

COWLES FOUNDATION
FOR RESEARCH IN ECONOMICS
AT YALE UNIVERSITY

MONOGRAPH 26

THE EFFICIENT USE OF ENERGY RESOURCES

WILLIAM D. NORDHAUS

NEW HAVEN AND LONDON YALE UNIVERSITY PRESS 1979

Copyright © 1979 by Cowles Foundation for Research
in Economics at Yale University.

All rights reserved. This book may not be reproduced, in
whole or in part, in any form (beyond that copying
permitted by Sections 107 and 108 of the U.S. Copyright
Law and except by reviewers for the public press), without
written permission from the publishers.

Designed by Thos. Whitridge
and set in Monophoto Bembo type
by Asco Trade Typesetting Ltd., Hong Kong.
Printed in the United States of America by
the Vail-Ballou Press, Binghamton, New York.

Published in Great Britain, Europe, Africa, and Asia
(except Japan) by Yale University Press, Ltd., London.
Distributed in Australia and New Zealand by Book &
Film Services, Artarmon, N.S.W., Australia; and in Japan
by Harper & Row, Publishers, Tokyo Office.

Library of Congress Cataloging in Publication Data

Nordhaus, William D

The efficient use of energy resources.

(Monograph—Cowles Foundation for Research
in Economics at Yale University; 26)

Bibliography: p.

Includes index.

1. Energy conservation—Economic aspects.

I. Title. II. Series: Cowles Foundation for
Research in Economics at Yale University.
Monograph; 26.

TJ163.3.N67

333.7

79-64225

ISBN 0-300-02284-0

CONTENTS

LIST OF FIGURES	ix
LIST OF TABLES	xi
ACKNOWLEDGMENTS	xiii
INTRODUCTION	xv
1. Market Allocation of Exhaustible Resources over Time	i
2. The Demand for Energy	22
3. Availability of Energy Resources and Alternative Energy Supply Technologies	35
4. Detailed Equations of the Energy Model	54
5. The Efficient Allocation of Resources over Time	70
6. A Quantitative Estimate of Market Power in the International Oil and Gas Market	93
7. Energy Allocation with Market Imperfections	110
8. Strategies for the Control of Carbon Dioxide	130
REFERENCES	155
INDEX	159

FIGURES

1.1 Resource royalty in a competitive market equilibrium	5
1.2 Resource price in a competitive equilibrium	6
1.3 Pricing pattern with two resources	10
1.4 Pricing of an exhaustible resource with a backstop technology	12
1.5 Demand curves and royalty curves shown as function of monopoly production	18
1.6 Price paths for monopoly and competition	21
2.1 Preference function over energy goods and nonenergy goods	24
3.1 Crude oil discoveries per foot of exploratory drilling footage in the United States, exclusive of Alaska, 1860–1967	39
3.2 Finding rate for oil-in-place as a function of time	40
3.3 Illustration of technique used to approximate the nonlinear cost function for use in the mathematical programming model	42
4.1 Linearized form of objective function in simple problem	67
4.2 Solution for activities in simple example	68
4.3 Solution for dual variables (“shadow prices”) in simple example	69
5.1 Actual gross energy consumption, 1960–75, and calculated 1975–2015 efficient path	78

5.2	Calculated and actual price of OPEC oil	83
6.1	Illustration of the technique used to modify the demand function so as to prevent more than total income being spent on energy products in the case of extreme price rises	96
6.2	Estimates of OPEC optimal or limit price	108
8.1	Estimated effect of doubling of atmospheric carbon dioxide on surface temperatures, by latitude	133
8.2	The marginal first order transfer process between the seven reservoirs of carbon dioxide	139
8.3	Calculated emissions of carbon dioxide along alternative paths, 1960–2080	145
8.4	Distribution of industrial carbon dioxide over time by reservoir, uncontrolled path	146
8.5	Total energy consumption (gross energy inputs), United States, for alternative control programs	148
8.6	Past and projected change in global mean temperature, relative to 1880–84 mean	149
8.7	Estimates of the effect of temperature increase on the level of oceans for alternative paths of carbon dioxide concentrations	150

