Making Technology Work

Applications in Energy and the Environment

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CAMBRIDGE
UNIVERSITY PRESS

PUBLISHED BY THE PRESS SYNDICATE OF THE UNIVERSITY OF CAMBRIDGE
The Pitt Building, Trumpington Street, Cambridge, United Kingdom

CAMBRIDGE UNIVERSITY PRESS
The Edinburgh Building, Cambridge CB2 2RU, UK
40 West 20th Street, New York, NY 10011-4211, USA
477 Williamstown Road, Port Melbourne, VIC 3207, Australia
Ruiz de Alarcón 13, 28014 Madrid, Spain
Dock House, The Waterfront, Cape Town 8001, South Africa

http://www.cambridge.org

First published 2004

Printed in the United States of America

Typeface Minion 10.5/13.5 pt. *System* $\LaTeX\ 2_\varepsilon$ [TB]

A catalog record for this book is available from the British Library.

Library of Congress Cataloging in Publication Data

Deutch, John M., 1938–

Making technology work : strategies and techniques in energy and the environment / John M. Deutch, Richard K. Lester.

p. cm.

Includes bibliographical references and index.

ISBN 0-521-81857-5 – ISBN 0-521-52317-6 (pb.)

1. Power resources. 2. Environmental protection. I. Lester, Richard K. (Richard Keith), 1954– II. Title.

TJ163.155.A1D48 2003
621.042 – dc21 2003046103

ISBN 0 521 81857 5 hardback
ISBN 0 521 52317 6 paperback

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1

Introduction

Applying new technology in our society is invariably a challenge, and those who try do not always succeed. New technologies are frequently of large scale, involve significant environmental or social consequences and must adhere to a complex framework of governmental rules and regulations whose economic impact may be far-reaching. Issues such as opposition to nuclear power, concern over the environmental effects of burning coal, the ethical dilemmas of stem cell research, and the threats to privacy, intellectual property, and even national security associated with the growing use of the Internet fill the daily newspapers. Learning how to manage the often-competing interests that come into play when new technologies are deployed in society will be increasingly important, especially for scientists and engineers whose professional lives are dedicated to the task of harnessing technology for economic and social ends.

Today the education of scientists and engineers in U.S. universities is still strongly influenced by the conventional view of technological innovation as a linear process. In this view, innovation proceeds through distinct stages: (1) research – the first step of knowledge creation, usually by scientists in a laboratory; (2) development – the step of reducing the knowledge to practice, normally the responsibility of the engineer; and (3) application – the crucial step of implementing a technology, mainly the province of nontechnical professionals, such as managers, financiers, lawyers, politicians, or public-interest advocates. Scientific and engineering education is organized according to this linear perspective. The curriculum of a typical student in physics, chemistry, and chemical or electrical engineering understandably stresses depth in the discipline and research skills. The student's experience, however, includes little if any exposure to other disciplines, to techniques that are useful for analyzing the multidimensional aspects of technology application, or to working with a multidisciplinary group to address a complex technology problem. Yet most science and engineering students will encounter the broad range of problems associated with technology application almost immediately in their professional careers. They will be relatively unprepared to deal with these problems.

As we shall see repeatedly throughout this book, successful application of technology requires that simultaneous consideration be given to the technical and nontechnical aspects of the situation, because of the interrelationships among these elements. This perspective on technology innovation stresses integration and differs significantly from the traditional linear view. A necessary consequence is that the application of technology cannot be left to nontechnical professionals alone. Scientists and engineers must be actively involved not only in creating new technology options but also in the complex process of determining the circumstances of technology application. The challenge for practicing technologists – and for education in science and engineering – is to achieve a better balance between inventing new technology and responsible application.

This book is addressed to science and engineering students (both graduate and undergraduate) who are aware of the limitations of the current educational approach and who are interested in learning about problems of technology application. The book is an outgrowth of the multidisciplinary subject called "Application of Technology – Case Studies in Energy and the Environment," developed with support from the Alfred P. Sloan Foundation and taught at MIT since 1992. The case studies presented in the book include applications of nuclear, coal-burning, solar, wind, and energy conservation technologies. Each case study presents a description of the relevant technology at a level accessible to anyone who is familiar with elementary concepts in basic science and engineering.

