating very high temperature heat.

Nuclear electricity is generally associated with very large units of 1 GW(e) capacity or more. The trend to even larger units is continuing and will probably evolve to the point of eventually aggregating power plants and other associated facilities into "energy parks." But at the same time it may turn out that one important aspect of nuclear power will be the location of smaller plants at appropriate nodes in order to improve the reliability of electrical grids. At the cost of economies of scale of large plants, smaller ones could be more readily "over-engineered." Decreased transmission costs and high grid reliability could perhaps make the final difference.

As soon as we consider smaller nuclear plants, many new applications become possible. Most of the low to medium grade heat in the output range of 20 megawatts or less is now supplied by oil and natural gas. Small nuclear plants could substitute in this market effectively, especially in conjunction with cogeneration of electricity. The cogeneration schemes are also very attractive for district heating systems. For such purposes, small LWRs seem to be appropriate. Finally, even by-products of nuclear power, such as isotopic heat sources, could be used for these low temperature applications.

Again, nuclear power is suited for propulsion of naval vessels. It takes very little imagination to consider unconventional nuclear vessels such as submarine cargo ships capable of mastering the Northwest Passage under the Arctic. Concentrated reactor fuel could be used for hauling a string of barges, perhaps DRACONE type plastic cargo carriers. This group of applications, ranging from mundane cargo hauling to even planetary exploration, would require special purpose reactors with particular design requirements.

Still, given all the listed opportunities, the large-scale generation of electricity and heat for chemical processes will probably still be the principal use of nuclear power. In our reference trajectory to an asymptotically self-sufficient nuclear system, the installed capacity that could be assigned to electricity generation is enough to supply all the electricity needs of the high energy demand scenario described in Chapter 8. Since electricity would also be generated by other means by 2030 (e.g., solar, hydropower, renewables) a considerable surplus of both electricity and high temperature heat exists in this hypothetical self-sufficient nuclear system, which offers yet another potential opportunity for nuclear power application.

As our scenarios indicate (see Chapter 8), the major energy sources produce electricity and heat, while the looming shortages in the world are associated with liquid fuels. The persistent need for liquid fuels is basically caused by the difficulties of transporting electricity over long distances (losses and costs) and the high costs of electricity storage. For these reasons, today the average electrical kilowatt-hour travels no more than 100 km before it is consumed.

Later, in Chapter 10 we take up the possibility of a hydrogen-electricity world that could meet the energy requirements of the globe, say, within 100 years. Here, we observe briefly that hydrogen would be an ideal partner to electricity in the future; it is a gaseous fuel that can be transported, stored, and used in the synthesis of liquid fuels. Both electricity and hydrogen are clean energy carriers. Essentially hydrogen leaves water as a combustion product, with some nitric oxides in the ppm range. Nevertheless, the use of hydrogen would necessitate a significant adaptation of the existing energy distribution and end use infrastructure. This problem of hydrogen use could be overcome through the synthesis of liquid energy carriers, particularly methanol. Roughly 50 percent of methanol's energy content is due to the carbon atom (that could come from coal or perhaps from atmospheric CO_2) while the remaining percentage is due to two of its four hydrogen atoms. Nuclear energy could provide both the required process heat and the hydrogen. The most straightforward route to hydrogen is electrolysis, while alternative routes make use of high temperature heat.

CONCLUDING REMARKS

The real potential of nuclear energy would be realized not only through the production of several terawatts of electric power, but also through the production of hydrogen and other energy carriers at similar rates. In the long run one can expect very large amounts of nuclear power. 17 TWyr/yr of thermal power, which is equivalent to a capacity of 10 TW(e), appear as an upper limit for the year 2030.

To exploit successfully this potential involves both the timely introduction of breeders and the use of a substantial part of our high quality natural uranium resource. With fission breeders, the uranium used is in effect not consumed, but invested in building a system where energy supply is not constrained by resources limitations. Such a mode of resource use we labeled "investive," a concept we elaborate on later in Chapter 10. Once installed, such a system could provide steadily increasing amounts of energy for millennia. Its essence would be the use of breeding, whether fission or fusion. And it would provide the return on the original investment of our natural uranium resources—a continuous provision of energy.

REFERENCES

INFCE. 1979. *International Nuclear Fuel Cycle Evaluation,* Working Group 1 on Availability of Nuclear Fuel and Heavy Water. Final Report. INFCE/W6.1/17. Vienna. Draft.

Lane, J.A. et al. 1977. Nuclear Power in Developing Countries. In *Proceedings of the International Conference on Nuclear Power and Its Fuel Cycle.* IAEA-CN-36/500. Vienna: International Atomic Energy Agency.

Nuclear News. 1979. World List of Power Plants. 22(2):59–77.

OECD-NEA/IAEA. 1977. *Uranium Resource Production and Demand.* A Joint Report by the Agency of the Organisation for Economic Cooperation and Development and the International Atomic Energy Agency. Paris: Organisation for Economic Cooperation and Development.

——. 1978. *World Uranium Potential: An International Evaluation.* A Joint Report by the Organisation for Economic Cooperation and Development, the Nuclear Energy Agency, and the International Atomic Energy Agency. Paris: Organisation for Economic Cooperation and Development.

Perry, A.M. 1979. *World Uranium Resources.* WP-79-64. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Weast, R.C., ed. 1974. *Handbook of Chemistry and Physics.* Cleveland, Ohio: CRC Press.

World Energy Conference. 1978. *World Energy Resources, 1985-2020.* Guildford, UK: I.P.C. Press.

5 SOLAR ENERGY: BIG INVESTMENTS FOR LARGE-SCALE USE

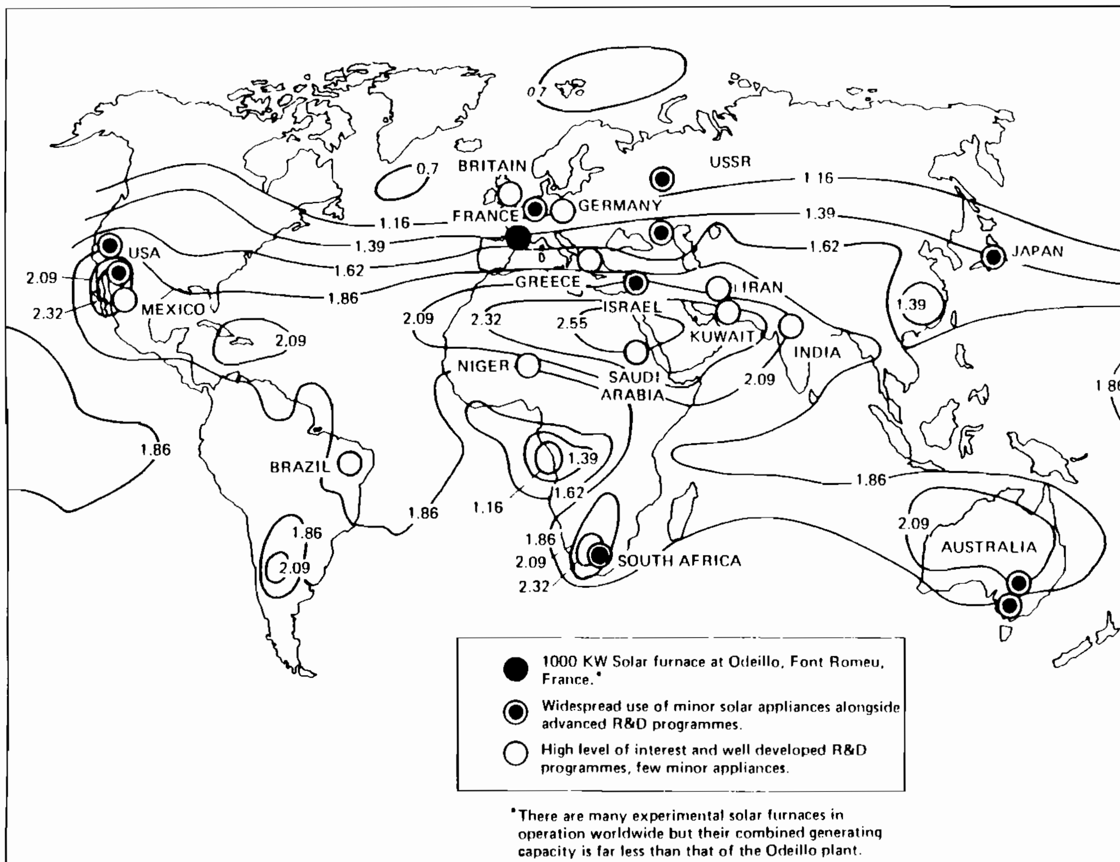
Each day the earth receives from the sun one hundred thousand times more energy than is produced in all of the world's electricity-generating plants. The average power input from the sun is some 178,000 TWyr/yr of thermal energy. Can the sun provide all the energy required for a growing world? The answer lies in finding ways to tap even small portions of this flow of natural energy.

In assessing the supply potential of solar power, we distinguish between soft and hard solar energy systems. Soft solar generally comprises small, local uses of both direct and indirect[a] solar energy for generating domestic hot water and comfort heating. Hard solar implies the use of solar energy on a large, centralized scale, as, for example, in solar power plants that thermodynamically convert steam into electricity and in photovoltaic (PV) systems that make use of solar cells to generate electricity.

Solar power can be both locally and globally significant. In Chapter 6 we examine the potential contribution of local, soft solar energy when we con-

[a]The labels "direct" and "indirect" are used to distinguish solar radiation that arrives at the point of collection directly from the sun, from radiation that reaches the point of collection only indirectly. Indirect radiation, which is also called "diffuse" radiation, includes radiation reaching the point of collection after having bounced off the ground, off various objects, or off water droplets in clouds. The distinction is particularly important when considering solar technologies that rely on mirrors to concentrate radiation onto an absorber. Radiation arriving at a mirror from a direction other than that of the sun will not be reflected onto the absorber but will be bounced off in some other direction entirely.

Figure 5-1. Average annual distribution of solar radiation and locations of potential solar sites. Radiations levels given in TWh/km^2 yr. *Source:* Crabbe and McBride (1978).



sider the renewable energy sources, most of which come ultimately from solar power. Soft solar, while important on the local level, will probably contribute no more than a few terawatts of energy, which for a high-energy-consuming world of, say, 36 TWyr/yr, is small.

But hard solar is definitely in the realm of the potentially large contributors. It is not an exaggeration to assert that sunlight—that is, hard, centralized solar power—could eventually be *the* primary energy source and, conceptually, even the only source of heat, electricity, and synthetic liquid and gaseous fuels for the entire world, continuously and indefinitely, on a scale similar to the potential of fusion and of fission via the breeder reactor. This could be achieved through a global network of solar conversion facilities that would be coupled with energy transport and storage systems. All this appears feasible within acceptable constraints on energy payback time, capital investment, and available suitable land.

The sociopolitical consequences of global solar are likely to be the most far reaching. While the breeder reactor, in principle, permits countries to eventually achieve complete energy independence, running the world from sunlight would require extensive, unprecedented international cooperation.

The average annual distribution of solar radiation and the location of potential solar sites are shown in Figure 5-1; Table 5-1 summarizes the basic characteristics of solar radiation as an energy source. The solar insolation in the sunny arid areas near the equator is three times higher than that in less sunny areas farther north. Whereas seasonal variations in the amount of radiation are only a factor of two in equatorial regions, solar radiation in northern Europe during winter months is only one-tenth of what it is in summer months. Extremes in the availability of direct beam radiation are even more severe. In areas such as the United Kingdom and central and northern Europe, where as much as 85 percent of total irradiation in winter months is received as diffuse radiation, the use of tracking mirrors or of tilted solar collectors cannot compensate completely for seasonal variations in sunlight.

Table 5-1. Characteristics of solar radiation as an energy resource.

The solar constant	1353 W/m^2
Effective radiation temperature of the sun	5760 K
Maximum direct beam irradiation at sea level	~1000 W/m^2

Region, Irradiance		*kWh/m^2-Day*	*W/m^2 (Average)*
Tropic, deserts	Annual	5-6	210-250
Temperature zones	average	3-5	130-210
Less sunny regions (e.g., northern Europe)	horizontal	2-3	80-130
Average annual direct beam irradiance in sunny regions		7-8	290-330
Monthly average direct beam radiation in sunny, arid regions		5-10	210-420

Source: Weingart (1978).

SOLAR TECHNOLOGIES: ON THE EDGE OF BREAKTHROUGHS

The dangers of speculating about the global potential of solar energy are even larger than they are for other global supply options. The development of most of the potentially important solar technologies is just beginning, with current emphasis only on hard, complex, and perhaps inelegant technologies that are closely patterned after known industrial and engineering capacities.

There is a large probability that research will open up totally new pathways for converting solar energy into electricity and into other secondary energy forms (such as hydrogen) so crucial to meeting the world's energy needs of the future. In fact, the large-scale use of sunlight could be achieved with technologies that are not yet available or perhaps not even known.

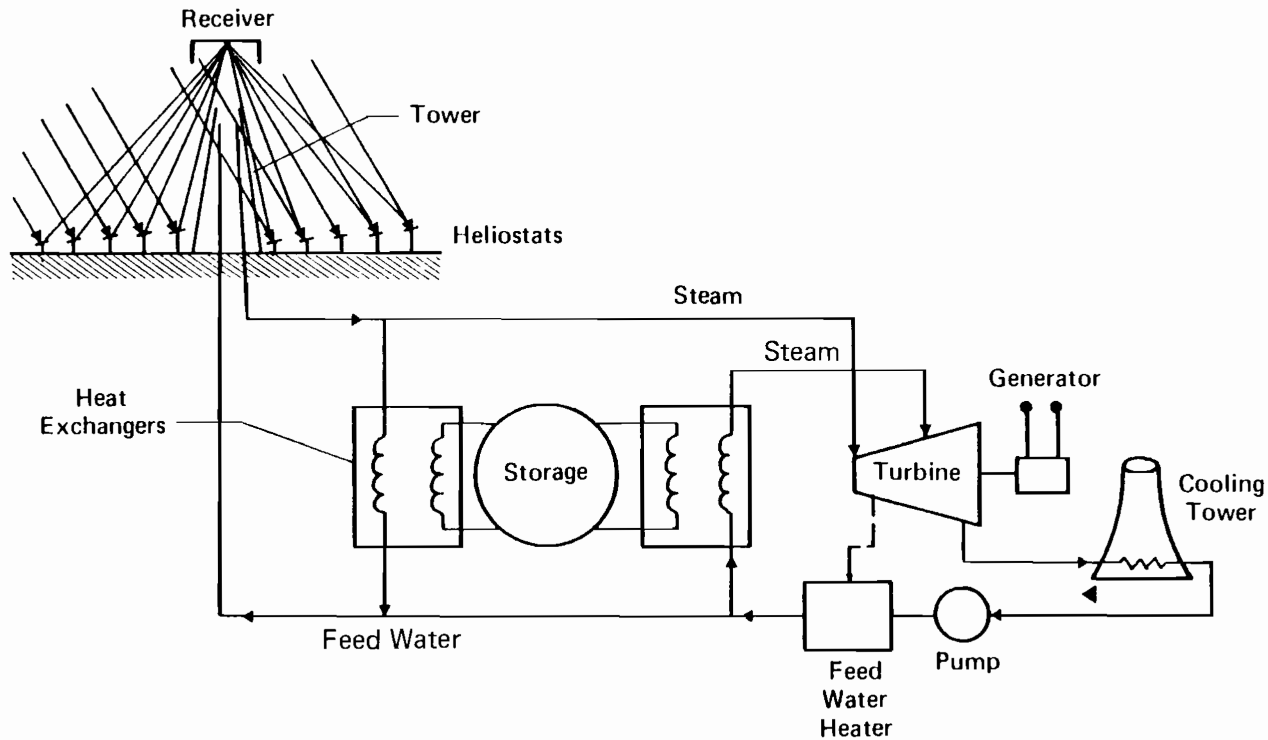
What is feasible always depends upon the frame of reference, and given the complexity and urgency of the energy problem, it seems likely that some of these technological advances will probably appear within our fifty year time horizon. It is from this perspective that we consider these in turn, examining their requirements and how the challenge of exploiting them fully might best be met.

Solar Power Plants: A System of Agriculture

One method for generating large amounts of high quality energy from solar power is to use power plants that convert the energy from the sun into electricity. One of the most promising methods, but one that is not without its technological problems, is solar thermal electric conversion (STEC). The challenge is to be able to concentrate enough direct solar beam radiation to produce temperatures as high as, say, 600°C. Figure 5-2 illustrates a specific configuration in which thousands of suntracking mirrors, so-called heliostats, are located on the earth's surface in order to focus the solar energy on a boiler situated atop a 100 to 250 meter power tower. The boiler, in turn, produces the superheated steam or hot gases that drive either a conventional steam cycle or a high temperature cycle that then generates electricity.

Figuratively speaking, the STEC process might be regarded as a form of agriculture—the "fields" in this instance being the extensive arrays of heliostats. The provision of 100 megawatts electric (MW(e)) of installed capacity, which is less than one-tenth of the capacity of a modern-day nuclear reactor, would require thousands of heliostats providing a mirror surface area of approximately 0.9 km^2 or, equivalently, about 3.8 km^2 of total land area. For these calculations we assume both an average insolation of 500 watts per square meter (W/m^2), which is the maximum value possible in sunny arid areas, and a 15 to 25 percent efficiency in converting direct beam solar radiation into electricity. The efficiency is relatively

Figure 5-2. Central receiver solar thermal electric power plant. *Source:* Fujita et al. (1977). Provided through the courtesy of the Department of Energy through an agreement with the National Aeronautics and Space Administration, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.



low, owing partly to losses incurred as the incident radiant energy is transferred via the mirror surfaces to the absorbers and converted to electricity and partly to the energy required to power the mirror tracking system.

Although STEC systems can function only when there is direct radiation and are therefore sensitive to daily, weekly, and seasonal changes in the amount of such direct sunshine, efforts have intensified since the oil crisis of 1973 to make STEC systems commercially successful. A large number of thermal cycles, spanning a range of a few kilowatts of installed electrical energy to a few hundred megawatts of such energy, are being developed. The United States, Japan, and Europe are constructing prototype plants that are expected to be operational within the next decade. Fully commercial STEC systems may be available in the 1990s.

Published cost estimates for central receiver STEC plants operating under optimum meteorological conditions indicate that currently they are much higher than those for more traditional fossil and nuclear power plants. The high costs of STEC material requirements are the major constraint. However, the mass production of heliostats—say, at a level of 250,000 per year—that could be forthcoming in the next few decades could reduce their costs considerably to about \$60 per m^2 of reflecting area (McDonnell Douglas 1976). This is, of course, an aggregate figure that may differ according to local conditions.

Based on recent cost estimates (Weingart 1978; see also Black and Veatch 1976; Blake, Walton et al. 1975; Blake et al. 1976; McDonnell Douglas 1973, 1974; Selcuk 1975; Smith 1976), the levelized busbar cost of electricity in sunny arid areas would be in the range of 50 to 100 mills per kilowatt hour of electrical energy (mills/kWh(e)). For orientation, 1 mill equals \$0.001. In less sunny regions such as central and northern Europe, the cost would be between 200 and 300 mills/kWh(e). The difference in these two ranges leads to a consideration of systems for producing electricity from STEC plants situated in lower latitudes and transporting it to less favorably located consumption centers. Estimates of the cost of long distance, high voltage DC transmission—say, from Spain to Oslo or from Phoenix to Boston—are on the order of 10 mills/kWh(e) (Caputo and Truscello 1976). The indication is that such systems—for example, using large areas of Spain and Portugal, Turkey, southern Yugoslavia, and southeast Bulgaria to produce electricity to be consumed in central and northern Europe—might be less expensive than on site electricity generation in the central and northern European regions.

STEC systems are really an attempt to imitate with concentrated sunlight what we do today with coal, oil, gas, or nuclear reactors—namely, to produce steam for running turbine generators. Thus, the development of such systems should, in principle, not be a problem. Yet these cumbersome machines, sophisticated thermal absorbers, heat transport and storage units, turbines, generators, cooling towers, and vast land areas may turn out to be museum pieces by the end of this century. The combustion of fossil fuels is probably not the ideal model for the design of large solar power plants. Rather, the best techniques will probably be either those that use the high inherent energy content of the visible light photons or those that bypass the complex thermal mechanical systems, or both. Among such candidates the most promising are PV systems.

Solar Cells: An Elegant Solution

The use of large, central station PV systems that make use of solar cells to convert solar energy directly into electricity has several advantages compared to STEC systems. First, PV systems do not require large sections of land to generate an installed capacity of 100 MW(e) and can, in fact, operate on "bits and pieces" of land. This makes them especially attractive for countries in middle latitude regions, as, for example, Western Europe and northern parts of the United States, where barren land is generally available only on a small, scattered basis. A second advantage of PV systems is that they function with both diffuse and direct solar radiation, allowing them to be used even in areas where cloudiness is a predominant meteorological feature. Moreover, PV systems operate without moving parts, have potential lifetimes much longer than those of existing commercial power plants, and exhibit efficiencies of up to 20 percent.

The use of PV systems can, in particular, be viewed from the perspective of the "investive use of resources," a concept we mentioned earlier in Chapter 4 and which we elaborate on later in Chapter 10. The lifetime of a PV system is long—much longer than the thirty years generally attributed to today's nuclear reactors. And, once the initial investment has been made in the PV system—specifically, for the cells and for other plant materials—sufficient energy would be generated on a continuous and inexhaustible basis to provide the desired services from energy. No further investments, whether physical or human resources, would be required other than for a minimum of maintenance.

The large-scale use of PV systems, like that of STEC systems, is currently being hampered by the high capital costs of setting up these systems. Here too, we expect technological progress to improve the situation. There appears to be no shortage of candidates—single crystal silicon cells, amorphous silicon, gallium arsenide, thermophotovoltaic designs, vertical multijunction silicon, polycrystalline silicon, cadmium sulfide-copper sulfide. At present the single crystal silicon cell is the most developed, primarily as a result of its use in communication satellites and spacecraft. The current cost of using these cells for the U.S. space program is high (about $10 per peak watt), and if they are to be used economically on the earth's surface, the cost would have to come down to about $0.50 per peak watt, based on a maximum insolation of 1 kW/m^2. Again, provided the problems hindering mass production can be overcome, such cost reductions will probably be realized.

Solar Satellite Power Station

Beyond what can be accomplished through technological improvements in the cells themselves, the potential of PV systems gains a new dimension if we consider locating them outside the filtering effects of the earth's atmosphere. The concept of the solar satellite power station (SSPS) in geostationary orbit originated with Peter Glaser of the Arthur D. Little Company in the United States and has since been expanded by scientists at the Argonne National Laboratory of the University of Chicago, working under a grant from the U.S. Department of Energy.

In the scheme pictured in Figure 5-3, a receiver panel (5 by 5 miles) would intercept 85 GW of radiant solar power in a geostationary orbit some 22,300 miles above the equator. Solar cells operating at 18 percent efficiency would convert this power into 15 GW(e) of power that would be converted into high frequency microwave beams to be transmitted to earth and reconverted by an antenna into some 10 GW(e) of power. This would be enough to meet the electricity needs of New York City. The receiving antenna would be about 36 square miles—about five to ten times the area needed presently for a coal-fired power plant of the same electrical capacity and about thirty times the area of an equal capacity light water nuclear reactor of today's design.

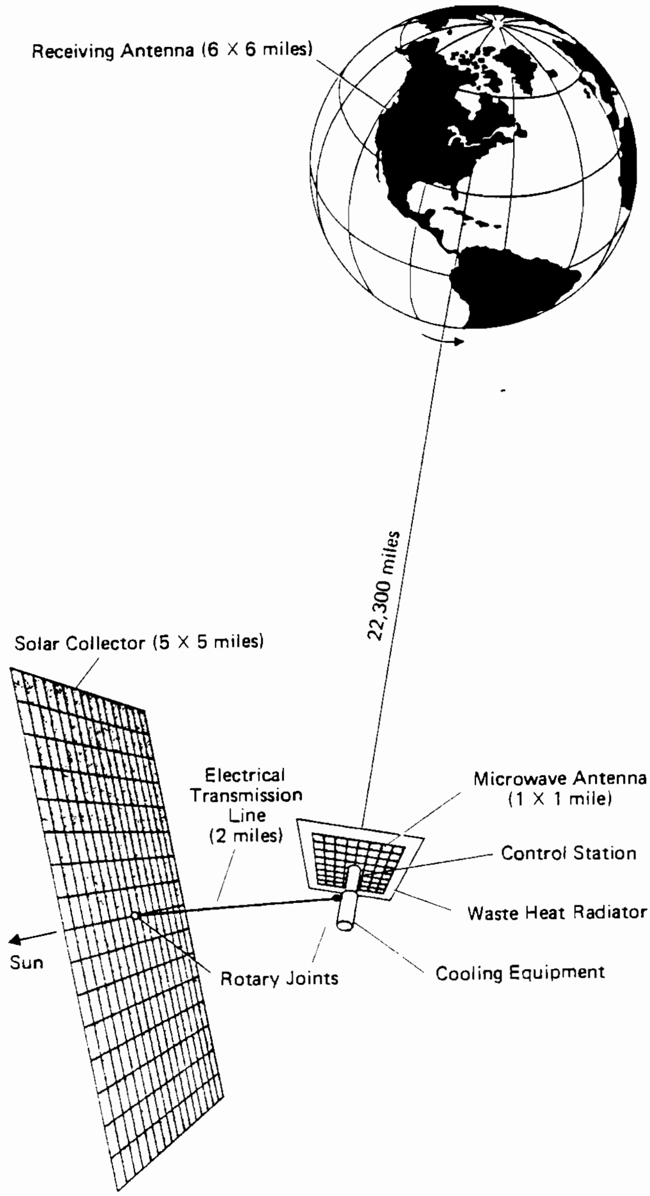
Often one hears arguments that this scheme is too futuristic and inherently too capital intensive to become a near-term reality. But our goal here is to explore the realm of the possible. Given the latest developments in space shuttle technology, the required advances in SSPS technology are not necessarily more difficult to achieve than the widely expected breakthroughs in PV systems. Moreover, the SSPS scheme has an inherent capital cost bonus. For terrestrial STEC systems, the cost per kW(e) of installed baseload capacity is approximately four times the cost per peak kW(e); the inclusion of storage costs for these STEC systems would increase this factor even further. For the SSPS system, the costs are equal: The sun always shines in space.

Biotechnology

A radical new approach to solar energy may come not from the old mechanistic approaches but from biotechnology—a broad class of systems that have at their core photosynthetic and biological energy conversion processes. For example, the development of high efficiency plants that are cloned and raised for feedstock for fuels and chemicals would represent a new level of industrialization of biomass systems. Other biotechnologies would combine biological processes into a mechanical matrix to convert sunlight and water into hydrogen and oxygen. We found these possibilities intriguing and explored them with interest.

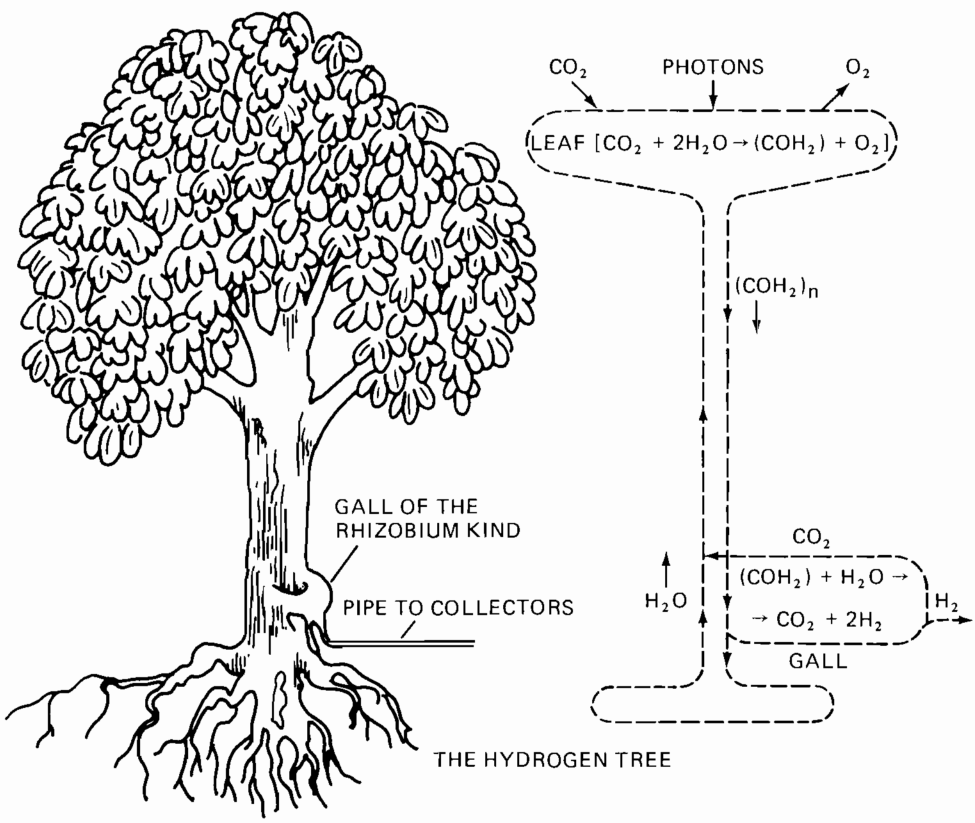
Plants have long "known" how to use the energy of sunlight to split water, but they do not evolve hydrogen explicitly, since it is needed only for internal energetic processes within the plant itself as a means for reducing carbon dioxide. However, it may be possible to develop new biological structures that in fact evolve hydrogen. At IIASA, Cesare Marchetti considered the concept of hydrogen-producing trees (see Figure 5-4).

Figure 5-3. Solar satellite power station. *Source:* Summers (1971).



The concept is essentially one of replacing expensive solar collectors and solar cells with tree leaves. Swollen plant tissues, so-called galls, located at the tree trunk would be genetically programmed to use the solar energy captured in the leaves for generating hydrogen gas as a by-product of photosynthesis. The hydrogen gas would be collected within the galls and piped to a central storage system. The essential features of such a system already

Figure 5-4. The hydrogen tree. Graphical presentation of the proposal with a very schematic chemistry. The gall actuates a reverse of photosynthesis and makes hydrogen (or methane) available in an enclosed cavity that can be tapped by a collector pipe.



exist in nature: Many insects and bacteria induce the formation of galls in different types of plants. These various kinds of galls, which number in the tens of thousands, then provide the shelter or nutrients needed by the organisms that caused them. In at least one case, that of Rhizobium bacteria in symbiosis with leguminous plants, substantial hydrogen is produced in the galls, though currently it simply escapes to the atmosphere. It has been estimated that in this way U.S. soybean plantations leak about 30 billion m^3 of hydrogen annually (Brill 1977). Adapting this potential so that the plants can be easily integrated with some sort of collection system will depend on the techniques of genetic engineering. Given the advances in this field in the last decade alone, the potential of biotechnology appears large. This only underscores for the use of hydrogen what was said earlier for electricity—that new approaches to production could be far more attractive both economically and environmentally than current, more mechanistic approaches.

ELECTRICITY, HYDROGEN, AND SOLAR POWER

For both STEC and PV solar power conversion systems, there is an inherent problem of matching supply characteristics with those of demand both in time and in location. For example, the vast amount of solar power available in December in the sunny arid areas of the south is needed much less there than it is for heating homes in the cloudy, cold areas of the north. But getting the energy from the point of origin to that of final use and having it available continuously to meet daily, weekly, or seasonal needs will require large-scale energy transportation and storage techniques. Electricity is not easily storable as such, and currently peak demand must be met with capacity.

Thus, to consider PV, and particularly STEC, technologies only as they might be used to supply electricity to a power grid is to immediately restrict their potential. If one is willing to look a little further than the traditional energy carriers with which we are so familiar (oil in tankers, coal carried by trains, natural gas in pipelines, and electricity carried by high tension wires) and to contemplate what might be available when large-scale solar facilities come of age, the real extent of the large-scale solar potential becomes apparent. Of particular interest is the possibility of using hydrogen gas as an energy carrier in the future. Hydrogen is especially attractive in connection with solar power because it is more easily transported over long distances and more easily stored than electricity. Moreover, with the right scheme for concentrating incoming sunlight, solar plants could attain the very high temperatures (2500 to 3000°C) needed to produce hydrogen directly from water.

Even if, for the moment, we restrict our attention to hydrogen generation processes less dependent on such high temperatures (see the accompanying boxed material for a brief description of the different ways in which hydrogen can be produced), it has been estimated that a commercially mature system operating under ideal desert conditions might produce hydrogen for approximately \$50 per barrel of oil equivalent (boe) (Weingart 1978).

HYDROGEN PRODUCTION PROCESSES

The source of most of the hydrogen used today in the fertilizer industry, for example, or in oil refining is one or another of the fossil fuels. But if hydrogen is to be used as an energy carrier on a scale comparable to electricity, a different primary source is needed. The obvious choice is water, which is simply a compound of hydrogen and oxygen in a ratio of two parts to one (as encoded in the formula H_2O). The problem of producing hydrogen from water is a problem of breaking the bonds holding the hydrogen and oxygen together. This requires the input of energy, and thus hydrogen production processes can be divided into four categories depending essentially on the form in which this input energy is added.

Electrolysis (Electrical Splitting). Perhaps the most established techniques of splitting water into its hydrogen and oxygen components are based on the input of electrical energy. The first patent on water electrolysis was awarded in 1888, and today research continues to reveal promising opportunities for increasing the efficiency of the process. Currently, most experience is with small units, and improvements will be needed before electrolyzers in the thousands of megawatt range become practical.

Thermolysis (Heat Splitting). Energy added to water in the form of heat raises the temperature of the water and weakens the bond between the hydrogen and oxygen. Once temperatures on the order of 2500–3000°C are reached, the bond fails completely. Because of the high temperatures needed for pure thermolysis, large-scale use of this technique is conjectured to be possible only in conjunction with highly concentrated solar energy.

Thermochemical Water Splitting. This category might properly be considered a subcategory of thermolysis. It refers to processes that rely partly on the input of heat and partly on the special properties of certain chemical catalysts that allow heat energy to be added at temperatures between 600 and 1000°C and applied to the problem of breaking the hydrogen-oxygen bond. Thus, by carefully designing the order in which heat is added and in which the critical chemical reactions take place, it is possible to produce hydrogen at temperatures well below those needed for pure thermolysis. The number of different possible thermochemical schemes is theoretically in the tens of thousands. So far only some twenty to thirty of these have been investigated thoroughly, and this area is therefore seen as one with tremendous potential for producing a hydrogen production process compatible with the sorts of heat sources already commonly available.

Photolysis (Light Splitting). In addition to electrical energy and heat energy, energy in the form of visible light might possibly be used to split water. As is mentioned in the text, plants use this energy source to power their internal chemical cycles, and it might even be possible to exploit plants directly to provide some hydrogen that we can tap for our own use. But beyond that, it is possible to design sequences of chemical reactions that can make use of visible light energy absorbed by "photocatalysts" in breaking the hydrogen-oxygen bond in water. However, of the four categories described here, the photolytic proposals are the least advanced.

Furthermore, using available technology, a pipeline system could transport this hydrogen from Turkey to Oslo or from New Mexico to Maine for about $2/MWh (Beghi et al. 1972), suggesting again the advantages of locating large solar facilities in the lower latitudes and then transporting the energy produced to where it is needed.

MEETING THE GLOBAL CHALLENGE (Design of a Global Solar System)

For sunlight to be a primary source of energy for the world, it will be necessary to decouple this resource in time and in location from the patterns of energy demand. This would require an integrated energy system for transporting solar energy over long distances (say, of 10,000 km) and for storing it for long periods. The requirements for such a global system or network of systems would be extensive and technologically complex and would display enormous regional variations in character and evolution. The features of this global system are given in the accompanying boxed material.

As we have seen, the problems of interfacing hydrogen with solar energy on a large scale might be resolved within a few decades. Likewise, transporting either liquid hydrogen via tankers or hydrogen gas via pipelines does not present insurmountable technical problems. Thus, the probable constraints on the buildup and operation of such a global system are land requirements and material requirements, mainly for steel and concrete. We examined these requirements explicitly. In both instances we drew heavily on insights

Large-scale Features (as Discussed in this Chapter)

- Solar electric power plants of various sizes located throughout the world primarily in sunny regions, interconnected through large, integrated electrical utility systems over distances of many thousands of kilometers.
- Solar fuel generation units primarily in sunny regions and interconnected globally via pipeline and, for a few locations (e.g., Japan), by tanker.

Smaller Scale Features (As Discussed in Chapter 6)

- Local use of solar-generated heat for space heating, water heating, and industrial process heat where economically and logistically suitable.
- Local and regional use of small-scale solar-mechanical, -electrical, and-fuel generating units, especially in developing countries.

gained from several published studies and from our case study of solar energy use in Austria, a densely populated industrialized country that has significant seasonal variations in solar radiation (Korzen 1979).

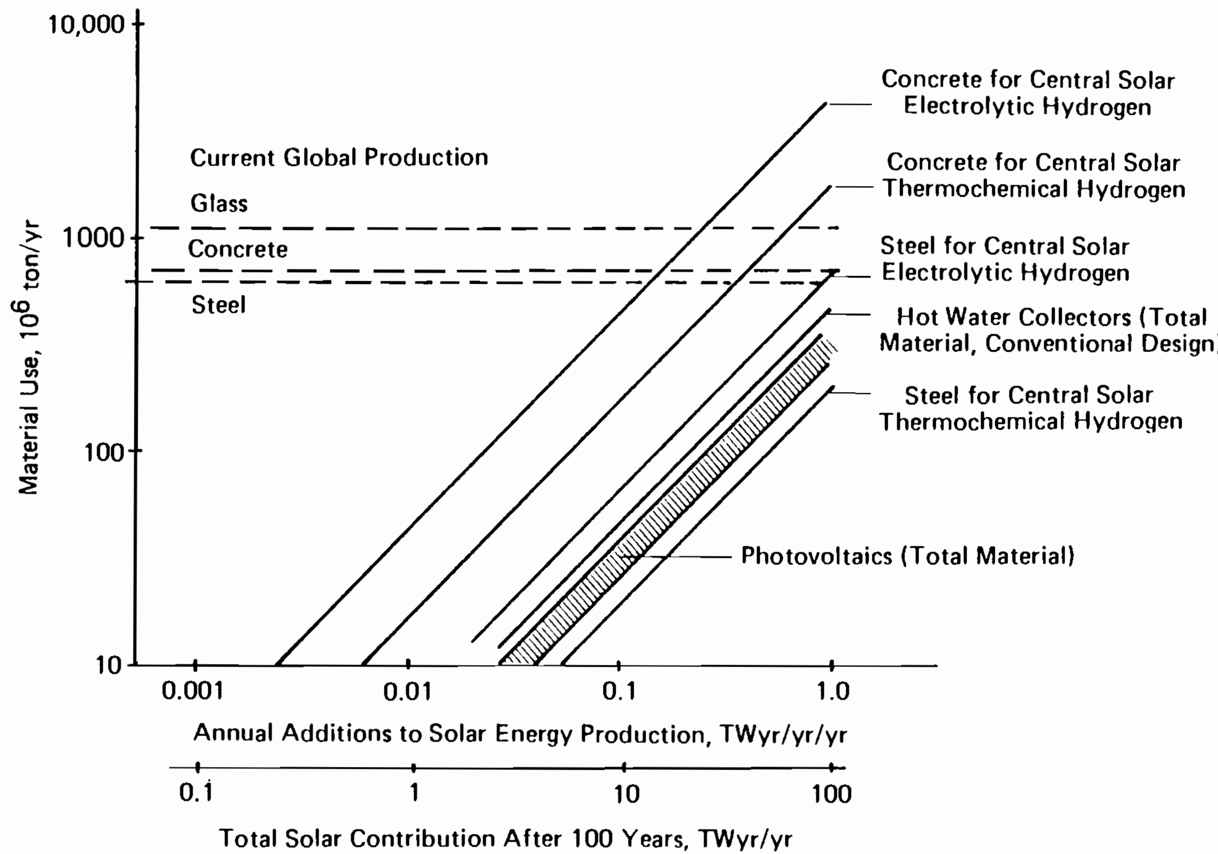
From this study, we saw that the potentials of both fallow land and marginal farm land demonstrate the considerable area that could be made available in Austria for solar energy use. If all the anticipated constraints (e.g., southern orientation of Alpine slopes) are included in the estimation, an overall usable land area of perhaps 2500 km^2 could be made available, even in such a densely populated country. This corresponds to 3 percent of the total land area of Austria. This is not to say that it would be easy to utilize the entire area. Because of complex land ownership arrangements, the potentially available land area could be used only if extensive social changes were to take place.

A comparable analysis done for the southwestern United States indicated that between 2 and 16 percent of the total land in an eight state area was available (Aerospace Corporation 1974). These states (California, New Mexico, Arizona, western Texas, Nevada, Utah, Colorado, and Oklahoma) represent one-third of the total continental U.S. land area, and the range from 2 to 16 percent represents 50,000 to 400,000 km^2. The approach taken listed reasonable exclusion criteria, such as land with a tilt greater than 20 percent, land with any reasonable crop or grazing potential, and land owned by Indian tribes or used as a local, state, or federal park. Some more stringent criteria were also introduced—for example, exclusion of all federal lands (which in one of these states amounted to half the land area).

On a global perspective, the waste, desert, and mountainous regions, exclusive of uninhabited islands and polar areas, cover 62 million km^2 (Doxiadis and Papaioannou 1974). Let us first assume that 20 million km^2 of this land is worth considering as arid, sunny wasteland available for central solar systems. Then, in line with the percentages for Austria and the southwestern United States as arrived at above, we take 5 percent of this number as an estimate of land with some potential for solar utilization. The result is 1 million km^2. (Note that for an electricity generation density of 20 W/m^2, this corresponds to 20 TW.) A completely independent estimate, based on (FAO 1969), of potential sunny wasteland excluding sandy regions and low use grazing land comes up with 4.3 million km^2. If sunny and other nonwaste regions were included, the number could be ultimately as high as 10 million km^2. The lesson to be learned from these sorts of calculations is that as long as only physical conditions and relations are reviewed, land availability is not likely to be a binding constraint on solar development.

Probably the most crucial constraint on the buildup of solar power on a large, global scale will be the material requirements. For the heliostat prototypes of today we need about 30 to 80 kg of steel and glass and some 155 kg of concrete and sand per m^2 mirror surface. In addition, 165 kg/m^2 concrete and 10 kg/m^2 of steel are required for the rest of the plant structure and machinery. Based on these figures and assuming that by 2080 solar energy may reach a level of 35 TWyr/yr, material requirements can be calculated as shown in Figure 5-5. For perspective, to reach a total solar con-

Figure 5-5. Material requirements for central solar systems.



tribution of 35 TWyr/yr within one hundred years, solar energy production would have to increase at an average rate of 0.35 TWyr/yr per year.

Figure 5-5 indicates that the annual material requirements of such a scheme based on thermochemical hydrogen production would correspond to about 10 percent of the world steel production and 2 percent of the world glass production in 1975. The concrete needed annually would match the 1975 world concrete production. This hardly seems feasible from the present perspective. However, the situation in 2030 might not be so critical, since it is envisaged that by that time steel production could well be four times higher and concrete production five and one-half times higher than at present. The buildup of such a large-scale solar capacity would then only absorb annually about 10 percent of the total production of these industries.

To put the material intensiveness of solar plants in perspective, we compare the amount of construction material required for solar thermal electricity generation with the material requirements of coal and nuclear plants per unit electricity generated over a plant lifetime of thirty years. For steel, the solar plant needs twelve times the material required for the coal system and seventeen times that used for a light water nuclear reactor system. For concrete, the requirements for solar energy are sixty times those for the light water reactor.

CONCLUDING REMARKS

The technologies that might form the basis of future large-scale, centralized solar energy conversion range from those already incorporated in prototype designs to those not yet conceived. It is a young field of research and, if one is willing to be imaginative, an especially promising one. What we have done in this chapter is twofold. First, we have tried to escape traditional engineering prejudices and look at novel systems for which we can only sketch the most rudimentary outlines. Second, for those systems based on more conventional technologies, we have tried to estimate the implications of building such systems on a global scale. The results of these investigations form the basis both for the quantitative analysis described in Chapter 8 and for the more qualitative exploration of Chapter 10 where we look beyond 2030 to the possible features of a truly sustainable energy system. For the moment, these results can perhaps best be summarized as follows:

First, clearly when one considers possible sustainable energy systems, solar energy technologies have their place alongside nuclear breeder reactors. Both sorts of systems could provide essentially inexhaustible long-term energy sources for mankind.

Second, land availability is not expected to be a binding constraint for large-scale solar power. Rather, material requirements (e.g., steel and concrete) will be unusually large and most likely the limiting constraint.

Third, currently the need for solar energy storage is a serious problem capable of inhibiting the introduction of such solar facilities on a large scale. But technological possibilities for solving this problem are promising.