TABLES

1.1 Concentration in Energy Markets, Recent Periods	15
2.1 Results of Energy Demand Estimates	29
2.2 Comparison of Estimates for Price and Income Elasticities	32
2.3 Demand Functions for Per Capita Net Energy Used in Programming Model	34
3.1 Cost of Intermediate Energy Products Exclusive of Royalties	44
3.2 Energy Resources, by Region and Resource, 1970	45
3.3 Technologies for Electricity Generation	48
3.4 Technologies for Conversion, Nonelectric Processes	50
3.5 Materials Balance for Nuclear Fuel Cycle	51
3.6 Technologies for Utilization	52
3.7 Transportation Costs	53
3.8 Taxes and Distribution Costs for Demand Functions	53
5.1 Basic Assumptions Used in the Efficiency Model Run	75
5.2 Processes in Efficient Program, United States	77
5.3 Royalties (Shadow Prices) on Energy Resources	79
5.4 Intermediate Energy Prices Other than Petroleum	81
5.5 Prices of Petroleum Products	82
5.6 Prices per Million btu Delivered by Demand Category, United States	84

5.7 Oil and Gas Imports into United States, in Efficient Program, 1970-2010	85
5.8 Sensitivity Tests on the Intrinsic Scarcity of Energy Resources	88
6.1 Basic Assumptions Used in the OPEC Model Run	97
6.2 Results of Sensitivity Analysis for Limit Prices for Oil Imports	99
6.3 Limit Prices in World Model: Equilibrium Prices When No OPEC Production Occurs	104
6.4 Techniques and Size of Models Used to Estimate Optimal or Limit Prices for OPEC	106
6.5 Optimal, Limit, or Equilibrium Prices for OPEC under Alternative Models	109
7.1 Dates and Levels of Introduction of New Technologies	112
7.2 Limits to the Annual Growth Rates of Production	113
7.3 Basic Assumptions Used in the Market Model Run	116
7.4 Processes in Market Program	117
7.5 Total Energy Consumption, United States, in Efficiency and Market Runs	119
7.6 Shadow Prices for Energy Resources, Efficiency and Market Runs	121
7.7 Calculated and Actual Intermediate Energy Prices, United States	123
7.8 Losses in Real Income between Market and Efficiency Runs	126
7.9 Calculations of Discounted Real Income and Efficiency Losses for Individual Components of Market Run	128
8.1 Emission Factors for Carbon Dioxide	137
8.2 One Year and 100 Year Distribution Matrixes	141
8.3 Industrial Carbon Dioxide Emissions and Concentration Predicted from Model	144
8.4 Comparison of Uncontrolled Model Projections with Observed Values, 1974, and Other Projections, 2000	147
8.5 Shadow Prices on Carbon Dioxide Emissions	152
8.6 Shadow Prices on Carbon Dioxide Concentrations by Stratum, Control Program III	154

ACKNOWLEDGMENTS

Many people have contributed to this study. The use of mathematical programming as a way of performing quantitative analysis has its basis in published works and informal discussions. Tjalling Koopmans of Yale was a pioneer in this field and helped me at several points. Alan Manne of Stanford University and Kenneth Hoffman of Brookhaven National Laboratories wrote the seminal work in the energy area. I benefited from the comments of William Brainard, William Hogan, Herbert Scarf, James Sweeney, and James Tobin.

In addition, a large number of researchers helped with computer programming and other chores. I particularly would like to thank Truus Koopmans, Ludo van der Heyden, Paul Krugman, Robert Litan, and Richard Peck. Nonincriminating institutional support was provided by the Cowles Foundation, the National Science Foundation, and the International Institute for Applied Systems Analysis.

To those about to embark, I can only say I hope you enjoy the voyage as much as I did.

INTRODUCTION

Another book on energy requires apology more than introduction. My basic apology is twofold: questions concerning energy and exhaustible resources are of fundamental importance to our economy and society, and many of them remain unanswered.

