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A.P.A. MUSTERS

Framework of the study

In order to obtain the M.Sc. degree in Industrial Engineering and Management Science from the Eindhoven University of Technology, a research project of 9 months must be carried out. This report presents the results of this research project which was conducted at the unit Policy Studies of the Netherlands Energy Research Foundation. I am indebted to many people for being able to accomplish this M.Sc. thesis. I would however like to acknowledge the particular contributions made by Ir. Maarten Splinter and Dr. Cees Withagen of the Eindhoven University of Technology. In addition, I am very grateful to Ir. Piet Boonekamp, Drs. Nico van der Linden, and Mr. Tom Kram of the Netherlands Energy Research Foundation. Their comments and encouragements were unvaluable.

Abstract

This study examines the Energy-Economy-Environment (3-E) interaction in general and the rebound-effect in particular. The rebound-effect can be defined as that part of the initially expected energy savings, resulting from energy efficiency improvements, that is lost because of the 3-E interaction. To estimate the magnitude of this rebound-effect, the MARKAL-MACRO model has been used. MARKAL-MACRO is an integrated computer model, which is created by coupling the systems engineering model MARKAL and the macroeconomic growth model MACRO.

CONTENTS

SUMMARY

Economic growth has become one of the most important economic topics of the post-war years. The reason for this is the fact that many argue that economic growth offers a solution to all sorts of economic and social ills. The thought that economic growth is necessary for solving the problems of unemployment, poverty, and environmental degradation is not new. Adam Smith, for example, considered economic growth as a desirable activity. In the long run, however, the classical school of economic thought argued that the wheels of progress would stop turning. Modern neoclassical scholars are more optimistic in their outlook on the future. The reason for this positivism is the inclusion of substitution possibilities and technical change in their analysis of economic growth.

The problem with unlimited economic growth, however, is that it places an excessive demand on our natural environment. Phenomena such as the greenhouse effect and the depletion of the ozone layer are warnings that man needs to pay greater attention to his physical surroundings. In order to deal with these phenomena, a paradigm shift in economics is required. This new paradigm should explicitly treat the energy system, the economy, and the environment integrative.

The acknowledgement of the energy-economy-environment (3-E) interaction leads to the notion that there are limits to the expansion of the economic system. The entropy concept can be used to clarify this finiteness. Any organism namely feeds on low entropy resources, which it takes from the environment and degrades into high entropy waste. Also the economic system feeds on low entropy. The three sources of low entropy resources that mankind has at its disposal are the energy received from the sun, the fossil fuel reserves, and the materials stored in the earth. And since low entropy cannot be created and can only be used once, the possibilities for unlimited economic expansion become questionable.

As a solution to the problem of economic growth in a finite environment, three different views can be distinguished. A rather optimistic view is given by the writers of the Brundtland report, who advocate a sustainable development. The concept of sustainable development implies a forceful economic growth that does however take into account the environment. Herman Daly is less optimistic. Daly advocates a steady-state economy, in which there is no place for economic expansion. Nicholas Georgescu-Roegen is of opinion that even a stationary state is not the solution. Georgescu-Roegen argues that the growth trend must be reversed into a negative economic growth.

Of these three solutions, Brundtland's call for sustainable development obviously offers the most appealing future. The writers of *Our Common Future* claim that continued economic growth remains possible when it is accompanied by efficiency improvements in the use of energy and materials. The underlying thought behind this approach is that energy efficiency improvements make it possible to have increasing economic growth rates without increasing demands for energy. There is however a problem with respect to this approach. It is namely not certain that energy efficiency improvements lead to proportionate decreases in the demand for energy. The rebound-effect is a means of quantifying this effect. The rebound-effect is a measure of the part of the initially expected energy

savings, resulting from energy efficiency improvements, that is lost because of the 3-E interaction.

The rebound-effect is not new. Already in 1865, W.S. Jevons wrote that a more efficient use of energy is not equivalent to a diminished energy consumption. But despite these wise words, there is still no agreement on the question of whether or not a rebound-effect exists. As an example of this disagreement, the polemic in *Energy Policy* can be mentioned. An important reason for the lack of consensus is that up to now, very few attempts are undertaken to determine the magnitude of the rebound-effect. The only way to resolve the debate on the rebound-effect is by means of a quantitative analysis.