Fourth, high capital costs are an immediate obstacle to the early introduction of solar energy. However, there is room to expect technological breakthroughs that could improve the capital cost situation significantly.

Fifth, the emergence of a global solar energy system could perhaps bring with it an unprecedented international interdependence and cooperation and a substantial potential for development and growth in many poor but sun-rich regions.

REFERENCES

Aerospace Corporation. 1974. *Solar Thermal Conversion Mission Analysis.* Volume 5, Southwestern United States Area Definition and Siting Analysis. ATR-74(7417-16)-2, November. El Segundo, California.

Beghi, G. et al. 1972. *Transport of Natural Gas and Hydrogen in Pipelines.* Ispra, Italy: EURATOM.

Black and Veatch, Consulting Engineers. 1976. Report on Preliminary Cost Estimation of Solar Energy Reference System for EPRI. Preliminary Internal Report, June. Palo Alto, California: Electric Power Research Institute.

Blake, F.A. et al. 1976. *Quarterly Report No. 1, Central Receiver Solar Thermal Power System, Phase 1.* January. Denver. Martin Marietta Corporation.

Blake, F.A., J.D. Walton et al. 1975. *Final Report, Solar Power System and Component Research Program (January 15 to November 15, 1974), by Martin Marietta Corporation and the Georgia Institute of Technology.* Denver: Martin Marietta Corporation.

Brill, W.J. 1977. Biological Nitrogen Fixation. *Scientific American* (March).

Caputo, R.S., and V.C. Truscello. 1976. Solar Thermal Electric Power Plants—Their Performance Characteristics and Total Social Costs. In *Proceedings of the Eleventh Intersociety Energy Conversion Engineering Conference.* La Grange, Illinois: American Nuclear Society.

Crabbe, D., and R. McBride, eds. 1978. *The World Energy Book: An A-Z, Atlas and Statistical Source Book.* London: Kogan Page Limited.

Doxiadis, C.A., and J.G. Papaioannou. 1974. *Ecumenopolis: The Inevitable City of the Future.* New York: W.W. Norton.

Food and Agriculture Organization (FAO). 1969. *World Atlas of Agriculture, Land Utilization Maps and Relief Maps.* Novara, Italy: Istituto Geografico de Agostini (IGDA).

Fujita, T.; N. El Gabalawi; G. Herrera; and R.H. Turner. 1977. *Projection of Distributed Collected Solar Thermal Electric Power Plant Economics to Years 1990–2000.* Pasedena, California: Jet Propulsion Laboratory, California Institute of Technology.

Korzen, W. 1979. Möglichkeiten und Grenzen technischer Solarenergienutzung für Osterreich. Ph.D. thesis, Technical University of Vienna, Vienna, Austria.

McDonnell Douglas Astronautics Company. 1973. *Solar Thermal Power Systems Based on Optical Transmission.* Progress Reports 1 and 2 under contract NSF/RANN/SE/GI/39456/PR, April 1973. Huntington Beach, California.

———. 1974. *Solar Thermal Power Systems Based on Optical Transmission.* Progress Report 2 under contract NSF/RANN/SE/GI/39456/PR, February 1974. Huntington Beach, California.

——. 1976. *Central Receiver Central Solar Thermal Power System.* Phase I Final Report, CRDL Item 1, Pilot Plant Preliminary Design Baseline Report, Volume 1, Book 2, System Analyses and Design. MDC-G-6040, UC 13. Huntington Beach, California.

Selcuk, M.K. 1975. *Survey of Several Central Receiver Solar Thermal Power Plant Design Concepts.* JPL Report 900-714, August 1975. Pasadena, California: Jet Propulsion Laboratory.

Smith, O. 1976. A Multimodule Solar Thermal Electric Power Plant. Private Internal Engineering Report, Electrical Engineering and Computer Science Department, University of California. Berkeley, California.

Summers, C.M. 1971. The Conversion of Energy. *Energy and Power.* San Francisco: W.H. Freeman and Co.

Weingart, J.M. 1978. The Helios Strategy: A Heretical View of the Potential Role of Solar Energy in the Future of a Small Planet. *Technological Forecasting and Social Change* 12:273–315; also WP-78-8. Laxenburg, Austria: International Institute for Applied Systems Analysis.

6 RENEWABLE ENERGY SOURCES: TOWARD A PLANTATION WORLD

There is a wide spectrum of renewable energy sources available to man on an inexhaustible basis. These include the direct energy from the sun, the energy content of biomass and animal and agricultural waste products, and the energy in flowing streams, wind, waves, ocean currents, and tides, as well as the turnover of heat from the oceans' surface layers to the depths and the geothermal heat flowing from the earth's interior to the surface.

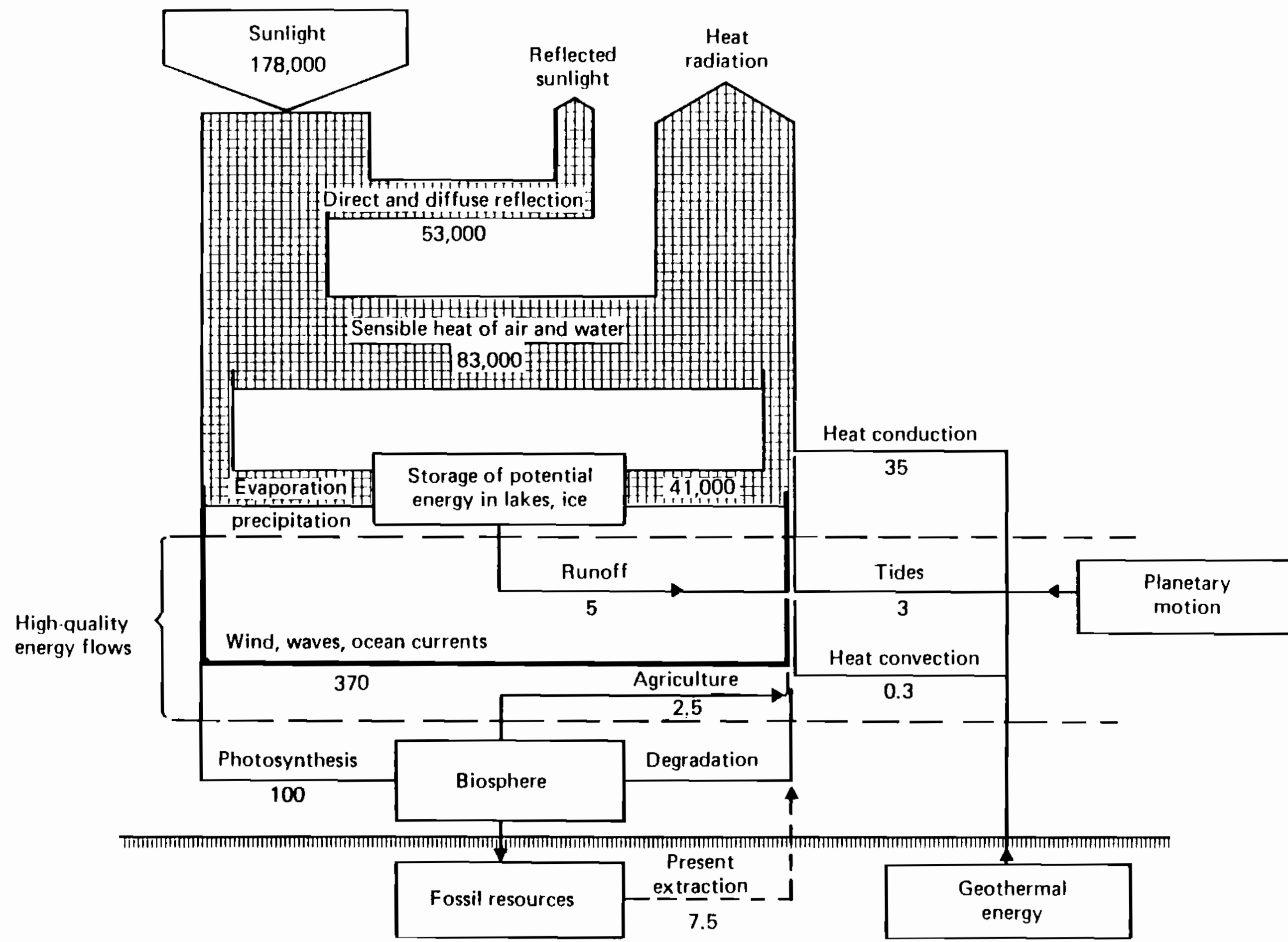
How large is the energy potential of each of these resources? How much of what is accessible can be used without disturbing the natural system too much? These are some of the questions we addressed in our exploration of the potential role of renewable energy sources in global energy supply. The results of our study are summarized in this chapter.

ENERGY FLOWS IN THE ENVIRONMENT

Renewable energy systems have one universal feature: They divert some of the natural energy flow present in the environment to serve useful human activities. Figure 6-1 depicts the structure of these dynamic processes, which are explained below in some detail.

The natural energy flows present in the environment include the power flowing through the atmosphere, the hydrosphere, the bedrock of the earth's surface, and the biosphere. The environment receives energy from three

Figure 6–1. Energy flows through the environment (power levels in TWyr/yr). In many of the numerical presentations extra significant figures beyond what is significantly valid are listed. This is done to make arithmetic identities valid.



independent primary sources—sunlight, geothermal energy, and planetary motion in the solar system.

The dominating inflow of power is the sunlight arriving at the upper layers of the atmosphere. The total energy flow of sunlight intersected by the earth is 178,000 TWyr/yr. Part of the solar radiation is scattered on its way through the atmosphere, and part is absorbed. On clear days, up to 80 percent of the initial intensity is measured in sunny arid places like the Sahara and the southwest United States. In middle latitudes, the power densities measured on a horizontal area reach a maximum of 35 to 45 percent of the extraterrestrial value. About 30 percent of the incoming radiation leaves the earth directly after reflection at the cloud, the dust particle, and the surface levels; about 70 percent is absorbed. Of the amount absorbed, approximately 83,000 TWyr/yr are found as sensible heat of air and water and 41,000 TWyr/yr as latent heat from the evaporation of water from the oceans and the wetland surface. This latent heat in the atmosphere is eventually released upon condensation. The absorbed solar energy finally leaves the earth in the form of infrared (heat) radiation.

The natural power flows generated by sunlight and by the two other sources in man's "direct" environment—that is, the thin boundary layers between the atmosphere, land, and the oceans—are much smaller than the direct energy transfer from sunlight. The continental runoff dissipates potential energy into heat via friction at a rate of only 5 TWyr/yr. Winds, waves, and the kinetic energy of ocean currents dissipate roughly 370 TWyr/yr, the majority being contributed by wind at high altitudes. The net conversion rate of solar energy to biomass is on the order of 100 TWyr/yr.

The second primary source of energy, geothermal energy, feeds a comparatively small power flow in the accessible environment. Through heat conduction, 35 TWyr/yr enter the atmosphere and the oceans from the bedrock of the earth. Only 1 percent of this amount comes by way of volcanoes or active geothermal fields through convection mechanisms, giving rise to significant temperature differences above the ambient conditions.

The third primary source, causing a still lower power flow, is the planetary motion in the solar system. Approximately 3 TWyr/yr are dissipated through tidal movements in the oceans.

Viewed against the background of these enormous flows from nature, renewable energy sources would seem able to contribute substantially to satisfying the world's thirst for energy and able to do so on an unlimited basis. But our ability to make use of these energy sources depends on the energy supply densities of the various forms, their locations, and the extent to which they can be used economically and without affecting climate and ecology systems significantly or diverting high value land from uses such as food production.

When such factors are taken into account, as will be discussed in this chapter, the technical potential of the renewables (not counting the direct solar heat that can be used at the point of collection) comes to about 15 TWyr/yr of secondary energy, as shown in Table 6-1. For direct solar heat that can be used at the point of collection, we came up with an additional

Table 6-1. Technical potential (as secondary energy) of renewable resources.

Type	*Power (TWyr/yr)*	*Comment*
Biomass	6	Requires cultivation of virtually all of the productive land of the world.
Hydroelectric power	3	A high quality product, equal to three times as much fuel; includes minor potential from glaciers.
Wind	3	High quality energy, but utilization must deal with difficulties of energy storage.
Geothermal (wet)	2	Much more stored heat is available for "mining," but technology is not available.
OTEC	1	Potential is greater if ocean heat can be diverted on a gigantic scale; still speculative.
Tidal	0.04	Very localized potential.
Waves and ocean currents	0.005	Minor quantities are available, but they do not add up to anything significant.
Total[a]	15	

[a]The additional technical potential of user-oriented direct solar heat was estimated at 2.2 TWyr/yr.

2.2 TWyr/yr. The term "technical potential" is intended to describe the upper limit defined when only technical constraints are considered. Environmental constraints and economic factors are not incorporated explicitly.

RENEWABLES ARE A MULTIPLE RESOURCE

This global potential of secondary energy indicates that renewable energy sources *collectively* should be given a similar consideration to that for fossil fuels, nuclear power, or centralized solar power. There is, however, one difference: This large sum does not come from a single source or from a single technology. Instead, it is derived by adding up a number of smaller sources and technologies. This affects our thinking in two ways that have opposing implications. On the one hand, it is easy to look at, say, only 1 TWyr/yr of wind power and conclude that it can make only minor contributions to solving world energy problems. Yet when this is done on a source-by-source basis, the promise of the renewable supplies can be lost in the statistical "noise" of the energy problem. On the other hand, when the addition has been made, it is all too easy to look at the total complacently, without realizing that to achieve the promise, it will be necessary to pursue not one, but a host of separate research, development, commercialization, and marketing activities different in both scope and character.

Among the renewables, biomass is especially important because it could be a self-renewing source of fixed carbon for use in producing liquid fuels. If economic obstacles can be overcome and ecological conditions satisfied, biomass eventually could play an equally important role in liquid fuel production as was discussed for coal in Chapter 3. This possibility, which is significant for the development of long-range energy strategies, is discussed later in this chapter.

Biomass

Of the approximately 100 TWyr/yr of fuel-equivalent biomass (net) produced from solar energy, about 23 TWyr/yr are fixed in swamps, grasslands, and tundras; 29 TWyr/yr in forests; 10 TWyr/yr in cultivated land; and the remainder in the ocean algae (Bolin 1979). Direct human food consumption is about 0.4 TWyr/yr (four billion people at 2000 kcal per day), while the consumption of animals is estimated crudely at 0.6 TWyr/yr. About 0.8 TWyr/yr could be withdrawn from forests as harvested wood (FAO 1975). We estimate about 0.7 TWyr/yr of the net carbon product is associated harvest from field and forest products that is returned to the soil. This would be the rate of production of agricultural and sylvicultural "waste" associated with human harvesting activity.

How much of this biomass can—or should—be harvested is a matter for speculation. In Europe, perhaps half of the total land that was available in primitive times is now being harvested, with acceptable levels of degradation of the biosphere. But for tropical forests, there are indications that even this much harvesting would bring about considerable soil degradation and a loss of photosynthetic potential. Thus we judge that a harvest of 40 percent of the 62 TWyr/yr of land biomass fixation would probably be the maximum that could be prudently cultivated. This is still an impressive 25 TWyr/yr. Of this, by the year 2030 a world population of eight billion people, double that of today, would require about 1 TWyr/yr to be in food (not food crops), 1 TWyr/yr in lumber and paper crops (producing between them about 2 TWyr/yr of "waste"). With these crops, there would be need for about 10 TWyr/yr of associated production in cultivated land. Under these subtractions, 25 TWyr/yr reduces to 11 TWyr/yr of available production, plus about 2 TWyr/yr of waste.

But even this amount cannot be exploited. Of this, at least half would be lost in collection and conversion processes: Some would be returned preferably to the soil as a conditioner; some (such as leaf and twig losses in forests or stubble in field crops) could not be collected. The efficiency of converting wood to charcoal is about 50 percent, the efficiency of converting sugar or cellulose to fuel is less than 30 percent, and so on. We therefore arrived at a total of 6 TWyr/yr of fuel, equivalent on the average to high quality coal, that would be technically available from biomass.

This implies a sophisticated, careful management of the "photosphere." The 6 TWyr/yr subsumes such uses as the formation of biogas from animal residues, the use of wood as fuel directly in villages and in forest product operation, and a residual fuel value of nonrecyclable waste paper and wood.

These may be important locally, and the use of wood as a cooking fuel in particular seems to double the amount of primary energy available. However, this last increment is illusory, as the efficiency with which heat is delivered to food that is cooked over wood is generally much lower than that using charcoal.

The technical potential of 6 TWyr/yr given for biomass in Table 6-1 therefore cannot be used commercially, because of the low quality of this fuel and because part of it would be consumed locally. Later, when we consider how much renewable energy could be employed as user-oriented sources, we identify the amount of biomass that could be diverted for such uses. Here, we state that 1.15 TWyr/yr of biomass would be used in poor rural areas; additionally, 0.8 TWyr/yr of forest products would be harvested noncommercially by individuals. A total of 1.95 TWyr/yr would be used locally, leaving 4.05 TWyr/yr of secondary energy to be commercially processed from biomass.

Hydroelectricity

Of the 5 TWyr/yr of mechanical power available from the continental runoff of water, no more than 3 TWyr/yr can be relied on technically. The remainder is considered technically unavailable for one of several reasons:

- Some fraction of the water flow energy must still be allocated to overcome the frictional losses of stream beds; otherwise, the water would evaporate without going downstream.
- A certain water velocity must be retained in natural stream beds in order to maintain riverine ecologies.
- Even if other uses of land and water were possible, it seems virtually impossible to channel all the water for hydroelectric power; some of the flow energy appears in myriad small streams at headwaters or in "lazy" rivers near their outlets.

Because of these aspects, even such advanced projects as the Tennessee Valley Authority (TVA) and the Bonneville Power Authority (BPA) in the United States actually capture much less than half of the runoff potential of their respective river basins, and it is unlikely that a larger fraction could be harvested anywhere else in the world. The potential of glacier power—that is, tapping the hydromechanical energy of glacier runoff (Partl 1977, 1979)—has been included in our total for hydroelectric power.

Wind

We estimated the technical potential of wind by considering the wind energy available at heights up to 200 meters above ground level. Geographically,we limited the areas to continental regions within 1000 km (on the average) of coasts running from 50° northern to 50° southern latitude. We excluded polar regions and high mountain, uninhabited areas. This exclusion may be considered an intrusion of the economic sphere on the technical potential, since at least for the generation of network electricity, it seems economically impractical to get the product competitively to the consumer.

There are a number of both pessimistic and optimistic assumptions in our estimate of the technical potential of wind power, which amounts to 3 TWyr/yr. On the pessimistic side:

- We assumed that the total capture of low level wind energy at coasts would create a several hundred kilometer zone of lower wind velocities in its lee. In other words, the windmills would act like a chain of low hills. Thus, we could not expect to capture more than the total low level wind energy entering the coast.
- We ignored the smaller contributions of winds in the interiors of continents.

On the optimistic side:

- We assumed that wind machines could be emplaced wherever the average wind fields are favorable, ignoring the difficulties of doing so in regions where these machines might be particularly vulnerable to destructive storms.
- We assumed that large wind machines can be used. As far as the technical potential is concerned, 200 meter wind machines capture more of the wind energy than do smaller machines.

Wind power (and hydroelectric power as well) generates high quality energy, and its product can be either electricity or stored mechanical energy (as with pumped water). To the extent that this high quality energy can be used, it is worth about three times as much as the same energy in low quality heat.

Geothermal Energy

It is useful to distinguish between wet and dry geothermal energy sources. Wet geothermal energy refers to steam or to hot water sources located near the surface that arise from anomalies in the earth's crust in a few areas of the world. The available temperatures of geothermal water or steam allow electricity to be generated at moderately low efficiencies compared with fossil- or nuclear-fueled electricity generation and to be used for many direct applications of low temperature heat, either domestic or industrial, provided the application is located near the source.

There are developments directed at using dry geothermal heat from deep boreholes (several kilometers) or from dry geothermal anomalies, but there will have to be more research before the difficulties of tapping this energy source are mastered. Moreover, the time required to deliver geothermal heat in quantity to a large body of rock, so as to heat it to useful temperatures, is large compared to the time over which that heat might be extracted. To be precise, this resource is really not a renewable one; like ocean thermal energy conversion (OTEC), it is an instance of natural heat storage rather than an actual heat flow.

Still the dry geothermal resource is very large. The total heat stored within the top 6 km of the earth's crust at temperatures above 200°C was estimated to be much greater than the energy content of all of the world's fossil fuel resources. Nonetheless, we did not consider this energy source in our estimate because, as already mentioned, we are awaiting the requisite development of a large-scale technology and because we cannot now say how much of the resource could ultimately be used. Other speculative resources, such as the geopressurized brines of the Gulf Coast of the United States, were also not considered.

Our estimate of the geothermal energy potential refers only to the wet heat sources that are known to exist in populated regions. Our starting point was the work of the Geothermal Resource Group (1979), which conducted studies of the geothermal potential of the United States, which seems to have a somewhat better than average resource of wet geothermal energy. Rapid development of U.S. resources could yield on the order of 0.7 TWyr/yr by 2010. The reference report did not consider resource depletion, but we assumed this power to be close to the maximum that could be extracted on a steady state. By multiplying by four to account for a whole world resource, we arrived at 3 TWyr/yr.

We also considered another estimate of geothermal potential (Wick and Schmitt 1977) that suggests a sustainable figure of 0.1 TWyr/yr of electrical power, corresponding to 0.5 TWyr/yr of heat, plus some tenths of a terawatt for direct application. From this, we might infer that up to 1 TWyr/yr of heat could be available. We averaged the two estimates to propose a technical potential of 2 TWyr/yr for wet geothermal heat.

Ocean Thermal Energy Conversion

Although OTEC would tap a heat source of very low thermodynamic quality, it would in principle provide access to extremely large quantities of such heat. OTEC is a speculative technique that requires a close look for two reasons. First, it could be a source of energy, once the technological difficulties were overcome. Second, through its analysis, we gain insights about how interferences with the mechanisms of the earth's system can be tolerated and are therefore in a better position to determine its technical potential.

We begin by reviewing the thermal phenomena of the oceans, as they form the basis for understanding how OTEC could perturb the global system for distributing heat energy. About 3000 TWyr/yr of solar energy is absorbed directly by the oceans, the largest part of this being in the equatorial zone between the two tropics. This heat is transported poleward by the giant ocean currents, such as the Gulf Stream and the Japanese (Kuroshiu) current. Almost all the heat is delivered to the atmosphere in the temperate and subpolar zones, which are thereby blessed with more moderate climates than would otherwise be the case. Some small fraction of the heat is delivered to polar seas, as a source of energy to melt ice. About 50 TWyr/yr is ultimately dissipated by convective mixing with cooler deep layers of the ocean (Wick and Schmitt 1977); it is this energy dissipation that at low efficiency is converted into the approximately 0.2 TWyr/yr of kinetic energy in the ocean currents.

To complete the physical description, we note a delivery of heat from the earth's mantle upward to the ocean as well. This geothermal energy is converted into chemical free energy in the ocean, but at such low efficiency as to be essentially dissipated. The depths of the ocean remain cool, in spite of heat deliveries, by the mixing of very cold saline waters from the polar regions, compensated in mass balance by the mixing of water across the thermocline.

Specific OTEC systems suggested in the literature transfer heat from the warm surface water of tropical or subtropical oceans directly to deeper cold water. The efficiency of conversion to electricity is extremely low—about 3 percent when the warmer tropical water is used exclusively. Technical difficulties in capturing all the heat in surface waters (owing mainly to the need to discharge water so that it is not drawn back into the system) limit the electric power capability to 0.25 W/m^2 of tropical ocean surface (ASA 1975). Taking the area of the tropical oceans to be 90 million km^2, this translates into a technical potential of 22 TWyr/yr of electricity and a diversion of 720 TWyr/yr from differentiated surface layers of the ocean to greater depths.

If all of the 720 TWyr/yr were subtracted from the heat transported north, the climatic impact would be severe. There would, of course, be compensating "induction" effects. For example, if the result were the cooling of the ocean currents, so that at the beginning of their poleward migrations their temperatures would be, say, 18°C instead of 25°C, they would lose less heat on their journey and pick up some more heat from the sun. Nevertheless, one would still expect a major impact.

There have been other experiments in which the rate of heat transfer across the thermocline was used to develop a yardstick for estimating the technical potential of OTEC (Wick and Schmitt 1977). The natural transfer between these two reservoirs is equivalent to a thermal power flow of 50 TWyr/yr across a temperature gradient of 12°C. Taking the same technical efficiency for OTEC systems as above, we arrived at a technical potential for OTEC systems of 1 TWyr/yr, only 4.5 percent of the nonequilibrium value of 22 TWyr/yr. In fact, harvesting this potential would be most practical at locations where cold water is warmed. These are regions of upwelling, with smaller available temperature differences and corresponding lower heat-to-electricity conversion efficiencies.

We are faced with a dichotomy between less than 1 TWyr/yr of electricity recoverable from possibly nonperturbing sources of OTEC and over 20 TWyr/yr of electricity that might be associated with large perturbations were OTEC deployed to exploit a natural energy storage reservoir, instead of simply diverting a natural power flow. We selected 1 TWyr/yr as the proper value to use for estimating the technical potential of OTEC for a number of reasons, not the least of which is that we shy away from schemes that would draw on the heat stored in all of the tropical ocean surface. Even 1 TWyr/yr would be a gigantic undertaking. And in view of the need to study the systematic side effects of going further, it appears to be a prudent upper limit at least for a few generations.

OTEC is an almost perfect example of the difficulties of arriving at responsible estimates for the global technical potential of renewable energy sources. It highlights the need for much more intimate knowledge of the hydrosphere, the atmosphere, and the ecosphere before these systems can be tapped on a grand scale. The problems of environmental disruption seem to depend as much on the amount of energy tapped as they do on the type. For some of the natural flows, the problems are more complex than they are for most types of manufactured energy.

Tidal Energy

From the total of 3 TWyr/yr of dissipated tidal power, a very small fraction is accessible for operating turbines: Only a few coasts have a form that would allow for the transformation of the kinetic energy of the global tide wave into sufficient tidal levels. In the few favorable coastal areas, the scarcity of basins for intermediate water storage—that is, natural bays that can be closed off by dams—reduces the technical potential of tidal power to a very low level on a global scale—about 0.04 TWyr/yr (Wick and Schmitt 1977; ASA 1975)

Ocean Currents and Waves

The contribution from ocean currents and waves is expected to be very small (0.005 TWyr/yr). As noted, the kinetic energy of ocean currents is only 0.2 TWyr/yr, and this kinetic energy plays a major role in shaping climates. Any significant harvesting of it therefore cannot be considered.

There are many schemes proposed for harvesting the energy of waves, particularly in the United Kingdom, where wave power is estimated as high as 8 to 9 GWyr/yr. The devices present problems, since they must be able to convert energy, with high efficiency, from 3 meter waves, while still being able to withstand the onslaught of 30 meter waves. This observation pertains essentially to all coasts where wave power has significant potential. No devices with this capability are yet in the offing.

USER-ORIENTED RENEWABLES

An important characteristic of renewable energy sources is that they allow a degree of user orientation and individual self-sufficiency; they can be collected and used directly at the point of collection. This characteristic applies principally to local uses of direct solar heat and biomass, and, to a lesser degree, to both hydroelectric and wind power. The user-oriented potential of direct solar heat was not accounted for in our estimate of the technical potential of renewable resources, although user-oriented applications were considered in estimating the individual potentials of biomass, hydroelectricity, and wind power.

User-oriented renewable energy sources are not limited to use in the developing regions and could also contribute greatly to the energy needs of an affluent society. In assessing their potential, we relied on the results of the case study, *Distributed Energy Systems in California's Future,* by the U.S. Department of Energy (1978). An objective behind this study was to get the maximum out of distributed, but not necessarily only noncommercial, energy sources. The study concluded that despite a twofold population increase and an increase by a factor of 3.1 in gross state economic product, California could become nearly self-sufficient in energy by 2025 by producing 0.13 TWyr/yr from biomass, wind power, solar heat, geothermal sources, and hydroelectricity. According to the California study a considerable conservation effort would be the prerequisite for achieving this energy self-sufficiency. Moreover, all biowaste from present forestry and agriculture, 50 percent of all noncommercial forests, and conversion of bush and grassland into wood plantation, as well as the installation of wind energy facilities over 6 percent of the state's land area, would be required, in addition to exploitation of the state's considerable hydroelectric and wet geothermal potential. Virtually all of the biomass would have to go for the production of liquid fuels that would enter the commercial distribution system for use as motor fuels and industrial feedstocks. Still, a shortfall of 0.023 TWyr/yr in liquid fuels persisted, and the suggestion was made to harvest "kelp farms" off the California coast in order to alleviate this situation. Central solar power plants would not be used; rather, electricity needs could be covered by integrating hydroelectric, wind, and wet geothermal energy into relatively large utility networks. This would be possible in spite of the projected rise of electricity's share in all energy end uses from the current 10 percent to 29 percent in 2025. Because of uncertain economics, PV systems were not considered.

In the California study, user orientation of renewable sources was observable only with regard to the use of insolation in the form of direct solar heat. The cogeneration of electricity was indicated whenever a solar heat source would be required to produce high temperature heat or steam. But not all of the produced electricity would be consumed locally; some would be distributed through the utility networks. Based on these findings, we assumed that in addition to the solar heat produced, one-third of the cogenerated electricity would be user oriented. We therefore ended up with an estimate of 0.052 TWyr/yr of solar heat and 0.002 TWyr/yr of solar electricity as user-oriented renewable energy sources that would be used either by the individual or the community that collects it. These numbers are, of course, for California only. What has to be considered here is the user-oriented contribution of direct solar heat to meeting the energy demands of all seven world regions defined in the IIASA study.

There is a rather quick but robust calculation that can provide a useful figure of orientation for the overall potential of user-oriented solar insolation. It is based on the observation that an area comparable to the available "roof surface" per capita should be indicative in assessing this potential, where the definition of "roof surface" is extended to include side walls and surfaces on which collectors could be mounted in the immediate neighborhood of the user. For the developed parts of the world—that is, regions I, II, and III—40 m^2 per capita turns out to be an accurate estimate of available roof area. Assuming that of the yearly average solar insolation in the middle latitudes, only about 40 W/m^2 can actually be collected, one arrives at a figure of 1.6 kWyr/yr per capita for user-oriented direct solar heat. Based on an expectation of a total population in these three regions of roughly one and a half billion people by 2030, we reach a potential of 2.4 TWyr/yr for user-oriented direct insolation. This value, it turns out, is quite close to that which was derived from a more careful extrapolation of the results of the California study—2.1 TWyr/yr of user-oriented solar heat and 0.08 TWyr/yr of cogenerated electricity.

For the developing parts of the world—that is, regions IV, V, VI, and VII—it is conjectured that most of the population lives in climates where there is little need for comfort heating in homes and offices. We therefore estimated a user-oriented direct solar heating potential in these regions of 0.1 TWyr/yr, with virtually all the solar energy going for hot water heating and excluding industrial possibilities for using solar heat. Thus, taking both developed and developing regions together, we obtain a global estimate of 2.2 TWyr/yr for the potential of user-oriented direct solar application.

We are now in a position to summarize how much of the 15 TWyr/yr of secondary energy from renewables has user-oriented applications in addition to the 2.2 TWyr/yr of direct solar heat. Table 6-2 shows that biomass has the largest potential. From the total of 6 TWyr/yr biomass available for harvesting, 1 TWyr/yr could be collected locally and used in the form of subsistence fuels such as charcoal and biogas, primarily in rural areas. In addition, user-oriented applications of charcoal and biogas in small-scale industry would amount to about 0.15 TWyr/yr, while local collection and use of forest products would contribute another 0.8 TWyr/yr. Thus, from the 6 TWyr/yr of biomass potential, 4.05 TWyr/yr would be left over for commercial applications.

The local generation and use of hydroelectric and wind electricity potential would be much smaller—about 0.05 TWyr/yr of electrical equivalent secondary energy each.

We observed limitations on the use of harvested renewable resources at or

Table 6-2. User-oriented supplies of renewable resources.

Technology Type	*Application*	*Energy Forms*	*Quantity (TWyr/yr)*
Insolation	Domestic and industrial heating	Low to medium quality heat	2.2
	Self-generated electricity (cogenerated)	Electricity	0.08
Biomass	Subsistence fuel[a]	Charcoal, biogas	1.0
	Small-scale industry	Charcoal, biogas	0.15
	Forest products	Industrial fuel	0.8
Hydroelectricity	Rural electricity	Electricity	0.05
Wind	Rural electricity	Electrical equivalent	0.05

Totals by Source Type	*(TWyr/yr)*	*Totals by Application Category*	*(TWyr/yr)*
Insolation	2.28	Electricity or equivalent	0.08
		Comfort and process heat	2.2
Biomass	1.95	Secondary industrial solid fuel	0.8
		Other secondary fuel	1.15
Hydroelectricity	0.05	Electricity or equivalent	0.05
Wind	0.05	Electricity or equivalent	0.05
Total	4.33	Total	4.33

[a]Although charcoal is the dominant secondary form, the "biomass" total for subsistence fuel also includes the more versatile form, biogas, as well as miscellaneous uses of wood, straw, and crop residues as fuel.

near their point of collection. Yet user orientation that allows the users to guarantee their own supply seems to indicate that the resource would actually be used and that the potential would be realized whenever possible.

Taking all the sources together, these tabulations indicate that, like the fossil fuels, renewable energy sources *collectively* have a promise for the year 2030 of the same order of magnitude as that of nuclear power. But, again like fossil fuels, the promise of the renewables does not continue to grow in the period after 2030 in the way that it does for nuclear power. One should neither underestimate the renewables, nor overstate their case. The 15 TWyr/yr of potentially realizable secondary energy from renewable resources and the 2.2 TWyr/yr additional energy from user-oriented direct solar heat applications must be looked upon as a figure to be used for exploring limits.

BIOMASS AND/OR COAL AS LIQUID FUEL

Earlier we alluded to the possible role for biomass in liquid fuel production; we now elaborate on this subject. After the "cheap" oil has run out, the next obvious step for getting a continued supply of liquid fuels is to use "dirty" oil. Following that step—or perhaps avoiding it—is the synthesis of liquid fuels from coal if environmental factors are favorable. But if we recollect that coal, too, is ultimately a depletable resource, albeit a very large one, we can speculate about what might happen when the coal runs out or is not used. At that point, the only available source of chemically reduced carbon would be biomass.

If eventually, why not now? Could biomass supplant coal sooner? Should we be looking harder at liquid fuels from biomass as a more desirable route than coal? We do not see any clear indication as to the preferable route. There are advantages both to coal and to biomass.

Coal's advantages are all intrinsically technological. Indeed, they are the same as those that led to the replacement of wood by coal during the Industrial Revolution, as was described in Chapter 3. The advantages of biomass are generally environmental and thus reflect more recent global concerns.

Vitiating the advantages of coal are two factors. First, the existing infrastructure of coal use is a decaying one. New life must be breathed into coal mining, coal hauling, and coal burning. Case studies dealing with the revitalization of coal use have shown that institutionally coal must be treated as a new industry. Second, with the shifts from burning coal directly to using it as a synthesis chemical, the amount of necessary preprocessing increases.

The advantages of biomass cannot be taken for granted either. Very large land areas are needed for a harvesting effort capable of ultimately providing up to 6 TWyr/yr of liquid fuels globally. Added to the needs of humanity for food and natural fiber, fully one-third of the biomass grown on land would then be under cultivation.

Even if we assume for biomass, as is recommended for coal, that allothermal methods be used so that the maximum of process heat and hydrogen is derived from nuclear and solar energy origins, then about 25 percent of all forests would have to be harvested. On the the other hand, the use of autothermal methods, such as fermentation or processes that rely on wood burning to produce heat and charcoal for further steps, would require a much larger number (about 40 percent). Harvesting even 10 percent of forest growth requires taking a step from ecological responsibility (always necessary) to ecological engineering. Time would be needed to achieve capabilities necessary to harvest 40 percent (or even 25 percent) of all forests in a truly benign way. For example, the introduction of fast-growing monocultures in an attempt to improve biomass yields and to achieve true "cultivation" of energy crops is an ecological risk that requires long experience to evaluate.

Our rather superficial study of how to make liquid fuels from biomass suggests that forests, rather than fields, are the more likely source and that chemical synthetic process routes (e.g., destructive distillation and oxidative hydrogenation to methanol) are more attractive than anaerobic fermentation routes (e.g., the alcohol route). In both these judgments, the chief concern is to have maximum yields of liquids so as to minimize both land requirements and particularly the intrusion of energy harvesting on land needed to grow food and fiber, to provide recreation, and to preserve natural habitats.

The wood-charcoal dichotomy for synthetic liquid fuel production should be studied in more detail. In particular, the conversion of wood to liquid fuels should be treated as a separate area of research involving both systems aspects and process development and under these circumstances, we cannot recommend for coal or for wood. Perhaps the biomass harvest would not be sufficient, but even if it were, we can expect different regions and countries would opt for one or the other: Coal supplies, the suitability of forests for exploitation, and the demand for imported liquid fuels would vary from place to place. And of course, we cannot discount the contribution of field crops such as sugar cane or grains to local liquid fuel supply or that of biogas to local gas supplies. There are and will continue to be opportunities of time and place for these sources, even though they are unlikely to loom large in the total energy picture.

Finally, in a philosophical sense, we should recognize that biomass and coal are part of a grand continuum—living biomass to dead biomass to peat to lignite to coal.At each step of the chain there is both a loss of carbon and a concentration of carbon. In looking for ways of substituting biomass for coal, we are really posing a challenge to human cleverness. Can we be more efficient than nature has been in turning biomass into concentrated energy supplies?

CONCLUDING REMARKS

There are numerous opportunities for renewable energy sources to be deployed successfully. The major question is not whether these exist, but how much they can actually contribute to the total energy demands of the world.

We assessed the upper limit, as determined solely by technical constraints, of renewable energy sources at 15 TWyr/yr of secondary energy and an additional 2.2 TWyr/yr of direct solar heat collected and used locally. This large resource of natural energy flows could be harvested, given reasonable extensions of current engineering capabilities. We outlined how each of these sources could be utilized in the future and have stretched our thinking to see a possible role for biomass in liquid fuels production.

Collectively, the potential of renewable energy sources is comparable to that of fossil resources, of solar energy, and of nuclear power in 2030, although it does not grow in the period after 2030 in the way that the nuclear and solar potentials do. Each and all of these supply options could provide large amounts of energy in the future, although none is homogenous and the realization of each of these potentials is contingent upon, among other things, technological progress. But renewable energy sources are distinct in that their potential is large only if we consider the sum of smaller, individual sources. To be sure, individually the contribution of most of these sources would not be significant, and it would be all too easy to dismiss them. But by so doing, we would err in not seeing a valuable, supportive role for these nondepletable sources.

Our estimates of what can be realized for renewable energy sources presupposes the fulfillment of two major conditions. First, they must be used in conjunction with other energy supply systems that would still be needed to provide reserve supplies and baseloads in grids and/or to supply poorly endowed regions and districts. This will ensure stability and resilience of the total energy system. Second, the use of renewable sources represents a large potential ecological disturbance: To consider relying on them to provide a substantial fraction of our energy supplies is to contemplate undertaking active ecological management of an awesome scale. We could no longer describe ourselves as simply caretakers of our environment—"redesigners" would be a more accurate term.

Considering, for example, that the average density of wood production in the global forests was 0.2 W/m^2 in 1975 (Revelle 1975), using biomass at a level of even 6 TWyr/yr would correspond to managing 30 million km^2 of forests. Extending our consideration to include all the renewables discussed in this chapter, 15 TWyr/yr would correspond to an area of 75 million km^2 (0.2 W/m^2 is, in fact, a good rough estimate of the average density for the renewables collectively, excluding direct solar insolation.) If this land area is compared to the 13 million km^2 of land currently devoted to agriculture, the enormity of such an undertaking becomes clear. It means managing the habitats of thousands of species, and it means dealing with more familiar problems on an unprecedented scale—problems of soil erosion, managing water systems, the stabilization and management of the nitrogen cycle and the phosphorus cycle, and the decreasing resistance of cultured plants against pests. It means operating a worldwide herbarium.

Whether we will be in a position to accept the responsibilities of the task is hardly clear. At the very least, a global ecological monitoring and control system would be required, and this, in turn, would have to be based on much improved knowledge of how the natural energy flows affect the globe—a knowledge that can be gained only by a commitment to large-scale research in the pertinent disciplines.

Thus, although each individual energy option, be it fossil, nuclear, hard solar, or the collection of renewables, promises much more energy than current global requirements, realistically, probably none of the opportunities will be fully realized in the next fifty years. In Chapter 8, where we present the results of two global scenarios for the year 2030, along with their underlying quantitative analysis, we will show to what extent these various supply opportunities might contribute realistically to the future global energy system. But before turning to that analysis, we next consider in detail the particular constraints that might prove most severe in limiting the degree to which the technical potentials of the fossil, nuclear, solar, and renewable energy options can be realized.

REFERENCES

ASA. 1975. *Energiequellen für morgen? Nutzung der Meeresenergien. Part IV.* Report of the Bundesministerium für Forschung und Technologie durch das Programm "Angewandte Systemanalyse in der Arbeitsgemeinschaft der Grosforschungseinrichtungen." Frankfurt: Umschau Verlag.

Bolin, B. 1979. Global Ecology and Man. In *Proceedings of the World Climate Conference* (February 1979), pp. 24-38. Geneva: World Meteorological Organization.

Food and Agriculture Organization (FAO). 1975. *Yearbook of Forest Products, 1964-1975*. Rome.

Geothermal Resource Group. 1979. *Geothermal Resources and Technology in the United States*. Report of the Geothermal Resource Group, Supply and Delivery Panel of the Committee on Nuclear and Alternative Energy Systems. Washington, D.C.: National Research Council, National Academy of Sciences.

Partl, R. 1977. *Power from Glaciers: The Hydropower Potential of Greenland's Glacial Waters*. RR-77-20. Laxenburg, Austria: International Institute for Applied Systems Analysis.

——. 1979. Hydropower Potential of Glacial Waters in Greenland. Paper presented at the UNITAR Conference on Long-Term Energy Resources, November-December 1979, Montreal.

Revelle, R. 1975. Energy Use in Rural India. *Science* 192:969-75.

U.S. Department of Energy. 1978. *Distributed Energy Systems in California's Future*. Vols. 1 and 2. Interim Report. HCP/P7405-01. Washington, D.C.

Wick, G.L., and W.R. Schmitt. 1977. Prospects for Renewable Energy from the Sea. *MTS Journal* 11(586):16-21.

7 CONSTRAINTS: THE THINGS THAT HOLD US BACK

In exploring the potential of each of the supply options, we observed that in reality it was highly unlikely that we could drive any of these supply systems to their theoretical limits, for we were continually made aware of the problems that could arise as these systems gained momentum. Collectively, we dealt with these as constraints. Simply stated, any endeavor, no matter how benign seeming, encounters real limits or negative feedbacks.

Moreover, all large systems exhibit inertia at all stages, owing to physical resources, capital acquisition, social acceptance lags, social and political infrastructures, and the like. If any and all of these systems were pushed too far, their effects on our land, water, materials, manpower, and climate could perhaps assume such large proportions as to limit the growth of the systems. Concomitant risks, as well as benefits, would also be magnified as these systems grow in size and numbers to the point where the risks would have to be viewed comparatively, so that societies could choose among them. It is a foregone conclusion that any and all systems and human activities pose some risk.

Thus, in the spirit of science, we looked at theoretic limits, and at the same time, in the spirit of practicum, we look at how some of the world might respond to those proposed systems and their extensions. Wherever possible, we quantified these constraints and used them in the design of our two scenarios for global energy demand and supply by the year 2030, which we report on in Chapter 8. For example, the buildup rates of new energy technologies entered directly into our scenarios.

Here, we summarize four types of constraints that we believe act as reins on society's capabilities for energy supply. These are market penetration, climate, WELMM (Water, Energy, Land, Materials, and Manpower), and risk. One important constraint is omitted here—that imposed by economics. The cost of energy supplies according to various criteria is, of course, important for determining which option to adopt and to what extent. We treat economic parameters as a major criterion of balancing supply and demand in Chapter 8.

Large-scale changes in global energy consumption patterns do not occur overnight, and time thereby becomes a significant (if not the most crucial) constraint on any new type of energy system that is to be deployed. Therefore, we look first at "market penetration."

MARKET PENETRATION: THE CONSTRAINT OF TIME

Throughout our examination of the potential of various energy supply options, time was found to be *the* factor limiting the full deployment of any system. Public and private support can advance development up to the point of prototype and demonstration plants; thereafter, a different set of factors is responsible for allowing a new energy technology to take over and replace an older, established one.

In our studies of the patterns of how new energy technologies may arise to substitute for others, we used a method that embraces the entire global system of primary energy consumption, testing this against three hundred individual cases concerning different energy subsystems in sixty different data bases encompassing thirty countries, over a long historical period from 1860 to 1975. Our findings reveal a regular pattern in the substitution of one source for another over decades.