The Basic Themes

The fundamental economic question about energy resources is: How fast should we consume our low-cost resources? (Of course, in a mixed market economy such as the United States there are no simple and direct levers to control the rate of consumption of our resources, and we must use policy instruments like interest rates, taxes, price controls or subsidies, and environmental constraints.) From a technological point of view, we face three different kinds of resources. First, there are inexpensive but limited oil and gas resources—ideal from an economic and environmental point of view. Second, there are abundant, but less attractive, resources that may be used when the low-cost resources run thin—coal, high-cost oil and gas, high-grade uranium in the current generation of nuclear power reactors. This second group generally suffers from the shortcoming that it is expensive and often environmentally risky or dirty.

A third group is the superabundant resources that would provide virtually limitless energy for centuries to come—these are fusion, fission, solar, and unknown. These share two

features—they are unproven for large-scale use, and they are relatively expensive. Beyond that, some are thought to be clean (solar energy), while some are thought to be environmentally very risky (some nuclear breeder reactors); some are virtually proven (the liquid metal fast breeder reactor), while others have not passed the test of technical feasibility (fusion); some are soft, some hard, and so forth.

This book asks a number of questions about the time pattern of use of these various resources:

1. What does economic theory have to contribute to the question of efficient use of energy resources? Quite a bit, as is shown in chapter 1. Efficient use of energy resources entails using cheap before expensive resources. A deeper set of results concerns the efficient pricing of resources. Each resource will, in a competitive market, have a "royalty" attached to it. The royalty will be zero for resources that are not scarce, positive for those that are. For all resources, the royalty will be rising at the market interest rate.

By working backward from exhaustion, we can determine what an efficient price for oil or other resources would be. The basic result can easily be seen where there are no extraction costs—roughly accurate for Mideast oil today. In this case, at the point when substitution of the next resource (higher-cost oil, coal, whatever) occurs, the price of Mideast oil and its substitute must be equal. For concreteness, call that year 2020. In 2020, then, the royalty on Mideast oil must equal the cost of the substitute. Since, in an efficient market, the royalty must rise at the interest rate, the royalty today must be the discounted value of the royalty in 2020. If the discount rate is 6 percent, and the substitute costs \$20.00, then in 1975 the royalty on Mideast oil, *and its efficiency price*, must equal $\$20.00/(1.06)^{45} = \1.45 .

2. How can we apply these simple economic theories to the real world? Clearly, casual examples like those presented in the last paragraph are insufficient to indicate what an efficient price would be in the real world. Chapters 2 through 4 describe the construction and components of a model designed to determine the efficient path for using energy resources.

The model has two different components. The first, discussed in chapter 2, describes the "demand" side of the energy market. It reports the results of a detailed econometric model of energy demand and then shows how these results can be used in the energy model. The second component is the technology, described in chapter 3, which presents estimates of the extent of energy resources, as well as the costs of extraction and conversion. Alternative models of cost of extraction are briefly described. Finally, chapter 4 lists the detailed equations used in the linear programming energy model.

One major spillover from the model construction is the estimates of energy demand functions in chapter 2. These rely on a combination of techniques for estimating the price-responsiveness of energy demanded in the United States and Europe. The basic result is that energy demand is shown to be moderately elastic with respect to price, with elasticities in the range of -0.5 to -1.0 depending on the sector, country, and specification.

3. The most important investigation, in my mind, relates to the estimate of the efficiency price of oil, given in chapter 5. Relying on the model, and the (clearly unrealistic) assumption that the energy market is competitive, we estimate that the efficient price of oil (for 1975 in 1975 prices) is \$3.00 per barrel. This compares with a price of approximately \$11.00 per barrel in 1978 (again in 1975 prices). The reason why the calculated efficiency price is so surprisingly low is basically the reason given in question 1 above—the cost of the next substitute resource is relatively modest, and the time at which substitution occurs is distant. Extensive sensitivity analysis in chapter 5 gives a range of \$2.03 to \$3.71 per barrel—still well below the present market price.