An estimation of the effect of energy efficiency improvements on the demand for energy can be obtained with the aid of the MARKAL-MACRO computer model. MARKAL-MACRO is created by linking the MARKAL model and the MACRO model. MARKAL is a technologically oriented linear programming model of the energy sector. MACRO is a neoclassical growth model, which takes an aggregate view of long-term economic development. Because the interactions between the energy sector and the economy are incorporated in MARKAL-MACRO, the rebound-effect can be determined with this integrated model. The MARKAL-MACRO estimation of the rebound-effect on the consumption-side of the economy amounts to 33%. The existence of such a rebound-effect is in agreement with economic theory. The objective of consumers is namely not to minimize energy cost, but rather to maximize utility.

The existence of a rebound-effect obviously has policy implications. One of the most important implications is that energy efficiency improvements cannot be seen as a new energy supply source. This means that besides oil, coal, gas, and uranium, energy efficiency cannot be regarded as the new fifth fuel.

Because of the existence of the rebound-effect, a part of the expected energy savings, resulting from energy efficiency improvements, is lost. Therefore, policy measures aimed at reducing the rebound-effect should be pursued. One way of reducing the magnitude of the rebound-effect is by taking energy efficiency measures that go beyond the economic optimum. The problem with this approach however is that it leads to a disruption of the economy.

INTRODUCTION

In his book *The Structure of Scientific Revolutions*, Thomas Kuhn (1970) argues that the evolution of every mature scientific discipline is characterized by a pattern of long periods of normal science and short periods of scientific revolutions. But before the first period of normal science emerges, a situation exists in which different schools of thought compete for dominance. Each school has its own foundation and uses its own body of concepts and techniques. This uncertain period which precedes the first period of normal science ends when one school makes that much progress as to become almost generally accepted. To illustrate this, Kuhn uses the history of the theory of physical optics. Although today's physics students are all taught the same theory which states that light exhibits properties of both waves and particles, this has not always been the case. From the beginning of time until the end of the 17th century, several theories about the nature of light namely existed side by side. It was only in the beginning of the 18th century that Newton's *Opticks* ended this long period of controversy and formed the basis for the first period of normal science on the subject of physical optics.

According to Kuhn, science means research that is characterized by one common scientific approach. This body of accepted theory supplies the foundation for further research and is portrayed in textbooks. These textbooks contain the theory, applications of the theory, and experiments that confirm the validity of the theory. The generally accepted theory of a certain scientific community is called a paradigm by Thomas Kuhn. A paradigm can be defined as a characteristic set of beliefs of preconceptions of a given research tradition. It is composed of four elements. These elements are symbolic generalizations, common values, concrete problem-solving techniques, and a metaphysical component. The study of paradigms prepares a student for the membership of a certain scientific group. Paradigms focus the attention of scientists on particular subjects and they facilitate communication. Because all the members of a particular community learned the same rules and practices, there is agreement on fundamental issues. The result of this is that a certain opposition to change exists in such a scientific community. According to Kuhn, "closely examined, whether historically or in the contemporary laboratory, normal science seems an attempt to force nature into the preformed and relatively inflexible box that the paradigm supplies. No part of the aim of normal science is to call forth new sorts of phenomena; indeed those that will not fit the box are not seen at all. Nor do scientists normally aim to invent new theories, and they are often intolerant of those invented by others. Instead, normal-scientific research is directed to the articulation of those phenomena and theories that the paradigm already supplies (1970, p. 24)" New and unsuspected phenomena however always take place. And when the existing paradigm cannot cope with a new phenomenon, a scientific revolution begins. In this crisis situation, the rules for normal science are loosened in an attempt to fit the new phenomenon in some theoretical concept. Ultimately, every crisis is resolved in one of two ways. Either the old paradigm proves to be able to handle the phenomenon or a new theory emerges as the next paradigm. The latter event is what Kuhn calls a paradigm shift. According to Kuhn, "the transition from a paradigm in crisis to a new one from which a new tradition of normal science can emerge is far from a cumulative process, one achieved by an articulation or extension of the old paradigm. Rather it is a reconstruction of the field from new fundamentals, a reconstruction that changes some of the field's most elementary theoretical generalizations as well as many of its paradigm methods and applications (1970, pp. 84-85)".

Although Kuhn's book is mainly concerned with revolutions in the natural sciences, paradigm shifts have also occurred in the economic science. In the course of time, the outlook of economics has namely changed from mercantilism to physiocracy, and from physiocracy to classical laissez-faire. This laissez-faire was succeeded by Keynesianism, which in turn was followed by the neoclassical growth approach. This neoclassical growth paradigm has been the dominant economic theory of the post-war years.