According to Cesare Marchetti and Nebojsa Nakicenovic (1978) of IIASA, forms of primary energy resemble the behavior of different technologies competing for a market. Broadly speaking, they are commodities competing in the market in the same way as, say, steel production technologies and household detergents. We are indebted to the pioneering work of E. Mansfield (1961) and to the many extensions of his theory of technological substitution, mostly notably that by J.C. Fischer and R.H. Pry (1970).

One of the problems of analyzing periods of one hundred years or more is posed by the underlying inconsistencies and gaps in the recorded data. Still, our substitution model is robust in that it produces stable estimates of so-called "takeover times" that are relatively constant for any given system and that extend over several decades.

The substitution rates that are evident with the substitution model can be characterized by the notion of takeover time—that is, the hypothetical time it would take a certain energy form to increase its market share from 1 to 50 percent. In general, the smaller the region or the country, the shorter the takeover time. For the European member countries of the Organisation for Economic Cooperation and Development (OECD), it has taken roughly thirty years for a new energy source to conquer 50 percent of the market. For the United States, the figure is seventy to eighty years, while for the world as a whole, about one hundred years are needed.

Figure 7-1 illustrates the remarkable regularity of the substitution process in the global primary energy market for five major resources—wood, coal, oil, natural gas, and nuclear energy. The outline in Figure 7-2 of the primary energy substitution pattern for the United States brings order to the welter of statistical data for the period 1860-1974. One sees that the process is smooth and rather fast until 1920: Coal peaks around that date, and oil about forty years later. If the projection had been based on data covering only a few decades around the year 1900, both of these peaks could have been anticipated much in advance. Thus, the peaks should not be associated solely with events such as wars, economic depression, or the recent oil embargo; for most of the other cases examined, these events produced only small deviations from the long-term substitution paths.

What cannot be explained by our model is the drop, during the Depression years, in the relative consumption of coal below the long-term substitution path, nor can we account for the corresponding increase in the use of oil while natural gas consumption remained essentially unaffected. Interestingly, by the 1940s these irregularities are "absorbed," and the overall system retains the long-term substitution patterns established at the beginning

Figure 7-1. Global primary energy substitution. Logarithmic plot of the transformation $f/(1-f)$ where f is the fractional market share. Smooth lines are model estimates of historical data; scattered lines are historical data; straight lines show the logistic model substitution paths.

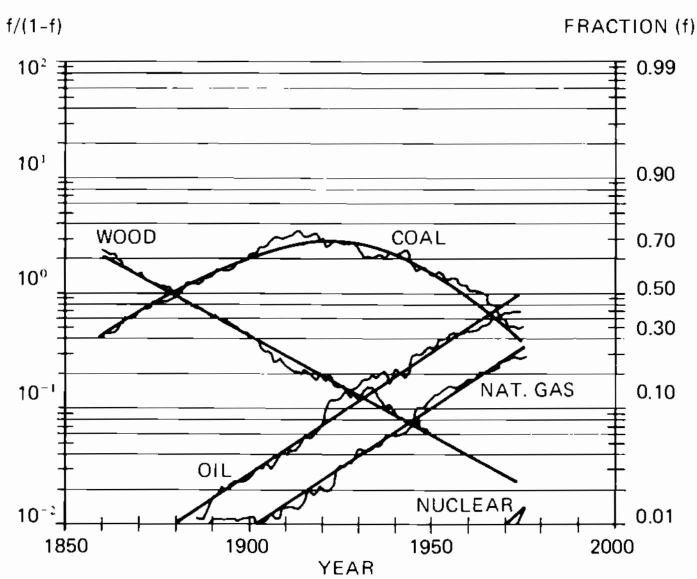
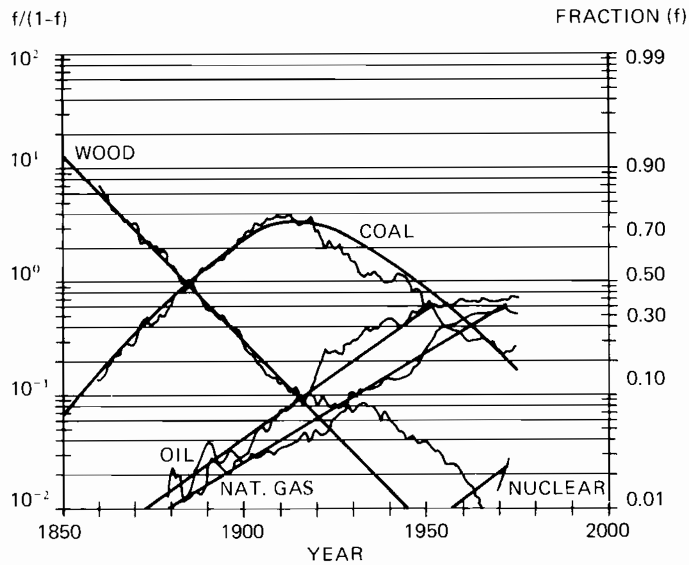


Figure 7-2. Primary energy substitution, United States. Logarithmic plot of the transformation $f/(1-f)$ where f is the fractional market share. Smooth lines are model estimates of historical data; scattered lines are historical data; straight lines show the logistic model substitution paths.



of the century, in spite of a perturbation that lasted some twenty years. We view this as an indication of the strong internal structure of the substitution process and of the rigid timetable that the system follows, largely independent of outside influences.

Related to takeover times is the concept of "buildup rates." As we studied the dynamics of how new technologies replace old ones, we observed that the new technology generally requires a long time to capture a sizeable part of the total energy supply market. The buildup rate may be defined as the exponential growth rate of the new technology in absolute terms as it grows from 1 to 10 percent of the market it serves. Table 7-1 gives the market penetration rates and the buildup rates of the five primary energy sources identified above. The buildup rates in this table have been estimated from model parameters rather than from historical data because of the often erratic behavior of the actual data when new technologies are just beginning to satisfy a share of supply. In the United States, for example, the buildup rate for nuclear power has been especially fast.

We consider it worthwhile to use our substitution model for exploring the market penetration constraints affecting the evolution of two "new" primary energy technologies in future energy systems—namely, solar and nuclear power. Both the starting points and the growth rates of these energy technologies were assumed exogenously for this exercise. The results are illustrated in Figure 7-3 and summarized below.

Table 7-1. New technology buildup rates.

	Technology	*Penetration[a] Rate (%/yr)*	*Buildup[b] Rate (%/yr)*
World primary energy supply	Oil	4.9	6.8
	Natural gas	4.8	6.8
U.S. primary energy supply	Oil	5.3	7.7
	Natural gas	4.5	7.0
OECD-Europe primary energy supply	Oil	10.0	13.3
	Natural gas	15.7	20.7
	Nuclear	6.9	10.4
U.S. inputs to electricity supply	Nuclear	31.0	36.0

[a]Penetration rate is the annual growth rate of the market shares $f(t)$ expressed as $\ell n\ f(t)/(1-f(t))$.
[b]Buildup rate is the exponential growth rate of the new technology in absolute terms as it grows from 1 to 10 percent of the market it serves.

- Nuclear power would begin to penetrate the primary market in 1979 at a commercially significant rate of 2 to 3 percent and, by 2030, would have increased its share to 40 percent.
- The entrance of solar energy into the market on a commercially significant scale would begin only in 2000, and assuming a growth rate the same as that for nuclear energy, solar would have a market share of 7 percent by 2030.

Figure 7-3. Global primary energy substitution, 1860-2030. Logarithmic plot of the transformation $f/(1-f)$ where f is the fractional market share. Smooth lines are model estimates of historical data; scattered lines are historical data; straight lines show the logistic model substitution paths.

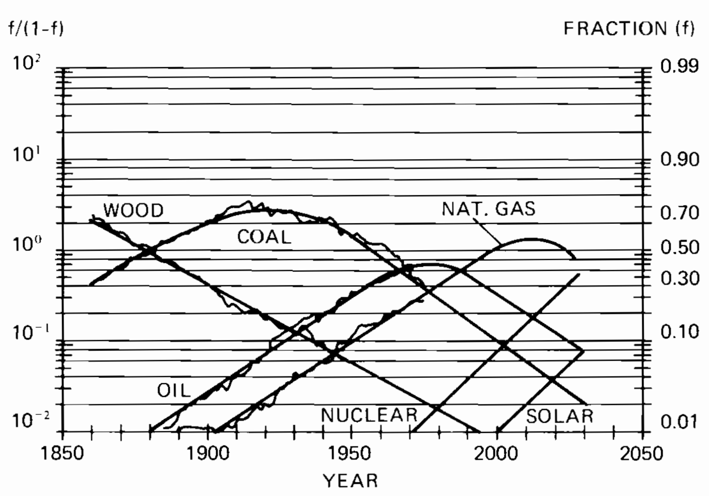


Figure 7–3 also indicates that natural gas would take on an ever-increasing share, reaching a peak of almost 60 percent around 2015 and declining thereafter. We do not find it too surprising that natural gas would hold such a high share at the beginning of the next century, since both conventional and unconventional gas reserves are large, and it is not inconceivable that the problem of long-range transportation of gas could be resolved by that time. Then too, as we point out later in Chapter 8, if there were a moratorium on the use of nuclear energy, gas would be called upon to play an even larger role than these figures project.

What do these figures tell us about solar and nuclear energy in the decades ahead? In our consideration of the nuclear option in Chapter 4, we saw that there would probably be an upper limit to the deployment of nuclear energy due to the problems of building up the nuclear system to the point where it could contribute more than 47 percent of primary energy. Accordingly, a 40 percent contribution by nuclear energy by the year 2030 based on our market penetration technique is within this range and thus consistent with these projections.

For solar energy, a 7 percent contribution in 2030 is probably much less than many people would hope for from this resource. We note, however, that a 7 percent solar contribution to a low energy demand world of, say, 22.4 TWyr/yr (as projected in the IIASA Low scenario) would be the equivalent of 1.6 TWyr/yr or 22 million barrels of oil per day (mbd), which is the total oil produced in 1975 in the Middle East and Northern Africa. This is a large undertaking when viewed in absolute terms.

We do not regard these observations as definitive forecasts. Yet they do tell us something about what to expect of the global energy system. Regional or local systems might more easily be made to behave differently.

In sum, the substitution model reveals the very ponderousness of the energy system—that is, the regularity of its evolution. This tends to confirm that because of the long lead times for introducing innovations and the long response time of the energy system, decisions taken today would have their full effect only in the decades to come.

CLIMATIC IMPACTS OF ENERGY ACTIVITIES

Energy and climate interact in several ways. The by-products of energy conversion—such as waste heat and carbon dioxide (CO_2)—can influence climate. In the other direction, climate influences the demand for energy—for example, changes in temperature affect requirements for heating and cooling. Also, climate can influence the supply of energy, especially with respect to solar power, wind energy conversion, and hydroelectric power.

The impact of energy systems on climate has received increasing attention recently as awareness of man's potential to alter the earth's climate has developed, as knowledge of the complexity and sensitivity of the climate system has increased, and as local and regional changes have been observed because of pollution. For example, temperatures in winter in urban areas are generally 2 to 3°C warmer than those in the surrounding countryside. Increased levels of CO_2 and other particles in the atmosphere, coupled with other energy-related effects on wind, have formed a haze over many of the large metropolitan areas that is decreasing the amount of sunshine they receive. Likewise, urban industrial pollution is believed responsible in large part for increased amounts of rain and snow in surrounding areas, even at distances of, say, 1000 km.

So far only local and regional meteorological changes have been ascribed to man's energy activities. But there could also be a global climate problem associated with increased levels of CO_2 concentration in the atmosphere if fossil fuels continue to play a dominant role in energy systems. The amount of CO_2 in the atmosphere is known to be increasing and, through the so-called greenhouse effect,[a] may be affecting the climate system. It would therefore be unwise to dismiss the possibility of undesirable and perhaps irreversible changes in the global climate pattern in light of the large-scale use of energy technologies projected for the coming decades.

Our examination of the various energy supply options showed that only two primary sources—namely, fossil fuels and nuclear power—have the potential for meeting a large fraction of the global primary energy demand over the next few decades, though looking farther into the future, there is the potential for solar power and the other renewable sources to gradually begin to cover a significant portion of demand. An understanding of the possible climatic implications of large-scale deployment of each of these resources is therefore important for determining which strategy should be deployed and at what level. For the different options we considered the possible climatic impacts of (1) substantial increases in the atmospheric concentration of CO_2 and of other gases and particles, (2) large-scale waste heat releases, particularly when concentrated in certain areas, and (3) major changes in the surface characteristics of the earth. Before we report on our investigations, it may be useful to describe the interactions of energy and climate and to define the climate system (see the accompanying boxed material and Figure 7-4).

Gaseous and Particulate Releases into the Atmosphere

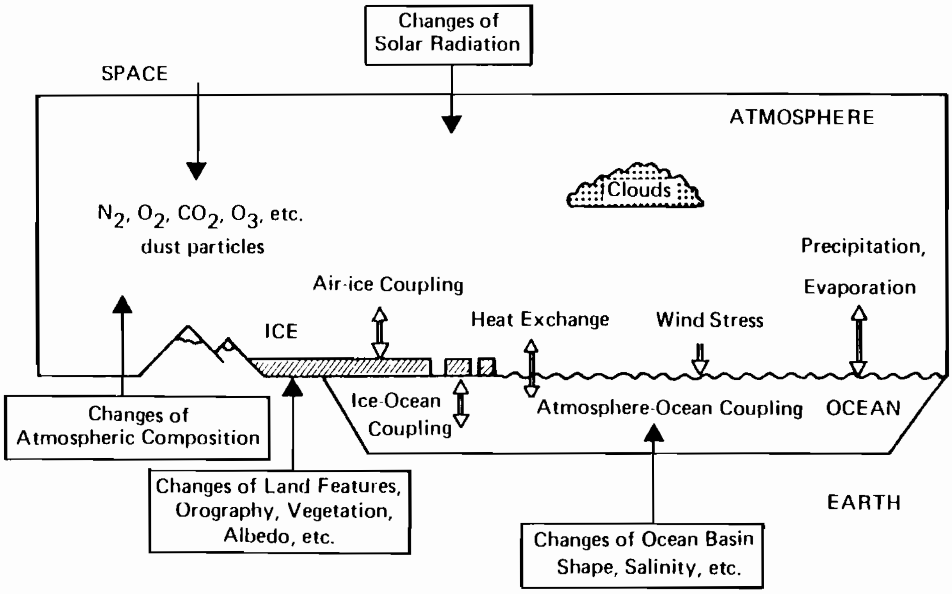
Fossil fuel combustion produces gaseous and particulate substances that could interact significantly with the climate system. These include CO_2, nitrous oxide (N_2O), methane (CH_4), ammonia (NH_3), freons, and other compounds that have potentially deleterious effects. All of these were considered, with the question of the effects of the buildup of carbon dioxide in the atmosphere receiving the most attention.

[a]The gas is virtually transparent to incoming solar radiation but absorbs longwave radiation coming from the earth's surface and reradiates some of it back to the surface. This is referred to as the greenhouse effect, although the analogy is not perfect; it is more like a "blanket effect." An increase in the concentration of the gas in the atmosphere would give an increased earth surface temperature with all other factors remaining constant.

As can be seen in Figure 7-4, the climate system consists of the atmosphere and four subsystems—the ocean, the cryosphere (ice and snow), land, and the biosphere. The arrows in the figure indicate how these components interact through a wide variety of processes (e.g., evaporation from land and ocean surfaces into the atmosphere, wind stress on the oceans). Historical data indicate that climate has varied and continues to vary on time scales ranging from short periods (season-to-season, year-to-year) to geologic time (millions of years).

Energy conversion systems can influence the climate system in three ways. First, all energy, after passing through various conversion processes, is ultimately released to the environment as waste heat. Second, the burning of fossil fuels adds certain gases and particles to the atmosphere. These can either alter the amount of solar radiation that is absorbed, scattered, or emitted by the atmosphere or by the earth's surface, or they can alter the amount of other gases in the atmosphere. Third, large-scale changes in the characteristics of the earth's surface, such as its reflectivity, roughness, moistness, or the temperature of the ocean surface, could cause climatic changes.

Figure 7-4. The climate system. Reproduced from *Understanding Climatic Change*, 1975, with the permission of the National Academy of Sciences, Washington, D.C.



We used a carbon cycle model and a climate model, hypothesizing several different energy strategies for the future use of fossil fuels for the period up to the year 2050. The results of our studies are subject to many uncertainties, owing mainly to lack of information about how much CO_2 could result from the destruction of the biosphere (e.g., from deforestation). Nevertheless, they do point to the magnitude of the CO_2 problem.

For one of these strategies, in which fossil fuels supply all of the world's energy consumption of 50 TWyr/yr by 2050 (see Figures 7-5 and 7-6), the average global temperature increase was 2°C by the year 2030 and 4°C by the end of 2050. For another strategy, global energy consumption by 2050 was set at 30 TWyr/yr, with fossil fuel use peaking around the year 2000 and declining thereafter to the level of 3 TWyr/yr by 2030 and solar and/or nuclear energy being used to fill the supply gap (see Figures 7-7 and 7-8). In this instance, there would be only a 0.5°C global temperature increase, beginning after 2030.

In order to gain perspective on how large a change this would be and what possible climatic effects it might have, we compared these changes with average global temperature changes over historical and prehistorical periods. An increase of 0.5°C would be perceptible, whereas a warming of 1°C would be equivalent to the increase in the earth's temperature that occurred after

Figure 7-5. Hypothetical 50 TWyr/yr fossil fuel strategy. *Source:* Based on data from Niehaus and Williams (1979).

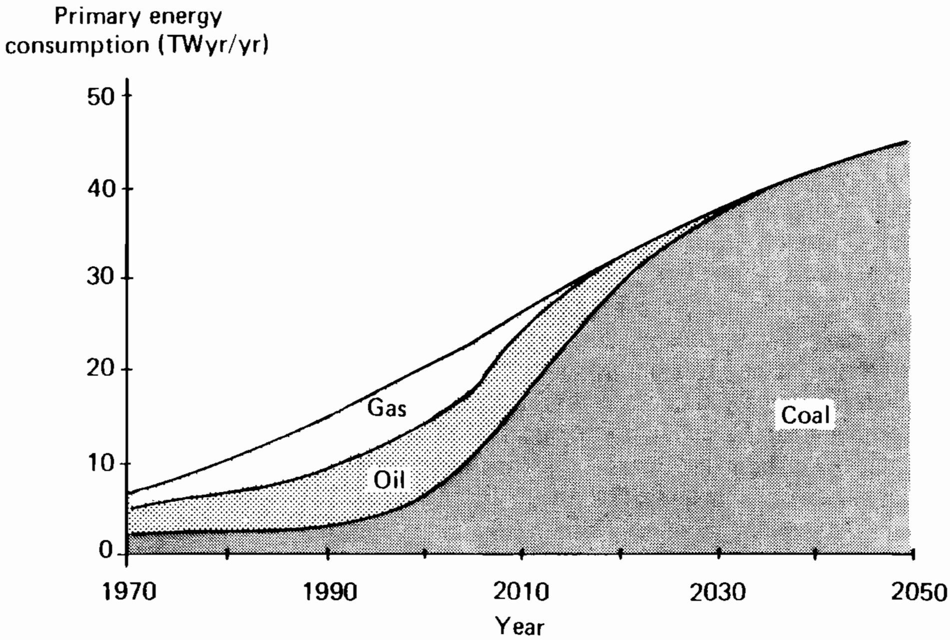
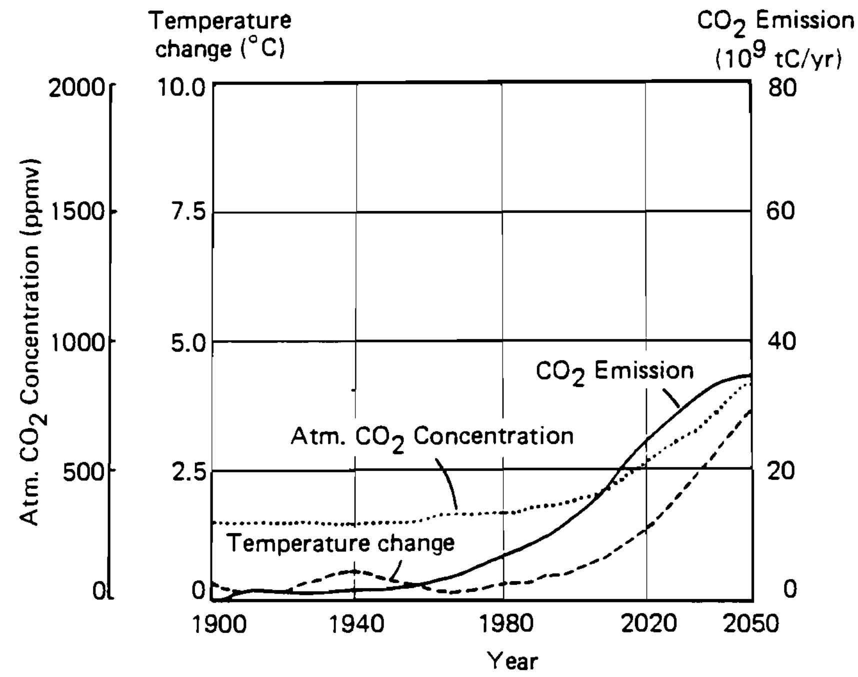


Figure 7-6. CO_2 emissions, atmospheric CO_2 concentration, and temperature change for 50 TWyr/yr fossil fuel strategy. *Source:* Niehaus and Williams (1979).



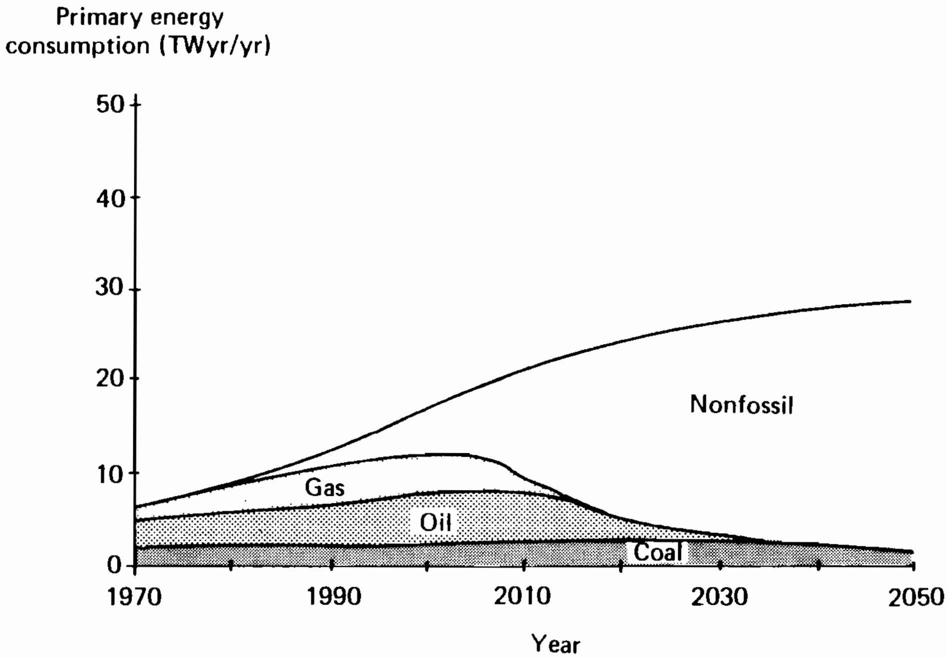
the last glacial period some 5500 to 6500 years ago; a 2 to 5°C increase would be equivalent to the temperature increase during the last interglacial period, about 125,000 years ago. Of particular concern was our observation that a warming of 4°C could lead to the situation where the ice covering the lands in polar regions would melt, with resulting increases in sea levels that would flood most of the world's coastlines. The changes at regional levels will be much larger in certain areas, with resulting changes in precipitation patterns and particularly in regional agricultural practices. Although these results may be welcomed in certain areas, they are likely to be viewed negatively in many more places.

The release of particulate material, especially that of sulfur and nitrogen compounds to the atmosphere, is also of concern, and has been observed to affect local condensation and precipitation patterns as well as the albedo of clouds. But until more data are available, it is difficult to determine what effects they might have on global climatic patterns.

Waste Heat Releases

Although present understanding of the climate system is not sufficient to reliably predict potential climatic changes attributable to waste heat releases

Figure 7-7. Hypothetical 30 TWyr/yr solar and nuclear strategy. *Source:* Based on data from Niehaus and Williams (1979).



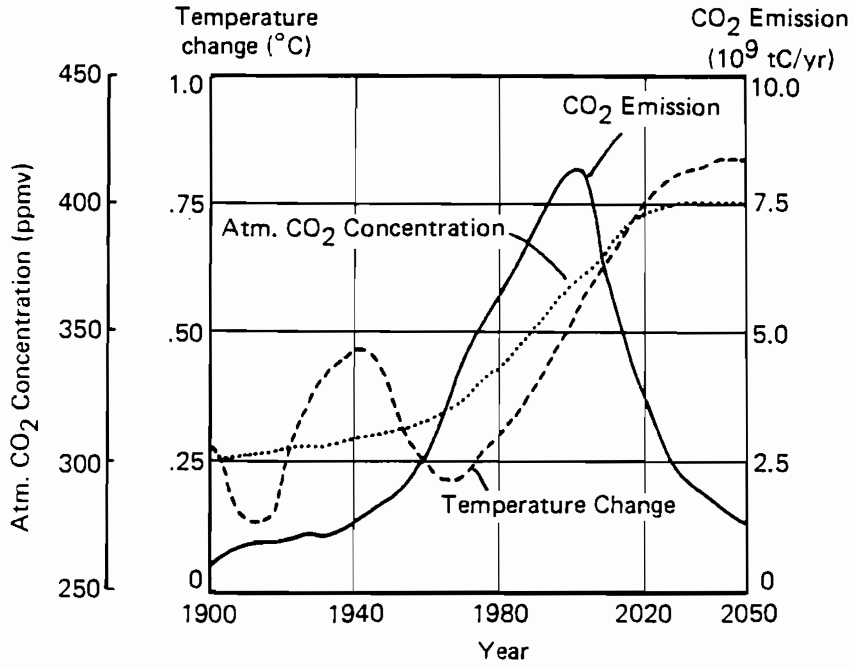
associated with different energy strategies, there are three methods for estimating these impacts. First, one can look at how the climate system has responded to natural anomalies and "predict" the impact of manmade perturbations by analogy. For example, the response of the climate system to large-scale anomalies in sea surface temperature could be taken as an analogy for the response to a widespread area of waste heat release. Or, on a smaller scale, the local meteorological effects of an ocean island heated by the sun could be taken as an analogy for the local effects of a power station.

A second approach is to use information on climatic history. For example, climatic areas in the past when the world was warmer than at present could provide the basis for scenarios of future climates due to manmade warming. Unfortunately, both of these approaches suffer from a lack of data and from questions of interpretation.

A third approach is to use models of the climate system to examine the sensitivity to manmade perturbations. A hierarchy of climate models exists, ranging from simplified models that essentially describe the energy balance of the system to complicated models that numerically describe the three-dimensional atmospheric circulation. It is models such as these that formed the basis for the results described here.

The amount of total waste heat released in 1975 as a result of the use of

Figure 7-8. CO_2 emissions, atmospheric CO_2 concentration, and temperature change for 30 TWyr/yr solar and nuclear strategy. *Source:* Niehaus and Williams (1979).



some 8.2 TWyr/yr of primary energy globally is about one-ten-thousandth of the solar energy absorbed by the earth's surface. Of course, with the projected doubling of the world's population over the next fifty years, more energy would be consumed, and larger waste heat releases would occur. In order to determine the effects of such increases on climate, we used a general circulation model that simulated the impact of heat inputs on atmospheric circulation and thereby on climate patterns. The model explored incremental annual energy releases globally, ranging from 30 to 300 TWyr/yr with the energy being released in limited geographical areas (440,000 km^2) located in the oceans of the northern hemisphere.

The results of our atmospheric model studies, and those of others (Krömer, Williams, and Gilchrist 1979; Llewellyn and Washington 1977; Murphy et al. 1976; Washington 1971, 1972; Williams, Krömer, and Gilchrist 1977a, 1977b, 1979), suggest that waste heat is a nonproblem on the global scale, in that it is unlikely to perturb the global average climate state in the foreseeable future. Only when extremely large amounts of heat (several hundred terawatts) are released in small areas do any significant changes begin to appear. Thus, we conclude that with a primary energy consumption level of 30 to 50 TWyr/yr, there appears to be little or no ground for concern regarding the global climatic impact of waste heat release. This is not to say that regional changes would not occur with waste heat emission from an energy supply of 20 to 50 TWyr/yr.

Large-scale Solar Energy Deployment

If solar energy is to meet a large fraction of man's energy needs at some time in the future, it would be able to do so mostly through the use of large, centralized hard solar systems such as those based on STEC and PV applications. Although soft solar energy conversion systems, such as wind, wave power, hydroelectric power, biomass, and OTEC can be used locally in favorable situations, they are expected neither to contribute greatly to the global energy requirement nor to affect the global climate.

From a review of the sparse literature and from our experiments (jointly with the Stanford Research Institute) on possible climatic impacts of STEC facilities, we feel safe in saying that the full-scale deployment of both STEC and PV systems will probably lead to regional climate changes, such as more humid air, increased precipitation, and increased cloud cover over cities. Again, certain regions would benefit from these altered climate patterns, while others would find such changes a hardship. More research is required on a range of STEC capabilities and their effects on different climatic conditions in different regions in order to provide factual guidelines for regional planning, especially of agricultural activities.

The global scale climatic impacts of STEC and other large solar systems are of concern for a more distant future, since large solar systems will probably not reach a high level of deployment—say, in the tens of terawatt level—until sometime in the latter half of the next century. This applies to both the hard systems mentioned in Chapter 5 and the soft ones included in our discussion of renewable energy sources in Chapter 6.

Policy Implications

Probably the most severe climate problem is the buildup of carbon dioxide in the atmosphere. In view of the present uncertainties in quantifying the effects of this gas, it seems premature to recommend only energy strategies that actively discourage the use of fossil fuels. Still, it would be unwise to build future energy strategies that continue to rely greatly on the uses of fossil fuels. A prudent policy, in our opinion, would be to maintain flexibility by having sufficient nonfossil options incorporated in the global energy supply system over the next few decades so as to allow expansion from that base, if necessary, as the effects of carbon dioxide become better known. A period of five to ten years is needed, and can probably be afforded, for vigorous research to narrow the uncertainties sufficiently, in order to be able to decide whether there should be a major shift away from fossil fuels because of the climatic implications.

CONSTRAINTS ON BUILDING BIG SYSTEMS: THE WELMM APPROACH

Another way of appreciating the magnitude of the tasks of building large energy systems is to trace all the stages of their development from raw resource to final energy use. To be sure, the value of an energy technology cannot be determined solely on the basis of resource availability. Energy resources generally go through at least one stage of processing from their primary state to the final state where they can provide the desired energy service at the user end.

Resource processing involves the use of other resources, as we illustrate here for the case of coal. The mining of coal can interfere with surface or underground water resources. Water is also required at a later stage for reclaiming the land that has been disturbed. Energy in the form of, say, electricity or motor fuel is also required for coal mining, to blast and remove the overburden and/or the coal and to transport the coal. Whether coal extraction is underground or, still more, open cast, a severe burden is imposed on the land used and on the landscape, although such disturbances are becoming more temporary. Materials handling is another problem that is encountered with coal mining, not only for the handling of the coal (or mineral) being gained but also for the overburden, the sterile rocks, and the like. The deeper the deposits exploited by surface mining, the larger the amount of materials to be handled, in addition to the water. And of course, all these operations call for manpower.

What has been briefly shown here for one operation—mining—and for one energy resource—coal—is applicable, at different levels, to other operations of all activities in the energy chain—that is, transportation, conversion, distribution, utilization—or to other energy resources, be they oil, gas, uranium, or renewable resources such as solar, tides, and wind. Although the use of processed energy resources calls for the use of other natural and human resources, it should not be such a burden on these other resources that it would create acute shortages and thus constrain the growth of the energy technology.

We categorized these constraints collectively under the acronym WELMM that denotes a systems analytic method for identifying the requirements of Water, Energy, Land, Materials, and Manpower for different technologies and energy resources exploration and for determining their availability in different parts of the globe. Two types of data bases were used, one detailing WELMM requirements for the buildup and operation of typical energy facilities, such as coal mines, oil fields, and power plants; and the second containing information on the potentially available WELMM categories of resources in different geographical areas.

Electricity Generation

WELMM comparisons at the global level were done for several electricity supply chains (Grübler and Cellerier 1979) and for different production processes for synthetic liquid fuels (Grenon, Merzeau, and Grübler 1979). The results of these studies are examined in detail in the following sections.

A WELMM comparison was made of electricity-generating chains, each chain being defined as a set of energy facilities needed to extract, upgrade, transport, and convert the primary energy into electricity. Nine chains were compared for producing the same amount of electricity, 6.1 TWh/yr, each with a thirty-year life span: Four chains produce electricity from coal, three from nuclear power, and two from solar power. The major characteristics of these chains are given in Table 7-2 and summarized below.

Coal 1 and Coal 3 reflect the present status of the technology, whereas Coal 2 and Coal 4 represent an advanced technology and meet environmental standards. Coal 1 and Coal 2 operate with an underground coal mine, and Coal 3 and Coal 4 operate with a surface mine with a stripping ratio of 2:1. The power plant in each of these cases is a unit of 1000 MW(e) of installed capacity.

One of the LWR chains is an extreme case because of the assumed low uranium ore content, but we considered this the maximum amount of uranium that could be extracted. For the LMFBR chain, we assumed that only a small amount of uranium would be extracted and that most of the fuel supply would come from depleted uranium in enrichment plants and from the plutonium produced from the spent fuel from LWRs. The transportation of uranium was not taken into account. The three nuclear chains comprise power plants each with 1000 MW(e) of installed capacity. The two solar chains, each with STEC plants with installed capacities of 100 MW(e), differ in terms of solar radiation—that is, the southern France type and the California type.

Results of this WELMM analysis are shown in Table 7-3 and Figure 7-9, the latter presenting information on the cumulative land requirements and the former on the materials (nonenergy plus energy) required to build and operate these nine chains for thirty years. These cumulative requirements, based on the aggregated data, offer insight into possible constraints for developing future electricity supply strategies.

The solar chains are the largest land-consuming chains by far—especially Solar 1, with a southern European direct solar radiation of 1500 kWh per m^2 per year. The smallest land consumer is the LMFBR chain. The land requirements for the solar chains are large, mainly because of the heliostat fields of the STEC modules. The land impacts are also considerable in the LWR 2 chain and in the four coal chains.

The STEC system would be the most demanding in terms of its requirements of land and construction material. Indeed the materials required to construct the two solar chains are more than one order of magnitude higher than those of the other chains because of the large quantities of concrete, sand, rocks, and other materials that would go into the construction of heliostat fields and towers. Yet the solar chains require practically no materials for their operation. Both the LMFBR and the LWR 1 chains show the best results if one compares the total material requirements (for construction plus thirty years of operation) for the various chains. The favorable results of the LWR 1 chain can be attributed to the assumed use of

Table 7-2. Characteristics of the electricity-generating chains (6.1 TWh/yr, 30 year life span).

	Coal 1	*Coal 2*	*Coal 3*	*Coal 4*
Mining	U.S. western underground coal mine, seam thickness 1.5 m		U.S. western surface coal mine, seam thickness 9.2 m	
Preparation	Coal preparation plant			
Transport	Rail, 900 km	Slurry pipeline, 900 km	Rail, 900 km	Slurry pipeline, 900 km
Power plant	1000 MW(e), load factor 70%, conventional	1000 MW(e), load factor 70%, fluidized bed, environmentally controlled	1000 MW(e), load factor 70%, conventional	1000 MW(e), load factor 70%, fluidized bed, environmentally controlled
Electricity storage	–	–	–	–
Reprocessing	–	–	–	–
Waste storage	Negligible	Negligible	Negligible	Negligible

high grade uranium ore. Only the LMFBR would appear to be practically independent of such resource constraints.

As is also evident from Table 7-3 and Figure 7-9, the LMFBR would be the least demanding in terms of land and materials requirements, followed closely by the light water reactor, provided that the fuel requirements of these reactors could be met by high grade ores (LWR1). The land and material-handling requirements for the operation of LWRs with poor quality uranium ore (LWR2) may even surpass those of equivalent coal-based systems. Of course, these are general features that would be different in different locations, and a complete assessment would have to consider the precise geographical location of the various facilities.

Synthetic Fuels

We also considered, in a preliminary way, the WELMM constraints associated with the production of synthetic liquid fuels by means of (1) coal liquefaction, (2) oil shales extraction, and (3) tar sands extraction. In our discussion of fossil resources in Chapter 3, we observed that each of these technologies relies on a large reserve. But if deployed on a large scale, each would considerably strain the available water and land resources, pose several material-handling and waste disposal problems, and require relatively higher amounts

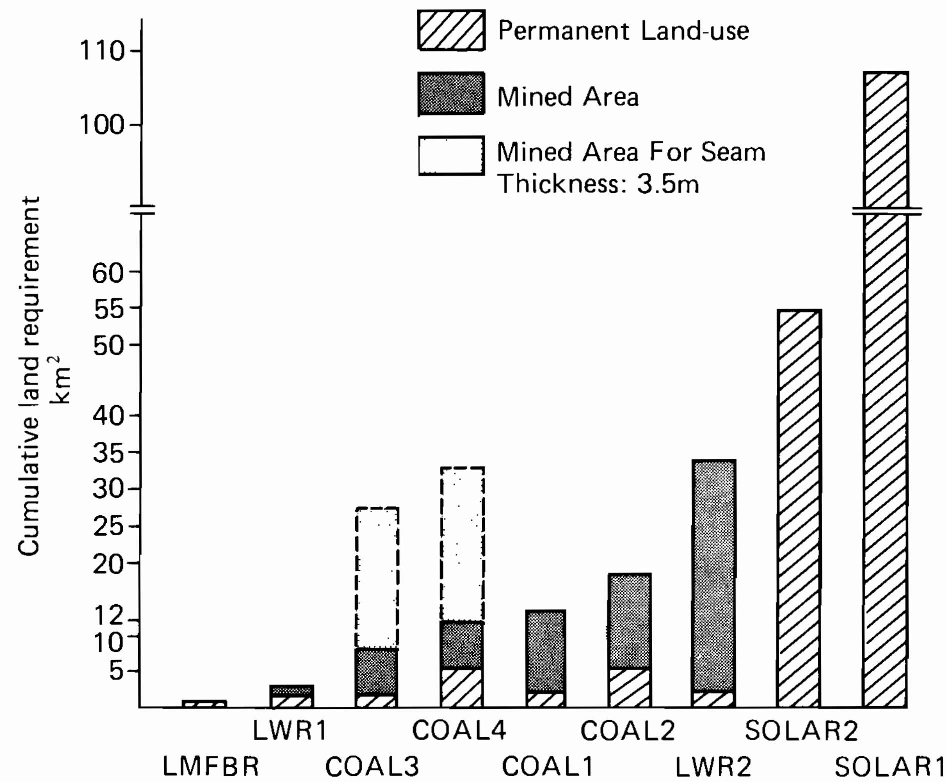
LWR 1	*LWR 2*	*LMFBR*	*Solar 1*	*Solar 2*
60% surface, 40% under-ground, 0.203% U_3O_8	Underground shale mine	Chattanooga 0.007% U_3O_8	—	—
Uranium mill, enrichment, fuel fabrication		Uranium mill, fuel fabrication	—	—
Negligible	Negligible	Negligible	—	—
1000 MW(e), load factor 70%, thermal efficiency 33%, 3.2% ^{235}U fuel		1000 MW(e), load factor 70%, thermal efficiency 40%, UF_6 tails and natural uranium fuel	28 × 100 MW(e), STEC, direct radiation, 1500 h/yr 1500 kWh/m²/yr	14 × 100 MW(e) STEC, direct radiation, 2700 h/yr, 3000 kWh/m²/yr
—	—	—	6 hours on site thermal	
Uranium reprocessing		Uranium and plutonium reprocessing	—	—
Low level waste storage, temporary (maximum 100 years), high level waste storage			—	—

Table 7-3. Material requirements for construction and operation of electricity-generating chains (10^3 tons).

	Metals for Construction	*Other Materials for Construction*	*Nonenergy Materials Operation (cumulative 30 years)*	*Energy Materials Operation (cumulative 30 years)*	*Total*
Coal 1	43	151	8287	79,000	87,480
Coal 2	65	140	23,566	84,000	107,770
Coal 3	44	142	4000	79,000	83,186
Coal 4	67	130	23,230	84,000	107,430
LWR 1	41.8-56.6	192.7	132	2700	3066-3080
LWR 2	43.4-58.2	192.7	132	119,300	119,668-119,683
LMFBR	33	276.3	na	800	1103
Solar 1	844.3-1930.4	3298-6778	na	0	4142-8708
Solar 2	666.4-965.7	2005-3390	na	0	2671-4355

na—not available.

Figure 7-9. Cumulative land requirements for energy chains producing 6.1 TWh/yr electricity. The importance of the seam thickness of opencast mining is indicated as an example for Coal 3 and 4. For explanation see Table 7-2.

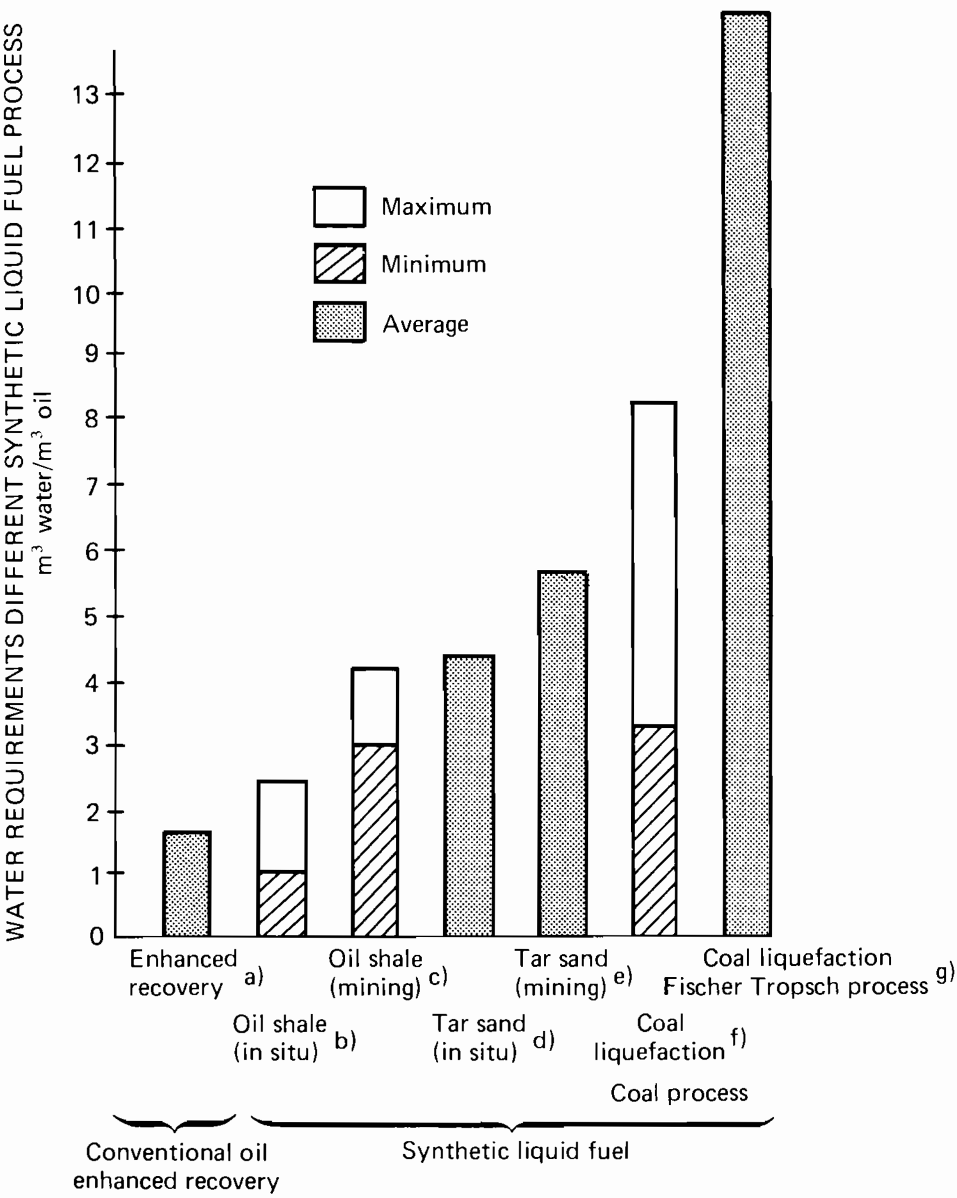


of skilled manpower than have been experienced with conventional oil production.