4. Given the enormous discrepancy between actual and calculated efficiency price, does this suggest that the Organization of Petroleum Exporting Countries (OPEC) is responsible for the difference? Chapter 1 investigates briefly the theory of monopoly in resource markets. Under limited but plausible assumptions it is shown that the monopoly price will be set at approximately the substitute price. In the example in (1)

above, then, if a monopolist had control of the oil market, he would set the price at slightly below the substitute (say, \$19.00), rather than at the competitive price of \$1.45.

Is OPEC responsible for the current oil price? It is a tempting hypothesis to attribute the rise of the world oil price from 1972 to 1974 to the effective monopolization of the world oil market by OPEC. This temptation is reinforced by the result in chapter 5 that the market price in the late 1960s and early 1970s was virtually equal to the calculated efficiency price. In chapter 6, we look more carefully at the empirical support for this hypothesis, both in the current study and in other studies. Most studies make a motivational hypothesis that OPEC is interested in maximizing its discounted profits (the "wealth maximizing monopolist"). The basic result of this and other economic studies indicates that the wealth-maximizing price for OPEC oil today lies at the bottom end of the \$10.00 to \$20.00 per barrel range (in 1975 prices). These studies confirm that the price rise of 1973-74 can be traced basically to the virtual monopolization of the international oil market. Although a large degree of short-run monopoly power exists, and given the undeniable presence of irrational elements in oil pricing, the evidence strongly suggests that any further substantial rise in the oil price would take prices well above the long-run monopoly price.

5. How likely is it that the future will see a repetition of the dramatic price rises of 1973-74? Chapter 6 describes the trajectory of wealth-maximizing oil prices for this model as well as for other studies. Although there are enormous uncertainties, these studies indicate that on economic grounds the 1973-74 increase attained the long-run monopoly price. Taking the median of the studies presented there, the real price of oil that would maximize the wealth of OPEC would rise about 2 percent per annum over the period 1975 to 2005.

6. What is the chance that global environmental effects will appear as a result of unrestrained market forces? There is widespread evidence that the combustion of fossil fuels—leading to buildup of atmospheric carbon dioxide—will be the first man-made environmental problem of global signi-

ficance. Chapter 8 outlines the essence of the problem and investigates possible control strategies. The conclusion is that we are probably heading for major climatic changes over the next 200 years if market forces are unchecked. Global temperatures would rise in the order of 5 degrees centigrade, with much more dramatic increases in the polar regions. Further consequences—on agriculture or the level of the oceans—would clearly follow.

Chapter 8 describes several control strategies, of which the most efficient one is a “carbon tax” on the combustion of fossil fuels. It is shown that (depending on the desired level of control) these can reduce the seriousness of the effects with modest but manageable economic costs.

Looking Backward

This study represents work done over the period 1970 to 1976. It was virtually complete when I was asked to become a member of President Carter’s Council of Economic Advisers. As a result, a few loose ends will appear, for chapters 3, 6, and 7 were written on the fly. Basically, however, the work represents a view of the world shortly after the oil crisis.

Looking backward, it seems useful to ask what seems right and what seems wrong. I view the results described here as primarily *methodological*, as indicating a technique by which economic and engineering tools can be used to analyze trends in markets and the contributions of new technologies. Since the original version was written in 1973, this class of technique has gained wide currency among energy modelers.

On the basic *empirical* results of this study, concerning the *efficiency price* of energy resources, nothing has arisen to change my view substantially. Undiscovered oil is being discovered and is turning into proven reserves at a good clip; demand for oil is growing at about what the energy demand functions would predict; no major new findings or analytical problems have been uncovered.

There are, however, three features of energy markets which pose very great uncertainties and may modify the empirical results, especially in the short run. These features are the cost of new technologies, the determinants of OPEC

pricing, and the regulation of the economy. When recent evidence of these three features is combined, it appears likely that, especially in the short run, the cost and price trajectories outlined below are understated.

The *costs of new or unproven technologies* must perforce be laden with uncertainty. Until considerable experience is developed with technology, there is no way of predicting the cost of future technologies except with a large margin of error. Studies of cost overruns—essentially errors of cost estimates—in large construction projects and in military aircraft development indicate that the ultimate costs routinely vary by a factor of two from first estimates. At the same time, it is just as routine to note that after development and when engineers begin to move down the “learning curve,” very rapid improvement in costs generally follows introduction.