As a result of the economic growth of the past decades, the impact of human activity on the environment has increased dramatically. The study of this highly complex interaction between man and his physical surroundings calls for an integrative approach. Or as Alvaro Umana put it: "since environmental problems do not fall into any of the compartments of organized knowledge, scientists from many different disciplines have had to study them jointly, and they have pointed to the necessity of interdisciplinary approaches to deal with questions of this kind. This approach is needed because many problems arise due to the interaction among different parts of a system. For example, human economic activity has a significant impact in the global cycling of carbon, nitrogen, phosphorus, and sulphur. In most cases economic forces are an important determinant of the types and levels of pollution, as well as the uses to which the natural environment is put (1981, p. 29)".

In order to allow for the interaction between the economy and the environment, a new paradigm in the economic science is gradually emerging. This new paradigm explicitly treats economic activity, energy use, and the natural environment integrative. The present study on the energy-economy-environment (3-E) interaction in general and the rebound-effect in particular is an exponent of this new paradigm in economics. The rebound-effect can be defined as that part of the initially expected energy savings, resulting from energy efficiency improvements, that is lost because of the 3-E interaction. The study begins with a description in chapter 1 of the concept of economic growth. Chapter 2 outlines the energy-economy-environment interaction. In chapter 3, the relationship between economics and thermodynamics is discussed. Chapter 4 contains three different views on the problem of economic growth in a finite environment. In chapter 5, an introduction into the rebound-effect is given. Chapter 6 deals with the rebound-effect on the consumption-side of the economy. In chapter 7, the rebound-effect is quantified with the MARKAL-MACRO computer model. The rebound-effect is placed in perspective in chapter 8. Finally, chapter 9 presents the conclusions and recommendations that can be drawn from this study.

1. THE MYTH OF ECONOMIC GROWTH

Economic growth is the grand objective;
it is the aim of economic policy as a whole.
Sir Roy Harrod.

1.1 Introduction

In this first chapter, the concept of economic growth is described. In paragraph 1.2, the thought that economic growth can be seen as a solution to all economic problems is outlined. In paragraph 1.3, some ancient theories of economic growth are discussed. Some modern theories of economic growth are outlined in paragraph 1.4. Finally, paragraph 1.5 discusses the attitude of growthmania.

1.2 Economic growth as a solution to all economic problems

Every period in the history of economic thought can be associated with one issue of outstanding importance. According to Jones (1975), the question of free trade versus protectionism was the most important economic topic in the middle of the 19th century. The issue of the gold standard and various currency reform plans were the prominent economic topics at the end of the 19th century. In the beginning of the 20th century, the problem of free trade versus protectionism emerged again. The years between the World Wars were dominated by discussions concerning the big depression. In this respect, Jones argues that the concept of economic growth has become the most important economic topic in the years after the second World War.

Economic growth, seen as an increase in Gross Domestic Product, has become a goal for economic and social policy and economic growth rates have become measures of success for nations throughout the world. The thought is that rapid economic growth offers a solution to all economic ills. It is, for instance, commonly urged that poverty can only be alleviated by a rapid economic expansion that provides more tax revenues for welfare programs. It is also urged that the problem of unemployment can be solved by means of economic growth. It is even suggested that economic growth is necessary in order to have both food and weapons.

The reason behind this glorification of the growth concept is the fact that economic growth postpones the discussion on an equitable distribution of wealth among the population. According to Daly, "growth takes the edge off distributional conflicts. If everyone's absolute share of income is increasing there is a tendency not to fight over relative shares, especially since such fights may interfere with growth and even lead to a lower absolute share for all (1973A, p. 22)". Wallich agreed with Daly: "growth is a substitute for equality of income. So long as there is growth there is hope, and that makes large income differentials tolerable (1972, p. 62)". The concept of economic growth thus enables man to recede into the background controversial issues such as the redistribution of wealth and income. With economic growth, the wealth of everyone can increase. Without it, the increase in wealth of one individual must be taken from another individual. Daly summarized this thought by stating that "the way to have your cake and eat it too is to make it grow (1973B, p. 151)".