We examined these production methods from two perspectives—first, the conventional method of surface mining and, second, extraction by means of underground liquefaction and gasification where the energy resource remains in the deposit and so-called in situ techniques are used for extraction. For coal liquefaction, we assumed the use of the currently popular Fischer-Tropsch method. Unfortunately, our comparative analysis was hampered by the fact that only a few projects of this type have been constructed thus far or are in the final design stages. Still, we judge that all three methods for liquid fuel production would have high WELMM requirements. Water and manpower resource requirements best illustrate this statement.

Figure 7-10 shows estimates of water requirements for the different technologies. In order to compare their relative impact on water resources, the production of one cubic meter of synthetic fuel was chosen as a reference. Coal liquefaction seems to require the largest amount of water, since for the

Figure 7-10. Water requirements for different synthetic liquid fuel processes compared to enhanced recovery of conventional oil. *Sources:* (a) Bechtel Corporation (1975, 1976, 1977); (b) and (c) Crawford et al. (1977); (d) Resources Management Consultants Ltd. (1978); (e) Syncrude Canada Ltd. (1971, 1973); (f) Bechtel Corporation (1975, 1976, 1977), Hittman Associates Incorporated (1974, 1975); (g) Synfuels Interagency Task Force (1975).



Fischer-Tropsch synthesis process, water is considered a chemical feedstock. For tar sands, the major part of the water consumption occurs at the conversion stage because of the current method of "hot extraction." One disadvantage of this process is that most of the water discharged with the tailings in the tailing pond contains solid particles and therefore cannot be recycled nor can it be discharged into a river because of the presence of bitumen. For oil shale, the critical steps are the waste disposal and oil shale upgrading, during which 60 percent of the water is consumed.

Manpower requirements were also judged a potential bottleneck to the large-scale synthetic liquid fuel production, as can be seen in Table 7-4. While oil extraction from conventional fields in northern Alaska requires only forty to fifty people to operate and maintain a 25,000 ton per day operation, extracting tar sand deposits of 20,000 tons of oil per day would require some 2000 people for operation and maintenance, and some additional 10,000 people during the construction phase of these plants. Coal liquefaction, using the Fischer-Tropsch process, would require a full-time staff of 7400 people to produce 5500 tons of fuel per day.

As we noted in Chapter 3, the investments needed to build up a new coal industry would be large in both physical and human terms. The fact that larger numbers of miners would be needed is evident from the experiment

Table 7-4. Manpower requirements for different synthetic liquid fuel processes.

Projects	*Design and Construction Manpower Requirements (person-hours)*	*Total Workforce at Peak Construction (number of persons)*	*Workforce for Operation and Maintenance (number of persons)*
Tar sand, SYNCRUDE, open pit mining (125,000 bbl/d)[a]	43×10^6	7500	2500
Tar sand, in situ process (141,000 bbl/d), Imperial Project[b]	55×10^6	9930	2036
Oil shale, open pit mining (100,000 bbl/d)[c]	8.7×10^6	2200	1800
Oil shale, underground mining (100,000 bbl/d)[c]	8.7×10^6	2200	2362
Coal liquefaction, underground mining, Fischer-Tropsch process (40,000 bbl/d)[d]	na	11,000-15,000	7400
Coal liquefaction, open pit mining, hydrogen coal process (25,000 bbl/d)[e]	7.0×10^6	na	820-1,000

na—not available.

Sources: (a) Syncrude Canada Ltd. (1978); (b) Resources Management Consultants Ltd. (1978); (c) Project Independence (1974); (d) Hoogendoorn (1975; 1978); (e) Bechtel Corporation (1976) and Synfuels Interagency Task Force (1975).

of the SASOL project in South Africa, where 3700 people are employed in the mines to supply the coal for liquefaction (Hoogendoorn, 1975; 1978). Undoubtedly, the influx of such large numbers of workers into remote areas will strain the present infrastructures' ability to provide transportation, housing, and other social services, and their upgrading would generate their own increased WELMM requirements.

These preliminary findings indicate that coal liquefaction using current methods would be the least favorable of the three processes. From a WELMM perspective, the adoption of less water-intensive processes is a prerequisite for large-scale coal liquefaction. Similarly, in situ technologies would have to be mastered before unconventional oil could be deployed on a large scale, mainly because of the large land requirements that go along with current methods.

The relative differences among these three technologies as to WELMM constraints are not very large, and local conditions would naturally have to be considered. For example, the water requirements for exploiting oil shales, per unit of oil produced, are estimated to be lower than those for tar sands; yet water scarcity in the state of Colorado, where major oil shales resources exist, may turn out to be a serious problem for exploiting its vast shale beds. By contrast, water does not now seem to pose any problem in the Canadian region of the Athabasca tar sands.

RISKS OF ENERGY TECHNOLOGIES

For people to be able to choose intelligently the kinds of energy technologies they prefer and decide what systems are the most appropriate, they must know something about how the use of these technologies will affect their lives. Choices made in the dark are not choices at all. Yet it is difficult to appreciate the differences among energy technologies in terms of their real risks, as well as their benefits, because experts are often at odds and because people have different value judgments.

How one compares cancer incidence to the incidence of black lung disease, or a near-term increase in power blackouts to a long-term increase in global atmospheric CO_2 will depend on one's personal values or preferences. These value judgments may be colored by positive or negative belief systems about deploying certain technologies. For example, a general faith in science or in technological progress will predispose a person to accept the technical judgment that the probability of, say, a catastrophic nuclear accident is comfortably small, while a person's distrust of the "system" and its proponents would predispose him to believe that such a statement was intentionally misleading and corrupt.

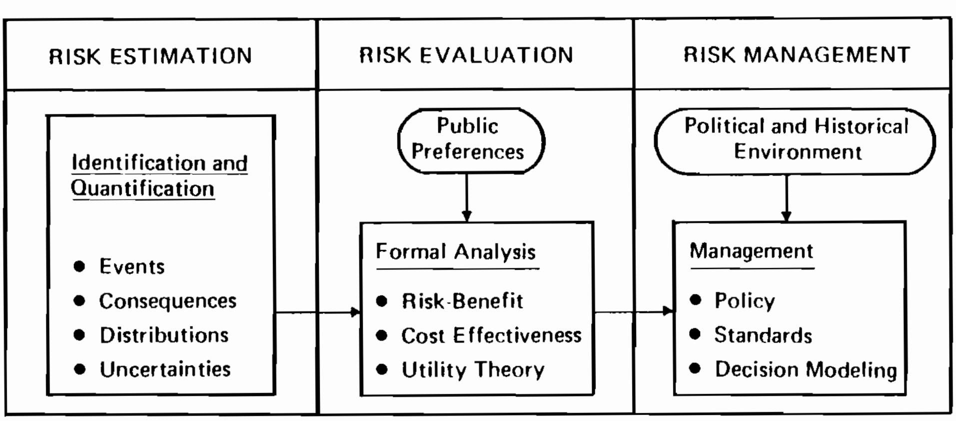
To be sure, differences between perceptions and realities constitute just one element–albeit an important one–of the sociopolitical problem of making choices about energy technologies. There are other factors that add to the complexity of the problem, most notably a lack of data and inadequate evaluation technologies for defining the nature of the risks and for providing decisionmakers with tools for incorporating the findings of risk analyses into energy strategies.

All human activities have some degree of risk, whether perceived or not. That realization, in a crude sense, was the starting point for our risk assessment project, begun six years ago jointly with the International Atomic Energy Agency (IAEA). Our goal was to establish categories and to define concepts related to risk assessment in order to set up a framework for more formal research in this field. We distinguish three elements in our risk assessment framework illustrated in Figure 7-11—risk estimation, risk evaluation, and risk management. Since risk estimation is by far the most studied aspect of the assessment process, we limited our research on this subject.

Before we report on the findings of our studies of the risks of various energy technologies, it may be helpful to consider the goals and methods used for each of the three elements of risk assessment. In brief, risk estimation makes use of one or two possible methods. For events of concern that are infrequent or have associated with them major consequences, it is neither possible nor desirable to estimate risks by just waiting for sufficient historical data to accumulate. Put another way, we can no longer base the development of a technology on trial and error, which is equivalent to hypothesis and experiment in science. With the implementation of larger technical systems on a global scale, man has entered the domain of "hypotheticality," where it is no longer acceptable to correct a hypothesis by the outcome of an experiment. This applies both to accidents in large, modern technical installations such as LNG terminals or nuclear power plants and to routine emissions from well-established technologies such as CO_2 emissions from fossil-fueled power plants.

For these sorts of risks, a second approach estimates low frequency risks that, in principle, can be predicted, usually by extrapolating statistical data. Examples of such methods are fault- and event-tree analyses, as well as

Figure 7-11. Risk assessment framework.



computer simulation models for determining failure rates of various facility components (e.g., pumps, automatic control systems, pipes, valves, vessels). Methods falling into this second category have certain shortcomings. For one, only those failures and event sequences that can be envisaged by experts can be included. Another limitation is that human failures, especially under stress, are difficult to quantify, and most studies of this sort rely essentially on expert judgment. Since the probability of many event sequences is as low as one in a million per year, there are no historical data with which to verify the analytic results.

Once the risks associated with different energy technologies have been identified and quantified, the problem is one of comparing the risks, first, with each other and, second, with other important energy system attributes such as investment and operating costs and reliability of supply. But such comparisons are difficult because the risk and attributes of concern differ in many ways. They may differ fundamentally in nature—for example, nuclear proliferation risks versus the risk of more frequent power blackouts. Or they may have different probability distributions—for example, the relatively low probabilities associated with a serious nuclear accident versus certain CO_2 increases due to the burning of fossil fuels. Or the may affect different populations—for example, occupational risks versus public risks or risks to the current generation versus those to future ones.

These factors, as well as the values or judgments people bring to the evaluation process, underscore the fact there is no single, objectively correct procedure for evaluating risks. Still, there are a variety of techniques that can increase our understanding of how to systematically apply one's own values to a complex, multidimensional choice and how to analyze the values held by others and possibly to incorporate such values in energy policy decisions. These techniques include procedures for measuring and analyzing public attitudes toward energy systems, as well as preference-based evaluation procedures known variously as decision analysis, risk-benefit analysis, and multiattribute utility measurement.

Risk management refers to the organizational and political aspects of the environmental management of energy systems. It involves the pragmatic problems that arise when competing groups, which most likely disagree on both the estimation and evaluation of risks, actually try to negotiate and implement an energy strategy. Since risk evaluation techniques often involve the political decisionmaking process, the line between risk evaluation and risk management is not always sharp. We studied standard setting, an important part of risk management, focusing on the dynamics of regulatory agencies setting standards for energy systems.

We now discuss these three aspects of risk analysis in more detail, bearing in mind the difficulties of drawing clear lines between them, as shown in Figure 7-11. Specifically, the approach one takes to estimating or quantifying risks suggests implicitly how one intends to evaluate these. For example, to assign dollar costs to human lives indicates that one is primarily interested in the economic effects of consequences.

For our discussion, we refer to methods that have been developed by others and by us in order to quantify the risk of energy supply systems. Our intent is to review the state of the art of risk analysis. But it would be presumptuous on our part to suggest that current methods are adequate to tackle the question of what is an "acceptable risk." The numbers given here are not definitive; rather, they serve to illustrate techniques and to represent the type of calculations that are being done today. What they do suggest, however, is the magnitude of the challenge facing sociopolitical institutions that wish to successfully manage the risks that would go along with higher levels of global energy use.

Quantifying Health Risks of Energy Systems

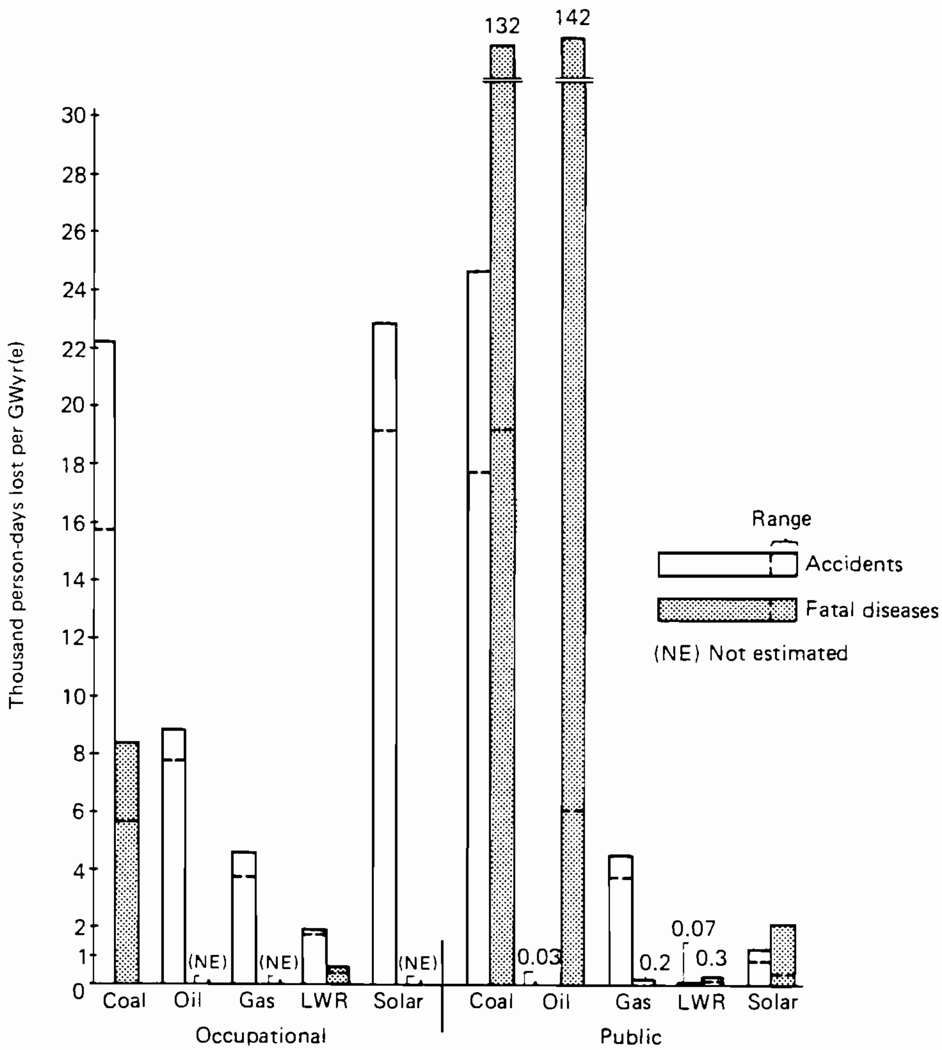
Risk studies generally use the average risk of acquiring a fatal disease as the yardstick for determining acceptable risk levels. Although the risks of many technologies can be reduced to this level, this method has its drawbacks. Not only do average values vary among people and circumstances, but averages may also mask important differences in the probability distributions of the accidents from which they were derived.

We adapted an approach by L.D. Hamilton and A.S. Manne (1977) that estimates the human health risk associated with energy systems and considers time lost on the job because of illnesses and injuries from occupational accidents. For perspective on the level of human health effects from energy-related accidents, we note that in the United States in 1975, between 2000 and 19,000 deaths and between 29,000 and 48,000 illnesses could be traced to electricity generation during that one year period.

Table 7-5 gives estimates of human health risks associated with 1 GWyr of electricity production annually for five primary energy sources—coal, oil, natural gas, nuclear energy (LWRs), and solar energy (STEC). These data cover not only the construction and operation of the power plant but also the extraction, processing, and transport of the energy fuel and the waste products. The estimates are based largely on statistics published by the U.S. Department of Labor and on various assessments reported in the literature. In certain cases, such as the public health effects of sulfur dioxide, particulates, and radiation exposure, the data are based on a linear, nonthreshold extrapolation from high level, acute exposures. But because of a lack of quantitative or even good qualitative data, we could not estimate certain power plant emissions. Although mercury, nickel, arsenic, and vanadium, or some of their compounds, are known to be toxic to humans and animals, we could not include in the table estimates of the impacts of the release of the first three elements from coal-fired plants or of the vanadium from oil-fired plants. Similarly, it was not possible to include estimates for the effects of radioactive emissions from fossil fuel combustion, of the emissions of methane and other hydrocarbons from oil- and gas-fired plants, and of oil lost in spillage.

Figure 7-12, based on data from Table 7-5, illustrates the health effects in both the occupational and public sectors resulting from accidents at the

Figure 7-12. Person-days lost annually due to supplying 1 GWyr(e) from each of five sources. Power plant life is thirty years.



five energy facilities. In plotting this figure, we assumed that one fatality is equivalent to 6000 person-days lost for workers or 1000 person-days lost for coal workers because of the high incidence of pneumonoconiosis. This allowed us to sum fatalities and injuries.

Figure 7-12 indicates that numerically, coal and oil systems pose the largest threats to the health of the public at large, while coal and STEC systems pose the greatest health risk to the worker. Some 19,000 to 23,000 person-days would be lost per GWyr(e) because of accidents incurred on the job in

Table 7-5. Estimated human health effects from 1 GWyr (8.76×10^9 kWh) of electricity generation.

Power Plant Type	Accidental Injuries (in person-days lost)		Accidental Deaths		Fatal Diseases	
	Occupational	*Public*	*Occupational*	*Public*	*Occupational*	*Public*
Coal						
Fuel supply	1920-3100		1.2-1.8		5.6-8.4	
Transport fuel and materials	640-880	1500-1800	0.63-0.73	2.7-3.8		
Normal operation	790		0.05			3.2-22
Construction	590		0.17			0.006-0.04[a]
Total	3940-5360	1500-1800	2.0-2.8	2.7-3.8	5.6-8.4	3-22
Oil						
Fuel supply	3850		0.38			
Transport fuel and materials	750	2-3	0.071	0.0048		
Normal operation	110		0.027			1-7
Construction	440		0.12			0.004-0.03[a]
Total	5140	2-3	0.6	0.0048		1-7
Gas						
Fuel supply	2200	2,200	0.23	0.16		
Transport fuel and materials	190	2	0.027	0.003		
Normal operation	110		0.027			0.003-0.02
Construction	200		0.054			0.002-0.014[a]
Total	2700	2,200	0.34	0.163		0.005-0.034
Light water reactor						
Fuel and reprocessing	300-400		0.12		0.05	
Transport fuel and materials	5	6	0.0025	0.011		
Normal operation	10		0.03		0.032	0.03
Construction	310		0.082			0.003-0.021[a]
Total	620-720	6	0.23	0.011	0.082	0.033-0.051

Solar thermal					
Material supply	450		0.071		0.05–0.35[a]
Transport of materials	32–44	75–90	0.032–0.037	0.14–0.19	
Construct plant	3400		0.95		
Construct storage	580–2300		0.28–0.29		
Normal operation	2200–2800		0.8–1.0		
Total	6700–9000	75–90	2.1–2.4	0.14–0.19	0.05–0.35

[a]Resulting from emissions from coal that was used to melt metals, etc.

Sources: Estimates based on data from U.S. Department of Labor and also on assessments of the U.S. Atomic Energy Commission (1974); Inhaber (1978); Bliss et al. (1977); Lane and Freeburg (1973); Caputo (1977); Hildebrandt and Vant-Hall (1977).

NOTES TO TABLE 7-5: One of the references cited for Table 7-5 is the Canadian Atomic Energy Control Board's report by Inhaber (1978), a report that has attracted strong criticism. While the only Inhaber results that are incorporated in Table 7-5 are those having to do with occupational health effects during construction, we feel that we should include here some supplementary data to this table. Presented below are the results from the Atomic Energy Control Board report along with the results of J.P. Holdren's critique (Holdren et al., 1979) of that report. The numbers attributed below to Holdren are the results of his trying to reproduce Inhaber's numbers using Inhaber's methodology. As is evident, there are some important inconsistencies between Holdren's results and Inhaber's. Unfortunately, we received the Holdren report too late in the editing process to incorporate into this chapter a proper treatment of his work. Still, we feel that the unresolved disagreements are important and that the reader should be aware of them, even if only in the rough form that we have been able to present them here.

	Person-days Lost/GWyr(e)[a]			*Person-days Lost/GWyr(e)*	
Energy Cycle	*Occupational*	*Public*	*Energy Cycle*	*Occupational*	*Public*
Solar Thermal			Coal Electric		
Inhaber	62,000–100,000	9400–520,000	Inhaber	18,000–73,000	20,000–2,000,000
Holdren	7400–15,000	1000–2700	Holdren	19,000–43,000	20,000–1,500,000
Nuclear (LWR)			Oil		
Inhaber	1700–8700	300–1500	Inhaber	2000–18,000	9000–1,900,000
Holdren	3100–12,000	300–70,000	Holdren	3000–19,000	9000–1,000,000

[a]One fatality was assumed equivalent to 6000 person-days lost except for coal workers, in which case a fatality was assumed equivalent to 1000 person-days lost.

STEC plants: For coal-fired plants the number is less (16,000 to 22,000 person days); and for LWR plants 2000 person-days would be lost because of occupational accidents.

For both coal and oil systems, most of the occupational accidents occur during the fuel supply and transportation processes, while for STEC plants they take place during the construction phase. For LWR plants, worker injuries result from accidents during plant construction and in the extraction-processing-reprocessing end—at an almost equal level.

For the public at large, the largest health risks come from accidents in transporting all of these five energy sources. Additionally, the sulphur dioxide emissions from both coal- and oil-fired plants affect public health. There are, of course, large uncertainties in these estimates that we hope will eventually be narrowed down by improvements to the data base.

There is yet another possible way to evaluate risks that assigns a monetary value to human life and considers this in determining production costs. While this may seem to be a harsh appraisal of human life, it is standard procedure for insurance companies and courts in awarding payments for health damages. On the basis of available, albeit limited, information and experiments, we compared the human health risks associated with five of the primary energy technologies, assigning monetary equivalents to these health effects. As was the case with electricity generation, our study revealed that coal-fired plants present the largest risk of accidents and diseases to occupational staff as well as to the public. The risks associated with nuclear energy (LWRs) amount to only a small fraction—less than 6 percent of those relating to coal-fired plants.

These results may appear surprising. Coal has long enjoyed wide public acceptance, in spite of historical data pointing to its ill-effects. Yet many people view nuclear power plants as being associated with much greater risk than the other energy technologies. In a survey conducted on heterogeneous sample of the Austrian public (Thomas et al. 1980), we observed a large discrepancy between the results of risk-benefit calculations, as mentioned above, and the public perception of these risks. The dialogue between those holding opposite views was often so emotionally charged that people seemed to be talking past one another. Among the energy technologies considered, the group perceived solar and hydroelectric power systems as having the lowest risks, with fossil fuels having only a slightly higher level of perceived risk. The largest disagreement concerned the use of nuclear energy. When we looked further, to the beliefs underlying the attitudes of the pro- and antinuclear groups, we found that psychological anxiety-inducing aspects and certain sociopolitical factors caused both groups to hold negative opinions about nuclear energy. However, in the case of the pro group, they were able to override these negative beliefs by stronger, more positive beliefs stemming from a number of other factors.

Thus, the risk evaluation process faces a dilemma: Public opinion does not reflect risks evaluated on purely technical considerations. Psychological factors and attitudes toward matters that are related only slightly to risk seem to affect peoples' perception of risk. It appears that the general public is very concerned about the possibility of large accidents, even though the probability of their occurrence is quite small. Yet low frequency, high consequence events generally contribute minimally to the aggregated risk.

One possible way to resolve—or at least to defuse—this conflict is to reduce any type of risk below a desirable level by incurring additional safety efforts and investments. To be sure, any technology can be made safer, but at an expense. One might ask, How safe is safe enough? Expenditures for safety in energy systems—and especially for nuclear energy systems—are approaching the level where the desired reduction in the risk is offset by additional risk in producing the safety equipment.

Since economies have limited resources that need to be directed toward the most cost-effective alternatives, the problem is one of determining these alternatives. Not only would the price of the electricity generated be higher because of the cost of producing such safety equipment but, as explained above, additional costs would be incurred as a result of worker injuries and deaths from accidents at the plants manufacturing the safety equipment.

Studies of safety measures conducted in the Federal Republic of Germany (Black, Niehaus, and Simpson 1979) showed that for each billion dollars of machine tool products and electrical equipment produced, there would be 8.2 deaths due to occupational accidents and to accidents in commuting to and from the job. The number of person-days lost was 52,000.

We used these figures to estimate the "true" costs of producing safety equipment. The production of $30 million of safety equipment would be associated with one death or with 600 person-years of work. We cite this figure here only to give orientation about what might be considered the reasonable maximum limit for safety expenditures and to show, albeit in a simplified way, how the cost effectiveness of risk reduction could be measured.

Risk Management

The estimation and evaluation of potential risks are prerequisites to the difficult task of translating the analytic results into policy and regulatory decisions. For risk management, standard setting has emerged as the most practical method for reducing environmental risk and hazards. It has also become a constraint for industrial operations, as well as a driving force, particularly for technical development. In the energy sector, standards are used to shape long- and short-term decisions, ranging from those about plant operation to long-term planning of optimal energy supply mixes.

What environmental burdens of energy systems could be tolerated, and what should be the criteria for limiting them at both the individual and societal level? We tackled these questions, first, by reviewing three case studies of past standard setting for radiation standards, chronic oil discharge standards, and noise standards respectively. The initial purpose of the case studies was to learn about critical similarities and dissimilarities among different procedures for resolving conflicts among regulators, energy facility developers, and the public exposed to environmental risks. For example, discharge standards for oil production platforms in the North Sea focused on the technical characteristics of the engineering equipment intended to protect the environment. In the case of noise standards for Japanese trains, it was the frequency of complaints, not the details of train design, that was the explicit subject and focus of the standards. Based on such insights, two quantitative models of simplified standard setting procedures were developed and used to study the setting of standards for atmospheric carbon dioxide, for train noise, and for chronic discharges from offshore oil platforms. The objective behind these models was not to determine what standards should be set, or even how standards should be set. Rather, it was to better understand some of the biases implicit in different possible standard setting processes. For example, the specific standards advocated by regulators, developers, or members of the public will depend not only on personal preferences, but also on what alternative regulatory mechanisms are considered, possible monitoring and inspection procedures, and the possible sanctions available for punishing violators. And adjusting a standard setting procedure can change not only the relative importance of the views held by different parties, but also the relative importance of these other factors—the set of regulatory alternatives considered, the enforcement procedures, the available sanctions.

The modeling efforts and the insights they produced were necessarily preliminary. Although societies have been managing risks for thousands of years, both the risks requiring management and the analytic study of risk management have developed significantly during the last ten years. The principal conclusion offered here is that the current understanding of how societies manage risks and how they might better manage risks is still very primitive, but nonetheless suggests that there is much to be gained from pursuing further study and improving the level of understanding.

CONCLUDING REMARKS

In this chapter we have examined four types of constraints on society's capabilities for supplying energy. From our exploration of the various energy supply options, it would appear that the energy problem could be resolved over the long term. However, as our considerations on constraints indicate, the exploitation of any or all of these options on a large scale would bring us into the realm of global impacts that could limit the further deployment of these technologies.

The task we now face is to be more vigorous in our efforts to define the interaction between these supply potentials and their limitations and thus to provide insights that might be useful in the design of global energy strategies over the long term. In the next chapter we report on our approach to synthesizing the potentials, limitations, and demand aspirations into two plausible scenarios of how the global energy picture might evolve over the next fifty years.

REFERENCES

Bechtel Corporation. 1975. *The Energy Supply Model, Final Report to the National Science Foundation.* NSF-C867. San Francisco.

——. 1976. *Manpower, Materials, and Capital Costs for Energy-Related Facilities.* San Francisco.

——. 1977. *Resource Requirements, Impacts and Potential Constraints Associated with Various Energy Features.* San Francisco.

Black, S.; F. Niehaus; and D. Simpson. 1979. *How Safe is "Too Safe"?* WP-79-68. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Bliss, C. et al. 1977. *Accidents and Unscheduled Events Associated with Non-Nuclear Energy Resources and Technology.* EPA-600/7-77-016. Washington, D.C.: U.S. Environmental Protection Agency.

Caputo, R. 1977. *An Initial Comparative Assessment of Orbital and Terrestrial Central Power Plants.* 77-44. Pasadena, California: Jet Propulsion Laboratory.

Crawford, K.W. et al. 1977. *Preliminary Assessment of the Environmental Impacts from Oil Shale Development.* Redondo Beach, California: T.R.W. Environmental Engineering Division.

Fisher, J.C., and R.H. Pry. 1970. *A Simple Substitution Model of Technological Change.* Report 70-C-215. Technical Information Series. Schenectady, New York: General Electric Company, Research and Development Center.

Grenon, M.; J.M. Merzeau; and A. Grübler. 1979. Systems Aspects of Development of New Liquid Fuel Sources. Paper presented at the IIASA/RSI Conference on Systems of Energy and Mineral Resources, July 1979, Laxenburg, Austria.

Grübler, A., and M. Cellerier. 1979. Comparaison de Châines Energétiques. *Revue de l'Energie* (316):505–12.

Hamilton, L.D., and A.S. Manne, 1977. Health and Economic Costs of Alternative Energy Sources. In *Proceedings of the International Conference on Nuclear Power and Its Fuel Cycle.* IAEA-CN-36/448. Vienna: International Atomic Energy Agency.

Hildebrandt, A.F., and L.L. Vant-Hall. 1977. Power with Heliostats. *Science* 197:1139–46.

Hittman Associates Incorporated. 1974. *Environmental Impact, Efficiency and Cost of Energy Supply and End Use.* Vol. 1. Springfield, Virginia.

——. 1975. *Environmental Impact, Efficiency and Cost of Energy Supply and End Use.* Vol. 2. Springfield, Virginia.

Holdren, J.P. et al. 1979. Risk of Renewable Energy Resources: A Critique of the Inhaber Report. Berkeley, California, University of California-Berkeley.

Hoogendoorn, J.C. 1975. The Sasol Energy Project. *Die Professionele Ingenieur* (4):40–48.

——. 1978. *Sasol 2.* Pretoria: Department of Environmental Planning, Republic of South Africa.

Inhaber, H. 1978. *Risk of Energy Production.* AECB-119. Ottawa: Atomic Energy Control Board.

Krömer, G.; J. Williams; and A. Gilchrist. 1979. *Impact of Waste Heat on Simulated Climate: A Megalopolis Scenario.* WP-79-73. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Lane, L.B., and L.C. Freeburg. 1973. Health Effects of Electricity Generation from Coal, Oil and Nuclear Fuel. *Nuclear Safety* (14):409–28.

Llewellyn, R.A., and W.M. Washington. 1977. Regional and Global Aspects. In *Energy and Climate.* Washington, D.C.: National Academy of Sciences.

Mansfield, E. 1961. Technical Change and the Rate of Imitation. *Econometrica* 29 (4).

Marchetti, C., and N. Nakicenovic. 1978. *The Dynamics of Energy Systems and the Logistic Substitution Model. Volume 1: Phenomenological Part.* Report prepared for the Stiftung Volkswagenwerk. AR-78-1B. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Murphy, A.H.; A. Gilchrist; W. Häfele; G. Krömer; and J. Williams. 1976. *The Impact of Waste Heat Release on Simulated Global Climate.* RM-76-79. Laxenburg, Austria: International Institute for Applied Systems Analysis.

National Academy of Sciences. 1975. *Petroleum in the Marine Environment.* Washington, D.C.

Niehaus, F., and J. Williams. 1979. Studies of Different Energy Strategies in Terms of Their Effects on the Atmospheric CO_2 Concentration. *Journal of Geophysical Research* 84(C6):3123–29.

Project Independence. 1974. *Potential Future Role of Oil Shale Prospects and Constraints.* Final Task Force Report. Washington, D.C.: U.S. Department of the Interior.

Resources Management Consultants Ltd. 1978. *Final Draft of Environmental Impact Assessment for Imperial Oil Limited.* Cold Lake Project. AERCB Application No. 770866. Edmonton, Canada: Alberta Energy Resources Conservation Board.

Syncrude Canada Ltd. 1971. *Environmental Impact Assessment.* Vol. 1. Edmonton, Canada.

——. 1973. *Environmental Impact Assessment.* Vol. 2. Edmonton, Canada.

——. 1978. *Facts and Figures Syncrude.* Edmonton, Canada.

Synfuels Interagency Task Force. 1975. *Recommendation for a Program on Synthetic Fuels Commercialization.* Washington, D.C.: Presidential Energy Resources Council.

Thomas, K.; D. Maurer; M. Fishbein; H.J. Otway; R. Hinkle; and D. Simpson. 1980. *A Comparative Study of Public Beliefs about Five Energy Systems.* RR-80-15. Laxenburg, Austria: International Institute for Applied Systems Analysis.

U.S. Atomic Energy Commission. 1974. *Comparative Risk-Cost-Benefit Study of Alternative Sources of Electrical Energy. A Compilation of Normalized Cost and Impact Data for Current Types of Power Plants and Their Supporting Fuel Cycles.* WASH-1224. Washington, D.C.

Washington, W.M. 1971. On the Possible Uses of Global Atmospheric Models for Study of Air and Thermal Pollution. In *Man's Impact on the Climate,* edited by W.H. Matthews, W.W. Kellogg, and G.D. Robinson. Cambridge, Massachusetts: MIT Press.

——. 1972. Numerical Climatic Change Experiments: The Effect of Man's Production of Thermal Energy. *Journal of Applied Meteorology* 11:763–72.

Williams, J.; G. Krömer; and A. Gilchrist. 1977a. *Further Studies of the Impact of Waste Heat Release on Simulated Global Climate: Part 1.* RM-77-15. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Williams, J.; G. Kromer; and A. Gilchrist, 1977b. *Further Studies of the Impact of Waste Heat Releases on Simulated Global Climate: Part 2.* RM 77–34. Laxenburg, Austria: International Institute for Applied Systems Analysis.

——. 1979. The Impact of Waste Heat Release on Climate: Experiments with General Circulation Model. *Journal of Applied Meteorology* 18:1501–11; also RR-80-21, Laxenburg, Austria: International Institute for Applied Systems Analysis.

8 BALANCING SUPPLY AND DEMAND: THE QUANTITATIVE ANALYSIS

In Chapters 3 through 6 we explored the potentials of different energy supply options under the most optimistic of assumptions. And in Chapter 7 we examined the sorts of constraints that could limit the extent to which those potentials could be exploited. Our intention was to stretch our thinking to the limits to determine the technical characteristics of each option that would ultimately determine its attractiveness in competition with the others. And, by so doing, we would be able to identify major side effects that could accompany the aggressive deployment of any of the options. It is only on the basis of such material that one can realistically examine how our current energy system might evolve over the next fifty years, and it is to these issues that we turn our attention in this chapter.

The quantitative analysis reported here combines an array of real-world constraints in order to build up (starting with details) a range of plausible energy futures. This is done regionally and has as a goal the balancing of energy demand and supply within the assumed constraints. The two scenarios and three alternative cases discussed here could be considered the pragmatist's guide to a range of plausible, global energy futures over the next fifty years.

In Chapter 10, we go beyond this and report on our explorations of some of the paths that may be taken over a longer time horizon to reach a truly sustainable energy world that is built around nondepletable resources. The material in that chapter and that presented here are complementary. The former seeks to explore the bounds of the possible; the latter seeks to balance constraining factors in order to identify the plausible. Chapter 10 defines a long-term goal; the current chapter charts a path with no explicit goal. However, the implications of what is reported in this chapter may lead to a more rapid development of the energy systems that are outlined later.

Since the objective of our analysis of supply and demand was to be realistic, we were necessarily led to the use of mathematical models. Generally, there are three types of mathematical models that lend themselves to such work. The first type, which is built upon the physical and chemical laws of nature, describes a large part of reality precisely. The second category includes econometric models—that is, the intelligent processing of time series data. These models also describe reality, but usually not with the same precision as those in the first category and with a time horizon of only two, three, or four years. The third type of mathematical model is that identified with the writing of scenarios, and it is this approach that we adopted for our study. Briefly, our set of mathematical energy models included models that were developed at IIASA and, in a few instances, some that were brought to IIASA and adapted for specific purposes.[a]

In writing scenarios, we were in no sense attempting to make predictions. Rather, we viewed scenario writing as a way to organize our thinking about available information: Specifically we insisted rigorously on two criteria—internal consistency and global comprehensiveness.

AN OUTLINE OF THE SCENARIOS

The purpose of the scenarios is to detail realistically the engineering and economic consequences that might follow from two different sets of reasonable assumptions. The results should be interpreted carefully. The numbers are meant to provide insights and to help in meeting the intellectual challenge of grasping the dominant characteristics, trends, possibilities, and constraints on global and regional energy considerations. They are not predictions, and should serve only as guidelines for determining what is feasible over the coming five decades, assuming there are no social and political constraints.

We analyzed energy supply and demand through many iterations and interpretations that finally led us to envisage a range of plausible global energy futures. These two benchmark scenarios are labeled "High" and "Low," the former referring to a situation in which the demand for energy is relatively high, the latter to one in which demand is relatively low. And we investigated three alternative cases, with necessarily less detail than the two scenarios. These cases comprise one in which there is a worldwide nuclear moratorium, one in which there is an all-out effort to develop nuclear energy, and one incorporating strong energy-saving measures for achieving a very low level of energy demand. By altering certain assumptions, we were

[a] A description of the IIASA set of energy models is given in Appendix C.

able to use these three cases to test the sensitivity of our results and to achieve additional measures of technical feasibility.

As noted in Chapter 2, we assumed an essentially surprise-free world—no global-scale disasters, no sweeping scientific and technological discoveries. These things could happen, but they were not considered in the design of our scenarios. We did not want to rely on them, nor could we in fact predict their occurrence.

Since it is neither possible nor desirable to write scenarios for some 150 nations, we chose instead to study seven world regions, as described in Chapter 2. These regions were analyzed both for their differences and for their roles in the overall future global energy situation. This enabled us both to preserve broad national similarities within each region and to treat major energy trade patterns among regions.

We began our analysis by postulating two basic development variables for each of the seven world regions to the year 2030—population growth, and economic development as measured by growth in the gross domestic product (GDP). We made two sets of estimates in order to suggest the range of likely developments over the next fifty years.

Our assumptions about population growth for the seven world regions, which are given in Table 8-1, are based on the projections of Nathan Keyfitz (1977), of Harvard University, who envisages a doubling of the world's population from the current four billion to eight billion by the year 2030. More difficult to predict than population are economic growth rates because of many determining factors such as technological progress, know-how, and skills of all kinds. Instead, one has to make assumptions. For both scenarios, we assumed declining economic growth rates throughout the study period. Further, we recognized that developing countries would be limited in

Table 8-1. Population projections by region, High and Low scenarios (10^6 people).

Region	*Population* Base Year 1975	*Projection* 2000	2030
I (NA)	237	284	315
II (SU/EE)	363	436	480
III (WE/JANZ)	560	680	767
IV (LA)	319	575	797
V (Af/SEA)	1422	2528	3550
VI (ME/NAf)	133	247	353
VII (C/CPA)	912	1330	1714
World	3946	6080	7976

Note: 1975 data are midyear estimates from United Nations *Monthly Bulletin of Statistics,* January 1978.

Source: Keyfitz (1977).

their growth potential to one or two percentage points above the growth rates of the developed countries (Hicks et al. 1976). This implies that for the next few decades, the developing countries will still be tied to the rest of the world economy through trade and other relations. We consider it unrealistic to assume high economic growth rates in the developing world while the Organisation of Economic Cooperation and Development (OECD) countries have a low or even a zero growth rate.

When constructing the scenarios, we found that growth rates are generally restricted by the conditions required for interregional consistency and the balance of energy demand and supply. Thus, if one connects the 1975 and 2030 points by an exponential curve (the decline of growth rates therefore not being expressed), one obtains a 3.4 percent rate of economic growth for

Table 8-2. Historical and projected growth rates of GDP, by region, High and Low scenarios (%/yr).

	Historical		*Scenario Projection*			
Region	*1950–1960*	*1960–1975*	*1975–1985*	*1985–2000*	*2000–2015*	*2015–2030*
A. High Scenario						
I (NA)	3.3	3.4	4.3	3.3	2.4	2.0
II (SU/EE)	10.4	6.5	5.0	4.0	3.5	3.5
III (WE/JANZ)	5.0	5.2	4.3	3.4	2.5	2.0
IV (LA)	5.0	6.1	6.2	4.9	3.7	3.3
V (Af/SEA)	3.9	5.5	5.8	4.8	3.8	3.4
VI (ME/NAf)	7.0	9.8	7.2	5.9	4.2	3.8
VII (C/CPA)	8.0	6.1	5.0	4.0	3.5	3.0
World	5.0	5.0	4.7	3.8	3.0	2.7
I + III[a]	4.2	4.4	4.3	3.4	2.5	2.0
IV + V + VI[a]	4.7	6.5	6.3	5.1	3.9	3.5
B. Low Scenario						
I (NA)	3.3	3.4	3.1	2.0	1.1	1.0
II (SU/EE)	10.4	6.5	4.5	3.5	2.5	2.0
III (WE/JANZ)	5.0	5.2	3.2	2.1	1.5	1.2
IV (LA)	5.0	6.1	4.7	3.6	3.0	3.0
V (Af/SEA)	3.9	5.5	4.8	3.6	2.8	2.4
VI (ME/NAf)	7.0	9.8	5.6	4.6	2.7	2.1
VII (C/CPA)	8.0	6.1	3.3	3.0	2.5	2.0
World	5.0	5.0	3.6	2.7	1.9	1.7
I + III[a]	4.2	4.4	3.1	2.1	1.3	1.1
IV + V + VI[a]	4.7	6.5	5.0	3.8	2.9	2.6

[a]Presented for purposes of comparison with data of WAES (1977) and of other global studies that exclude centrally planned economies.

Note: Historical and projected values of GDP in constant (1975) U.S. dollars are given in Chant (1980).

the High scenario and a 2.4 percent rate of growth for the Low scenario. Disaggregated in time and space, the picture is as explained in Table 8-2.

Some suggest that we are being too conservative in our estimates and that national economies will grow faster than we envisage. Then too, others maintain that our growth rates are too high. Our intent was to hew to reality as we picture it. To be sure, economic growth rates lower than what we projected could ease the energy problem, but in our opinion they would exacerbate other problems.

HOW MUCH ENERGY WILL BE NEEDED? (The Problem of Energy Demand and Conservation)

Quite simply, in a finite world, exponential growth must ultimately stop. Over the previous twenty-five years, global primary energy demand has grown at a surprisingly consistent 4.8 percent per year. A 5 percent per year growth in global energy use, if continued over the next fifty years, would necessitate an increase in one year (2030) of 75 percent of our base year figure of annual global primary energy consumption (8.2 TWyr/yr). And at this rate, by 2037, the growth in energy use in that year alone would exceed the total amount of primary energy consumed in 1975. The question then is not whether energy growth will slow down, but when, at what level, and in which world regions? What are the implications of such a slowdown?

For estimating energy demand, we found it necessary to first determine the appropriate methodological approach. The econometrical method has been widely used for estimating energy demand by considering elasticities—that is, the ratio of relative increases of demand with relative increases of prices or income. Provided there is a good statistical base, it is possible to extract such elasticities and to base a mathematical approach on it that forecasts energy demand evaluation over a period of a few years. But for our analysis, we chose to look ahead fifty years and to consider not only those world regions that have a good statistical data base but also those regions where that is not the case. Thus, we opted for a different approach that accounted for the physical end uses of energy (final energy) for the economy as a whole and in the private sector as well. This led us to consider how the use of energy would affect the lifestyles of people, and how technological progress could be expected to improve the efficiency of energy usage, among other things.

We examined in great detail the four factors that influence energy demand—population growth, economic growth, technological progress, and structural changes within economies. However, in this book we have chosen not to devote a separate, more qualitative chapter to energy demand but to consider it within the framework of our quantitative analysis of supply and demand. By accounting quantitatively for these demand factors we were able to apply certain schemes—as, for example, to study energy use and GDP ratios and to test the appropriateness of our scenario assumptions.

It may be helpful to look at some globally aggregated data for the use of commercial energy across the various sectors, as given in Table 8-3. The amount of final energy used in 1975 was 5.7 TWyr/yr. Of this amount, the household service sector held a share of 26 percent, the industry sector 45 percent, transportation 23 percent, and feedstocks some 5 percent. By including transportation and conversion losses, we come to a primary energy consumption of 8.2 TWyr/yr.

We complete the picture by looking at energy demand in the developing regions, as revealed by the data in Table 8-4 for regions IV and V. In 1975, in region IV, as much as 35 percent, and in region V some 61 percent, are based on noncommercial energy sources such as wood and agricultural wastes. This distribution is important not only in terms of supply but equally for considerations of the end-use technologies selected, since the efficiency from noncommercial sources is usually very low, often much less than 5 percent. Therefore, as efficiencies improve a completely new feature of energy demand in the future is expected to evolve for the developing regions (IV, V, VI, VII) somewhat independently along the lines governing energy demand in developed regions (I, II, III).