Given these inherent uncertainties, I have particular concern that the cost of the first generation of new technologies—particularly synthetic fuels such as shale oil and gasified and liquefied coal—may have been substantially underestimated. The most recent studies of synthetic fuels indicate that costs are from 25 to 60 percent higher than the figures used in the present study. Assuming the most recent estimates are accurate and that no learning occurs after introduction, this would lead to higher costs, higher prices, and lower energy demands.

A second area in which there continue to be considerable uncertainties concerns *OPEC pricing* of oil and gas. In chapter 6 it is shown that there is substantial uncertainty about the wealth-maximizing price in the short run—the main uncertainty deriving from the uncertainty about the short-run price-elasticity of the demand for oil. In the long run, however, the different studies cluster fairly closely. There are no major new developments that would change these estimates; the most recent studies show no change from those given in chapter 6.

Many observers question the validity of such studies, however, because the models generally ignore the role of noneconomic factors in decisions about production and pricing. One problem is that the concept of maximizing net wealth is clearly too narrow an objective for many governments. Other

important objectives are to preserve the "black gold" for future generations (to diversify the portfolios away from paper wealth) and to use the oil weapon for political ends. Some countries (Saudi Arabia, Kuwait, United Arab Emirates) are probably simply glutted with cash. There appear to be irrational elements in decision-making, in that discount rates placed on oil are different from rates placed on other goods.

Another set of concerns is the dynamics of cartel behavior. Countries whose reserves have but a short lifetime may put strong pressure, including military threats, to restrain production on countries with large reserves. There are, of course, pressures in the opposite direction. Many oil-producing countries are poor, and they will have a strong inclination to expand production as rapidly as possible as long as they are but a small fraction of the world market. These countries also generally have very high discount rates, which will tend to incline them to bring reserves to market quickly. All these and other factors make the use of the monopoly models suspect, indicating that the quantitative results are of limited validity.

A final area where the fundamental structure of the model can be questioned concerns the effect of *regulatory and environmental* policy. The fundamental assumption that runs through the analysis is that regulatory and environmental policies do not significantly impede market forces. Thus it is assumed that there is no further tightening of the environmental screws beyond levels of 1975. Further, it is assumed that (outside of OPEC) prices reflect costs of production and that there are no non-market impediments to developments or introduction of new technologies.

Each of these assumptions is probably too optimistic. The regulatory problems are perhaps best illustrated for environmental policy. Environmental policy in the energy sector in the United States presents flaws which lead to serious economic inefficiencies. The flaws stem from two basic areas. First, the technique of regulation for environmental spillovers relies on a series of detailed, specific technological requirements for individual firms and utilities as to how they should produce energy. As a result, we spread around our environmental dollars extremely inefficiently. A well-documented example is

the \$40-billion regulation proposed by the U.S. Environmental Protection Agency in 1978 to reduce sulfur emissions from coal-fired plants. This regulation mandates techniques be used to remove sulfur after mining in preference to using low sulfur coal. It does so on a nationwide basis. As a result, sulfur removal is inefficient—the nation pays more than needed for sulfur removal. More troubling is the possibility that overall health effects will be *worse* under the original, full-control proposal than under a well-designed standard. These and other inefficiencies are troubling because they may lead to costs that are two or three times what is efficient and to the stifling of new technologies.

The assumption of insignificant nonmarket impediments to energy production is also unrealistically optimistic. In the United States government regulation determines a significant fraction of price, allocation, and technical decisions. New technologies are largely funded by government. More troubling, however, is the increasing tendency to eliminate or slow development of energy technologies—like nuclear or coal—due to a “zero-risk” philosophy.

To a considerable extent, such inefficient and irrational policies make technological change and substitution uncertain or extremely expensive. If they become prevalent, there is little hope that we can make a gradual and inexpensive transition from oil and gas to alternative fuels.