Each case study integrates technical analysis with the economic, political, environmental, and social aspects of the technology application under consideration. Where appropriate, international considerations are also included. It is the integration of these aspects that both defines the barriers to technology application and points to possible solutions. To take just one example, it is often said that nuclear waste disposal is a political rather than a technical problem. This distinction implies that the implementation of this technology is the responsibility of politicians rather than scientists and engineers, and that the political constraints are separable from technical considerations of repository design, siting, construction, operation, and cost. But this kind of separation is impossible. As we shall see, responsible progress requires the simultaneous consideration of political, economic, environmental, and technical factors.

Of course, not all new technologies present the same range of issues as energy technologies. Information technologies such as computers, telecommunication networks, and the Internet clearly do not raise the sort of thorny environmental issues that figure in the application of many energy systems. On the other hand, other public policy issues are critical in the information and communications industries. For example, there are no internationally accepted rules for encryption of personal or commercial communications; fundamental privacy issues are raised by the Internet and electronic commerce; and the relative economics of long-distance land-line, wireless, satellite, and cable transmission technologies are importantly affected by government policies regarding taxes, antitrust, and price regulation. The central point is that the successful application of technology in any industry – from health care to transportation, from energy to biotechnology – requires simultaneous consideration of technical and nontechnical factors. Although the case studies in this book are drawn from the energy and environmental sectors, the reader should gain an appreciation for the integrated approach required for progress on a wide range of applications of complex technologies.

Serious students are not interested in merely hearing "war stories" about the difficulties of applying technology. Rather, they wish to learn techniques and skills needed to address the problems they will encounter in their professional careers. The second objective of the case studies is thus to present techniques in the context of realistic application that the student will be able to apply in new situations. The reader should expect to accumulate a "toolbox" of techniques that will be useful in analyzing new problems. Examples of the types of tools that are introduced in this book include: (1) energy and materials balances; (2) cost-benefit analysis; (3) the treatment of external costs and benefits; (4) present worth analysis of costs and benefits; (5) probabilistic risk assessment; and (6) life cycle costing.

Every public policy issue involves many groups that have an interest in the outcome – entrepreneurs, politicians, financiers, public interest groups, and others. By understanding the consequences of technology applications for each group, the different stakeholders can expect to achieve their objectives more readily and more responsibly. In most cases, of course, there is no perfect outcome. There are invariably winners and losers, and some interests that come closer to being satisfied than others. No single outcome can be identified as – or is perceived to represent – "the public interest." Still, understanding the views of all the stakeholders in the decision-making process helps to reach the most satisfactory resolution.

In the following paragraphs, we illustrate the approach that will be taken in subsequent chapters with two brief examples.

PAPER OR FOAM PLASTIC CUPS?

In December 1990, in a highly publicized press release, the McDonald's Corporation and the Environmental Defense Fund (EDF), a nationally known environmental public interest group, jointly announced that McDonald's had decided to replace polystyrene foam food and drink containers with paper containers to achieve environmental benefit. Whatever they are made of, whether plastic or paper, these boxes and cups are waste byproducts of producing and consuming McDonald's meals. At first glance, the decision appeared uncontroversial – paper is recyclable and biodegradable, whereas plastic is not – and McDonald's, a good corporate citizen, decided to switch from one product to another because a public interest group pointed out the environmental benefits of doing so. (The decision was also economically rational. The switch did not actually involve any extra costs to McDonald's, and the favorable public response was expected to yield economic benefits to the corporation.)

Then Martin Hocking, a professor of chemistry at the University of Victoria in British Columbia, published an article questioning whether the selection of paper over plastic did, in fact, have environmental merit. Hocking compared the waste streams generated in the production of paper and plastic cups.[1] Although Hocking's analysis has been criticized by paper advocates,[2] it is instructive on two points that often arise in technology applications.