Table 8-3. Global commercial energy use in 1975 (TWyr/yr).

	Coal	*Oil*	*Gas*	*Electricity*	*Distributed Heat*	*Hydro*[a]	*Nuclear*[a]	*Total*
Transportation	0.045	1.272	0	0.016	0	0	0	1.333
Industry[b]	0.729	0.722	0.620	0.359	0.170	0	0	2.600
Household-service	0.285	0.547	0.382	0.249	0.048	0	0	1.511
Feedstocks[c]	0	0.298	0	0	0	0	0	0.298
Final energy	1.059	2.839	1.002	0.624	0.218	0	0	5.742
Transportation and distribution losses	0.038	0	0.097	0.091	0.010	0	0	0.236
Secondary energy	1.097	2.839	1.099	0.715	0.228	0	0	5.978
Inputs to electricity[d] and distributed heat	1.069	0.534	0.359	-0.734	-0.277	0.497	0.119	1.567
Other losses[e]	0.091	0.455	0.049	0.019	0.049	0	0	0.663
Primary energy	2.257	3.828	1.507	0	0	0.497	0.119	8.208

[a]Hydro- and nuclear-generated electricity are given in terms of fossil primary energy input equivalent.

[b]Industry includes agriculture, construction, mining, and manufacturing.

[c]Feedstocks include nonenergy use of fuels. (Natural gas used to make fertilizers is included in "industry.")

[d]The inputs to electricity generation are primary equivalents of the sources; these figures include primary sources used in cogeneration facilities. (The -0.734 figure under "electricity" represents the secondary (busbar) electricity generated from the several primary sources.)

[e]"Other losses" include all primary to secondary losses (e.g., primary transport, oil refining); they also include bunkers (0.21 TWyr/yr of oil in 1975)—energy used in international shipments of fuel.

Table 8-4. Energy in two developing regions, 1965 and 1975.

	1975	
	Total	*Rural Fraction*
Population (10^6)		
Region IV (LA)	319	0.40
Region V (Af/SEA)	1422	0.78
	Total	*Share of Agriculture*
GDP (10^9 \$)		
Region IV (LA)	340	0.12
Region V (Af/SEA)	340	0.36
	1965	*1975*
Total primary energy (including noncommercial) (TWyr/yr)		
Region IV (LA)	0.278	0.447
Region V (Af/SEA)	0.442	0.672
Share of oil		
Region IV (LA)	0.46	0.51
Region V (Af/SEA)	0.15	0.24
Share of noncommercial energy[a]		
Region IV (LA), of which	0.35	0.24
Wood	0.28	0.18
Agricultural wastes	0.07	0.06
Region V (Af/SEA), of which	0.61	0.51
Wood	0.41	0.34
Agricultural wastes	0.20	0.17

[a]Noncommercial energy is expressed here in terms of its calorific heat content and *not* as a replacement equivalent of fossil fuels. The efficiencies of use of noncommercial and commercial fuels are quite different.

Table 8-5 shows the aggregate results of final energy use for the seven world regions and their differences with respect to historical trends. Both scenarios provide for a degree of energy conservation, with the level being higher in the High scenario and for the developed regions.

Energy would be saved in the developed regions through more fuel-efficient automobiles, better insulated buildings, and greater efficiencies in using energy in the industrial sector. The extent of such improvements in final energy use for all regions can be seen in Figure 2-3 of Chapter 2, which shows the ratio of final energy use to GDP or, in other words, the overall energy intensiveness of the past and that embodied in the scenarios. Energy intensiveness in the developed regions decreases in line with the historical trends. The ratio for all of the developing regions increases initially, but flattens off and eventually starts to decrease in the case of regions IV and VI.

A certain regularity can therefore be observed in the different trends that is characteristic of our demand scenarios. That is, those regions building up their industrial base require more energy than those regions that have

Table 8-5. Final energy in the two scenarios compared to final energy calculated with historical elasticities (2030).

Region	High Scenario (GWyr/yr)	With Historical ϵ_f [a] (GWyr/yr)	Difference[b] (%)	Low Scenario (GWyr/yr)	With Historical ϵ_f [a] (GWyr/yr)	Difference[b] (%)
I (NA)	3665	6921	47	2636	4036	35
II (SU/EE)	4114	5355	23	2952	3850	23
III (WE/JANZ)	4375	6037	28	2987	3761	21
IV (LA)	2640	4385	40	1656	2481	33
V (Af/SEA)	3173	6900	54	1876	3121	40
VI (ME/NAf)	1638	2590	37	868	1015	16
VII (C/CPA)	3196	8849	64	1589	3536	55
World	22,801	41,037	44	14,564	21,800	33

[a]Calculated using historical (1950–1975) final energy-to-GDP elasticity (ϵ_f) for each region.
[b]Calculated as final energy, using historical ϵ_f minus IIASA scenario projection divided by final energy using historical ϵ_f.

achieved a relatively high level of industrialization. The significance of this fact will become evident when we turn our attention later in this chapter to the role of liquid fuels in supporting development.

Globally, the use of final energy per capita increases from a 1975 figure of 1.46 kWyr/yr to 2.86 kWyr/yr in the High scenario and to 1.83 kWyr/yr in the Low scenario. For the developed regions consumption would grow relatively slowly and would be more rapid in the developing regions, although moderated somewhat by high population growth rates in the developing world. Still, the present inequities in energy use among regions would abate only slightly by 2030, as shown by the data on per capita final energy use in Table 8-6. Regions are distinctly different. For example, in developed region I, final energy was being used in 1975 at a per capita level of 7.89

Table 8-6. Per capita final energy consumption, two scenarios, 1975–2030 (kWyr/yr,cap).

Region	Base Year	High Scenario		Low Scenario	
	1975	2000	2030	2000	2030
I (NA)	7.89	9.25	11.63	7.95	8.37
II (SU/EE)	3.52	5.47	8.57	4.98	6.15
III (WE/JANZ)	2.84	4.46	5.70	3.52	3.90
IV (LA)	0.80	1.75	3.31	1.28	2.08
V (Af/SEA)	0.18	0.42	0.89	0.32	0.53
VI (ME/NAf)	0.80	2.34	4.64	1.76	2.46
VII (C/CPA)	0.43	0.93	1.87	0.64	0.93
World	1.46	1.96	2.86	1.58	1.83

Note: The figures are average rates of final energy use, averaged over the population and the year.

kWyr/yr; for the Low scenario, we arrived at a modest per capita increase by the year 2030 of 8.37 kWyr/yr. To be sure, this is not a large increase, essentially implying zero energy growth per capita for this region over the next fifty years. The increase in the High scenario is only slightly higher. Nevertheless, energy continues to be used there at a prodigious rate.

Looking at developing region IV, where final per capita energy consumption in 1975 was only 0.8 kWyr/yr, we see that in the High scenario this level increases substantially to 3.3 kWyr/yr per capita, exceeding the 1975 per capita consumption level of developed region III. This projection therefore reflects our high expectations for overall development in Latin America over the coming decades.

We found it useful to evaluate the demand scenarios by several indicators. One was the ratio of final energy use to GDP, as shown in Figure 2-3 of Chapter 2. Another indicator was the final energy elasticity with GDP, which is shown in Table 8-7. It is interesting to consider how the developed regions might achieve lower elasticities, while the elasticities of the developing regions may be consistently higher. Again this indicates that it takes more energy per dollar value added to build an economic infrastructure than to operate and upgrade it.

Table 8-7. Final energy-GDP elasticities (ϵ_f) 1950–2030.

Region	*Historical* 1950–1975	*1975–1985*	*1985–2000*	*2000–2015*	*2015–2030*
A. High Scenario					
I (NA)	0.84	0.31	0.43	0.53	0.48
II (SU/EE)	0.68	0.59	0.58	0.52	0.53
III (WE/JANZ)	0.84	0.77	0.65	0.58	0.51
IV (LA)	1.21	1.07	1.01	0.97	0.90
V (Af/SEA)	1.42	1.20	1.08	1.05	1.01
VI (ME/NAf)	1.17	1.12	1.07	0.95	0.81
VII (C/CPA)	1.53	1.10	1.02	1.02	0.96
World	0.87	0.69	0.73	0.78	0.77
B. Low Scenario					
I (NA)	0.84	0.24	0.38	0.53	0.46
II (SU/EE)	0.68	0.54	0.57	0.50	0.41
III (WE/JANZ)	0.84	0.67	0.64	0.60	0.49
IV (LA)	1.21	1.10	1.03	0.95	0.88
V (Af/SEA)	1.42	1.19	1.12	1.14	1.06
VI (ME/NAf)	1.17	1.21	1.11	1.01	0.93
VII (C/CPA)	1.53	1.02	0.98	0.99	0.90
World	0.87	0.64	0.73	0.79	0.74

Note: Historical values were computed by linear regression (see Chant 1980). Values for the projection period result from the scenario data.

Table 8-8. Two supply scenarios, primary energy by region, 1975-2030 (TWyr/yr).

		High Scenario		*Low Scenario*	
Region	*1975*	*2000*	*2030*	*2000*	*2030*
I (NA)	2.65	3.89	6.02	3.31	4.37
II (SU/EE)	1.84	3.69	7.33	3.31	5.00
III (WE/JANZ)	2.26	4.29	7.14	3.39	4.54
IV (LA)	0.34	1.34	3.68	0.97	2.31
V (Af/SEA)	0.33	1.43	4.65	1.07	2.66
VI (ME/NAf)	0.13	0.77	2.38	0.56	1.23
VII (C/CPA)	0.46	1.44	4.45	0.98	2.29
Total[a]	8.21[b]	16.84	35.65	13.59	22.39

[a]Columns may not sum to totals because of rounding.
[b]Includes 0.21 TWyr/yr of bunkers.

The bottom line of any traditional energy accounting is total primary energy use, and within that total, the various energy sources must be identified. We therefore consider global primary energy, disaggregated by regions as shown in Table 8-8. By the year 2030, the total global demand for primary energy is roughly 36 TWyr/yr for the High scenario and 22 TWyr/yr for the Low scenario. This compares with 8.2 TWyr/yr of 1975. Thus, between 1975 and 2030, the demand for primary energy globally increases by a factor of 4.4 and 2.7, respectively, for the High and Low scenarios; on a per capita basis there is a 2.2- and 1.35-fold increase, respectively, in globally primary energy demand.

The projections for primary energy demand also point to continued inequalities in energy use. The ratio of primary energy use in the developing regions, compared with that in the developed regions, shows only a slight improvement. The ratio improves by a factor of 3 from 0.23 to 0.75 in the High scenario and by a factor of 2.6 from 0.23 to 0.6 in the Low scenarios. Realistically, one must expect the growth of energy demand, at least in the developing regions, to continue increasing beyond the year 2030, for reasons of both population growth and economic growth. Thus, any supply option must be evaluated against a yardstick of 2 to 3 TWyr/yr if a contribution of about 10 percent of the 20 to 30 TWyr/yr of the total global demand is to be envisaged.

Extreme Energy Conservation

It is possible in principle to design scenarios of extreme energy conservation. Balancing supply and demand can be achieved either by going to the extreme on the supply side, which means facing all the troubles of enhanced supply, or by going to the extreme on the demand side, which means encountering all the hardships of enhanced energy-saving measures. But in either situation, we must first understand what is meant by the term "extreme."

We explored this issue by examining an extremely low case of energy demands, which was proposed by Dr. Umberto Colombo, a member of the Club of Rome and director of the Italian Atomic Energy Commission. In 1978, he proposed an alternative scenario—a simple doubling of the 1975 rate of global primary energy use of some 8 TWyr/yr to some 16 TWyr/yr by 2030. (This proposed doubling of energy use compares to the projected scenario increases of factors of 4.3 (High) and 2.7 (Low) by 2030.) With the doubling of population envisaged for this period, this would lead to a constant global average primary energy use per capita. But the energy use per capita distribution among regions would change. Growth for some—namely, the developing world—would imply decreases for other regions, specifically regions I and III. Later in this chapter, we delve further into the issues not only of demand but also of supply for this very low case.

LIQUID FUELS: AN ENERGY PROBLEM WITHIN THE PROBLEM

The "energy problem," viewed with a sufficiently long-term and global perspective, is not so much a general energy problem: Strictly speaking it is a liquid fuels problem—or, more precisely, an oil problem. Thus, the problems of balancing global supply and demand for liquid fuels pose a unique challenge.

In our scenario writing we restricted the use of liquid fuels to their most essential purposes only—that is, as transportation fuels and as feedstocks for the chemical industry. While in 1975 some 64 percent of the world's total liquid fuels went to supplying the transportation sector and the chemical industries, the scenarios project that 92 percent (High scenario) and 88 percent (Low scenario) of all liquid fuels in 2030 would be used for these two purposes only.

Nevertheless, as Table 8-9 shows, inspite of vigorous measures to conserve liquid fuels, these fuels still represent the major component of energy use in the scenarios in 2030. Over the next fifty years, liquid fuel use would grow at a rate of 2.4 percent per year for the High scenario and 1.6 percent for the Low scenario, compared to a growth of 2.5 percent per year (High scenario) and 1.7 percent per year (Low scenario) for all final energy.

It is relatively more difficult to conserve liquid fuels in the developing regions than in the developed regions for several reasons. Whereas liquid fuel use, as a share of total final energy, is projected to decline (from 56 to 46 percent) by 2030 in the developed regions, its share would increase slightly (from 48 to 50–54 percent) in the developing regions. Liquid fuels are easy to transport and store, and meet demand flexibly. High degrees of storability and transportability also mean a minimum of required infrastructure, which is of utmost importance for the developing world. In short, liquid fuels serve the purposes of development and industrialization rather well. Thus,

Table 8-9. Shares of electricity and liquid fuels in final energy.

	Base Year 1975	*High Scenario 2030*	*Low Scenario 2030*
Regions I (NA) and III (WE/JANZ)			
Final energy (TWyr/yr)	3.5	8.0	5.6
Electricity (%)	12	21	21
Liquids (%)	56	46	46
Region II (SU/EE)			
Final energy (TWyr/yr)	1.3	3.7	2.6
Electricity (%)	10	23	20
Liquids (%)	34	32	30
Regions IV (LA), V (Af/SEA), VI (ME/NAf), and VII (C/CPA)			
Final energy (TWyr/yr)	1.0	10.6	6.0
Electricity (%)	6	13	13
Liquids (%)	48	50	54
World			
Final energy (TWyr/yr)	5.7	22.8	14.6
Electricity (%)	11	17	17
Liquids (%)	50	45	46
Motor Fuel and Feedstocks in Liquid Fuel			
Final demand (%)	64	92	88

wherever possible, the developed regions should conserve liquid fuels by using them only where essential, and there more efficiently, leaving the world's oil supplies for the developing regions.

HOW CAN NEEDED ENERGY BE SUPPLIED?

Unless the preceding considerations of future energy demand are very wrong, they would lead quickly to a simple, far-reaching observation: Energy, and particularly liquid fuels, must be supplied in enormous amounts over the next fifty years.

Here, in considering energy supply, we recall an observation made in Chapter 2 about the various time phases of energy. When we began our analysis, we anticipated only one major energy transition, which would be completed within fifty years. But by 1978–1979, as our analysis developed, we realized that the transition to a sustainable global energy system built around nondepletable resources would not happen within this time horizon. Instead, we saw that there was not enough time to build up the infrastructure of nonfossil energy systems to allow them to contribute sufficiently to global energy supply in 2030. Thus, during the next fifty years, we would have to turn more and more to costly and difficult, albeit unconventional, fossil resources to carry us through until 2030. This major change in supply patterns—from conventional to unconventional fossils—would probably occur before the end of the century.

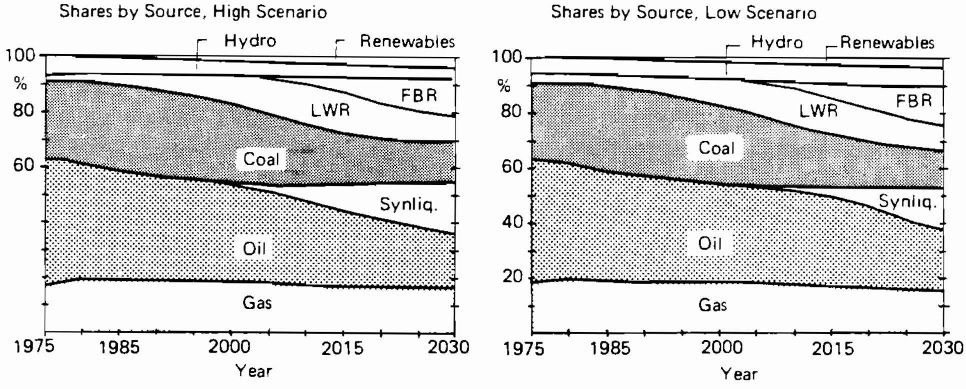
The relative shares of primary energy supply by source, in the High and Low scenarios, for the world by the year 2030 are shown in Figure 8-1. Although one can observe a somewhat constant share of gas and a decline in the share of oil, the oil and natural gas era would not be over. By 2030, they would still provide large amounts of energy—two and a half times their 1975 levels in the High scenario by 2030—but a large fraction of this oil would be unconventional oil.

Coal production, after growing slowly until the end of this century, would expand rapidly thereafter, as coal begins to play its strategic role as a raw import for producing synthetic liquid fuels. Indeed, it is because of coal-based synthetic liquids that the demand for oil can be reduced. Coal would therefore have to be set aside for this purpose and not be used as before for electricity generation. This, in turn, would be possible because nuclear energy would take over large portions of electricity generation.

In fact, nuclear energy would meet effectively all new non-peak-load electricity demand in the developed regions, in both scenarios. Hydroelectric power can be seen to hold a somewhat constant share of primary energy supply over the period, while other renewable energy sources, including hard solar energy, would have a rather low share. This is more an outcome of cost considerations rather than a statement of the potential or desirability of such renewable energy sources.

In both scenarios, two major technologies appear on the energy scene around the year 2000 that influence the supply situation significantly. These are the production of synthetic liquid fuels and the fast breeder reactor. Synliquids should be interpreted as synthetic hydrocarbons of any kind—as, for example, the two liquid fuels, methanol and gasoline, or even the gas,

Figure 8-1. Global primary energy, two supply scenarios, 1975-2030.



methane. But in the scenarios, because of the pressing demand for energy in liquid form, we emphasized the production of synliquids.[b]

According to the High scenario, by 2030 only 61 percent of the liquid fuel demands would be met by crude oil. The remainder, 39 percent, would come from synthetic liquid fuels made from coal. The level of demand for liquid fuels is the engine for change in these scenarios, especially after the year 2000, when most of the major changes in energy supply patterns are expected. In combination with this, a ceiling on oil production would have a large impact on the extent and time of oil alternatives: As imports become restricted, alternatives would appear sooner and to a greater extent. Thus, some 56 percent of the coal needed at this time would be used to produce synthetic fuels.

The significance of the breeder reactor can be grasped when we consider the large changes expected in the mix of sources for generating electricity. For example, the use of liquid fuels would be restricted to the chemical industry and for transportation activities. Coal would be reserved more and more for producing synthetic fuels. And, unfortunately, gas would probably not be able to substitute globally, since the problems of transporting it over long distances would, according to our assumptions, not be resolved by that time. Thus, around the year 2000, nuclear energy would be called upon to produce some 30 percent of secondary electrical energy in the High scenario and some 20 percent in the Low. These are, of course, global figures that would vary according to different regions.

The disaggregation of global primary energy supply by source, in absolute terms, which is given in Table 8-10, shows a prodigious consumption of resources, particularly of fossil fuels. Do we have enough energy resources? Typically, the answer is, Yes and no.

Initially, we were somewhat naive and thought that assessing the resource situation would be relatively straightforward. But as our explorations of the various supply potentials indicated, this was not the case. We discovered that the traditional categories of resources—that is, the cheap and easy conventional ones—were not the only ones we would have to consider. Fossil fuel resources are a good example of why we had to look also at the categories of tomorrow and consider not only the amount of resources but production limits as well.

Traditional wisdom has it that 1000 TWyr is a good indicative figure for global fossil resources, and this is consistent with 1091 TWyr which is the global total of what might be referred to as conventional fossil resources. The 560 TWyr of category 1 coal listed in Table 8-11 are the equivalent of some 600 billion tons of coal, which is essentially the conventional com-

[b]Since neither nuclear nor solar energy systems could be built up to the level at which they could supply large amounts of energy by the year 2030, we were led in the scenarios to assume the production of synthetic liquid fuels by the autothermal process. This would mean the use of three to four times more coal and the concomitant environmental problems than would be incurred with the allothemal method. Chapter 3 gives more information on these two methods for coal-based synthetic fuel production.

Table 8-10. Global primary energy by source, two supply scenarios, 1975-2030 (TWyr/yr).

Primary Source[a]	Base Year 1975	High Scenario 2000	High Scenario 2030	Low Scenario 2000	Low Scenario 2030
Oil	3.83	5.89	6.83	4.75	5.02
Gas	1.51	3.11	5.97	2.53	3.47
Coal	2.26	4.94	11.98	3.92	6.45
Light water reactor	0.12	1.70	3.21	1.27	1.89
Fast breeder reactor	0	0.04	4.88	0.02	3.28
Hydroelectricity	0.50	0.83	1.46	0.83	1.46
Solar[b]	0	0.10	0.49	0.09	0.30
Other[c]	0	0.22	0.81	0.17	0.52
Total[d]	8.21	16.84	35.65	13.59	22.39

[a]Primary fuels production or primary fuels as inputs to conversion or refining processes—for example, coal used to make synthetic liquid fuel is counted in coal figures. (For definition of energy types, see Figure 1-1.)

[b]Includes mostly "soft" solar—individual rooftop collectors—and also small amounts of centralized solar electricity.

[c]"Other" includes biogas, geothermal, and commercial wood use.

[d]Columns may not sum to totals because of rounding.

ponents of coal resources. The situation is similar for oil, with 264 TWyr, and for natural gas, with 267 TWyr.

When one includes the higher cost categories shown in the table, one gains additional resources amounting to a threefold increase. That is, not 1000 TWyr but 3000 TWyr is the more appropriate figure. But these additional resources are not of the same nature as the first 1000 TWyr. The difficulties that go along with category 2 and 3 resources are significant, making them more costly not only in monetary terms but also as to their environmental and social impacts.

The Oil Era is Not Over

Let us look first at the oil situation, since this is the most critical problem. In Figure 8-2, for the High scenario, we see that known reserves of conventional oil in the world's market economies are almost exhausted by the year 2010. This is essentially the man in the street's perception of the energy situation, and in this respect, he is correct. We therefore had to search for new reserves of conventional oil, Mexico being a case in point. But in our scenarios we accounted for all the Mexicos to come, and still oil production did not go above the level of 25 million barrels per day. We were then forced to turn to unconventional oil sources, such as the Athabasca tar sands in Canada and the Orinoco heavy crude oils in Latin America, recognizing the

Table 8-11. Summary of estimates of ultimately recoverable resources by cost category (TWyr).

Resource[a] Cost Category[c]	Coal[b]		Oil			Natural Gas			Uranium	
	1	2	1	2	3	1	2	3	1	2
Region										
I (NA)	174	232	23	26	125	34	40	29	35	27
II (SU/EE)	136	448	37	45	69	66	51	31	d	75
III (WE/JANZ)	93	151	17	3	21	19	5	14	14	38
IV (LA)	10	11	19	81	110	17	12	14	1	64
V (Af/SEA)	55	52	25	5	33	16	10	14	6	95
VI (ME/NAf)	<1	<1	132	27	d	108	10	14	1	27
VII (C/CPA)	92	124	11	13	15	7	13	14	d	36
World	560	1019	264	200	373	267	141	130	57	362

[a]For oil, gas, and coal, see estimates given in the text (translated here into units of TWyr); for uranium, see estimates given in Chapter 4.

[b]For coal, only a part of the ultimate resource (~15 percent) has been included, because the figures are already very large for the time horizon of 2030 and because of the many uncertainties about very long-term coal resources and production technologies.

[c]Cost categories represent estimates of costs either at or below the stated volume of recoverable resources (in constant 1975$).

For oil and natural gas:	Cat. 1:	12$/boe
	Cat. 2:	12-20$/boe
	Cat. 3:	20-25$/boe
For coal:	Cat. 1:	25$/tce
	Cat. 2:	25-50$/tce
For uranium:	Cat. 1:	80$/kgU
	Cat. 2:	80-130$/kgU

A subcategory of oil, 1A, exists only for regions I (NA) and IV (LA) and includes oil available at production costs of $12 to $16/boe. Also, a subcategory of gas, O, exists only for region VI (ME/NAf), with gas available at $2/boe.

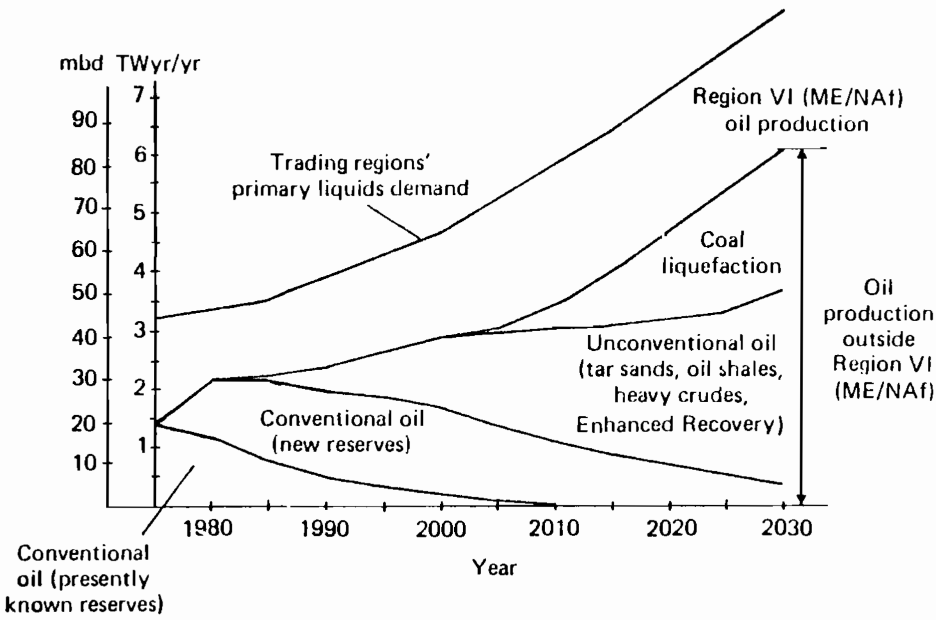
[d]No estimate was made.

Sources: Ashley et al. (1976); Eckstein (1978); Grenon (1977); Grossling (1976); Institute of Geological Sciences (1978); Lambertini (1976); Meyer (1977); *Oil and Gas Journal* (1978); O'Shaughnessy (1976); Penner and Icerman (1975); Perrine (1978); Uhl (1977).

new geopolitical patterns that would develop when the unconventional oils began to play such a major role.

But even turning to unconventional oil sources was not enough, and sometime around the year 2000, large-scale coal liquefaction would become a necessity, yielding a total oil production outside region VI that still would not meet the minimum demand for liquid fuels required even for essential uses. Oil imports from region VI would still be needed, and it is indeed one of the crucial assumptions of our analysis that region VI would continue to have a production ceiling of 33 million barrels of oil per day. This ceiling is

Figure 8-2. World oil supply and demand (excluding centrally planned economies), High scenario, 1975-2030.



some 50 percent greater than the 1975 oil production of this region and about 30 percent above its 1977 production rate. Region VI is not quite the same as OPEC. The difference between region VI oil production rates and capacities and OPEC oil production rates and capacities is detailed in Table 8-12. We were led to conclude that the worldwide struggle for oil would continue, and that only some time after the year 2030 could this situation change.

As Figure 8-3 shows, in 1975 there were two net oil-consuming regions (regions I and III), three oil supplier regions (regions IV, V, and VI), and two regions that are relatively energy self-sufficient (regions II and VII). But in order to have a feasible match between demand and supply in 2030 in our High scenario, we assumed that regions I, II, IV, and VII would be self-sufficient in oil supply. At that time, only region VI would be an oil exporter, with regions III (a developed region) and V (a developing region) competing for these oil exports, creating a set of political implications somewhat different from those of today. Significantly, as can be seen from Table 8-10, the production and consumption of oil in both scenarios goes up, not down, compared with 1975. While the relative share of oil declines, the absolute numbers increase.

Table 8-12. Region VI (ME/NAf) oil production rates and capacity and assumed production ceiling (mbd).

	Production Rates	
	1975	1977
OPEC member countries	27.19	31.53
non-region VI OPEC[a] member countries	- 5.82	- 6.52
OPEC and region VI[b] countries	21.37	25.01
non-OPEC region VI[c] countries	+ 1.05	+ 0.99
Region VI	22.42	26.00
of which exported	21.23	24.64
	Production Capacities	
	1975 DOE Estimate[d]	1977 PIW Estimate[e]
Saudi Arabia	10.7	10.8
Iran	6.5	6.8
Iraq	3.0	2.6
Kuwait	2.9	3.0
Libya	2.3	2.5
UAE	2.3	2.3
Algeria	1.3	1.0
Qatar	0.6	0.7
Estimate of other region VI[f] countries	1.4	1.4
Region VI	31.0	31.8
Estimated Long-Term Region VI "Ceiling":	33.6	

[a]Non-region VI OPEC countries are Venezuela, Ecuador, Nigeria, Gabon, and Indonesia.

[b]Eight OPEC member countries are in region VI—six in the Middle East (Saudi Arabia, Kuwait, UAE, Iran, Iraq, Qatar) and two in Northern Africa (Algeria and Libya).

[c]Seven countries in the Middle East—Bahrain, Jordan, Lebanon, Oman, Syria, Yemen and Yemen (Democratic)—and one in Northern Africa (Egypt).

[d]U.S. Department of Energy estimate, International Energy Indicators, April 1979.

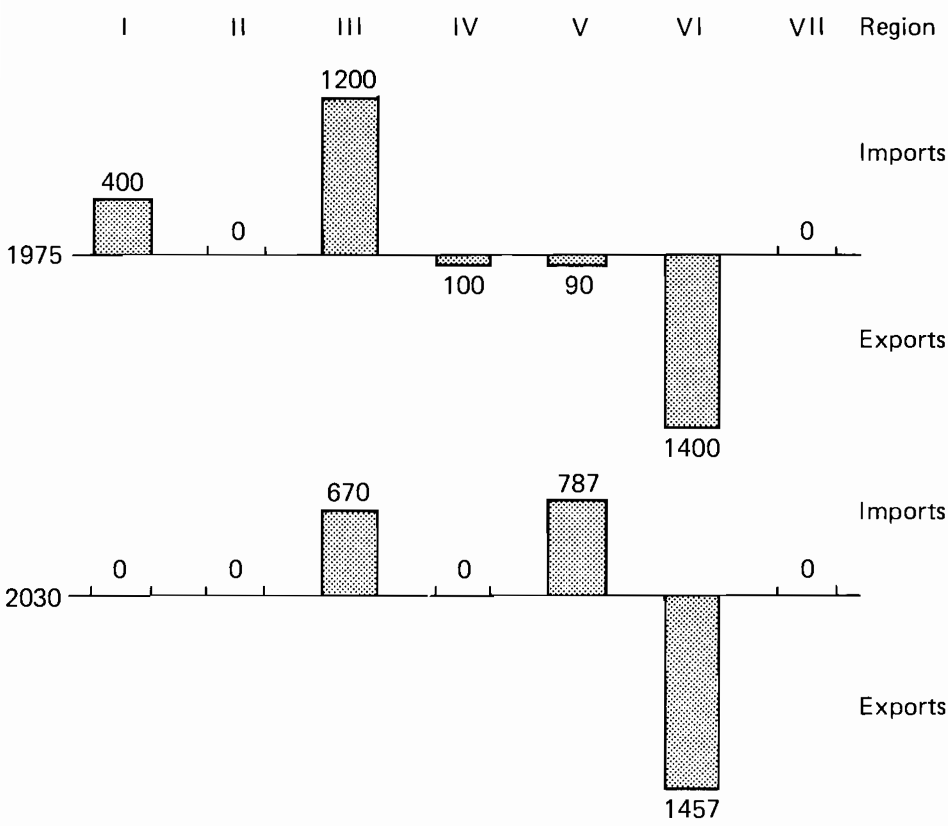
[e]*Petroleum Intelligence Weekly* (1979).

[f]IIASA estimate.

Coal

The trend toward larger resource consumption is even more pronounced in the case of coal, from 2 TWyr/yr in 1975 to 12 TWyr/yr by 2030 in the High scenario and 6.5 TWyr/yr in the Low scenario—an increase of almost six times in the High scenario and three times in the Low scenario. Although it could be argued that producing 12 billion tons of coal per year is an impossible task, the question that must be asked is, If not coal, what other primary energy source could assume the burden instead? Relieving the pressure on

Figure 8-3. Oil trading between regions, High scenario, 1975-2030.



one resource would only increase the pressure elsewhere. Or one might argue that the High scenario is impossible altogether, that only the Low scenario should be considered or perhaps even the conditions of the very low, 16 TW[c] demand case should be the target. However, for such considerations, it is important to understand the implications of lower energy use levels, especially in the developing parts of the world. Again, if we insist on being globally comprehensive—and we do—there is no escape.

The high coal figures come on top of the above-considered production of oil from shales and tar sands. Although this may appear impossible by today's yardstick, the global energy problem is of such a dimension that solutions will also have to extend beyond the realm of tradition. In any event, one would expect coal to be in short supply sometime around the

[c]Throughout the discussion we will refer to the very low demand case—in which primary energy use in 2030 reaches only 16 TWyr/yr—as the "16 TW case." Strictly speaking, although this is in violation of our convention restricting the use of the TW unit to the description of energy facility capacitities, it is less cumbersome and we hope less confusing for the reader.

year 2000. (The fact that the autothermal method of coal liquefaction and gasification is assumed in the scenarios to be used at this time would only aggregate the tight coal supply situation.) Also, the possible global climatic impacts of burning fossil fuels and of thus releasing large amounts of carbon dioxide into the atmosphere would have to be monitored. The related CO_2 buildup for the two scenarios is illustrated in Figure 8-4.

Energy from Gas

In the scenarios, we cautiously assumed that gas would not be transported intercontinentally. This is not to say that we do not hope for the technological progress in gas transportation discussed in Chapter 3, but here again, we hewed to real world constraints, and considered gas to be of regional significance only. Its contribution, while increasing in absolute terms, would remain somewhat constant in relative terms. The resource situation would allow for higher energy contributions from gas, but only for a couple of decades given present knowledge. Where 837 TWyr is the total recoverable oil (categories 1, 2, and 3 in Table 8-11), 538 TWyr is the total recoverable gas (categories 1, 2,and 3), its share of conventional resources (category 1) being 267 TWyr.

Nuclear Power

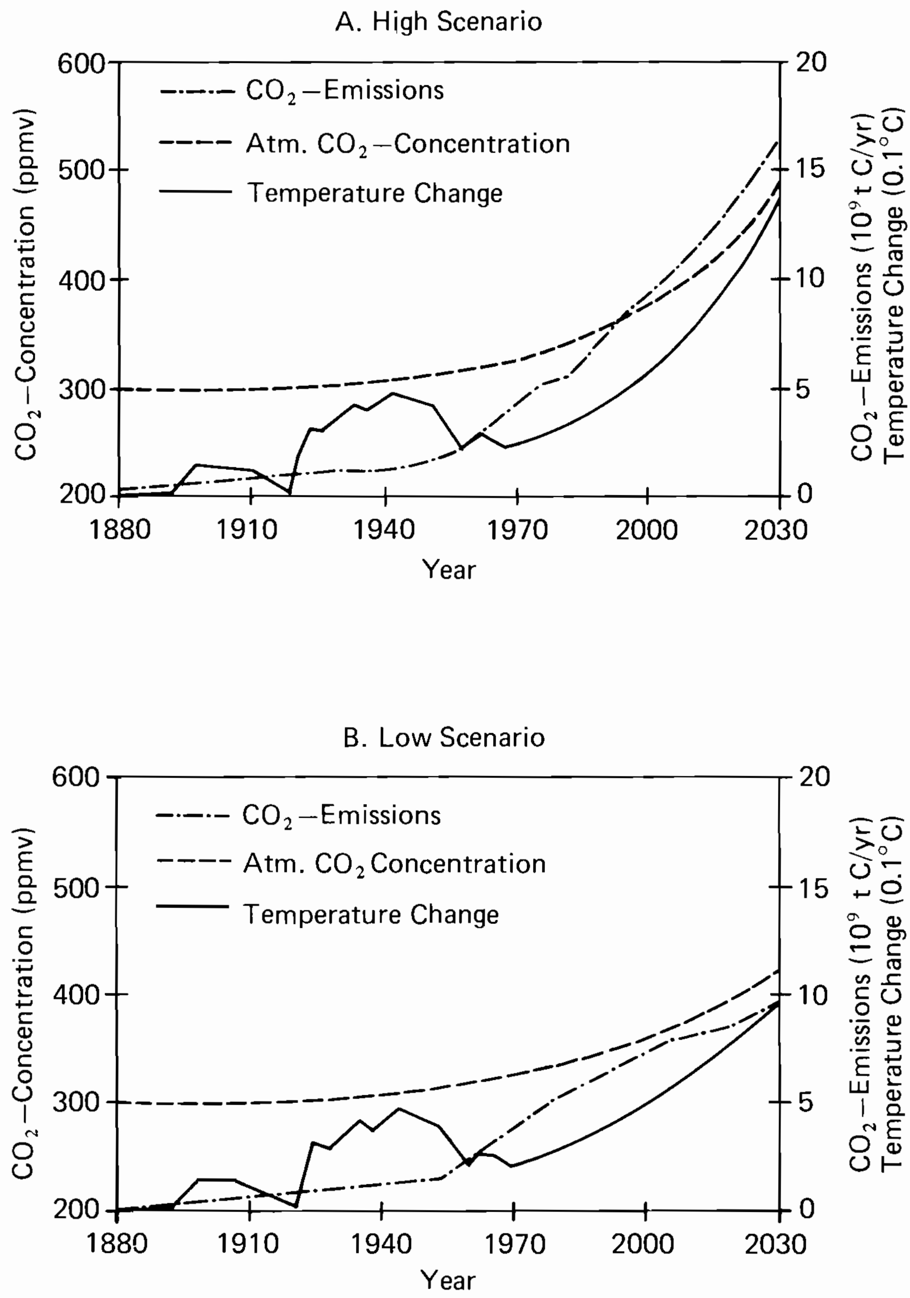
Nuclear power in our supply scenarios is represented on a medium scale. The share of 8.1 TWyr/yr in the High scenario and 5.17 TWyr/yr in the Low scenario relate to 4.8 TW(e) and 3 TW(e) of installed capacity by the year 2030. To be sure, this is considerably below the 10 TW(e) of installed capacity that we considered an upper limit for exploring the nuclear option in Chapter 4. But as we observed there, in order to achieve 10 TW(e) of installed capacity by 2030, there would have to be a worldwide and lasting effort beginning *now* to develop nuclear power.

For our scenarios, we saw that there is just not enough time to build up the nuclear industry to a level higher than that projected. Likewise, we realistically envisaged the use of LWRs of current design initially and the large-scale introduction of the fast breeder reactor around the year 2000.

Hard and Soft Solar Energy

From our explorations of the potential of hard solar power in Chapter 5, we saw that material requirements and their concomitant capital investments were too large to allow solar to be a major global energy source before 2030. Likewise, we concluded in our quantitative analysis that the produc-

Figure 8-4. CO_2 emissions, atmospheric CO_2 concentration, and temperature change, High and Low scenarios.



tion capacity of solar power would be negligible at 2030 and would not reach substantial levels until after the year 2030.

What is left is the soft version—local uses of solar energy. While such power might very well be of local significance over our study horizon, on a global scale, its contribution would be limited. For example, the total roof area per capita could amount to 40 m^2, but on average globally only one-fourth of this area might be suitable for collecting solar power. With 40 m^2 of effective solar power being harnessed in the low temperature domain, one would obtain 400 W per capita or, for eight billion people, a total of 3.2 TWyr/yr. This back-of-an-envelope calculation does not take into account such problems as low temperature storage or costs or special local conditions. The argument is sufficiently robust to conclude that such soft solar power does not match the scale of global energy demand. It turns out to be a valuable, but limited, contribution. In the scenarios, the contribution of soft solar is small—0.5 TWyr/yr (High) and 0.3 TWyr/yr (Low).

Other Renewable Energy Sources

In addition to solar power, there are renewable energy sources with a somewhat local character that invite special consideration. Indeed, because local conditions are different and sometimes unique, there are important local opportunities that do not become explicit in a global study. Often these sources are referred to as "soft." But since we are interested here in balancing global supply and demand, we shall view these resources through the global lens only.

Although renewable energy sources are in principle available on an infinite basis, their commercial use has been limited thus far by generally unfavorable economics. This may change as costs of traditional energy supplies rise. Also, the difficulties of exploiting, harvesting, transporting, distributing, and using renewable energy sources are today generally greater than for fossil fuels. Nonetheless, some renewable sources are in wide use—notably hydroelectric power in both the developed and the developing regions and biomass as a noncommercial energy source in some developing regions. Large-scale, centralized hydroelectric capacity plays an important role in the scenario projections and is used at the level of 1.5 TWyr/yr in both scenarios. In addition, small-scale hydroelectric power facilities and wind converters may have useful applications in certain favorable locations. These potentials are not incorporated explicitly in the supply schemes of the High and Low scenarios, but are assumed to be implicitly covered in the shares of hydroelectric power projected for the developing regions.

Other renewable energy sources that might also be used are biomass, wet geothermal, and commercial fuelwood. Together, these energy forms contribute 0.8 TWyr/yr (High) and 0.5 TWyr/yr (Low) to global supplies. These numbers refer to the commercial uses of such sources, which are constrained by competitive economics of energy supply technologies. These global figures therefore exclude noncommercial uses, although we recognize their importance in satisfying energy demand in many developing countries.

AN EXPLORATION OF EXTREMES: THREE CASES

In developing our scenarios we probed three extreme cases in order to gain insight into the meaning and implications of the more plausible course of events. Once we had quantified the High and Low scenarios, three additional alternatives were explored. These included two supply cases—a Nuclear Moratorium case and an Enhanced Nuclear case—and a very low, 16 TW demand case.

At least two broad and polarized views on future energy supply problems exist today. One view maintains that nuclear energy is unsafe, uneconomical, and/or unnecessary. Another view contends that with long-term oil replacement as the highest priority, nuclear energy—not nuclear energy solely for electricity production—can be called upon to contribute to liquid fuel supply. One view would put a stop to the expansion of nuclear capacity or, at an even greater extreme, close down all existing capacity; the other view would accelerate nuclear growth.

The very low case of 16 TWyr/yr, which represents a simple doubling of the 1975 world primary energy consumption of 8.2 TWyr/yr, also represents an essential redistribution of energy usage patterns and calls for significant conservation and radical changes in how people live. The implementation of such an energy strategy, which has proponents around the world, carries many weighty implications for all regions and should likewise be explored.

Highlights of our three cases studies are presented here, especially in the accompanying tables and charts. The energy supply system implications of these two perspectives are sketched here. Table 8-13 summarizes the main defining parameters of the Nuclear Moratorium and Enhanced Nuclear cases.

Table 8-13. Summary definition of two alternative supply cases.

Assumptions	*Nuclear Moratorium Case (based on Low scenario's demand)*	*Enhanced Nuclear Case (based on High scenario's demand)*
FBR[a] buildup	None	1995 onwards (all regions)
LWR[b] buildup	No new installations	Same as High scenario
Oil production limits	Higher than Low scenario	Same as High scenario
Coal production limits	Higher than Low scenario	Coal consumption is "minimized"
Centralized solar electric (STEC)	2000 onwards (all regions)	Unchanged

[a]Fast breeder reactors or other advanced converter reactors.
[b]Light water reactors or other conventional reactors.

The Nuclear Moratorium Case

The Nuclear Moratorium case is based generally on the Low demand scenario, with the additional constraint that no new (post-1979) nuclear capacity is ordered. To accommodate this, the nuclear moratorium case allows (by assumption) higher fossil fuel annual production rates than the Low scenario, including a higher ceiling on regional coal production, and allows an earlier buildup of centralized solar electricity generation.

A nuclear moratorium in the future would almost certainly have its greatest impact in the developed regions (I, II, and III), where nuclear energy's contribution is expected to be the largest. In these regions, in the Nuclear Moratorium case, even if annual coal production is allowed to rise to the level of the High scenario, there would still not be enough coal to completely replace nuclear electric capacity. The balance would therefore have to be met by centralized, large-scale (hard) solar, with solar having to contribute some 6 percent to total primary energy by 2030. In the Low scenario, hard solar would not contribute noticeably to primary energy needs before 2030.