1.3 Ancient theories of economic growth

The thought that economic growth is the solution to all sorts of economic problems is not new. In 1776, *An Inquiry into the Nature and Causes of the Wealth of Nations* was published by the Scottish professor of moral philosophy and founder of the classical school of political economy Adam Smith. The classical school thought that economic growth was a desirable activity. Adam Smith claimed that "every individual is continually exerting himself to find the most advantageous employment for whatever capital he can command (1776, p. 421)". Because each individual was the best judge of his own interest, he should therefore be left free to pursue it in his own way. In this way, each individual would not only attain the best situation for himself, but he would also serve the common good. This outcome was obtained when society was organized in harmony with an inherent natural order. According to Smith, human conduct was so carefully balanced that the advantage of one individual could not impede the advantage of all other individuals. It was this belief in the natural balance of human conduct, which led Smith to make his well-know statement regarding the invisible hand: "Each producer intends only his own security; and by directing the industry in such a manner as its produce may be of the greatest value, he intends only his own gain, and he is in this, as in many other cases, led by an invisible hand to promote an end which was no part of his intention. Nor is it always for the worse for society that it was no part of it. By pursuing his own interest he frequently promotes that of society more effectually that when he really intends to promote it (1776, p. 423)". Unrestricted competition would thus lead to the best conditions for economic expansion and, therefore, ultimately to the highest increase in the satisfaction of the wants of all members of the community.

In the long run, however, the classical school of economic thought argued that there were limits to this continued increase in the common welfare. Adam Smith thought that profits tended to fall with the progress of society. The accumulation of wealth would lead to increasing competition among capitalists and this would ultimately reduce profits. In 1798, Thomas Robert Malthus published *The Essay on the Principle of Population as it Affects the future Improvement of Society*. According to Malthus, people's power of producing more food was not as great as their ability to reproduce themselves. He explained this thought by arguing that a population tended to increase in a geometrical progression (2,4,8,16,..), while the supply of food increased only in arithmical progression (2,3,4,5,..). The basis for this theory of population was the law of diminishing returns. According to Turgot (1776), this law implied that a doubling of the capital invested in agriculture would not double the yield. When an increased application of labour to a given piece of land began to produce a less than proportionate increase in yield after some time, more and poorer land would have to be taken into cultivation. This meant an increase in the difficulty of providing food for a growing population, and this would ultimately stop the wheels of progress turning. Another representative of the classical political economy was David Ricardo. He also drew a pessimistic picture of the future in his most important book *On the Principals of Political Economy and Taxation* (1817). Ricardo believed that a progressive decline of the fertility of land was an obstacle to an increasing wealth and population for the future.

1.4 Modern theories of economic growth

Modern neoclassical theories of economic growth are more optimistic in their outlook on the future. The reason for this positivism is the inclusion of substitution possibilities and technical change in their analysis of economic growth. It is often argued that there are no limits to economic growth because it is a function of an unlimited supply of human ideas. According to Julian L. Simon (1981), for example, the problem of the scarcity of fossil fuels and other natural resources will not stop human progress, because there is no natural resource problem. In fact, the opposite is the case. Simon asserts that "the only scarcity of natural resources is in the sense that it costs labour and capital to get them, though we would prefer to get them for free (1981, p. 3)". Simon argues that the cost of natural resources in human labour and their prices relative to wages and other goods, all suggest that natural resources have been becoming less scarce over the long run, right up to the present. If the past is any guide, Simon claims that natural resources will progressively become less scarce and less costly, and will constitute a smaller proportion of our expenses in the future years. Therefore, Simon argues that special efforts need not be made to avoid using these natural resources. Our present use is not at the expense of future generations. Future generations will be faced by no greater economic scarcity than we are now, but instead will have just as large or larger supplies of resources to extract, despite our present use of them. Simon's positivism is based on the fact that the ultimate resource is human knowledge. According to Simon, the stock of knowledge is the main fuel to speed human progress: "resources in their raw form are useful and valuable only when found, understood, gathered together, and harnessed for human needs. The basic ingredient in this process, along with the raw elements, is human knowledge. And we develop knowledge about how to use raw elements for our benefit only in response to our needs. This includes knowledge for finding new resources of raw materials such as copper, for growing new resources such as timber, and for finding new and better ways to satisfy old needs such as successively using iron or aluminum or plastic in place of clay or copper. Such knowledge has a special property: It yields benefit to people other than the ones who develop it, apply it, and try to capture its benefit for themselves. Taken in the large, an increased need for natural resources usually leaves us with a permanently greater capacity to get them, because we gain knowledge in the process. And there is no meaningful physical limit to our capacity to keep growing forever (1981, p. 346)". According to Simon, even a growth in population will probably have positive consequences on the natural resource situation, because more people implies more knowledge being created.