[1] Martin B. Hocking, *Science* 251, 504–5 (1991).
[2] Red Caveney, *Science* 252, 1362 (1991); Henry Wells, *Science* 252, 1361 (1991).

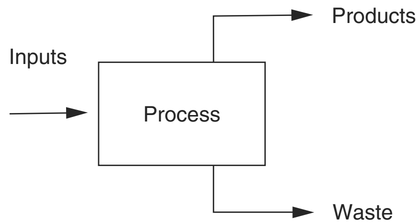

Figure 1.1. Conceptual diagram of an industrial process.

Internalizing External Costs

The conceptual flow diagram in Figure 1.1 applies to any industrial process. The process takes inputs (raw materials) and converts them to products, while generating wastes that are assumed to be valueless. The wastes may be in solid, liquid, or gaseous form, and their disposal can impose a burden on the environment, for example, by requiring unsightly landfills or by polluting streams or the atmosphere.

In the past, the environmental impacts of waste streams were usually disregarded, and accordingly, the costs of those impacts that were actually borne by the producer were negligible. They were "externalized." The cost to the producer of manufacturing the product was simply the cost of the inputs and the cost of building and operating the production facility.

Today a great deal of attention is given to reducing the environmental burdens of waste disposal, and accordingly, the monetary costs of disposing of wastes have risen. Companies can be expected to act rationally in selecting processes that minimize the overall cost of production, including the cost of waste disposal. In some cases the monetary cost of disposal borne by the company may also include the residual cost to the environment inflicted by the waste streams, that is, the residual environmental costs are "internalized." If the cost to the company for waste disposal properly reflects the environmental burden, then one can expect that the company will select the process that is most efficient for society, which is the process that minimizes the total social cost. However, even under these circumstances, environmental groups may not be satisfied. First, there may be disagreement as to whether the residual environmental costs have been correctly internalized. Second, there will always be some environmental advocates who place greater value on reducing harmful environmental impacts than can be justified on the basis of economic optimization. One cannot expect to satisfy all environmental concerns, any more than one should expect to satisfy all the concerns of any interest group. However, the governing principle is clear: To the extent possible, environmental costs to society should be internalized, in the sense that these costs should be included in the total cost incurred by the company in producing its product, and therefore in the price paid for the product by the company's customers.

The problem arises when the cost of waste disposal paid by the company does not reflect the actual environmental burden. This is surely the case for McDonald's, where carryout food is sold in paper or plastic containers. When the consumer throws the wrappers away, someone else pays for the cost of disposal. The environmental costs are "externalized," in the sense that they are not included in the price the company

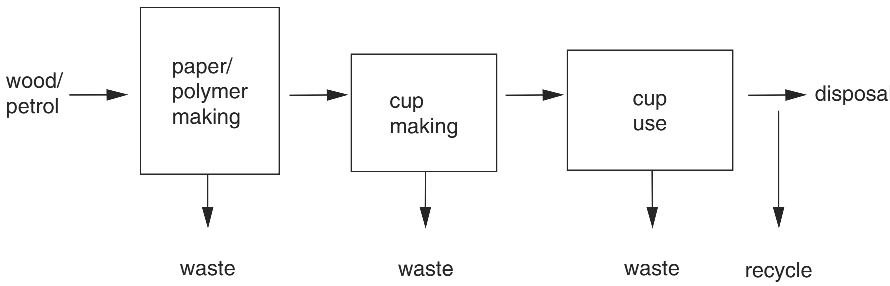

Figure 1.2. Flow diagram for making paper or plastic cups.

pays for waste disposal. Under these circumstances, the public is justified in insisting on regulations that force the company to make the choices it would have made had the external costs been internalized. Public interest groups deserve support in urging companies to take actions that are consistent with taking external costs into account in their business decisions.

The controversy here is essentially about the external environmental costs associated with the use of paper versus plastic. Because the environmental impacts occur outside any market framework, it is necessary to estimate the magnitude of the environmental burden and its associated costs. Different stakeholders (such as business firms and environmentalists) will have different perceptions of the severity of these environmental impacts. Resolving disputes about the magnitude of the external costs and how they should be taken into account is one of the central obstacles to the application of many technologies.