The overall primary energy supplies for the Nuclear Moratorium case and for the Low scenario are presented in Table 8-14. Coal and solar energy would largely fill the "nuclear gap"; gas and especially oil may have limited capacity for expansion over the Low scenario estimates. Yet natural gas could hold a greater potential for contributing to the liquid fuel problem than is reflected in the Nuclear Moratorium case.

A methane-to-methanol scheme, for example, could unlock what are thought to be vast natural gas resources in many regions of the world as a substitute for tight oil supplies. This would be quite apart from simply expending the gas trade—by means of liquefied natural gas (LNG), for example. But gas as a source of liquid fuels more closely meets market needs. A possible boost to such uses of gas may come if coal production limits were lower than those assumed here, with consequently less coal available for liquefaction. This prospect would seem to be plausible.

Fossil fuel consumption figures show coal use increasing significantly

Table 8-14. Primary energy, Nuclear Moratorium case and Low scenario, 2030 (percent of total primary energy).

Energy Form	*Low Scenario*	*Nuclear Moratorium Case*
Coal	29	39
Oil	22	24
Natural gas	15	20
Nuclear	23	
Hydro-geothermal	7	7
Solar and other renewable sources	4	10
Total	100	100

from the Low scenario to the Nuclear Moratorium case, with gas use growing only moderately. Oil production is already near conceivable upper limits in the Low scenario, so little additional capacity can be called upon for the Nuclear Moratorium case.

The sources for electricity generation, with no new nuclear capacity, shift moderately among load regions. Coal-fired plants that would operate in the peak and intermediate load regions in the Low scenario would take over the nuclear-based load share in the Nuclear Moratorium case. Solar energy and gas would then provide peak load power.

Coal inputs to power production would be so great under the conditions of the Nuclear Moratorium case that the coal available for liquefaction would actually be less than in the Low scenario—in spite of raised coal production limits in the Nuclear Moratorium case. As a result, the share of synthetic liquid fuels from coal in global liquid fuel supply drops from 39 percent (Low scenario) to 33 percent (Nuclear Moratorium case) by 2030.

The amounts of fossil resources remaining in 2030 in the Low scenario and the Nuclear Moratorium case (Table 8-15) show the effects of the larger fossil fuel consumption of the latter: Resources are seriously depleted, leaving uncomfortably small amounts for post-2030 needs. Time, then, becomes an increasingly constraining factor also in this case.

One observes two main features of these Nuclear Moratorium case results. First, primary energy needs can be met for the period up to 2030 without new nuclear capacity (for a low energy demand). Fossil fuel supplies would be depleted more alarmingly; solar electric would expand at its maximum rate; gas would become a more important fuel of the future (with even greater potential). But needs could be met—that is, up to the year 2030. However, the second important point is that the price would be high. Large-scale exploitation of fossil fuels carries environmental, climate, cost, and social burdens. These could be critical, and the choices are not easy ones.

The Enhanced Nuclear Case

The Enhanced Nuclear case is based generally on the High scenario, with a somewhat tighter constraint (by assumption) on fossil fuel supplies (particularly coal) and with a somewhat earlier introduction of breeder reactors. Here, in fact, the case introduces nuclear energy at its maximum possible rate, partly to make possible the use of the generated heat to produce a liquid fuel.

This expanded nuclear option is conceived as a long-term scheme to make use of an essentially infinite heat supply, from nuclear breeders and/or from advanced converter reactors such as high temperature reactors. This heat source could generate hydrogen, either through electricity generation and then electrolysis or directly through thermochemical means. The hydrogen could be combined with coal to produce methanol, making breeders a source of liquid fuel. This option would use coal much more efficiently than otherwise for producing synthetic fuels.

Table 8-15. Fossil fuel consumption, Nuclear Moratorium case and Low scenario.

Resource Type and Cost Category[a]	*Low Scenario*	*Nuclear Moratorium Case*
A. Percent of Original Resources Remaining at 2030		
Coal		
Category 1	65	44
Category 2	100	100
Oil		
Category 1	21	14
Category 1A	24	27
Category 2	86	90
Category 3	100	100
Gas		
Category 1	51	32
Category 2	96	96
Category 3	100	100
B. Years of Resource Remaining After 2030 (expressed in 2030 annual production rate)		
Coal		
Category 1	52	30
Category 2	158	136
Oil		
Category 1	11	7
Category 1A	2	2
Category 2	27	25
Category 3	62	54
Gas		
Category 1	30	15
Category 2	39	28
Category 3	38	27

[a]Cost categories represent estimates of costs at or below which the stated volume of resources are recoverable (in constant 1975 US$).

For oil and gas:	Cat. 1:	12$/boe
	Cat. 2:	12-20$/boe
	Cat. 3:	20-25$/boe
For coal:	Cat. 1:	25$/tce
	Cat. 2:	25-50$tce
For uranium:	Cat. 1:	80$/kgU
	Cat. 2:	80-130$/kgU

A subcategory of oil, 1A, exists only for regions I (NA) and IV (LA) and includes oil available at production costs of $12 to $16/boe. Also, a subcategory of gas, O, exists only for region VI (ME/NAf), with gas available at $2/boe.

In addition to supplying an alternative source of liquid fuels, the Enhanced Nuclear case seeks to minimize fossil fuel production in general and coal production in particular. In spite of the increased nuclear capacity, in this case, global coal production would be reduced by just 2 TWyr/yr by 2030. This coal production is not unimportant. And the modest reduction somewhat conceals the rather major changes in global coal trade. A reduction of 500 to 1000 million tons per year of coal production and export from each of regions I and II could be seen as a major benefit of a regional enhanced nuclear strategy for the otherwise coal-importing region III.

The Enhanced Nuclear case increases the role of nuclear energy to 29 percent of total primary energy supply by 2030, compared to 23 percent for the High scenario (see Table 8-16). This seemingly modest increase is all but that; it means roughly an additional 1000 GW(e) of installed nuclear capacity by 2030. These extra 1000 (or so) power plants need to be sited, built, and integrated into national grids. The analyses of the nuclear option (Chapter 4) indicated that, globally, this expansion (and more) could be done, although regional and national singularities would make the task a challenging one.

The unsettling depletion of fossil resources apparent in the scenarios and in the Nuclear Moratorium case is just slightly abated in the Enhanced Nuclear case. This case would stretch cheap (category 1) coal resources by just six years and more expensive (category 2) coal by eight years. Gas resources are depleted somewhat faster in the Enhanced Nuclear case than in the High scenario, but their exploitation is, in any case, regarded as more market limited than supply constrained. The Enhanced Nuclear case adds some six years to the High scenario projections of resources remaining after 2030 for all four categories of oil taken together. By 2030, the supply of liquid fuels in the Enhanced Nuclear case would be a mix of crude oil, methanol, and synthetic liquids produced from coal.

As with the Nuclear Moratorium case, there are perhaps two main features of the Enhanced Nuclear case results. First, nuclear capacities could be expanded beyond the High scenario estimates and could contribute to the liquid fuel supply problem—pending, of course, the successful development

Table 8-16. Primary energy, Enhanced Nuclear case and High scenario, 2030 (percent of total primary energy).

Energy Form	*High Scenario*	*Enhanced Nuclear Case*
Coal	34	29
Oil	19	17
Gas	17	17
Nuclear	23	29
Hydro-geothermal	4	4
Solar and other renewable sources	4	4
Total	100	100

and commercialization of methanol-producing technology. Second, one observes that the achievement of this potential could not be as large, by 2030, as one might hope. Realistically, in our scenarios we were led to project a nuclear contribution between 5.17 TWyr/yr and 8.1 TWyr/yr by 2030 and not our exploratory trajectory of 17 TWyr/yr as given in Chapter 4. The reasons are legion and have to do with constraints in each region on expected nuclear buildup, availability of cheaper alternatives, and so forth. Global projections of "maximum potential" capacity miss these regional considerations. For example, the methanol from breeders option may be an attractive one for region III but less so for coal-rich regions I and II or, particularly, for oil-rich region IV.

The 16 TW Case: Zero Per Capita Growth

Energy supply systems for the High and Low scenarios and for the two alternative supply cases just discussed would be impressively difficult to build. While it is maintained here that it could be done, that the necessary energy supply systems could be established, it seems worthwhile to consider a popular alternative to large supply schemes—that is, much lower energy use than that projected in the High and Low scenarios. The alternative being proposed is to restrict global energy use per capita to the present rate of 2 kWyr/yr—or, quite simply, to stop growing completely.

Lower energy demand, of course, would ease the pressure on energy supplies. It would also ameliorate somewhat the environmental impacts of ever-increasing energy use, and (perhaps most compellingly) it would offer a bonus of time—time to develop oil alternatives or to discover some viable and sustainable energy source. But a serious question is whether or not it is feasible in the context of continuing global economic growth and stability.

Table 8-17. Assumptions on GDP growth rates, 16 TW case and IIASA scenarios (%/yr).

Region	*High Scenario (1975-2030)*	*Low Scenario (1975-2030)*		*16 TW Case[a] (1975-2030)*	
I (NA)	2.87	1.68	2.09	1.70	2.00
II (SU/EE)	3.91	2.99		2.37	
III (WE/JANZ)	2.93	1.88		2.04	
IV (LA)	4.37	3.48		3.94	
V (Af/SEA)	4.32	3.27	3.24	3.34	3.84
VI (ME/NAf)	5.09	3.57		4.79	
VII (C/CPA)	3.77	2.64		3.44	
World	3.44	2.37		2.50	

[a]*Source:* U. Colombo communication to W. Häfele, 13 October 1978.

Notes: Figures are average real GDP growth rates over the period 1975-2030. The IIASA scenarios assume declining growth rates; the 16 TW case assumes constant average growth rates over the fifty-five-year period.

A major premise of the 16 TW case is that requirements for energy in the developed regions would decline, as economies mature and population growth rates decline, while energy growth in the developing regions would continue to increase, although probably slowed by resource availability difficulties. The next fifty years would be the critical period, after which global energy use may well stabilize.

The population projection for the 16 TW case is identical to that for the High and Low scenarios, and the GDP assumptions differ only slightly between the 16 TW case and the Low scenario (Table 8-17). Somewhat greater economic growth was assumed for developing regions in the 16 TW case than in the Low scenario and a slightly higher overall global growth as well. But it seems fair to say that the 16 TW case is, in general terms, similar to that of the Low scenario. Large differences are noticeable with respect to energy-saving measures and their impacts on current lifestyles, with the 16 TW case calling for more drastic conservation.

Table 8-18. Major assumptions for the 16 TW case compared to the Low scenario.

	Region I (NA)			*Region III (WE/JANZ)*		
	Base Year 1975	*Low Scenario 2030*	*16 TW case*	*Base Year 1975*	*Low Scenario 2030*	*16 TW case*
Macroeconomics, lifestyle						
Manufacturing (% of GDP)	24.5	23.8	20.0	33.6	29.7	20.0
Services (% of GDP)	64.8	65.8	69.6	48.5	55.0	64.7
Basic materials (% of manufacturing-VA)	24.8	23.2	20.0	33.0	29.4	20.0
Machinery and equipment (% of manufacturing-VA)	43.2	47.0	50.2	42.0	47.1	55.0
Intercity passenger transportation						
Distance traveled per person per year (1000 km)	10	15	10	7.5	10	7.5
Persons per car	2.0	1.9	2.0	5.21	3.20	4.0
Distance driven per car per year, intercity (1000 km)	7.0	7.8	5.0	5.0	5.6	5.0
Bus (% of public transportation)	15	12	30	35	29	35
Train (% of public transportation)	5	5	20	50	56	60
Plane (% of public transportation)	80	83	50	5	15	5
Dwellings						
Electrical use for appliances (1000 kWh/dwelling)	3.85	6.25	3.85	1.95	4.50	2.20
Useful energy for air conditioning per dwelling (1000 kcal)	4472	5800	4472		3000	
Dwelling with air conditioning (%)	39	50	20	0	20	0

Note: These assumptions are selected from an array of changes. They both represent the largest changes and have the most energy-reducing impact. In some instances (e.g., automobile efficiency or home insulation), the assumptions for the Low scenario were regarded as sufficiently rigorous so that only rather minor further improvements could be introduced into the 16 TW case.

Any increase in the per capita energy demand in the developing regions would therefore require decreases in the demand in the developed regions. It is along such lines that, for the year 2030, target values of primary energy of 8 kWyr/yr per capita in region I and 3.2 kWyr/yr per capita in region III were obtained. The corresponding 1975 values are 11.2 kWyr/yr per capita in region I and 4.0 kWyr/yr per capita in region III.

It is crucial that such decreases be made consistent with the assumed positive GDP growth of 2 percent per year. To that end, a number of assumptions had to be made, each of which is somewhat arbitrary, to ensure that the overall brackets of decrease in energy demand and of increase in GDP are met. Such assumptions relate to the structure of an economy, as well as to lifestyles.

For the Low scenario, only a slight adjustment to the assumed GDP growth rate of 2 percent per year was necessary. The situation is entirely different for the 16 TW case. In Table 8-18, such major assumptions are compared with those of the Low scenario. It appears that the targets of the 16 TW case can only be met by drastic changes in economic conditions and lifestyles, in addition to technological improvement: There, the manufacturing and basic materials sectors would go down, while the services sector and the share of machinery and equipment within the manufacturing industry

Table 8-19. Final energy results, 16 TW case and Low scenario (absolute figures in GWyr/yr).

	Region I (NA)				*Region III (WE/JANZ)*			
	Base Year 1975	*Low Scenario 2030*	*16 TW case 2030*	*Percent Reduction[a]*	*Base Year 1975*	*Low Scenario 2030*	*16 TW case 2030*	*Percent Reduction[a]*
Total Final Energy	1871	2656	1819	-32	1589	3143	1723	-45
By sector								
Transportation	541	688	410	-40	313	716	394	-45
Industry	757	1327	818	-38	805	1588	725	-54
Household-service	573	641	591	-8	417	839	604	-28
By fuel type								
Substitutable fossil fuels[b]	921	964	789	-18	801	1012	607	-40
Centrally supplied heat[c]	0	0	0	n.a.[d]	0	103	68	-34
Soft solar	0	74	61	-18	0	71	46	-35
Electricity	228	547	265	-52	201	640	285	-55
Motor fuel	597	804	510	-37	381	864	518	-40
Coke and feedstocks	125	267	194	-27	206	453	199	-56

[a]Percentage reduction is the reduction from the Low scenario to the 16 TW case, as a percentage of the Low scenario.

[b]Substitutable fossil fuels are substitutable (mostly heat) uses of oil, gas, and coal.

[c]Centrally supplied heat is heat produced by district heat and cogeneration facilities.

[d]Not available.

would go up. Intercity transportation would remain at 1975 levels, despite the assumed 2 percent per year GDP growth. For region I, bus services would double and train services quadruple, whereas air traffic services would be reduced. The energy needed for appliances in people's homes would remain essentially at the present level, but air conditioning would be cut down significantly (in region I) or not be used (in region III).

After additional assumptions have been made that are not shown in the table, one can proceed to envisage further improvements on the technology side. The final energy demand that then results is explained in Table 8-19. For both regions I and III, the reductions in energy use are given in percentages of the Low scenario requirements, which, as one should note, already incorporate significant shares of energy conservation. Over and above these, the reductions range from 8 percent (region I) to 56 percent (region III), resulting in 32 percent and 45 percent decreases in the total final energy demand.

Thus, the developed regions would have to reduce or phase out completely their use of electricity for heating purposes, greatly improve efficiency in all energy end uses, and shift their economies move toward services and away from energy-intensive heavy industries and toward less energy-intensive industries.

REGIONS ARE DIFFERENT

So far we have emphasized the global trends evidenced in our scenarios. But regions differ—often quite distinctly. We now focus our attention on the features of the energy situation in each of the seven world regions.

Features of Region I, North America

The character of the North American energy future is dominated by three considerations—a post industrial, mature economy, "slowdown"; substantial energy savings because of technological advances and some restructuring of economic activities; and a rapid buildup of a coal liquefaction industry to replace domestic and imported oil. None of these changes, except possibly the last, is expected to produce profound or sweeping changes in lifestyles of North Americans.

The North American economy is projected to grow at real rates declining to 1 to 2 percent per year after 2015, from more than 3 percent per year in the 1950s and 1960s. Per capita GDP growth rates would be somewhat lower. People's traveling and other energy-consuming activities are expected to saturate, meaning that aggregate growth would be slower.

People are likely to use public transit more; live in better insulated homes; live more in apartments, townhouses, or condominiums; consume a less energy-intensive mix of industrial products. They would still commute to jobs, take vacations, drive automobiles. An all-bicycle or an all-high-rise apartment future is not likely.

Energy conservation will be important. Automobiles averaging 35 miles per gallon (mpg) in 2030 rather than the 17 mpg of today, homes 40 percent more efficient in terms of heat loss, and solar collectors attached to 50 percent of all post-1975 single family dwellings would be the main ingredients of this conservation program.

Oil use would be cut back wherever possible. Nonetheless, liquid fuel demands would grow sufficiently to require major exploitation of synthetic liquid fuels—from shales or from coal. Coal production is projected to reach 1.5 to 2.7 TWyr/yr by 2030, 3.1 to 5.6 times its 1975 level. Some 55 percent of this production would go to a synthetic liquid fuel industry (in the High scenario).

The environmental, labor, water, and transportation issues surrounding coal production in the United States cast some doubt about rapid coal production increases. Yet the liquid fuel demands seem irreducible, and the coal resource is available. The world would need the coal-based liquid fuel supply that region I could export. By 2030, in the High scenario, region I would produce 750 GWyr/yr of coal for export, either as coal to produce synthetic liquid fuels elsewhere or as synthetic liquid fuels produced internally. The major global alternative to coal liquids would seem to be shale oil—also an export from this region.

Primary energy use would grow from some 2.65 TWyr/yr in 1975 to more than 6 TWyr/yr in the High scenario (4.4 TWyr/yr in the Low) by 2030. Of this, the dominant sources would be nuclear energy and coal. In 1975, nuclear energy and coal together were 0.55 TWyr/yr (21 percent), while oil and gas together provided 1.93 TWyr/yr (73 percent). In 2030, nuclear energy and coal together would give 2.9 to 3.9 TWyr/yr (65 percent), while primary oil and gas together would total just 1.2 to 1.8 TWyr/yr (27 to 30 percent). The supply mix of the future seems to be driven toward coal and nuclear energy, based on the aggregate of supply constraints and market restrictions. With greater flexibility in these constraints, a conceivable big energy source for the future in region I could well be natural gas.

Features of Region II, The Soviet Union and Eastern Europe

In the centrally planned economies of this region, the energy future would be shaped by a clear intent to expand industrial production and productivity while minimizing oil use wherever possible. Central economic management seems necessary to do this, as does the successful development of the energy riches in inhospitable Asian portions of the region.

Economic growth rates are expected to be high—higher than in other developed regions, yet lower than the rates of the 1950s and 1960s. The growth rates of both scenarios give GDP per capita levels 40 to 100 percent higher in this region than today's level in region I. Much of the GDP in region II would be industrial output, as it is today. Slow population growth makes labor supply a major constraint on economic growth prospects.

Industrial productivity gains are expected to be the main source of energy savings. Soviets and East Europeans already drive small, fuel-efficient cars (and relatively few cars); they generally do not lead as energy-intensive lifestyles as do consumers in region I or in region III.

The shift away from a reliance on oil has three main elements. First, communities would be sited so as to maximize public transit use and minimize automobile travel. Second, oil would not be used in power plants—these shifting more to gas (now), coal, and nuclear energy. And third, district heat and combined heat and power capacity would be rapidly expanded for buildings and industrial heat supplies.

The intent thus to minimize liquid fuel use and to exploit the vast gas and coal resources of Soviet Asia for district heat and power supplies leads to the expectation that the Soviet Union will not become an oil importer in the foreseeable future. Some oil exporting from the Soviet Union to Eastern Europe would most likely continue, and expanded net exports of gas and coal from the region as a whole could occur.

The greatest shift in region II among primary energy sources would be toward nuclear energy and, to a certain extent, toward coal. In the High scenario, nuclear power provides 33 percent of total primary energy by 2030; coal adds 38 percent. Oil production, as a share of total liquid fuel supply, declines substantially in these estimates as coal liquefaction largely takes over liquid fuel supply. Gas production remains high, at over 1 TWyr/yr in 2030 or 16 percent of total primary energy in the High scenario. These primary energy trends look, in the aggregate, very much like those of region I. This is perhaps instructive, since the underlying energy demand structure and mix of economic activities in the two regions are very different.

Features of Region III, Western Europe, Japan, Australia, New Zealand, South Africa, and Israel

Region III is a highly heterogenous region. Though all these countries are industrialized to varying degrees, they differ considerably in their energy resource endowments. Today the region as a whole depends extensively on imported oil. This dependence is likely to continue in the coming decades, even as the region's economic growth slows and indigenous coal and (to a lesser extent) domestic oil resources are developed. A strong reliance on nuclear power for electricity production could free domestic coal resources for synthesis of liquid fuels; ultimately, nuclear breeding may be a viable source for hydrogen for liquid fuels in this capital-rich but basically energy resource-poor region.

Growth in GDP would likely decline as these national economies mature and as population stabilizes. By 2030, real annual economic growth could be as low as 1 or 2 percent per year. At the same time, these economies would continue to shift toward services. In 2030, GDP per capita levels would exceed (by 20 to over 100 percent) those in region I in 1975. Yet the region is not likely to take on entirely North American lifestyles. Extensive use of public transit systems would continue, air conditioning use would remain rather small, and electricity use for home appliances would not reach 1975 U.S. levels. High energy costs have affected, and would continue to affect, the specific development paths for this region.

Because of its high costs, energy is currently being used more efficiently in region III than anywhere else. The potentials for energy savings through technical fixes are smaller there than in region I. Still, various measures can reduce energy demand growth—by dampening tendencies of increased automobile travel and by building even more energy-tight buildings.

The high oil import dependence of this region would cause it, in these projections, to shift strongly away from using liquid fuels, wherever possible. Yet liquid fuel demand would necessitate 1400 to 2100 GWyr/yr of secondary liquid fuels by 2030, from just 980 GWyr/yr in 1975. If for the region domestic oil production were 300 GWyr/yr (High scenario) by 2030, and if domestic coal production were 1000 GWyr/yr, and if 400 GWyr/yr of this coal were turned into synthetic liquids, then nearly 1600 GWyr/yr of coal *imports* (or, equivalently, 1000 GWyr/yr of synthetic liquid fuel imports) would be required from regions I and II simply to meet secondary liquid fuel demands. These imports, coupled with oil imports of 600 GWyr/yr from region VI in 2030, paint a discouraging picture of continued import reliance for essential liquid fuels in region III. (The Low scenario would be, *in these terms,* more encouraging; no coal imports would be required. But oil imports from region VI would total 1100 GWyr/yr, instead of 600 GWyr/yr, by 2030 in the High scenario.)

Region III's primary energy demand could reach 4.5 to 7.1 TWyr/yr by 2030, compared to 2.26 TWyr/yr in 1975. Nuclear power represents the largest single addition to the primary mix, accounting for about 34 percent of primary energy by 2030 in the High scenario. If domestic oil and, especially, natural gas were expanded at the highest feasible rate, their contribution grows to just 1.8 TWyr/yr by 2030 in the High scenario (from 1.49 TWyr/yr in 1975), while their share, together, of total primary energy drops from 66 to 25 percent for the scenarios. The massive exploitation of coal in this region, both domestic and imported, still leaves an approximately constant (25 percent) share for coal.

Features of Region IV, Latin America

Oil has been, and will continue to be, the dominant energy source of Latin America. Adding the recent increased oil resource estimates for Mexico to the vast heavy crude oil potential in Venezuela and Colombia shows total oil resources that appear capable of supporting even the high growth prospects of this region.

Like other developing regions, Latin America is projected to have a more rapid growth in GDP than that of the developed regions. The projected range is 3.5 to 4.4 percent per year (average) to 2030. These rates are high, by global standards, but still show reductions from those of the recent past. In the High scenario, per capita GDP in 2030 exceeds that in region III in 1975. But the challenges to such development are formidable; Latin America population could be 800 million in 2030, two and a half times its 1975 population. Providing sufficient services—and jobs—for so many people will require all the energy and other wealth that the region can generate.

Assuming that some fraction of heavy crude oil can be produced at relatively low cost, then all of the oil production necessary for domestic needs in the scenarios to 2030 could be provided from resources at $16 per barrel or less. In the scenarios, total oil production grows from 4.6 mbd in 1975 to 16 to 25.5 mbd by 2030. These are 2.3 to 3.2 percent per year annual increases in output; from 1975 to 1978 the growth was 2.6 percent per year. A serious question is whether or not region IV can sustain 3 percent per year growth over the next fifty years.

The IIASA assessment is that region IV could increase its oil output to meet domestic needs, but would choose not to export oil. Too rapid rises in income can be destabilizing; there are signs already that the oil-rich countries of the region would build up their petroleum industries only at a carefully measured pace. Also, oil production solely for internal purposes would be enormous, aside from any production for export. The oil production rates for region IV in 2030 in the scenarios equal 30 to 45 percent of the total global production in 1975.

Major nonoil energy sources in the supply mix of the future are expected to be hydroelectricity and some other renewable sources—notably commercially distributed wood (e.g., charcoal for industry and households) and ethyl alcohol from plantation crops (e.g., in Brazil).

The primary energy source mix in the High scenario shows that oil, while growing in magnitude, would be about constant as a share of total primary energy, while renewable sources and nuclear energy would grow to account for some 18 to 23 percent of total primary energy by 2030 (from essentially 0 percent in 1975). Natural gas use could be somewhat market limited in this region, but the resources base would allow gas to play a larger role than that in the scenario projections.

Features of Region V, Africa (Except Northern Africa and South Africa), South and Southeast Asia

Region V would seem to be facing the bleakest energy future of all the regions. Endowed with neither energy resource riches nor capital wealth (skills, technological know-how), while having large and rapidly growing populations, the favorable energy options for the long term seem few. In terms of development objectives for the region, the situation is challenging, somewhat discouraging, but not hopeless.

Region V is the poorest, in per capita GDP, of all the seven world regions. According to both scenarios, it would still be the poorest by 2030, in spite of "vigorous" assumptions made about the regions' economic and energy prospects—namely, real GDP growth rates averaging 3.3 to 4.3 percent per year from 1975 to 2030, higher than the rates in the developed regions. The development path for this growth would continue the presently observed shifts toward the industry, service, and energy sectors and a decline of the agriculture share (from 36 percent of GDP in 1975 to around 16 percent by 2030 in the High scenario). Energy savings are not expected to any appreciable extent in region V.

Currently, the region is a net oil exporter, because Nigeria, Gabon, and Indonesiá are exporters and because aggregate liquid fuel demands are relatively low. The scenarios project region V to become a net oil importer within the next decade; by 2010, imports would be greater than domestic crude oil production. Coal liquefaction is then expected to provide a small, but growing, domestic source of liquid fuels.

Although liquid fuels offer a convenience and flexibility of use that makes them highly desirable for broad development objectives, they are becoming steadily more expensive. Region V would therefore be wise to tap other sources where possible. Over the long term, renewable sources should play a growing role in the scenarios, with biogas and charcoal assumed (in the High scenario) with an aggressive policy to meet up to 16 percent of household and industrial final energy needs. All renewable sources combined (including hydroelectric power) could account for some 20 percent of total primary energy by 2030 in the High Scenario or even 30 percent in the Low scenario. Electricity needs, growing at 4.7 to 5.9 percent per year in the scenarios, would be met by coal, nuclear energy, and hydroelectric power.

Features of Region VI, Middle East and Northern Africa

To the entire world, oil is the major feature of region VI, but there is much more to be known and understood in the dynamics of this oil. This world region includes the large, swing producers of OPEC, in particular Saudi Arabia, Kuwait, and the United Arab Emirates. These countries dominate the aggregated region VI.

The swing producers of OPEC, those who can easily expand or restrict oil output, hold about one-third of the world's oil reserves, and they could theoretically expand their annual production by several times. Within this core, Saudi Arabia holds the ability to be quite literally the residual supplier for the world, varying its production up or down to meet the fluctuations in demand and supply of the rest of the globe.

With very large oil reserves, it is in the region's self-interest to stretch out the lifetime of its reserves—to avoid an early, high peak of production followed by rapid decline. Oil revenues, optimally, should keep pace with (but need not exceed) development needs and should continue as long as possible—that is, until alternative sources of income (new industries, business, etc.) can be created. The translation of the oil riches of this region into a broad solar energy capacity (that could last forever) is one of the more obvious options. The region as a whole would be wise to constrain its long-term oil output, since oil resources would be seriously depleted by 2030 with a sustained production rate of just 33.6 mbd (as envisaged in the scenarios).

GDP growth rates are expected to be high for quite some time. Development would come with the growth, and region VI could, by 2030 in the scenarios, be at GDP per capita levels comparable to those in regions I and III today. Development also signals growing shares of manufacturing and services in GDP and a relative decline in the energy production sector share.

Oil and natural gas together provide about 90 percent of primary energy in region VI over the scenario period in the High scenario. An assumed quantity of cheap natural gas, used for domestic purposes, leads to gas taking at least 50 percent of the primary energy market by 2030. Gas could even be used rather extensively for electricity production.

Features of Region VII, China and Other Asian Centrally Planned Economies

Of all the regions, the least is known about the energy future of region VII, at least in the world outside. Here, however, are a few key assumptions and resulting generalizations.

GDP growth seems likely to be high, but so does population growth. With the projection of average GDP growth rates of 2.6 to 3.8 percent per year and of an average population growth rate of 1.2 percent per year, by 2030 per capita GDP could reach levels comparable to those of region IV today.

We expect region VII to be neither a net exporter nor an importer of energy. But domestic oil resources are not likely to be able to keep pace with rising demands; coal liquefaction would most likely be needed after the year 2000.

Coal production, required for liquid fuel synthesis and electricity generation, could reach nearly 3.5 billion tons per year (3.2 TWyr/yr) by 2030 in the High scenario, from 0.48 billion tons per year (0.45 TWyr/yr) in 1975. Over 2 billion tons per year of this would be needed simply for synthetic liquid fuel production. This coal production would exceed that of region I in 2030.

The main primary energy source for the future in these projections is coal. Natural gas and nuclear energy could grow noticeably, but still represent less than 20 percent of primary energy by 2030 in the scenarios.

CONCLUDING REMARKS

What we have presented here are quantitative results for two supply and demand scenarios and three alternative approaches to balancing global supply and demand. In all instances we have stressed internal consistency and global comprehensiveness. We saw no other way. In the end we arrived at several different approaches that are not meant to define a unique set of conclusions.

To be sure, no one can predict the future. And, equally surely, there will be only one future. Thus, our findings are not predictions of a futuristic energy world. Our intent has been to indicate the paths that would most likely have to be followed if we want to be realistic about getting from today's energy situation to a less problematic one.

Although not definitive, our findings are suggestive. In the next chapter we reflect on the implications that our findings might have for global energy strategies.

REFERENCES

Ashley, H.; R.L. Rudman; and C.G. Whipple. 1976. *Energy and the Environment: A Risk-Benefit Approach*. Oxford: Pergamon.

Chant, V.G. 1980. *Two Global Scenarios: Evolution of Energy Use and the Economy to 2030.* Laxenburg, Austria: International Institute for Applied Systems Analysis (forthcoming research report).

Eckstein, L. 1978. *E.P.A. Program Status Report: Oil Shale.* Cameron Engineers, Inc. Springfield, Virginia: N.T.I.S.

Grenon, M., ed. 1977. *First IIASA Conference on Energy Resources.* CP-76-4. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Grossling, B.F. 1976. *Window on Oil: Survey of World Petroleum Resources.* June 5, 1976. London: Financial Times.

Hicks, N.L. et al. 1976. A Model of Trade and Growth for the Developing World. *Eur. Econ. Rev.* 7:239.

Institute of Geological Sciences. 1978. *Shale Oil, Tar Sands and Heavy Oils.* Briefing Paper 78/03. London.

Keyfitz, N. 1977. *Population of the World and Its Regions 1975-2050.* WP-77-7. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Lambertini, A. 1976. *Energy and Petroleum in Non-OPEC Developing Countries 1974 and 1980.* WP 229. New York: World Bank.

Meyer, R., ed. 1977. *Future Supply of Nature Made Petroleum and Gas. Proceedings of the UNITAR/IIASA Conference, Laxenburg, Austria, July 1976.* Oxford: Pergamon.

Niehaus, F. 1976. *A Nonlinear Eight Level Tandem Model to Calculate the Future CO_2 and C-14 Burden to the Atmosphere.* RM-76-35. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Oil and Gas Journal. 1978. Issues of March 27; April 17; July 17; July 29; August 14; August 28; and September 11.

O'Shaughnessy, H. 1976. *Oil in Latin America.* London: Financial Times.

Penner, S.S., and L. Icerman. 1975. *Energy. Volume 2: Nonnuclear Energy Technologies.* Reading, Massachusetts: Addison-Wesley.

Perrine, R., ed. 1978. *Enhanced Oil Recovery Potential in the U.S.* Washington, D.C.: Office of Technology Assessment.

Petroleum Intelligence Weekly. 1979. Special Supplement. February 5.

Uhl, W.C. 1977. *North Sea Petroleum, An Investment and a Marketing Opportunity.* New York: McGraw-Hill.

Workshop on Alternative Energy Strategies (WAES). 1977. *ENERGY: Global Prospects 1985-2000.* New York: McGraw-Hill.

9 ADDING IT ALL UP

At this stage, we have completed the presentation of our quantitative analysis. As stated at the outset in Chapter 2, the numerical results cannot, of course, define a unique set of conclusions directly useful to energy policy decisions, but they are suggestive. And it is to these suggestions that we now turn our attention.

The solution to the world's energy problem is contingent upon many sets of circumstances that are cultural, technical, political, economic, and environmental in nature. Formal scientific methods alone cannot resolve the dilemma of balancing the supply and demand of energy around the globe. The problem is a complex one. It is, in fact, a typical systems problem, a question of synthesis.

But it is precisely because of these aspects, and not in spite of them, that the findings of our study have to be assessed and their implications for future energy policies determined. Making that distinction is not a totally objective task.

To have achieved a consensus at this point among the more than 140 scientists who contributed to the study would have been impossible. Certainly some of the assumptions incorporated in the analysis are controversial, though we hope realistic. The level of controversy encountered when one tries to interpret and qualitatively extrapolate the final results is greater still. But to a large extent, such interpretations are controversial because they are so important. To shy away from addressing them would be to leave our study incomplete in a critical dimension. What we present here—in an effort to deal with these issues without suggesting that either the member organizations of IIASA, the staff of IIASA, or even the staff of the Energy Systems Program have achieved some sort of heroic consensus—are the interpretations of one person only—specifically, Wolf Häfele, the leader of the Energy Systems Program.

They reflect the results of the scenarios described in the last chapter, as well as the more exploratory aspects of the earlier discussions of supply options (Chapters 3 through 6) and their constraints (Chapter 7). Moreover, they reveal an underlying, unifying theme that, while not surprising in hindsight, was hardly obvious originally and that has to do with a general pattern of response to the increasing scarcity and expense of energy resources.

- *Balancing energy demand and supply means striking a balance between energy, capital, labor, and skill to provide a desired energy service.*

As we have become ever more aware of the problems of energy resources throughout the 1970s, we have begun to adapt in ways that effectively make better use of the limited energy currently available. Sometimes we label these adaptations conservation; sometimes we call them improvements in efficiency; sometimes they are referred to as productivity increases. Whatever we call them, they all involve reducing the energy needed to produce some service (be it a well-heated sitting room or intercity jet travel) by replacing it with something else. In some cases this replacement might be in the form of capital resources (e.g., investing in home insulation); in others it might be better classified as labor (e.g., periodic tune-ups of an automobile to increase its gas mileage); and in still others it might best be labeled simply ingenuity or know-how (e.g., anything from more carefully planned shopping trips to large-scale reconfigurations of industrial processes).

At a personal level, we are all familiar with such substitutions, of capital or labor or know-how for energy in the production of services. At more collective levels, ranging from small business enterprises to international alliances, we are becoming more familiar with them. And what will reappear throughout the discussion to follow is the conviction that what may now seem to us to be perhaps quite sophisticated, energy-conserving arrangements of our resources of capital, labor, know-how, and energy indicate only the direction in which we can travel. They in no sense even begin to suggest the limits of what can be done.

Of particular importance is the notion of investing these resources to eventually increase the stock available in each category. Again, these ideas are hardly unfamiliar—investments in education, in research and development, in capital equipment, in exploratory drilling all have contributed, and continue to contribute, to the amounts of capital resources, skilled manpower, energy resources, and know-how that we can put to use. What is less familiar is what these same concepts lead us to when applied from a global perspective contemplating the next half a century and beyond.

- *It could be done.*

Our aim when we began our global analysis some seven years ago was to take a fresh look at the energy problem facing the world over the next fifty years and to characterize demands, supply opportunities, and constraints as objectively as possible. Working from the premise that the principal fuels in use today are finite, we questioned whether civilization would be able to meet the energy challenge. Based on the analysis of technological and economic factors, we conclude that with the technologies at hand or potentially at hand, and using the world's resources as perceived today, it is possible to provide enough energy for a world of eight billion people in the year 2030. It could be done! This is not a trivial statement, given the degree of cultural pessimism that one often encounters.

Contrary to our original expectations, fifty years proved too brief a period to allow a complete transition from our current fossil-fuel-based energy system to a truly global sustainable energy system. Rather, what will occur during the next fifty years is a transition of a less sweeping nature, from clean fossil fuels to dirty fossil fuels.

Nonetheless, we can go beyond the conclusion that it is possible to provide for the energy needs of a world of eight billion people in 2030. Specifically, the analysis did not demonstrate any insurmountable obstacles to the world's eventually supporting eight, ten, or even twelve billion people indefinitely. To the contrary, it pointed to several technological features that might be incorporated in a global energy system supporting such a world. So, even with respect to a sustainable energy system, our analysis suggests that it could be done, although the transition to such a system could not be completed by 2030.

We are faced with two goals that must be pursued simultaneously. First, we must manage the more immediate transition—that is, we must use the dwindling amounts of fossil fuels prudently. Second, we must concurrently manage the initial stages of the more extensive transition with equal wisdom. In particular, we must build up the nuclear and solar energy industries progressively so that they are able to assume the role we envisage for them in the period after 2030.

VARIOUS LEVELS OF ENERGY DEMAND

What has emerged quite starkly from our study is that any way of balancing demand and supply, whether high, medium, or low, would lead to some form of hardship. Moreover, energy conservation measures of any degree would cause unavoidable pain.

- *Only radical changes in lifestyles could lead to very low energy demand.*

We considered the implications of a very low energy demand world, using some of the data for the 16 TW case, as discussed in Chapter 8. In a low energy demand world, global average energy use per capita would remain at the current ratio of 2 kWyr/yr. GDP would continue to grow, but only modestly, at 1.7 percent per year for region I and 2 percent per year for region III.[a]

Fundamental changes would also have to take place in the structure of economies in order to achieve these values. For instance, in the developed regions, economies would have to shift more to services, with that sector contributing as high as perhaps 65 to 70 percent to the GDP, and there would have to be a reduction in the level of energy-intensive industries in these countries. Energy conversion processes would have to be redesigned to reduce losses in converting primary energy into final forms (e.g., in converting coal into electricity). Both passenger and freight transportation activities would have to be minimized. Per capita energy demand would have to be reduced by rigorous insulation of single family houses and more energy-efficient apartment houses. And much more would need to be done. Obviously, extreme energy-saving measures would have to be introduced in almost every sphere of human activity relating to energy, mandating a radical change in lifestyles of the peoples of all regions.

- *The conservation measures implied in our Low scenario are strong, but are probably more realistic than those of the 16 TW case.*

If the world elects to travel a moderate path toward, say, that of a primary energy use of 22 TWyr/yr (our Low scenario), there are important contingencies that need to be recognized. Energy conservation measures required at this moderate level, while certainly less than in the 16 TW case, are still at the limit we consider feasible if present lifestyles and freedom of choice are to be maintained. In our Low scenario projections for the seven IIASA world regions (see Table 9-1), we see that there would have to be a saturation in the per capita energy consumption in the regions of the OECD—basically regions I and III—and only modest increases in per capita energy consumption in the developing regions (IV, V, VI, and VII).

This observation is supported in part by a comparison of the ratio of final energy use to GDP for the different regions, as shown in Figure 2-3 of Chapter 2. The fact is evident that the developing regions, in building up their economies, require more energy per unit of GDP than those regions that have an advanced industrial infrastructure. In addition to possible reductions in energy use in the developed regions, we also envisaged only modest increases in energy use in the developing regions, pointing to a decreasing energy intensiveness in general.

- *Our High scenario projects economic growth rates that might be considered moderately satisfactory but that would transfer the hardship to the supply side.*

[a]Throughout our study, we have assumed declining growth rates. The numbers here are not meant to indicate constant and, by implication, ongoing growth rates; rather, they link the years 1975 and 2030.

Table 9-1. GDP growth rate, energy consumption per capita, elasticities, 1975-2030.

A. Primary Energy Consumption per Capita (kWyr/yr,cap), 2030

Region	*Base Year 1975*	*High Scenario*	*Low Scenario*	*16 TW Case*[a]
I (NA)	11.2	19.1	13.9	8.0
II (SU/EE)	5.1	15.3	10.4	6.2
III (WE/JANZ)	4.0	9.3	5.9	3.2
IV (LA)	1.1	4.6	2.9	2.8
V (Af/SEA)	0.2	1.3	0.7	0.7
VI (ME/NAf)	0.9	6.7	3.5	3.6
VII (C/CPA)	0.5	2.6	1.3	1.2
World	2.0	4.5	2.8	2.0

B. Comparison of Assumptions about GDP Growth Rates (%/yr)

Region	*High Scenario*	*Low Scenario*		*16 TW Case*[a]	
I (NA)	2.87	1.68		1.70	
II (SU/EE)	3.91	2.99	2.09	2.37	2.00
III (WE/JANZ)	2.93	1.88		2.04	
IV (LA)	4.37	3.48		3.94	
V (Af/SEA)	4.32	3.27		3.34	
VI (ME/NAf)	5.09	3.57	3.24	4.79	3.84
VII (C/CPA)	3.77	2.64		3.44	
World	3.44	2.37		2.50	

C. Primary Energy-GDP Coefficient, ϵ_p [b]

	High Scenario		*Low Scenario*		*16 TW Case*	
Region	*1975–2000*	*2000–2030*	*1975–2000*	*2000–2030*	*1975–2030*	*2000–2030*
I (NA)	0.42	0.67	0.36	0.89[a]	-0.20	0.06
II (SU/EE)	0.65	0.67	0.62	0.62	0.75	0.01
III (WE/JANZ)	0.70	0.77	0.65	0.73	0.04	0.10
IV (LA)	1.04	0.98	1.06	0.97	0.96	0.82
V (Af/SEA)	1.15	1.11	1.18	1.19	1.38	0.90
VI (ME/NAf)	1.16	0.96	1.23	1.10	1.04	0.75
VII (C/CPA)	1.06	1.17	0.98	1.27[a]	1.12	0.54
World	0.70	0.90	0.67	0.93	0.50	0.34

[a]*Source:* U. Colombo communication to W. Häfele, 13 October 1978.

[b]This elasticity, ϵ, is defined by the following relationship:

$$\frac{E(t_2)}{E(t_1)} = \left\{ \frac{GDP(t_2)}{GDP(t_1)} \right\}^{\epsilon},$$

where t_1 and t_2 are two given times, E is energy consumption measured in physical units, and GDP is gross domestic product measured in real noninflated monetary units. This elasticity is calculated with respect to primary energy, ϵ_p.

[c]Derived from U. Colombo's specification of GDP and primary energy consumption growth (U. Colombo's communication to W. Häfele, 13 October 1978) and is not consistent with methodology of IIASA scenarios.

Finally, we looked at the implications if the world elects to work toward higher energy demand, on the order of 36 TWyr/yr of primary energy (our High scenario). Table 9-1 also gives comparative data on the evolution of growth rates of GDP, energy consumption per capita, and the resulting elasticities for the seven world regions over the period 1975-2030 for the two reference scenarios and the 16 TW case.

In the High scenario the world would have taken on the formidable task of providing energy for a planet that has doubled its population, as well as doubled the average energy consumption to a per capita level of 4.5 kWyr/yr. For some people this would mean relief from the hardship of having to live with very low energy demand, including all the difficulties on the individual and local group level. Still, these hardships would not be eliminated; instead, they would be transferred to the supply side, and others would have to learn to live with the social and environmental problems of supplying large amounts of energy from unconventional oils or lower grades of coal. To satisfy these higher energy demands, there would have to be a well-functioning world market for oil, coal, and probably for gas that would create its own set of socioeconomic and environmental issues. Nonetheless, these would most likely stimulate economic growth and technological innovation in the developing countries.

SOME REALITIES OF THE ENERGY PROBLEM

- *The hard-soft controversy is essentially a political issue and not a technical one.*

In a certain sense, demand is a word that cloaks a great multitude of what, for lack of a better term, we may call sociopolitical and psychological issues. It ranges all the way from what people really need for bare survival, to what they insist upon having, to what they may faintly hope for.