What is the System?

Hocking's analysis is interesting because he examines several intermediate steps in the overall process of making and using paper and plastic cups. Hocking includes in his analysis the paper-making process, the process of making polystyrene polymer from petroleum, and the potential for recycling used cups of both types.

A simplified diagram of the cup-making process considered by Hocking is given in Figure 1.2. With the intermediate steps of paper and plastic manufacturing included, a simplified summary of Hocking's analysis is given below:

Category	Foam cup	Paper cup
input: wood	0 g	33 g
input: petroleum	3.2 g	4.1 g
weight	1.5 g	10.1 g
cost	x	$2.5x$
recycle	some	low
biodegrades	no	yes
burns	clean	clean

By including the step of paper-making in the process, Hocking reverses the traditional conclusion that paper cups use less petroleum than plastic. The key to his analysis and the subsequent debate over the relative environmental benefits of paper versus plastic is the definition of the process system under consideration. Different conclusions are reached depending upon how the system boundary is drawn.

Critics from the paper industry object to Hocking's estimate of the amount of petroleum needed to make a paper cup (they estimate less than 2 g compared with his estimate of 4.1 g), and they take a different view of both the volume needed for landfill disposal and the potential for recycling paper versus plastic. The balance is not clear. What do you think?

ELECTRIC VEHICLES IN CALIFORNIA

In 1990, the California Air Resources Board (CARB), a department of the California Environmental Protection Agency, mandated that by 1998 2% of all cars and light trucks sold in California by the major automobile manufacturers must be "zero emission vehicles" (ZEV). The target rose to 10% of new vehicle sales by the year 2003 and increased further thereafter. Other states followed California's lead.

In taking this action the California government was seeking to compensate for an external environmental cost – the effect of auto emissions on air quality, especially in urban areas in southern California – that was not being adequately taken into account by the market. By mandating the dates by which fixed percentages of zero emission vehicles would have to be introduced, the state was pursuing a "command and control" approach to internalizing these costs.

An alternative regulatory mechanism is taxation. If the state taxes polluting vehicles in proportion to the amount of pollution they emit into the atmosphere, there will be an economic incentive for automobile manufacturers to introduce lower emitting vehicles. Presumably there is some level of taxation that would result in the same improvement in atmospheric air quality as the command and control approach. And there is merit in relying on an indirect taxation mechanism rather than the direct regulatory approach, because the former permits private companies to respond in a manner that is most efficient for them instead of being required to conform to a single design solution. (As it turns out, CARB later replaced its original 1990 requirements with more flexible targets, although key aspects of the command and control approach were retained.)

At the time of the original regulations – and still today – only electric vehicles conform to the zero emission standard. At the present level of battery technology, electric vehicles still have severe performance constraints, including limitations on acceleration, battery recharging time, and range. In order to achieve reasonable round trip travel ranges of about 50 mi, the electric vehicles must be quite heavy (due to the weight of the batteries required) and are relatively costly. The electric vehicles cannot travel very far from an electrical recharging point.

The appropriate environmental objective is to improve air quality by reducing emissions below current levels. The ultimate objective is not to introduce electric vehicles; that is merely the means to the end, and there are several other alternatives to the current conventional gasoline-powered car that should also be considered, for example:

Base case	**Alternatives**
Conventional gasoline-powered vehicles	Battery electric vehicles
	New low or ultra-low emitting gasoline-powered vehicles
	Compressed natural gas-powered vehicles
	Hybrid electric vehicles

A comparative analysis of these alternatives is not presented here. Our more limited purpose is to point out that by relying on regulations that effectively specify a particular vehicle type – ZEV – consideration of other interesting alternatives is precluded. For example, the hybrid electric vehicle (HEV) carries on board a small constant rpm engine that can very efficiently and with very low emissions charge batteries. The fuel for this small engine generator could be either natural gas or gasoline. With this design, the HEV circumvents the major disadvantage of the pure electric vehicle, because the small electric generator permits long-distance trips. Emissions per mile traveled are dramatically reduced compared with conventional vehicles; this is due to the very low gasoline consumption that is achieved by the HEV as a result of relying on the constant rpm engine. Specifying a particular system in the regulations may not lead to the desired outcome.