There is an ongoing worldwide debate between the proponents of the "soft" evolution paths of energy systems and those who would choose "hard" paths. We consider it worthwhile to examine briefly each of these positions and their influence on the energy demand situation.

Low per capita energy use favors a way of life without much long-range transportation and with an emphasis on local affairs and local self-supply. The economy favors soft products and services, arts and skills, and handcrafts, rather than the products of high technology, large-scale production and distribution systems. The low energy path implies decentralization, modest technologies, and a deeply conserving, traditional way of employing resources.

For some people, such a mode of life appears highly desirable and the panacea to the world's problems; it seems to them resilient, nonaggressive, and contented. For others, for those who left the farm to go live in the big cities, such a mode of life seems highly restricting. The relative lack of physical mobility, and the lack of rich communication and interaction, implies a lack of role mobility whereby people can experiment over an ever-wider range of creative behavior and give expression to innate powers that might otherwise be stifled.

Of course, there are other human costs associated with each of these life-styles. In effect, there is no clear-cut case. If one were a utopian, one might argue for a world divided into two areas, one where people may elect to live in the decentralized agrarian way, in the style of the millennium, and another where people might elect to live with the scale of interaction that has been achieved in the industrialized societies. Indeed, such a world already exists, is not utopian, and, most importantly, is not by choice!

It was not our intention to clarify such societal visions, which are but implicit features of the attempt to quantify global energy demand and supply. Our purpose in addressing the hard-soft controversy was to provide insights into the problem.

- *The demand for liquid fuels is a principal driving force of the energy problem. We have an energy problem within the energy problem.*

Oil-based liquid fuels have become a mainstay of industrial civilization and are vital in the early stages of third world development. But as our study revealed, they will not be as easily available and as cheap to obtain as is necessary to meet projected demands. This is why many people say that the energy problem is a liquid fuel problem.

In any world energy strategy, it will therefore be extremely important to restrict the uses of liquid secondary energy carriers (in all cases, hydrocarbons) to those uses where nothing else can be substituted for them in a significant way, at least not much before 2030: This means principally as transport fuels and as feedstocks for the petrochemical industry. These sectors alone will challenge the world with a large demand for liquid hydrocarbons (see Table 9-2). This is not to say that eventually transportation could not be accommodated by means other than the use of liquid hydrocarbons. Later, in Chapter 10, we picture a world in which hydrogen could be the base for the necessary liquid fuels. But since the advent of such a

Table 9-2. Percentage of total use of liquid hydrocarbons for motor fuels and feedstocks, High and Low Scenarios, 1975-2030.

Region	*Base Year 1975*	*High Scenario 2030*	*Low Scenario 2030*
I (NA)	74	94	91
II (SU/EE)	65	100	100
III (WE/JANZ)	52	86	76
IV (LA)	69	90	89
V (Af/SEA)	58	91	88
VI (ME/NAf)	74	94	91

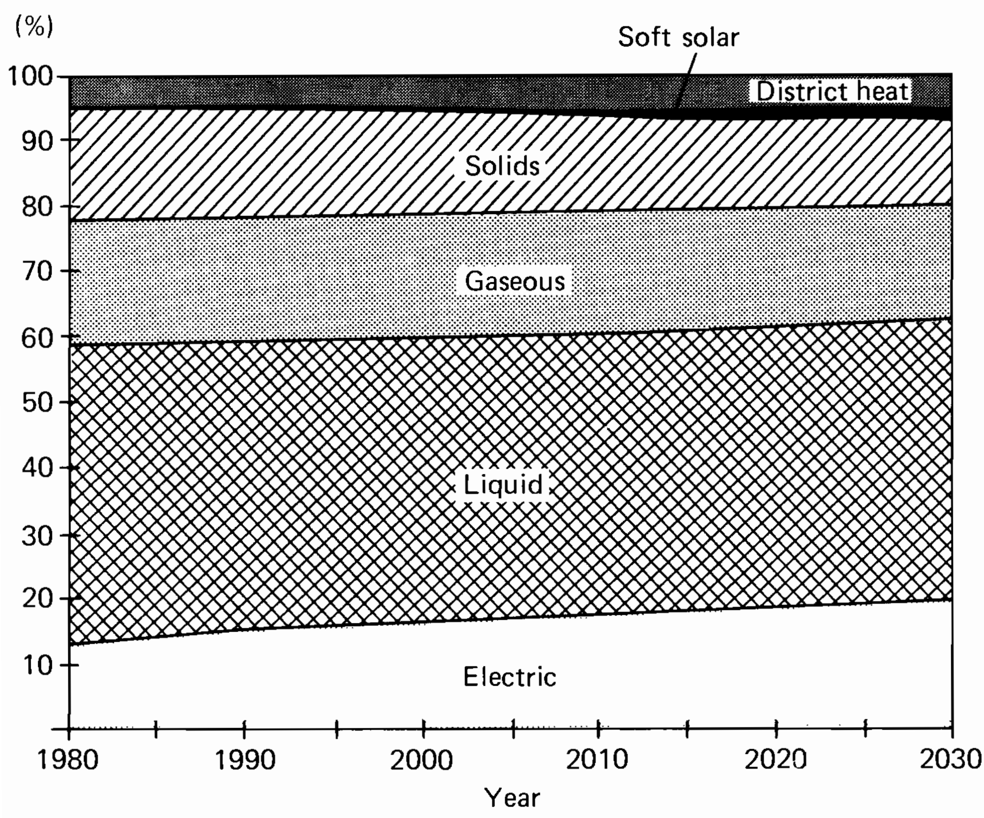
prominent role for hydrogen will probably not happen before 2030, we must concentrate on what might be done now to reach such a world.

What would be called for would be a reversal of the trends during the 1950s and 1960s when the liquid hydrocarbons were rising to their dominant position in the world market. The situation varies, of course, in different regions (see Table 9-2): Developed regions I and III, where home heating had been progressively turning to oil, are now experiencing strong pressures (economic and otherwise) to brake and turn to other means. In developed region II, on the other hand, a high degree of district heating has been an implemented policy for decades.

- *The structure of secondary energy demand over the next fifty years will not change very much, and whatever change that might occur would be at a very slow rate.*

Figure 9-1 depicts the slow and relatively few changes in the global secondary energy demand shares for the High scenario. Our study came to

Figure 9-1. Global secondary energy demand, High scenario, 1980-2030.



the somewhat surprising conclusion that the share of the demand met by electricity would grow much more slowly than we initially expected. In the High scenario, for example, the share of electricity in global demand increases from 14 percent in 1980 to only 20 percent by 2030.

Of course, there are regional differences: Regions I and III would have higher rates; still, the trend is not toward an all-electric society by 2030. This trend is governed chiefly by the high investments that would accompany the application of electricity in other than its most appropriate sectors of demand.

- *Over the next fifty years under any set of circumstances, economic growth rates will be limited.*

A major qualitative finding of our study is that it will be difficult, if not impossible, for the world as a whole to exceed annual economic growth rates of 3.5 percent[b] because of energy supply characteristics. That is, under any conceivable set of circumstances, economic growth rates will be limited. This conclusion stands in contrast to higher projections of several recent world studies, such as the World Energy Conference (1978), the Workshop on Alternative Energy Strategies (1977), and the Leontief study (1977) sponsored by the United Nations. This concerns us for even though the estimates for the Group of 77 in the Leontief study are not the results of an analysis dealing with economic feasibilities, they reflect a declaration of political will. Indeed, this study (done in 1977) evaluated world trade along the line of the data from the United Nations Council on Trade and Development (UNCTAD), projecting a global energy demand for the year 2000 of 29 TWyr/yr. This is some 53 and 93 percent more than our projections in the High and Low scenarios for this year, respectively.

These numbers are irrelevant. What is important is the goals of the developing countries reflected in the UNCTAD targets. The lower the growth rates, the higher the probability for economic warfare in ways that are difficult to anticipate. The global instability apparent in the events of the late 1970s and 1980 is probably only a forerunner of the unrest that will surface in the near future.

- *Political, societal, and institutional problems will probably make the situation more grim than has been described in our two scenarios.*

It could be done: The energy problem could be solved physically. To reach this conclusion, we relied greatly on the quantitative analysis of our scenarios, as reported in Chapter 8. Still, our overall picture is based on the accounting of regional differences among the seven world regions. We must therefore face the political reality of having many more countries in the world. The situation is complex and certainly less than optimal.

At which points would reality be more grim? For our analysis we have

[b]Op. cit. p. 172.

assumed a constant value for the U.S. dollar. What we have not done is to translate these into real monetary terms, which means incorporating the effects of inflation and the problem of the balance of payments. Decoupling the terms of trade from the side effects of these problems is not optimal, but is consistent with the determination to focus throughout this study on the factual basis of the energy problem.

As a result of our findings, we see that a further extension into the political realm might also be an analysis of the stability or, more precisely, of the resilience of the global energy supply system. The security of energy supplies is indeed a problem. Oil embargoes would impede growth. Likewise, the supply situation for natural uranium is being hindered by fear about the proliferation of nuclear weapons and by the antinuclear movements. In fact, there is practically no free uranium market today.

For our scenarios, we assumed that over the next few decades, region VI would set a production ceiling of 33.6 million barrels of oil per day. We alluded to the relative inelasticity of demand. Eventually, disturbances in the oil production levels of this region are a possible source of major global instability. Let us examine this from the standpoint of three world regions (Figure 9-2). In our scenarios, sometime around the year 2000, region I will arrive at oil self-sufficiency. Any imports to region I would then have to be made at the expense (in terms of supply) of region V, which has the lowest purchasing power even at that time. A similar situation could exist for region III if it were to import more oil than that projected for this region in our scenarios. Region III is particularly vulnerable to any instabilities in energy supply—be it for coal or natural gas or oil—because of its limited indigenous supply situation.

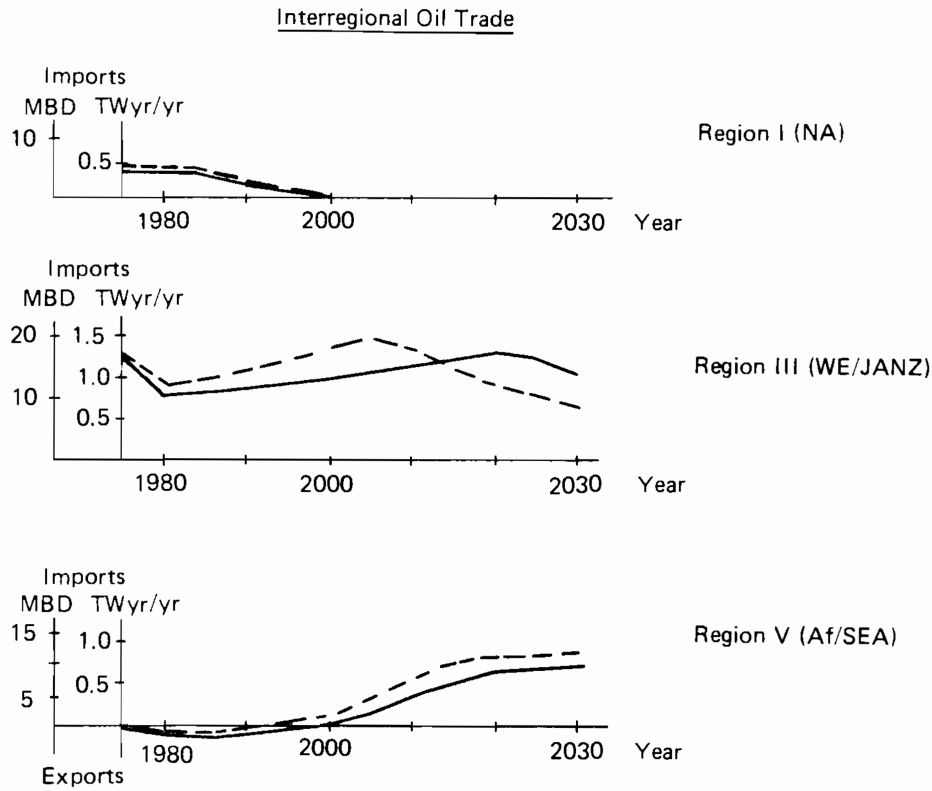
ENERGY SUPPLY

- *Fossil fuels will continue to be available but will become increasingly unconventional and expensive.*

Both of our scenarios are fundamentally fossil in nature, which for some people may seem unrealistic in light of the many statements they hear today about the world running out of fossil resources. But as we discussed in Chapter 8, what is at a premium are the cheap, easily accessible fossil fuels (see Table 8-11.) The world will therefore have to look farther and dig deeper, which also means that costs will increase, as well as environmental hazards.

This transition to low grade fossil fuels is nearly a complete reversal of the trends of the past several decades, when the world turned from coal to oil because it was cheaper, easier to handle, convenient, and comparatively clean. In the past, it was normal to have energy investments on the order of $3000 per barrel of oil per day, or less, for the production facilities of an oil field. Already, these investments have risen three to six times, with production capacities at costs of $10,000 to $20,000 per barrel oil per day

Figure 9-2. Interregional oil trade, High and Low scenarios, primary equivalent, 1975–2030.

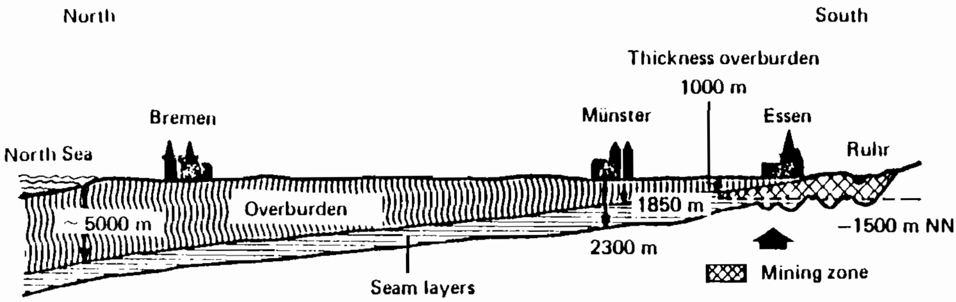


being more the rule. Such costs begin to reflect the complexity and difficulty of obtaining oil from areas like the North Sea and Alaska. We probably have to expect such conditions as the move to unconventionals progresses.

We can look at these investment costs in yet another light. One barrel of oil per day is equivalent to some 71 kW of caloric power. Presently, production costs of $20,000 per barrel of oil per day correspond to $300 per kW of installed thermal capacity, which relates roughly to $1000 per kW(e) of installed capacity. Indeed, we came close to this figure in our quantitative analysis of the capital costs of electrical power generation. Then too, future abatement measures and control technologies that would have to go along with the use of low grade fuels may bring investment costs as high as $500 per kW of installed thermal capacity or even higher over the longer term. Ultimately, in purely economic terms, the use of unconventional oil, for example, could approximate the use of other primary energy sources, and oil's inherent advantage would most likely disappear.

The environmental impacts of harnessing low grade fossil fuels cannot be overlooked here in our discussion, although it is not clear now how large

Figure 9-3. Schematic vertical section of northern area of the FRG.



these impacts will be. For instance, to mine for the requisite quantities of coal, or to extract tar sands and shale oil, will devastate large land areas. The future coal-mining operation in the northern region of the Federal Republic of Germany may offer insights into what we might have to expect.

As Figure 9-3 depicts, only the last "bit" of the coal stratum underneath northern Germany is near the surface and accessible. Mining "only" to the depth of some 1200 meters would still tap only some 25 billion tons of coal equivalent. In order to harness the more than 300 billion tons of coal equivalent that lie dormant in this stratum, it will probably be necessary to dig as deep as 3000 to 5000 meters. Whole cities, villages, and landscapes might have to be destroyed and later reclaimed. The Garsdorf open lignite pit, regarded as one of the most modern and advanced mining operations, could then be seen as only a small beginning to such large-scale operations.

By introducing this example here, we are not trying to actually propose such operations. Rather, our intent is to paint a realistic picture of what might happen if the world were to choose to look the other way as more and more fossil resources were used up in a consumptive manner.

But why, one may ask, are we led to such a high degree of consumptive uses of resources in our scenarios? Are there, perhaps, some ameliorative factors that have been overlooked? Although the shaping of our scenarios was a complex process, two major reasons stand out as instrumental in driving us to the high fossil consumption.

One reason has to do with capital investments in energy systems. To abide by the decision to make the reference scenarios as realistic and as "middle of the road" as possible, we were led intuitively to supply structures with low investment requirements. This proved to be a "forcing function," making the world stick with fossils probably much longer than it ought.

The second reason has to do with our estimated fossil fuel production for the seven regions (see Figure 9-4). Such production figures emerge out of the reality that neither nuclear nor solar, however forcefully they are pushed, will achieve a really high share of power needs by 2030. In general, what

Figure 9-4. Domestic fossil fuel production, High scenario, 1980-2030.

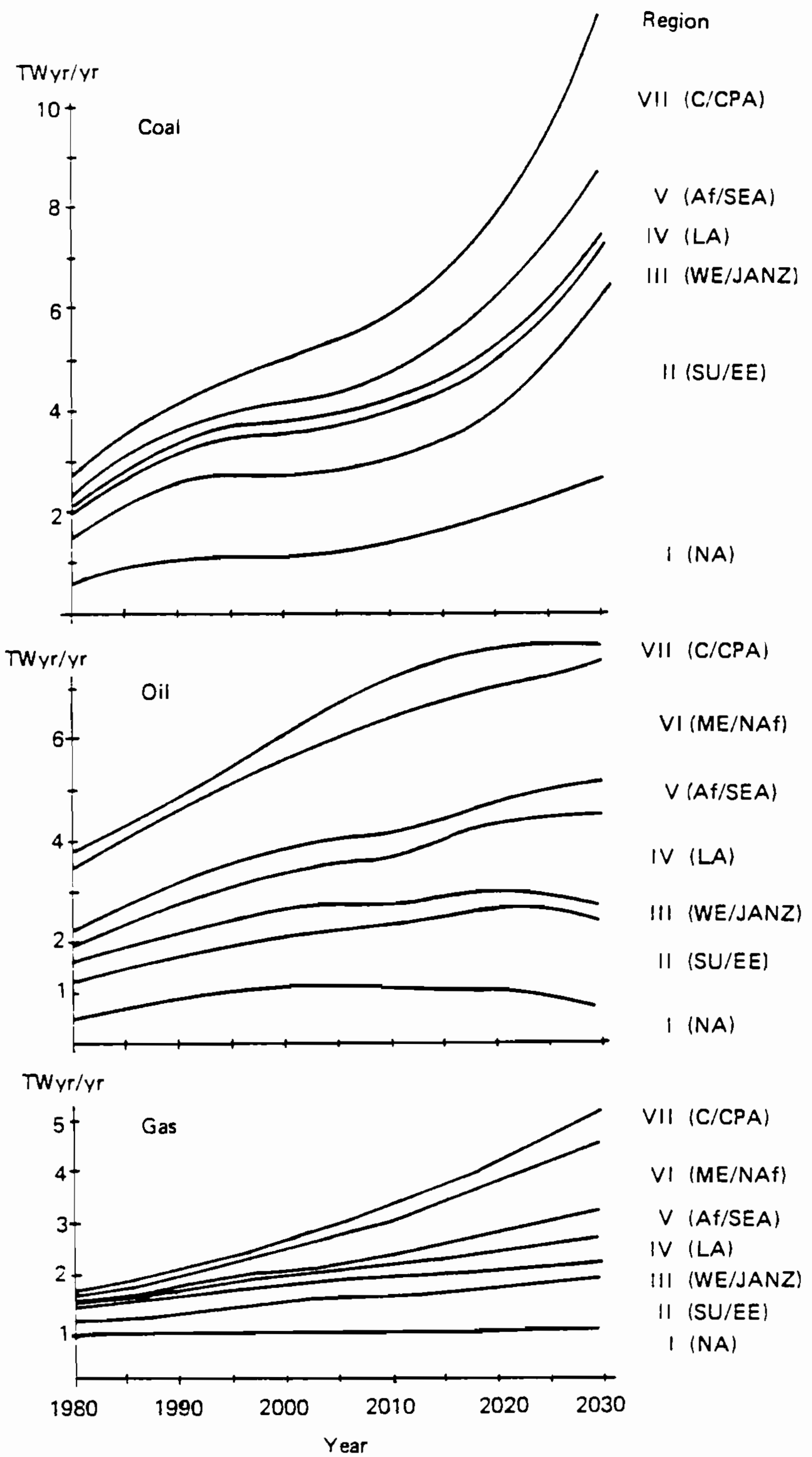


Table 9-3. Cumulative uses of fossil fuels, High and Low scenarios, 1975-2030.

	Total Resource Available[b] (TWyr)	High Scenario		Low Scenario	
		Total Consumed (TWyr)	Remaining Resource (yr)[c]	Total Consumed (TWyr)	Remaining Resource (yr)[c]
Oil					
Categories 1 and 2[a]	464	317	22	264	40
Category 3	373	4	45	0	62
Gas					
Categories 1 and 2	408	199	35	145	76
Category 3	130	0	22	0	38
Coal[d]					
Category 1	560	341	18	224	52
Category 2	1019	0	85	0	158

[a]For definition of terms and cost categories, see Table 8-11 of Chapter 8.
[b]Total resources, including those to be discovered, as of 1975.
[c]Number of years that the remaining resource would last if it were consumed at the 2030 annual rate of fuel use and if all of the resource came from the designated category.
[d]Coal use includes coal converted to synthetic liquids and gas.

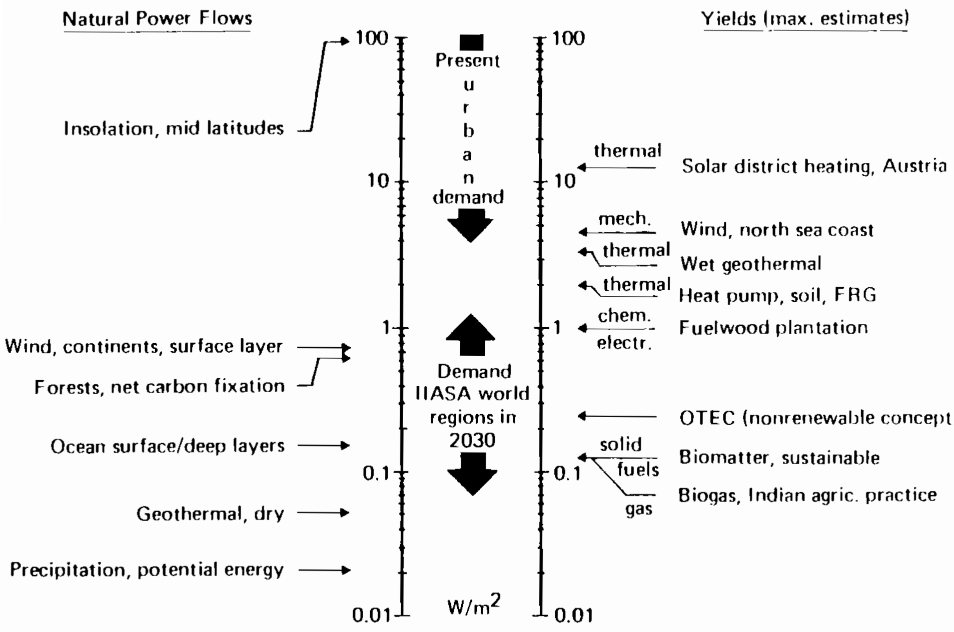
becomes apparent in the study of energy is that total energy production between now and 2030 is constrained mostly by the time and effort it takes to build up production facilities, not by the quantities of resources. Table 9-3 points this up: For instance, in the High scenario, only 68 percent of categories 1 and 2 oil and 61 percent of category 1 coal will have been consumed by 2030. After 2030, that situation begins to change, and resources become a major constraining feature.

- *Renewable energy sources can contribute in an important, albeit limited, way to meeting demand.*

How might local uses of solar power, wind power, water power, biomass, and the like be integrated into the global supply picture to take some of the pressures away from the fossil fuels? In Chapter 6 we identified the maximum technical potential for renewable sources, which is some 15 TWyr/yr of secondary energy or somewhat less than twice the current global primary energy consumption. However, harnessing this amount of energy from these renewable sources has serious implications for the very features that make these sources so attractive—namely, decentralization and local availability.

A crude but nevertheless good indicator of the possible impacts of large-scale deployment of renewable sources is their production densities. If we assume an average production density of 0.2 W/m^2 (Figure 9-5), we see that some 75 million km^2 of open space would be needed to produce 15 TWyr/yr—whether for the harvesting of wood, wind, or the like. For perspective, the amount of land being used today around the globe for

Figure 9-5. Energy supply densities.



agriculture is some 13 million km². Renewables if pushed hard enough could come into competition with existing land and water uses. To be sure, the larger the output expected from renewables, the more difficult this option becomes; similarly, the less that is envisaged for these sources, the more they would be able to retain their attractiveness.

Of course, this is a general observation that may be more or less true in the aggregate but that may vary from locality to locality. Still, we maintain that, realistically, the total contribution from all renewable sources would be significantly smaller than what is technically possible.

- *The oil-exporting countries will continue to dominate the oil market, but an international coal market must develop as well.*

One important feature of our quantitative analysis is the energy trade links among the seven world regions, primarily for oil, but also eventually for gas. We developed our thinking somewhat formally along the lines of a gaming approach, which allowed us to observe important interplays between suppliers and consumers. Some might consider our assessment rather unsophisticated. Perhaps it would have been best to focus directly on world trade and not only on energy trade, but our goal was to assess a world energy trade pattern, using identifiable rules.

A salient point is that region VI will continue to dominate the oil market. Figure 8-2 of Chapter 8 presents one way of seeing this. The world production of oil outside of this region is large and continues to grow after the year 2000, yet the relative inelasticity of demand for liquid fuels allows region VI to make the crucial difference between an oil glut and an oil shortage. Even by reducing the use of liquid hydrocarbons to their most essential uses and by taking into account the contributions of a young coal liquefaction industry, we still see a dominant role for region VI in the oil export market.

A crucial assumption is that region VI establishes an oil production ceiling of 33.6 million barrels of oil per day, which would permit the stretching out of the region's resource base. Table 9-4 relates oil production of region VI in 1975 with that of the other OPEC countries and that of the OPEC countries not included in region VI.

The world's trading relationships become even more problematic when we consider how oil exports and imports are allocated among world regions, as shown in Figure 8-3 of Chapter 8. Although in 1975, developing regions IV and V were oil exporters, by 2030 both the High and the Low scenarios envisage a significant oil import to region V. For our two supply scenarios, we assumed that regions I, II, IV, and VII would be self-sufficient in oil supply by the year 2030 and that region III would decrease its oil imports almost by half, thus setting some of the oil free for region V.

The only mechanism that, in these scenarios, could accomplish this change in the oil picture is the successful deployment of a large-scale coal liquefaction industry in regions I, II, and, especially, III. Coal liquefaction would be the best means for region III, and to a lesser extent for region I, to hold down their requirements for imported oil.

In our scenarios, beyond 2010, there is a strong possibility that regions I and II would become exporters of liquefied coal, possibly to region III, which even at this time would have to import liquid fuels. Will regions I and

Table 9-4. Oil production in 1975 (thousand barrels per day).

Region VI Countries (excluding OPEC member countries)		*Region VI and OPEC Member Countries*		*OPEC Member Countries (excluding region VI countries)*	
Bahrain	6.1	Algeria	1020.3	Ecuador	160.9
Egypt	23.3	Iran	5350.1	Gabon	223.0
Syrian Arab Republic	18.2	Iraq	2261.7	Indonesia	1306.5
Jordan	0	Kuwait	2084.2	Nigeria	1783.2
		S.P. Lybian A.J.	1479.8	Venezuela	2346.2
Lebanon	0				
Oman	34.1	Qatar	437.6		
Yemen	0	Saudi Arabia	7,075.4		
Yemen, Democratic	0	United Arab Emirates	1663.8		
Total	81.7	Total	21,372.0	Total	5819.8
	Total region VI	21,453.7	Total OPEC	27,192.7	

Sources: Data for region VI countries from United Nations (1978); data for member countries of OPEC from OPEC (1978).

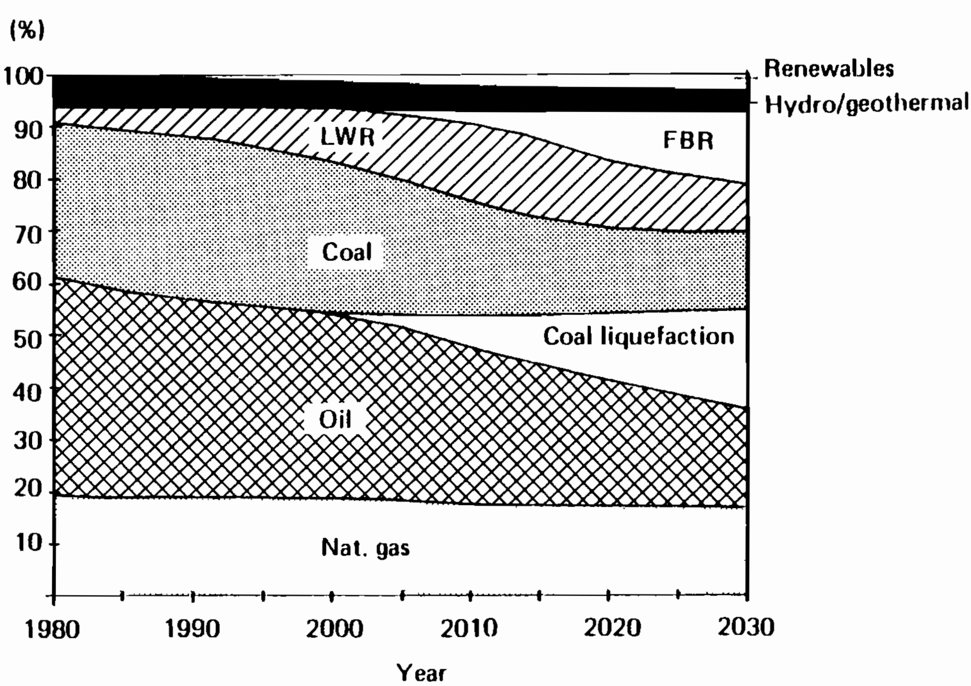
II be willing to provide these exports? In what form? As solid coal or as a liquid synthetic hydrocarbon? There could be a fundamentally new interplay between region VI (oil supply) and regions I and II (coal supply) and regions III and V (demand).

All these factors reinforce the general conclusion that it will not be market forces but political forces that will govern the quantities and prices of world oil trade. This, as we see it, is a relatively new situation, in which new institutional mechanisms are needed to make things manageable. A vision of the evolution of energy systems on a world scale could provide the conceptual framework needed to foster such institutions linking different economic and political groups.

- *Coal liquefaction must be installed with a strategic view.*

Given the significance of coal liquefaction in balancing demand and supply of liquid fuels in regions I, II, and III, more needs be said about it here. Our reference scenarios show coal being used at the rate of 12 billion tons equivalent per year, most of it devoted to satisfying the internal energy needs of the various regions and with only moderate amounts left for trading on the world market. Figure 9-6 shows how the relative shares of global

Figure 9-6. Primary energy (or equivalent) demand, High scenario, 1980-2030.

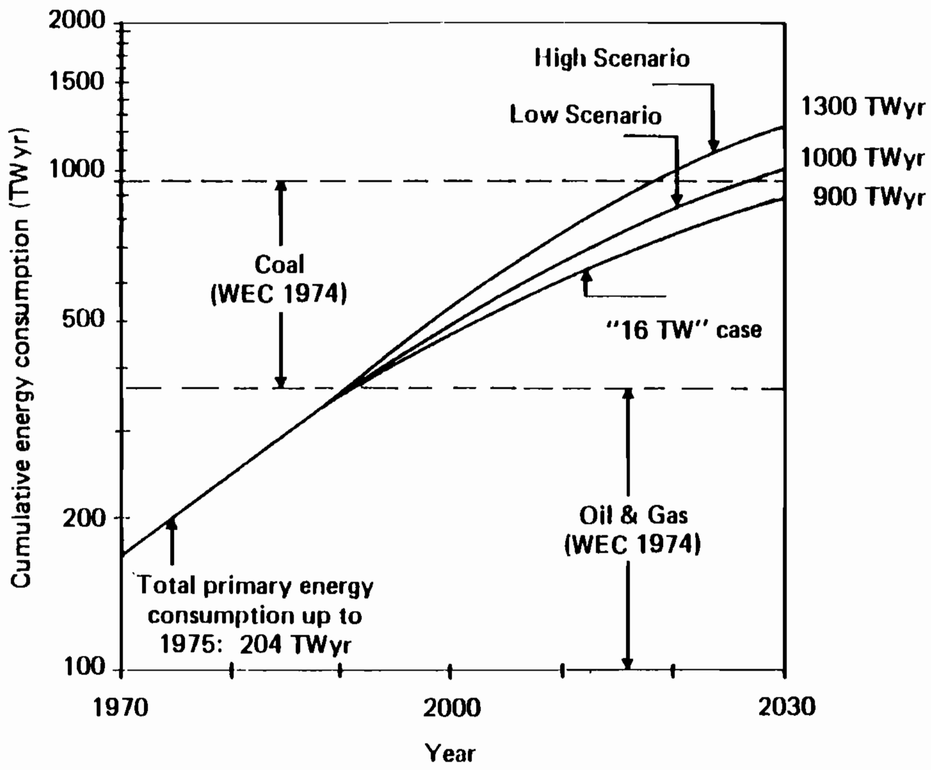


primary energy change for the High scenario. As oil drops off, coal-based synthetic fuels rise sharply, with nuclear power and renewables filling the gaps.

When coal-based synthetic fuels begin to take on such a large role, the technical processes by which they are produced also become most significant. We explained how these two processes differ in Chapter 3. Besides using three to four times more carbon resources than the allothermal method, the autothermal method leads to the release of three to four times more carbon dioxide into the atmosphere.

The degree to which the CO_2 problem might be aggravated is suggested by the estimate that the natural CO_2 content of the atmosphere is equivalent to the burning of roughly 500 TWyr of fossil fuels. If, however, 1000 TWyr of fossil fuels are actually burned (see Figure 9-7), one can assume roughly that 50 percent of the CO_2 would remain in the atmosphere, thus doubling the natural CO_2 content. This is approaching the limits that we consider prudent, and it is our conviction that the world would be far wiser to adopt allothermal coal liquefaction methods.

Figure 9-7. Evaluation of conceivable cumulative world energy consumption, 1970–2030.



- *If nuclear energy is used primarily to supply the process heat in coal liquefaction, there would be enough coal to produce liquid fuels for one hundred years or more.*

In our enhanced nuclear alternative supply case (discussed in Chapter 8), we hypothetically explored the use of allothermal methods of coal liquefaction, using a nuclear energy supply close to our trajectory of 17 TWyr/yr (considered in Chapter 4). To be sure, the burden on coal was greatly relieved, stretching out the lifetime of coal for one hundred years or more.

But for our scenarios, we hewed to the criterion of feasibility over the next fifty years, and we saw that it would not be possible to build up the nuclear contribution to the 17 TWyr/yr level by 2030. Thus, over the next fifty years, until the completion of the final transition to a nonfossil world, coal will have to be used strategically, implying a minimum primary energy role and its prudent use for producing synthetic fuels. On the aggregate level, we envisaged the autothermal method. On the local or national basis, allothermal coal liquefaction schemes could appear much earlier than what we considered for the aggregate—as, for example, in region III, when coal imports become less feasible than has been projected in our reference scenarios.

- *If there is a nuclear moratorium, gas resources would be largely exhausted by the year 2030.*

Because our scenarios are globally comprehensive and internally consistent, we decided to hypothetically explore the effects on the energy supply system if there was a moratorium on the use of nuclear energy. In such a case, our results show that a substantial burden would be placed on natural gas to make up for the projected energy shortfall. As shown in Table 9-3, some 49 percent of categories 1 and 2 gas would be consumed by 2030 in the High scenario, leaving 339 TWyr of conventional and unconventional gas still in place. But for such gas to be substituted for oil, they would have to be transported over long distances, which involves the development of large technical facilities—gas pipelines, special tankers for transporting liquid gas, and conversion facilities. As we observed in Chapter 3, some of these technological developments will probably be possible within the next few decades, and it is likely that the role of natural gas will indeed be more important than that projected in our scenarios.

All things considered, a nuclear moratorium may seem an interim solution to the highly polarized situation for the next few decades, but from a long-term global perspective it would have its price.

CONSTRAINTS

- *While the growth of energy investments will be significant, they will not be a large portion of GDP in the developed regions.*

Table 9-5. Capital cost assumptions for major energy supply and conversion technologies.

	Capital Cost (1975 $/kW(e))
Electric Generation	
Coal	480-550
Nuclear	700-920
Hydroelectric	620
Oil- or Gas-fired	325-350
Gas turbine	170
Other	
Coal gasification or liquefaction (*autothermal*)	400
Crude oil refinery	50

Ideally, the study of investments should involve an input-output procedure that embraces not only the energy sector but also all economic sectors. The pilot model of George Dantzig of Stanford University is a prominent example of such a procedure, but such models are very data intensive and their application to the global level is enormously complex. In our scenarios we examined only direct investments in the energy sectors and those in the energy-related sectors that indirectly contribute to energy development. We made a number of assumptions; Table 9-5 gives a summary of the major ones. We assumed that costs would remain unchanged throughout the period up to 2030. This led to some rough overall orientations.

Table 9-6 compiles the cumulative investments for the two reference scenarios and the two alternative supply cases. Comparing the data, we see that the nuclear moratorium case would call for higher investments than, say, the Low scenario, which has some 23 percent of nuclear power by 2030.

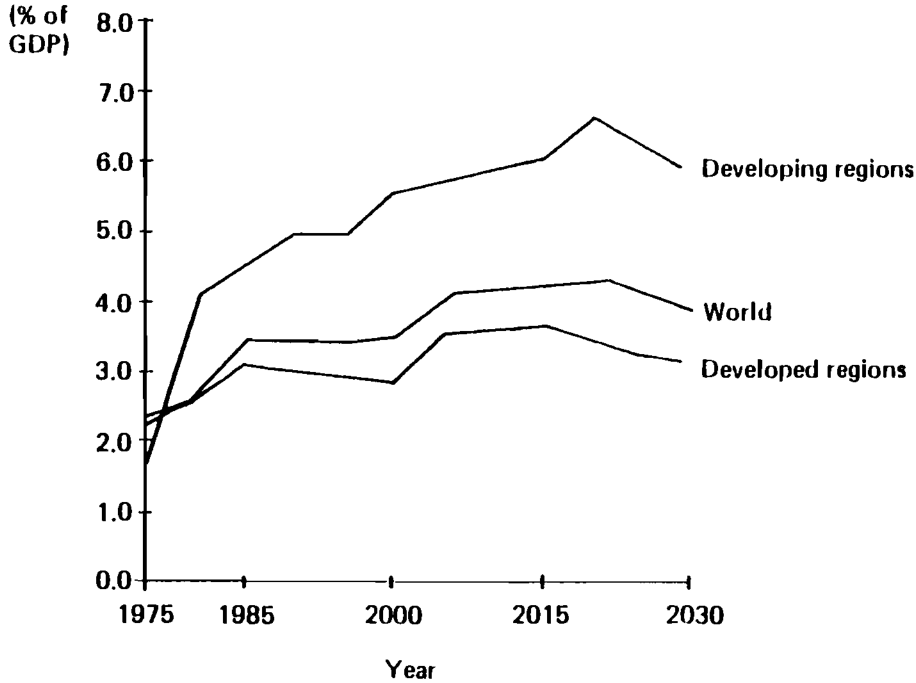
The absolute size of the cumulative energy investments for the world over this period would range between $29 and $48 trillion. This is in line with our propositions presented at the World Energy Conference in 1977. As can be seen from Figure 9-8, the share of energy investment of 2 percent (in 1975)

Table 9-6. Cumulative energy sector capital cost requirements, 1981-2030 (10^{12} $).

	Developed Regions[a]	*Developing Regions*[b]	*World*
High Scenario	28.0	18.5	46.5
Low Scenario	18.8	10.9	29.7
Nuclear Moratorium Case	22.0	12.0	34.0
Enhanced Nuclear Case	28.4	15.3	47.7

[a] Regions I (NA), II (SU/EE), III (WE/JANZ).
[b] Regions IV (LA), V (Af/SEA), VI (ME/NAf), VII (C/CPA).

Figure 9-8. Share of total energy investment in GDP, High scenario, 1975-2030.



is typical. For the developed regions, such investments increase and peak at values close to 4 percent around the year 2015. For the developing regions, the investments rise more sharply, coming close to 7 percent by the year 2020. For the world as a whole, the investment maximum is 4.5 percent. What is not so clear is whether such amounts are large or small. The more we tried to clarify this issue, the more complex it became.

Comparing the figure of 4.5 percent with, say, the total military expenditures in the world today, we see that both are of the same order. Then too, changes in the saving rates globally have been of the same magnitude over the past few decades. For example, in Japan during the 1960s, the savings rate was between 30 and 35 percent, whereas now it is closer to 30 percent. This difference does not seem to have produced fundamental changes, which leads us to speculate that the world as a whole could manage energy investments of a similar order.

But there are further complications that ought to be considered. In our scenarios, we assumed constantly declining economic growth rates globally over the next fifty years. When integrated energy investments were compared with integrated GDP, the ratio turned out to be rather low, because of the pocket of relatively large GDP projected to exist before 2030. Of course, this ratio would have been higher if we had assumed constant economic growth rates.

What is really needed is an analysis of the impacts of energy investments sector by sector, using the above mentioned input-output techniques for the whole of the economy, in order to trace the sectoral impacts that are hidden or averaged out in the aggregate pictures. For the world energy trade situation, the problem of analysis is particularly complex. We did not undertake such an extensive analysis. Nonetheless, we observe that the aggregate impacts globally would not be too large, while the sectoral impacts would probably be very pronounced.

- *Global impact of waste heat is probably a nonproblem.*

Climate is a complex and noisy phenomenon, noisy in the sense that there can be large variabilities in how the climate system behaves, as simulated by climate models. In addition to changes in averages of such factors as temperature, pressure, and humidity, there are fluctuations—and indeed, changes in these fluctuations—that make up both the temporal and the spatial pattern of the climate system. It is how these changes affect the pattern that interests us.

Using numerical models of global atmospheric circulation, which are presently the best means available, we simulated the climatic effects of energy releases of 30 to 300 TWyr/yr from certain geographical locations and areas. We observed that the thermal pollution effects from such waste heat releases were not greater than the inherent noise levels of the model. Nonetheless, the release of very large amounts of energy—say, several hundreds of terawatts—from small, concentrated areas could alter the global average climate state significantly. When considering the global energy demand levels of our High and Low scenarios (36 TWyr/yr and 22 TWyr/yr, respectively), waste heat releases would probably not perturb the global average climate state in the foreseeable future. Of course, this is not to exclude the possibility of serious effects from waste heat releases in the vicinity of the release.

- *The carbon dioxide buildup caused by fossil fuel combustion is probably the most severe climate issue.*

While it is too early to make alarming statements about the specific climatic impacts of large-scale deployment of any of the major energy strategies, our study revealed that the impact of the combustion of fossil fuels on the global climate over the next fifty to seventy years could lead to global average temperature increases of from 1 to 4°C. Of course, different regions would experience different effects, and some might benefit from these changes, whereas others would suffer hardships. For example, increased precipitation (rainfall) in certain areas could result in changes in regional agricultural practices, with hitherto arid areas flourishing agriculturally, while others struggle to adapt their cropping patterns to more arid conditions. The hydrosphere, too, might undergo changes, with certain rivers being enlarged and others being reduced in volume. To be sure, the implications of these climatic changes are potentially large.

Ideally, the world should begin now to monitor the possible climatic effects of high atmospheric CO_2 levels, in order to be able to ward off major problems. But reality is often far from the ideal, and no organized global actions of this nature are in sight. Present knowledge of the climatic implications of raising the CO_2 level is limited, but it appears that between five and ten years would be needed—and most likely could be afforded—for vigorous research to narrow down uncertainties.

It may be unrealistic to expect political agreement among nations on the avoidance of CO_2 impacts, in view of the benefits that would accrue for some. We are faced with the dichotomy of having a highly disaggregated political power on the globe and the truly global problem of atmospheric CO_2 buildup. Are we doomed to encounter this dilemma? Probably, yes. Still, we believe it imperative to maintain flexibility in designing energy supply policies and to restrict the buildup of CO_2 to a prudent level.

- *Low density energy collection devices spread over large areas could have climatic impacts as well.*

We examined what might happen to the earth's surface characteristics (e.g., its heat balance, roughness, and hydrological conditions) as a result of energy conversion and use. These include large-scale deforestation in tropical or subtropical areas, large-scale harnessing of energy from the thermal gradient of tropical oceans, large-scale deployment of windmills, and even the tens of terawatt scale of unconventional fossil fuel production.

There are indications that such changes are to be expected with dispositions of energy flows on the order of 100 TWyr/yr. Agriculture is a case in point. Albedo changes of 0.1 seem to take place with the establishment of farm land. Envisaging 10 million km^2 of land, one arrives at resulting dispositions of energy flows on the order of 100 TWyr/yr. Given the influx of 178,000 TWyr/yr of solar power, one might consider 100 TWyr/yr only a minute fraction and therefore too small an amount to warrant concern.

But, it does not take much to change the climate pattern, and that is what matters. For example, precipitation and cloud formation patterns change upon such dispositions of energy flows. Unfortunately, the state of the art did not permit us to set upper limits on the uses of these energy collection devices or to translate our concern into operational constraints.

- *The debate on the issues of waste disposal and on the proliferation of nuclear weapons because of the civilian uses of nuclear power could limit the buildup of nuclear energy over the next fifty years.*

The often heated worldwide debate beclouding these two issues reflects the level of people's concern about the deployment of nuclear energy, and as such it has become a constraint. We did not deal with these issues explicitly in our study for two reasons. First, a large number of capable and sizeable groups are already studying these problems, and we did not wish to compete with these efforts. This is not to say that individual members of our team are not personally involved with or at least well informed on these matters, but as a group we decided to abstain. In this connection we note the work of the International Fuel Cycle Evolution (INFCE) that was carried out in close geographical proximity with, and over the same period as, our study.

The second, more commanding, reason why we abstained from delving into these issues is that we view the problems of nuclear waste handling and proliferation as political issues. Indeed, the establishment of related standards and regulations is largely a sociopolitical process that was outside our factual frame of reference.

- *Society has not yet developed adequate mechanisms for treating the risks associated with energy supply technologies.*

This is the major finding of our study of the relatively young science of risk analysis. The lack of data and the inadequacy of both evaluation techniques and decisionmaking formalisms for standard setting add to the problem of assessing the risk of energy technologies. Our risk assessment framework, illustrated in Figure 7-11 of Chapter 7, was developed in order to define certain categories that we hope will add to the discussion of this subject and permit more formal research in this field.

Our study of public attitudes toward energy-related risks revealed that the public is generally more concerned with the risks of events that have a low probability but large consequences than it is with those that have a high probability but low consequences. Indeed, there is a large discrepancy between the public's perception of a risk and the best technical judgments of the risks of using a certain energy technology. Psychological and sociopolitical factors were seen to greatly influence how individuals and societies as a whole view the risks of energy technologies. This finding bears directly on the political process of establishing the standards and regulations for energy technologies.

In many ways, standards and regulations are driving forces behind technological developments. This is in contrast with the past, when the traditional approach of the engineer was optimization, usually for minimal costs, while observing only certain constraints. Today the criterion being applied to a project is whether it can be "carried through" to its completion and not whether design technologies are optimal in terms of their costs alone. (In fact, when costs are considered, they are usually regarded as a constraint.) More precisely, "carrying through" a project usually means obtaining the necessary licenses and permits. Consider, for instance, a nuclear reactor designed in country X. Although this reactor is successfully operating in country X, it may not be licensed for operation in country Y. The reasons for this seemingly illogical situation lie within the sociopolitical domain. The decisions on licensing a particular technology are influenced by the many different perceptions of reality that are held by the different societies in different countries.

There is another dimension to the problem of obtaining a license. Lead times for constructing certain facilities—say, a nuclear power plant—are increasing. Currently, it is some ten years from the time a decision is made to build such a facility to its actual operation, with five years usually required for construction and the other five years for obtaining the necessary licenses and permits.

Moreover, the fact that regulatory bodies often have difficulty at arriving at such regulations and standards adds to the complexity of the problem. Engineers may be confused as to what standards and regulations they should aim to meet. Several examples come to mind here—nuclear waste disposal, pressure vessel safety codes, and codes for the design of fatigue ruptures. All too often, codes, regulations, and standards are contested in the courts, which are used perhaps inappropriately for de facto legislative and standard-setting purposes. This can not only increase the uncertainty about what standards and regulations to apply, but also may inhibit responsible bodies from functioning properly. Uncertainties are, of course, a fertile ground for fear, and one can conclude that certain sociopolitical factors foster fear about possible risks of energy technologies.

One possible solution would be to develop a "language" to overcome these fears—that is, to create some means for consciously addressing these fears and, in so doing, of managing the risk by resolving the conflict between perceived fears and realities. Without such a language, the problem of managing risk is too often reduced to dealing with numerical information about a technology. Numbers often appear easier to deal with than deep-seated beliefs, although in the long run, they are not useful. What is a "safe" radiation rate? One has only to look at the Gofman-Tamplin debates of the late 1960s and early 1970s about permissible dose rates to grasp the difficulties of resolving such problems by numerical approaches. As we stated earlier in this chapter, while numbers can be helpful they can hardly be definitive.

REFERENCES

Chant, V.G. 1980. *Two Global Scenarios: Evolution of Energy Use and the Economy to 2030.* Laxenburg, Austria: International Institute for Appled Systems Analysis (forthcoming research report).

Leontief, Wassily et al. 1977. *The Future of the World Economy.* New York: Oxford University Press.

OPEC. 1978. *OPEC Annual Statistical Bulletin.* Vienna: Organization of Petroleum Exporting Countries.

Rürup, H. 1978. Exploration am Nordrand des Ruhrreviers. Heft 6. Essen, FRG: Ruhrkohle AG.

United Nations, 1978. *World Energy Supplies, 1972-1976.* ST/ESA/STAT/SER.J./21. New York.

Workshop on Alternative Energy Strategies (WAES). 1977. *Energy: Global Prospects 1985–2000. Report of the Workshop on Alternative Energy Strategies.* New York: McGraw-Hill.

World Energy Conference (WEC). 1978. *World Energy Resources 1985–2000: Executive Summaries of Reports on Resources, Conservation, and Demand to the Conservation Commission of the World Energy Conference.* Guildford, United Kingdom: I.P.C. Press.

10 PATHS TO A SUSTAINABLE FUTURE

We have concluded that the possibility of a sustainable global energy system is at least fifty years away. Yet in this chapter we propose to discuss what the characteristics of such a system might be, and how we, the human race, might get there from here. To embark on such a discussion is adventurous, to say the least. The technological landscape in 2030 and beyond will probably be vastly different from what we know today. It was, after all, only sixty-six years between the Wright brothers' first flight at Kitty Hawk and Neil Armstrong's landing on the moon. We cannot predict the future, but we can at least partly anticipate it, and, perhaps, affect it. Indeed, we can anticipate that population will grow and that fossil fuels will be depleted—despite the fact that we cannot predict the rates with perfect precision. And the investments we make today, whether in environmental protection or nuclear research and development, affect profoundly the opportunities we leave ourselves and our successors in the twenty-first century.

We do not advertise what is discussed as "*the* solution to the energy problem." In particular, the presentation is not in the form of a series of policy prescriptions for either politicians, administrators, entrepreneurs, or consumers. The intent is to illuminate those possible features of a future sustainable energy system that can be discerned if we look hard enough at technologies already available. The discussion is meant to be exploratory and suggestive. It starts, quite naturally, by considering the essentially inexhaustible primary energy sources.

PRIMARY ENERGY: CONSUMPTIVE AND INVESTIVE MODES OF USING RESOURCES

A sustainable energy future can only be one that is not based on the consumption of resources. In light of this, it is one of the striking features of the supply scenarios of Chapter 8 that they are still very much fossil in nature. Instead of reducing our use of oil, we realized that we will have to expand it, and the same observation applies for both natural gas and coal. Somewhat surprisingly, the fossil resources to do so exist. But as we know, they become dirtier and dirtier, and in the end, looking beyond the year 2030, this will lead to unacceptable situations.

It is important to realize that there is a quite different mode of using resources—the investive mode. This mode can best be explained by contrasting the function of fissile material in the case of the fast breeder reactor to its function in burner reactors. While today's burner reactors burn the little stockpile of fissile material that nature has endowed us with, this is not so in the case of the fast breeder.

There, the fissile material functions as a "catalyst" for the conversion of fertile material, as explained in Chapter 4. In the end the fissile material inventory increases, multiplying itself slowly. Consuming only fertile material is no hardship at all. In view of the extremely high energy yields per gram and of the exceedingly large amounts of fertile material available, the deployment of the breeder eventually decouples the energy supply from resource supply problems. The same reasoning, it should be noted, also applies to the D-T fusion breeder. The difference between the consumptive and the investive modes of using fissile material can perhaps best be illustrated by repeating the resource potentials—300 TWyr for the consumptive mode and 300,000 TWyr for the investive mode.

But breeders are not the only example of such investive uses of resources. Another case in point is solar power. In Chapter 5, we elaborated on the material requirements associated with solar power—specifically, the need to install materials at a density on the order of 50 kg/m^2. Providing 20 TWyr/yr, assuming energy production at 20 W/m^2, would require 50 billion tons of material, mainly in the form of steel and concrete. Yearly production in 1975 was close to 0.7 billion tons for each, so we are talking of large amounts of materials indeed. In this case, however, it is not so much the scarcity of such materials but the impacts associated with their production that is particularly important. But in line with the reasoning considered here the critical observation is that once the material is invested, energy is provided without any further consumption of materials.

One can interpret renewable energy sources in a similar fashion. For example, extracting energy from wood on a continuous basis necessitates maintaining forests or plantations as investments. If overharvesting occurs, as has often happened in the past, the inventory is eventually consumed. But if care is applied and the harvest rate equals the rate of renewal, the inventory is maintained.

It is on this basis that we suggest nuclear and solar energy, as well as the renewable energy sources, as primary energy supplies in a future sustainable energy system. This could be a fundamental change in the situation of mankind.

And it is in sharp contrast to the situation of today, where in our exploitation of the earth's resources (excluding water), we must devote roughly 75 percent of these resources solely to energy purposes. What the optimal mix between nuclear, solar, and renewable energy sources will turn out to be is not critical to our discussion here. What is more important is that these sources exist.

Earlier in our considerations, we elaborated on the various important characteristics of secondary energy carriers, including their transportability and versatility and the ease with which grids can be built up. In brief, they must be user oriented. Thus, the three sources of primary energy mentioned above share a common feature that they require conversion into appropriate forms of secondary energy.

SECONDARY ENERGY CARRIERS: ELECTRICITY AND HYDROGEN, CLEAN AND COMPLEMENTARY

The use of electricity is already widespread today. The features of versatility and to an extent transportability most certainly apply to this secondary energy carrier, as is reflected in the high growth rates of electricity, which are well above average energy growth rates and well above economic growth rates. But electricity is not without disadvantages. For example, it is difficult and expensive to store. To date, the electrical system has scaled its capacity to peak demand rather than average demand as a means of solving the storage problem. That is, it has been cheaper to build peaking plants (power plants used only at those times when electricity demand is much higher than average) than to store the spare electricity that could be generated when demand is much less than average. In addition to its storage problems, electricity is difficult to transport over very long distances. Currently, we rely on chemical energy carriers, principally in the form of the fossil fuels, in those situations where favorable storage and transport characteristics are particularly important. Thus, gasoline-powered automobiles have been preferred to electric cars, and oil and gas pipelines and tankers are preferable to intercontinental high tension wires. But it is precisely these fossil energy carriers that are getting scarcer, and while electricity can replace them to some degree, for the reasons listed above we might be better off developing an alternative that is itself a chemical, rather than an electrical, energy carrier.

A possible candidate that has reappeared often throughout this book is hydrogen. It is attractive for several reasons. First, the technology for converting electricity to hydrogen via the electrolysis of water is rather well developed. Second, processes for converting nuclear or solar heat directly to hydrogen without the intermediate step of electricity production appear promising. Third, hydrogen is much more easily stored than electricity and might be particularly suited to large-scale storage in depleted natural gas reservoirs. Fourth, the pipeline networks and the infrastructure associated with further large-scale use of natural gas would be especially suited for a gradual replacement of natural gas by hydrogen. And fifth, when hydrogen is burned (recombined with oxygen), it produces essentially only water vapor, thus making its use environmentally attractive. Of hydrogen's disadvantages, perhaps the most severe is that it is a gas at standard temperatures and is therefore not well adapted to the liquid fuels demand of, particularly, the transportation sector.

But there is another advantage of hydrogen, and this is related to the transition from clean fossil fuels to dirty fossil fuels. One of the central problems of this transition is that just when demand is moving progressively toward fuels rich in hydrogen—typically, methane—an ever larger portion of our reserves will be constituted by fuels poor in hydrogen—typically, coal and heavy crude oil. In other words, hydrogen is in short supply in even our current chemical fuel system. Thus, any efforts toward developing hydrogen as a possible successor to the fossil fuels has the added bonus of more immediately enhancing the usefulness of those fossil fuels that remain.

Using the Carbon Atom Prudently

The fact that, based on current technologies, hydrogen could not immedately satisfy the liquid fuel demand now met by oil, coupled with the fact that our remaining fossil resources are becoming increasingly hydrogen poor suggests that we look for combinations of fossil resources with nuclear- or solar-generated hydrogen that are particularly addressed to the need for relatively hydrogen-rich liquid fuels. Coal liquefaction—more precisely, allothermal coal liquefaction as discussed in Chapter 3—is an immediately promising option. This refers to processes, existing or proposed, where the hydrogen and heat needed for the production of methanol (or other appropriate synthetic liquid hydrocarbons) from coal come not from the coal itself but rather from some external source. As mentioned in Chapter 3, such schemes both conserve coal and release less CO_2. Autothermal processes, where the hydrogen and heat come from the coal, use three to four times as much coal and produce three to four times as much CO_2.

Still, to produce and use synthetic liquid hydrocarbons from coal and other fossil resources is to consume the store of carbon atoms that are available in those particularly convenient forms. And while the transportation sector may no longer need liquid hydrocarbons in one hundred years, it would be cavalier to presume that we will be able to do without them entirely. The problem then becomes one of recycling carbon, by extracting CO_2 from the atmosphere and combining such carbon, rather than fossil fuels, with hydrogen to produce liquid hydrocarbons.

The simplest way to exploit the carbon reservoir in the atmosphere is to use the plants that are already continuously extracting carbon dioxide. Much technology for converting biomass into liquid fuels has been developed, and here again, external sources of hydrogen and heat can help conserve the carbon resource. There is, of course, a more direct way to conserve the carbon atoms incorporated in synthetic hydrocarbons, and that is to immediately capture the combustion gases released when the fuel is burned and then recycle them. Research on such schemes is currently being pursued in the Federal Republic of Germany at the Jülich Research Center (1974).

Thus we see that while a sustainable energy system based on solar and nuclear sources of energy and using electricity and hydrogen as secondary energy carriers might eventually be possible, it is both in our best interests and within our capabilities to carefully use the carbon atom to construct a bridge to such a future.

Possible Opportunities

As we have just seen, with a little judicious orchestration of how we use hydrogen and how we use coal, we can apply them together to alleviate a liquid fuel demand, in a way that goes beyond the capabilities of either alone. However, this is not the only way in which some of the technologies that we have investigated might be particularly productively integrated, and in this section we draw attention to some opportunities.

Observing that the difficulty of directly storing electricity has led to generating capacity that is often idle, one can imagine initially introducing electrolyzers and fuel cells at generating stations, whether fossil, nuclear, or solar. Such a development would provide both experience with and improvements in hydrogen technology, and initially would not be constrained by hydrogen demand, as there already exists a hydrogen market for ammonia synthesis and oil refining. If hydrogen were used for storing off-peak electricity, then the system would be closed. If, further, we were to introduce the synthesis of methanol (or whatever synthetic liquid hydrocarbon turns out to be the most appropriate), then the hydrogen market would be practically unlimited. The methanol produced would help satisfy the pressing demand for liquid fuels, and the experience gained would help prepare us for a time when electricity and hydrogen might be the principal secondary energy carriers.

In line with such possible developments, an additional opportunity should be mentioned. In investigating various coal gasification and liquefaction processes—in particular, those allothermal methods using external sources of hydrogen and heat—it became clear that a by-product of these processes might be a considerable amount of slag, which would have to be disposed of. The use of large quantities of low grade fossil fuels would, in addition, create substantial amounts of ash requiring disposal. If, however, we remember the concrete requirements calculated in conjunction with building up a solar capability of 35 TWyr/yr over one hundred years, these quantities of slag and ash can be considered an important material resource rather than a waste disposal problem. In particular, when the concrete requirements described in Chapter 5 were compared with the waste material produced by coal liquefaction and gasification technologies used at the levels incorporated in the High scenario of Chapter 8, the orders of magnitude fit. Again, such a comparison is not definitive—but it is suggestive.

IMPLICATIONS OF A SUSTAINABLE ENERGY SYSTEM

Does the world possess the productive and institutional capabilities, the capital and material resources, and the discipline to achieve such a goal? What does it mean to mobilize building programs on such a scale around the world or to build the productive plants to turn out the dozens of billions of tons of concrete and steel to build these grandiose new plants? These are challenging questions that we hope the old and new generations will be able to tackle. Again, it will take time and material inputs—especially capital. There will also be institutional barriers of all kinds at all levels to overcome. Above all, it would demand generally much greater productivity worldwide, and this would mean increased levels of interregional trading of all kinds—of labor, of skills, of technologies, of knowledge, of energy, of products, of food, and so forth.

In capital terms, taking into account the construction of facilities for energy transmission and distribution, breeder technologies, and solar technologies, the investment may be on the order of \$2 to \$3 per watt of achieved capacity. Thus, even a 20 TWyr/yr energy demand world (which is lower than our Low scenario) would require an investment on the order of \$40 to \$60 trillion (10^{12}).

In economic terms, we must ask what this investment means as compared with world investments in energy today. If we take the average per capita demand of 3 kWyr/yr of our Low scenario in the year 2030, we arrive at a capital stock requirement for the energy system of \$6000 to \$9000 for each citizen of the globe.

If we assume further that the portion of the world's capital stock devoted to the energy system were 33 percent (compared to 25 percent today), the \$6000 to \$9000 per capita capital stock in the energy system translates to some \$18,000 to \$27,000 total capital stock per capita. This is indeed a high investment when compared with 1975 values, particularly for developing countries. Their per capita average in 1975 was only \$380, as contrasted with \$8500 in the developed market economies and \$2700 in the centrally planned economies excluding region VII (Ströbele 1975). The 1975 world average was \$2000 per capita.

If one looks at these figures and envisages the need to raise the average value to \$18,000 to \$27,000, then one sees that building a sustainable energy system is hardly a straightforward possibility even within the next one hundred years. This is why it is so important that the eight billion or so people living in 2030 be rich, not poor, and much richer than today. That they be rich does not mean that they discover some new treasure of physical resources that has been completely overlooked in this book; it means that they learn how to use the limited resources available more efficiently, more ingeniously, more productively. The process is continuous, and it is cumulative.

The higher our productivity—that is, the more wisely we invest our current resources of energy, labor, capital, and know-how—the closer we will come to transforming the possibility of a sustainable energy system into a reality. To succeed would be to cross a distinct threshold—to decouple the world's energy supply from the problem of resource supplies. It is a threshold perhaps as great as that passed by our distant ancestors when they launched the era of domestic farming. To cross it is the modern challenge—and it is not beyond our capabilities.

REFERENCES

Jülich Research Center 1974. *Feasibility Studie, Transport von Hochtemperatur-Kernreaktor-Wärme mittels chemisch gebundener Energie.* Report of the Kernforschungsanlage Jülich GmbH and the Rheinische Braunkohlenwerke AG, Cologne: FRG.

Ströbele, W. 1975. *Untersuchungen zum Wachstum der Weltwirtschaft mit Hilfe eines regionalisierten Weltmodelles.* Dissertation. Hanover: Technische Universität.

ABBREVIATIONS AND ACRONYMS

AGR—advanced gas-cooled reactor
bbl—barrel
boe—barrel of oil equivalent
BPA—Bonneville Power Authority
BWR—boiling water reactor
C—carbon
°C—degree Celsius
cap—per capita
CF—confinement factor
CH_4—methane
CO_2—carbon dioxide
DOE—U.S. Department of Energy
D-T—deuterium-tritium
FBR—fast breeder reactor
GDP—gross domestic product
GW or GW(e)—gigawatt or gigawatt electric
h—hour
H—hydrogen
HTR—high temperature reactor
HWR—heavy water reactor
I—iodine
IAEA—International Atomic Energy Agency
INFCE—International Nuclear Fuel Cycle Evaluation
kcal—kilocalorie

kg—kilogram
km—kilometer
Kr—krypton
kW or kW(e)—kilowatt or kilowatt electric
kWh or kWh(e)—kilowatt-hour or kilowatt-hour of electricity
LMFBR—liquid metal fast breeder reactor
LNG—liquefied natural gas
LWR—light water reactor
mrem—millirem (one-one thousandth of a rem)
m, m^2, m^3—meter; square meter; cubic meter
mbd—million barrels of oil per day
mpg—miles per gallon
MPC—maximum permissible concentration
mtce—metric ton of coal equivalent
mtoe—metric ton of oil equivalent
MW or MW(e)—megawatt or megawatt electric
NH_3—ammonia
N_2O—nitrous oxide
N_p—neptunium
OAPEC—Organization of Arab Petroleum Exporting Countries
OECD—Organization for Economic Cooperation and Development
OPEC—Organization of Petroleum Exporting Countries
OTEC—ocean thermal energy conversion
Pa—protactinium
ppm or ppmv—parts per million or parts per million volume
Pu—plutonium
PV—photovoltaic
PWR—pressurized water reactor
rem—dosage of ionizing radiation causing same biological effect as one roentgen of X-ray of gamma-ray dosage
SSPS—solar satellite power station
STEC—solar thermal electric conversion
t—ton
tce—tons of coal equivalent
Th—thorium
THTR—thorium high temperature reactor
TVA—Tennessee Valley Authority
TW or TW(e)—terawatt or terawatt electric
U—uranium
UF_6—uranium hexafluoride
U_3O_8—uranium oxygen compound called yellowcake
UNCTAD—United Nations Council on Trade and Development
VA—value added
VR—Voronezh reactor
W—Watt(s)
WELMM—acronym of Water, Energy, Land, Material, and Manpower
yr—year

A THE SEVEN WORLD REGIONS

REGION I: NORTH AMERICA (NA)

Developed market economies with energy resources.

Canada
United States of America

REGION II: THE SOVIET UNION AND EASTERN EUROPE (SU/EE)

Developed centrally planned economies with energy resources.

Albania
Bulgaria
Czechoslovakia
German Democratic Republic
Hungary
Poland
Romania
Union of Soviet Socialist Republics

REGION III: WESTERN EUROPE, JAPAN, AUSTRALIA, NEW ZEALAND, SOUTH AFRICA, AND ISRAEL (WE/JANZ)

Developed market economies with relatively few energy resources.

Member Countries of the European Community

Belgium
Denmark
France
Germany, Federal Republic of
Ireland
Italy
Luxemburg
Netherlands
United Kingdom

Other Western European Countries

Austria
Cyprus
Finland
Greece
Iceland
Norway
Portugal
Spain
Sweden
Switzerland
Turkey
Yugoslavia

Others

Australia
Israel
Japan
New Zealand
South Africa

REGION IV: LATIN AMERICA (LA)

Developing economies with many energy resources and significant population growth.

Argentina
Bahamas
Belize
Bolivia
Brazil
Chile
Colombia
Costa Rica
Cuba
Dominican Republic
Ecuador
El Salvador
Guadeloupe
Guatemala
Guyana
Haiti
Honduras
Jamaica
Martinique
Mexico
Netherlands Antilles
Nicaragua
Panama
Paraguay
Peru
Puerto Rico
Surinam
Trinidad and Tobago
Uruguay
Venezuela
Other Caribbean

REGION V: AFRICA (EXCEPT NORTHERN AFRICA AND SOUTH AFRICA), SOUTH AND SOUTHEAST ASIA (Af/SEA)

Developing economies with some energy resources and significant population growth.

Africa

Angola
Benin
Botswana
Burundi
Cameroon
Cape Verde
Central African Republic
Chad
Congo
Ethiopia
Gabon
Gambia
Ghana
Guinea
Guinea Bissau
Ivory Coast
Kenya
Lesotho
Liberia
Madagascar
Malawi
Mali
Malta
Mauritania
Mauritius
Morocco
Mozambique
Namibia
Niger
Nigeria
Reunion
Rhodesia
Rwanda
Senegal
Sierra Leone
Somalia
Sudan
Swaziland
Tanzania, United Republic of
Togo
Tunisia
Uganda
Upper Volta
Western Sahara
Zaire
Zambia

Asia

Afghanistan
Bangladesh
Brunei
Burma
Comoros
Hong Kong
India
Indonesia
Korea, Republic of (South)
Macau
Malaysia
Nepal
Pakistan
Papua New Guinea
Philippines
Singapore
Sri Lanka
Taiwan
Thailand
East Timor
West South Asia n.e.s.

REGION VI: MIDDLE EAST AND NORTHERN AFRICA (ME/NAf)

Developing economies with large energy resources.

Member Countries of the Organization of Arab Petroleum Exporting Countries (OAPEC)

Algeria	Libyan Arab Republic
Bahrain	Qatar
Egypt	Saudi Arabia
Iraq	Syrian Arab Republic
Kuwait	United Arab Emirates

Others

Iran
Jordan
Lebanon
Oman
Yemen
Yemen, People's Democratic Republic of

REGION VII: CHINA AND CENTRALLY PLANNED ASIAN ECONOMIES (C/CPA)

Developing centrally planned economies with modest energy resources.

China, People's Republic of
Kampuchea, Democratic (formerly Cambodia)
Korea, Democratic Republic of
Laos, People's Democratic Republic of
Mongolia
Viet-Nam, Socialist Republic of

B UNITS AND DEFINITIONS

CONVERSION FACTORS

The following gives the definitions of units of measure used throughout this book as numerical multiples of coherent Standard International (SI) units. The exact definition is indicated by √; other numbers are approximate to the number of digits shown.

1 acre	= 4046.8564224 m^2	√
1 bar	= 100,000 N/m^2	√
1 barrel (petroleum, 42 gallons)	= 0.1589873 m^3	
1 Btu (British thermal unit)	= 1055 J	
1 calorie (thermochemical)	= 4.184 J	√
1 electron volt	= 1.60210×10^{-19} J	
1 erg	= 10^{-7} J	√
1 foot	= 0.3048 m	√
1 gallon (U.K., liquid)	= 4.546087×10^{-3} m^3	
1 gallon (U.S., liquid)	= $3.785411784 \times 10^{-3}$ m^3	√
1 hectare	= 10,000 m^2	√
1 horsepower (metric)	= 736 W	√
1 inch	= 0.0254 m	√
1 kilopond	= 9.80665 N	√
1 langley	= 41,840 J/m^2	√

1 pound force	= 4.4482216152605 N	√
1 pound mass	= 0.45359237 kg	√
1 mile (U.S. statute)	= 1,609.344 m	√
1 millibar	= 100 N/m^2	√
1 nautical mile	= 1852 m	√
1 ton (long)	= 1016.0469088 kg	√
1 ton (metric)	= 1000 kg	√
1 ton (short, 2000 pounds)	= 907.18474 kg	√
1 Wyr	= $31{,}536 \times 10^3$ J	√
1 yard	= 0.9144 m	√

USEFUL APPROXIMATIONS

1 million barrels of oil per day (1 mbd)	≅ 71 GWyr/yr
1 million barrels of oil per day	≅ 50 million tons of oil per year
1 Btu	≅ 1 kJ
1 TWyr	≅ 30 Quad
1 TWyr	≅ 10^9 tce

PREFIXES

Factor	Prefix	Symbol
10^{18}	exa	E
10^{15}	peta	D
10^{12} [a]	tera	T
10^9	giga	G
10^6	mega	M
10^3	kilo	k
10^2	hecto	h
10^1	deka	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

[a] 1TW (terawatt) = 10^{12} W.

CONVERSION TABLE FOR COMMON ENERGY UNITS

		J	*Btu*	*Quad*	*kcal*	*mtce*	*10^6 mtce*	*boe*
1 J	=	1	947.9×10^{-6}	947.9×10^{-21}	239×10^{-6}	34.14×10^{-12}	34.14×10^{-18}	163.4×10^{-12}
1 Btu	=	1055	1	1×10^{-15}	0.2522	36.02×10^{-9}	36.02×10^{-15}	172.4×10^{-9}
1 QUAD	=	1055×10^{15}	1×10^{15}	1	252×10^{12}	36.02×10^{6}	36.02	172.4×10^{6}
1 kcal	=	4184	3.966	3966×10^{-18}	1	142.9×10^{-9}	142.9×10^{-15}	683.8×10^{-9}
1 mtce	=	29.29×10^{9}	27.76×10^{6}	27.76×10^{-9}	7×10^{6}	1	1×10^{-6}	4.786
10^6 mtce	=	29.29×10^{15}	27.76×10^{12}	27.76×10^{-3}	7×10^{12}	1×10^{6}	1	4.786×10^{6}
1 boe	=	6119×10^{6}	5.8×10^{6}	5.8×10^{-9}	1462×10^{3}	0.2089	208.9×10^{-9}	1
10^6 boe	=	6119×10^{12}	5.8×10^{12}	5.8×10^{-3}	1462×10^{9}	208.9×10^{3}	0.2089	1×10^{6}
1 mtoe	=	44.76×10^{9}	42.43×10^{6}	42.43×10^{-9}	10.7×10^{6}	1.528	1528×10^{-9}	7.315
10^6 mtoe	=	44.76×10^{15}	42.43×10^{12}	42.43×10^{-3}	10.7×10^{12}	1528×10^{3}	1.528	7315×10^{3}
1 m^3 gas	=	37.26×10^{6}	35.31×10^{3}	35.31×10^{-12}	8905	1272×10^{-6}	1272×10^{-12}	6089×10^{-6}
1 ft^3 gas	=	1055×10^{3}	1000	1×10^{-12}	252.2	36×10^{-6}	36×10^{-12}	172.4×10^{-6}
1 kWyr	=	31.54×10^{9}	29.89×10^{6}	29.89×10^{-9}	7537×10^{3}	1.076	1076×10^{-9}	5.154
1 GWyr	=	31.54×10^{15}	29.89×10^{12}	29.89×10^{-3}	7537×10^{9}	1076×10^{3}	1.076	5154×10^{3}
1 TWyr	=	31.54×10^{18}	29.89×10^{15}	29.89	7537×10^{12}	1076×10^{6}	1076	5154×10^{6}

		10^6 boe	*mtoe*	*10^6 mtoe*	*m^3 gas*	*ft^3 gas*	*kWyr*	*GWyr*	*TWyr*
1 J	=	163.4×10^{-18}	22.34×10^{-12}	22.34×10^{-18}	26.84×10^{-9}	948×10^{-9}	31.71×10^{-12}	31.71×10^{-18}	31.71×10^{-21}
1 Btu	=	172.4×10^{-15}	23.57×10^{-9}	23.57×10^{-15}	28.32×10^{-6}	0.001	33.45×10^{-9}	33.45×10^{-15}	33.45×10^{-18}
1 QUAD	=	172.4	23.57×10^{6}	23.57	28.32×10^{9}	1×10^{12}	33.45×10^{6}	33.45	33.45×10^{-3}
1 kcal	=	683.8×10^{-15}	93.47×10^{-9}	93.47×10^{-15}	112.3×10^{-6}	3966×19^{-6}	132.7×10^{-9}	132.7×19^{-15}	132.7×10^{-18}
1 mtce	=	4.786×10^{-6}	0.6543	654.3×10^{-9}	786.1	27.76×10^{3}	0.9287	928.7×10^{-9}	928.7×10^{-12}
10^6 mtce	=	4.786	654.3×10^{3}	0.6543	786.1×10^{6}	27.76×10^{9}	928.7×10^{3}	0.9287	928.7×10^{-6}
1 boe	=	1×10^{-6}	0.1367	136.7×10^{-9}	164.2	5800	0.194	194×10^{-9}	194×10^{-12}
10^6 boe	=	1	136.7×10^{3}	0.1367	164.2×10^{6}	5.8×10^{9}	194×10^{3}	0.194	194×10^{-6}
1 mtoe	=	7315×10^{-9}	1	1×10^{-6}	1201	42.43×10^{3}	1.419	1419×10^{-9}	1419×10^{-12}
10^6 mtoe	=	7.315	1×10^{6}	1	1201×10^{6}	42.43×10^{9}	1419×10^{3}	1.419	1419×10^{-6}
1 m^3 gas	=	6089×10^{-12}	832.3×10^{-6}	832.3×10^{-12}	1	35.31	1181×10^{-6}	1181×10^{-12}	1181×10^{-15}
1 ft^3 gas	=	172.4×10^{-12}	23.57×10^{-6}	23.57×10^{-12}	28.32×10^{-3}	1	33.45×10^{-6}	33.45×10^{-12}	33.45×10^{-15}
1 kWyr	=	5154×10^{-9}	0.7045	704.5×10^{-9}	846.4	29.89×10^{3}	1	1×10^{-6}	1×10^{-9}
1 GWyr	=	5.154	704.5×10^{3}	0.7045	846.4×10^{6}	29.89×10^{9}	1×10^{6}	1	1×10^{-3}
1 TWyr	=	5154	704.5×10^{6}	704.5	846.4×10^{9}	29.89×10^{12}	1×10^{9}	1000	1

mt = metric tons.

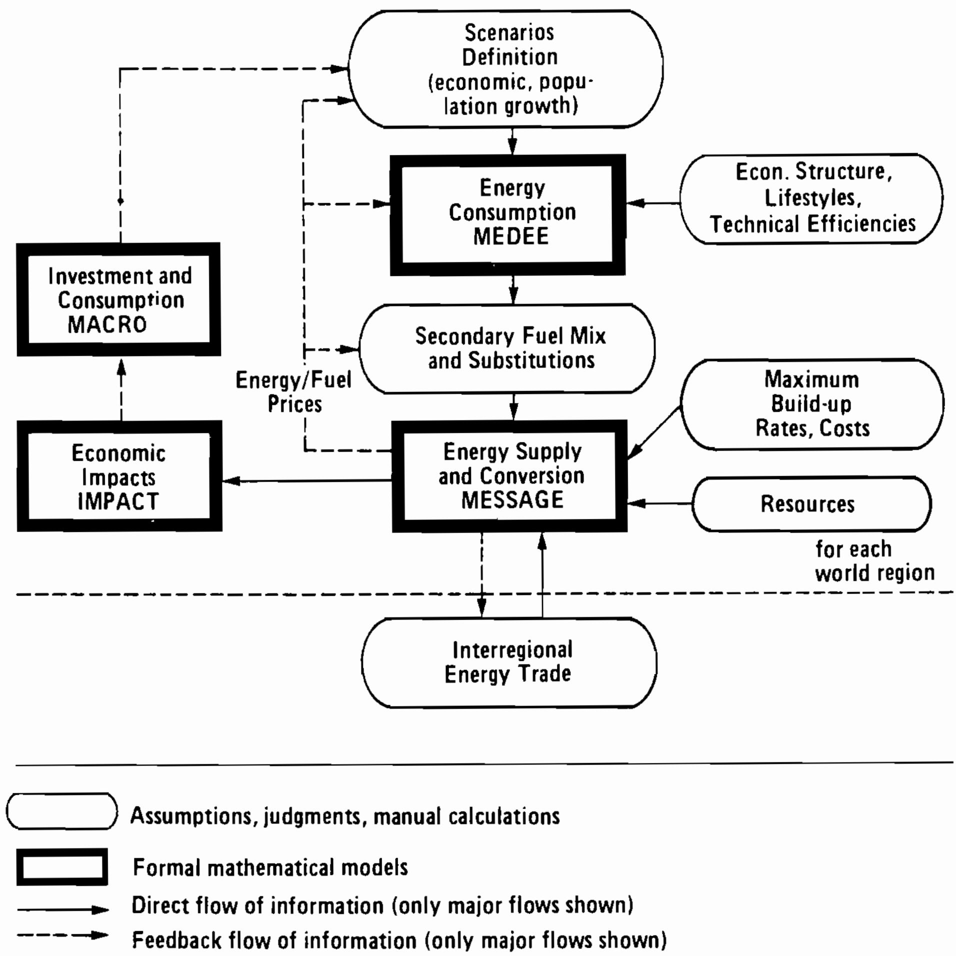
C THE SET OF IIASA ENERGY MODELS

The set of IIASA energy models is interconnected through the information flow between the models within a model loop (see Figure C-1).

The demand for final energy in each of the seven world regions is evaluated in the demand model MEDEE (Lapillone 1978), which is driven by the population and economic growth that are initially specified exogenously. The supply model MESSAGE (Agnew, Schrattenholzer, and Voss 1979) then determines the optimal cost-supply ratio of the required energy, subject to resource availability, technological, environmental and other relevant constraints. The economic and other impacts of these energy supply strategies are evaluated in the model IMPACT (Kononov and Por 1979), and the corresponding macroeconomic issues are assessed in the aggregated economy model MACRO (Norman 1977). This whole procedure is iterated region by region, taking into account interregional energy trade, until a globally consistent energy demand and supply pattern evolves. This also has a corrective bearing on the originally exogenous specification of economic growth of all seven regions.

Consistency checks are also carried out on the information flow between the models in each step of the iteration. This is possible since the models are not "hard wired," but allow for human judgement. All of the inputs and outputs of the models are examined to be sure that credible results appear at all steps. Furthermore, the interpretative results from IMPACT, MACRO, international trade analyses, and the economic price and elasticity determination offer additional consistency checks.

Figure C-1. IIASA's set of energy models: a simplified representation.



REFERENCES

Agnew, M.; L. Schrattenholzer; and A. Voss. 1979. *A Model for Energy Supply Systems Alternatives and Their General Environmental Impact.* WP-79-6. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Kononov, Y., and A. Por. 1979. *The Economic IMPACT Model.* RR-79-08. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Lapillonne, B. 1978. *MEDEE-2: A Model for Long-Term Energy Demand Evaluation.* RR-78-17. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Norman, M. 1977. *Software Package for Economic Modeling.* RR-77-21. Laxenburg, Austria: International Institute for Applied Systems Analysis.

INDEX

PROFILE OF THE INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS

The International Institute for Applied Systems Analysis (IIASA) cameinto being officially on October 4, 1972. On that day, representatives of distinguished scientific bodies from 12 nations gathered at The Royal Society in London to sign its Charter. But the signing was only the last of several major steps in an international cooperative effort that had begun much earlier.

Another critical meeting had taken place in 1967, when two men met in Moscow and agreed that their nations would work to establish an international scientific institution. They were McGeorge Bundy, former national security adviser to President Lyndon Johnson of the US, and Professor Jermen Gvishiani, Deputy Chairman of the State Committee for Science and Technology of the USSR Council of Ministers. The idea that brought them together had been proposed by President Johnson, who had hoped that such an institution could serve as a way to bring peoples of the world together.

Progress came slowly. For more than five years, spurts of negotiation were followed by long periods of seeming inactivity. Yet progress was being made. During those years, ten more nations joined the discussions, and the Charter gradually emerged. It was a document designed to accommodate many points of view, and its provisions have shaped IIASA's evolution.

Principal Features of IIASA

A key provision of the Charter makes IIASA international without being governmental. Its members are not nations, but scientific institutions from each participating nation. This structure helps keep IIASA free of international political pressures.

IIASA's founders reached another important agreement on the name of the institute. With "systems analysis," they wanted to convey the impression that research at IIASA would apply modern analytic tools to address major problems of international concern. The word "applied" was meant to stress IIASA's concern with practical, real-life issues. "Applied Systems Analysis" is deliberately general—allowing the Institute to deal with a wide range of topics.

The agreement reached on financing the Institute was also important to its future. The scientific organizations from the US and the USSR had taken leading roles in establishing the Institute. They agreed to pay the largest amounts, which would be equal. Each of the scientific bodies from other nations would contribute smaller but equal amounts, 15 percent of the larger contributions. In 1980, the contributions of the two large category A members were some 32 million Austrian schillings. Category B members, currently 15 in number, each contributed some 4.8 million Austrian schillings in 1980.

Two other important decisions by the founders helped establish IIASA.

One was the decision to make English the Institute's sole official language, thereby facilitating working relations among its international staff. The other was to accept an offer by the Austrian government to locate the Institute at Schloss Laxenburg, a former summer residence of the Habsburgs, 16 kilometers south of Vienna. The palace has been generously restored and adapted to IIASA's needs by the Austrian authorities, who have made it available to the Institute for a symbolic rent of one schilling per year.

The Institute's governing body is its Council, comprising one representative from each National Member Organization (NMO). The Council approves the principal research directions and budget, sets financial and management policies, deals with questions of membership, and appoints the Director and Deputy Directors. The Chairman of the Council is Professor Jermen Gvishiani.

The Director of IIASA, its chief executive officer, is responsible for formulating, managing, and administering all the Institute's activities, including preparing the budget and research plan and implementing the plan after Council approval. Under the guidance of the Council, he represents the Institute in dealings with research agencies, governments, and multinational bodies, and he is also an ex-officio member of the Council. The Director of IIASA is Dr. Roger E. Levien, formerly of the Rand Corporation in the US.

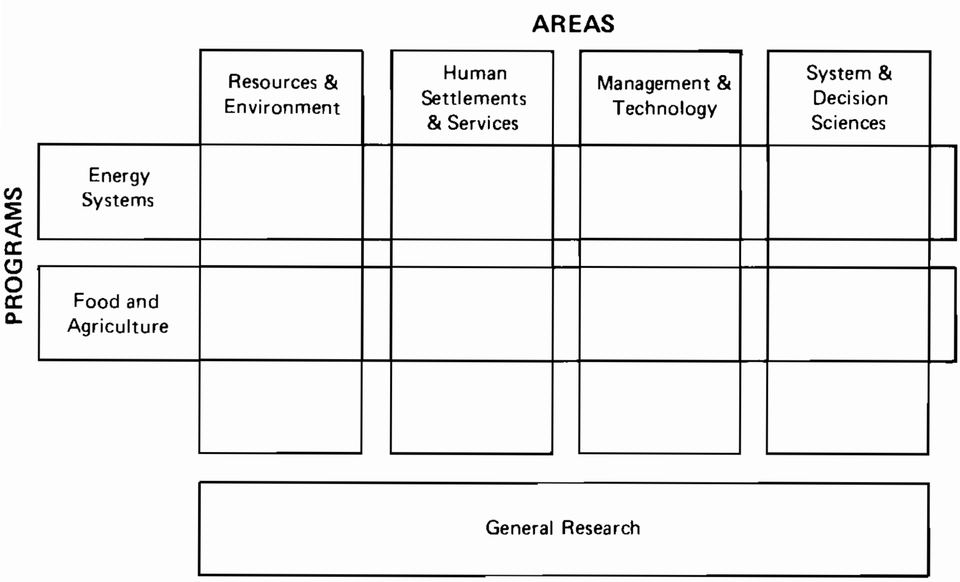
Structure of Research Activities

In 1973, IIASA's first Director, Professor Howard Raiffa from Harvard University in the US, welcomed the first scientists who came to Laxenburg to work on six applied projects (energy systems, water resources, management of urban systems, biological and medical systems, ecological systems, and integrated industrial systems) and three supporting projects (methodology, computer science, and design and management of large organizations). By the end of IIASA's second year—just 16 months after the arrival of the first full-time scientists—the Institute had established a full complement of research activities and a scientific staff of 80.

In 1975 IIASA's second Director, Dr. Levien, proposed a two-dimensional "matrix" organization for the Institute's research activities. The horizontal rows of this matrix represent the two major cross-cutting research Programs, which address major international issues. The *Energy Systems Program* examines strategies, at global, regional, and national levels, for achieving the transition from oil- and gas-based energy systems to those based on more sustainable sources. The *Food and Agriculture Program* is concerned with the development of effective national food policies and the international interactions among them. Each of these Programs has a four to five year lifetime. Programs on regional development, industrial change, and risk and hazards are under consideration.

The programs draw upon the broad range of talents that reside in the four continuing research Areas, represented by the vertical columns in the matrix. The *Resources and Environment Area* studies problems concerning the ex-

Figure 1. IIASA's research matrix.



ploitation of the earth's resources and the protection of its environment. The *Human Settlements and Services Area* investigates the earth's population, its distribution, and its needs for resources and services. The *Management and Technology Area* pays attention to the design and operation of organizations and the prospective development and consequences of technology. The *System and Decision Sciences Area* applies and develops the mathematical and computational tools that assist in the investigation of complex systems or decision problems. For activities that do not fit into the matrix, there is a *General Research* category.

IIASA's Mandate

IIASA has three principal objectives, which derive from the aspirations of its founders and the wishes of its members:

(1) To promote international collaboration, understanding and cooperation by bringing together scientists of different disciplines and nationalities for work on problems of concern to all mankind and by creating networks of scientific institutions for collaborative research.

(2) To advance both systems analysis and the sciences contributing to it.

(3) To apply IIASA's findings to problems of international importance by providing decision makers with relevant information and appropriate tools for dealing with these problems.