Moreover, in this case (as in the previous example of paper versus plastic) the issue arises as to what system is under consideration? If the atmospheric emissions from a pure electric vehicle are compared with those from a gasoline vehicle, it is clear that the pure electric vehicle has the lower emissions. But if a comparison is made between the system comprising ZEV and its attributable utility generation and the gasoline-powered car and its fuel supply system, the outcome for air quality is less clear. The result will partly depend on whether the electricity is generated by nuclear, coal, or oil-fired power plants. It is always important to define the system under consideration in comparative analysis.

For the comparison between conventional gasoline-powered autos and electric vehicles, consider the following, simpler question: Which is more energy efficient? Suppose that all the electricity generated comes from oil (which is actually not true in California.) The comparison is shown in Figure 1.3. For the case of the electric vehicle, there is an efficiency loss of two thirds associated with the conversion from oil to electricity, and a further 25% loss incurred in transmitting the electricity from the power plant to the wall plug used to charge the electric vehicle. If it takes 1 kwhr of electric energy to drive the electric vehicle 1 mi, we find that 13,650 British Thermal Units (BTUs) of oil are required for 1 mi of travel in this case.[3] For the conventional gasoline-powered car, there is a 10% loss associated with the conversion of oil to gasoline at the refinery. If the

[3] A British Thermal Unit (BTU) is the amount of energy required to increase the temperature of a cubic foot of water by 1°F. The energy industry in the United States has unfortunately not yet adopted metric (SI) units. 1 kwhr of energy is equivalent to 3,412 BTU.

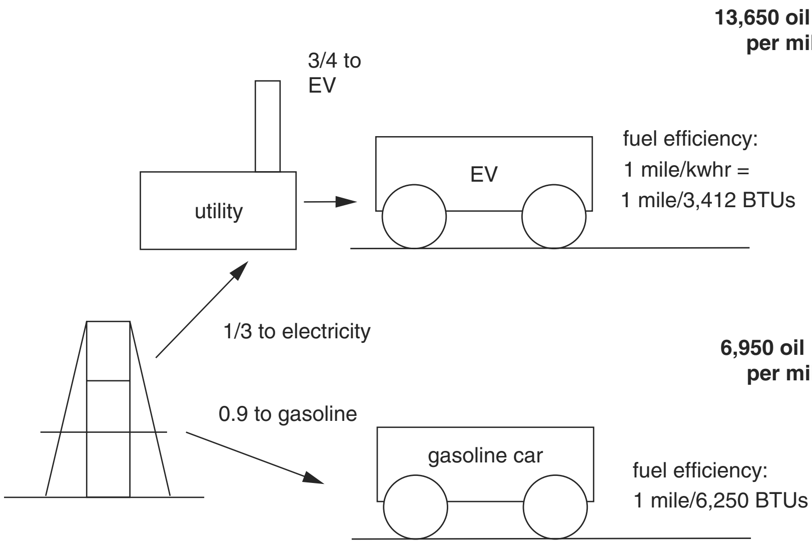

Figure 1.3. Oil required for an electric vehicle (EV) to travel one mile compared with a gasoline-powered car (assumed car mileage of 20 mpg of gasoline @ 125,000 BTU per gal).

car does 20 mpg of gasoline, this translates into an oil requirement of approximately 7,000 BTUs of oil per mile. Thus on energy efficiency grounds, given today's technology, a conventional gasoline-powered car is almost twice as efficient as an electric vehicle charging from an oil-fired electric power plant. The question is whether the emission advantages of the electric vehicle would override the considerable economic penalty revealed by this difference in energy efficiency.

The key insights from these brief examples are developed more fully in subsequent chapters. In the next chapter, on the production of gasohol fuel from corn, we further demonstrate the importance of clearly defining the boundaries of the system being analyzed. And in several later chapters we revisit the problem of external costs and consider how alternative ways of dealing with these costs can affect the application of new technology.