Similar thoughts were expressed by Judith Rees (1990). According to Rees, resource scarcity is not an obstacle to continued economic growth. Rees' argumentation of this view is founded on three interrelated characteristics of the resource system. First, Rees argues that "natural resources are products of the human mind; their limits are not physical, but are set by human demands, institutions, imagination and ingenuity (1990, p.424)". Second, Rees asserts that "the process of technological change is deeply rooted in the economy, and there is little evidence of a slackening rate of innovation (1990, p. 424)". Third, Rees argues that "the economic system in advanced nations has inherent adaptive mechanisms to combat shortages of specific resources when they are needed to sustain the process of growth and capital accumulation. The potential for recycling and conservation, the development of new supply materials, and shifts in the output mix of production makes the resource system highly dynamic

(1990, p. 425)". Rees thus argues that the expanding economic system has built-in mechanisms to maintain the input flow of natural resources that is necessary for its continuance.

A theory of natural resources has thus evolved, which states that natural resource scarcity cannot be a serious long-term problem because the economic system counteracts resource-related problems by substitution and technological change. Empirical justification for this thought seemed to be provided by Barnett and Morse (1963). In *Scarcity and Growth*, one of the most important neoclassical analyses of resource scarcity, they argue that increasing natural resource scarcity would reveal itself in an increasing trend of unit costs of these resources. Therefore, Barnett and Morse collected data on the unit costs of extractive products in the United States from 1870 to the end of the 1950s. These data show that the unit costs of extractive goods have declined during the period under review. From this, Barnett and Morse conclude that natural resources have not become more scarce from 1870 to 1959. According to Barnett and Morse, the reason for the decline in unit costs is technological progress. They argue that "the cumulation of knowledge and technological progress is automatic and self-reproducing in modern economies and obeys a law of increasing returns. Every cost-reducing innovation opens up possibilities of application in so many new directions that the stock of knowledge, far from being depleted by new developments, may even expand geometrically. Technological progress, instead of being the adventitious consequence of lucky and highly improbable discoveries, appears to obey the principle that changes tend to induce further changes in the same direction (1963, p. 236)". Barnett and Morse further argue that "the process of growth thus generates antidotes to a general increase of resource scarcity. Technological and many other advances are causally integrated with the growth process. To the extent that there is an actual or anticipated tendency for energy costs to increase in one industry or another, resource-saving technologies are introduced to avoid the cost increases (1963, p. 240)".

Further support for this thought was given by Robert Solow (1973, 1974A, 1974B). According to Solow, the prices of natural resources have not risen over the past 50 years, compared with the prices of other things. From this, Solow draws the conclusion that "there have so far been counterweights to any progressive impoverishment of deposits (1973, p. 47)". Solow argues that these counterweights are natural resource saving technical progress and the substitution of labour and capital for exhaustible resources. According to Solow, there is in principle no natural resource problem: "the world can, in effect, get along without natural resources, so exhaustion is just an event, not a catastrophe. At some finite cost, production can be freed of dependence on exhaustible resources altogether (1974B, p. 11)". Solow grounds his optimistic outlook on the fact that "in a simple aggregate model of a resource-using economy, one can prove that if the elasticity of substitution between exhaustible resources and the other inputs is unity or bigger, and if the elasticity of output with respect to reproducible capital exceeds the elasticity of output with respect to natural resources, then a constant population can maintain a positive constant level of consumption per head forever (1974B, p. 11)".

1.5 The concept of growthmania

This positivism leads to an almost religious devotion to economic growth, which Mishan (1967) called *growthmania*. Growthmania is the attitude that always gives priority to growth. It is the attitude in economic theory that takes the view that the technological possibilities to produce more and more goods to satisfy people's infinite wants are unlimited. Because the concept of utility cannot be measured, the nation's annual production volume has become the indicator for economic well-being. In this context, Weisskopf remarked that "there is hardly any disagreement among economists, businessman, and politicians about the desirability of a growing GNP. There are differences about the details of national-income accounting and serious differences about the means of accomplishing economic growth. The desirability of overall growth for the individual and for society is hardly ever questioned (1973, p. 241)". An increasing GNP growth rate has thus become a major policy goal. A decline in the rate of growth of the Gross National Product is seen as a disaster.

Bertrand de Jouvenel (1959) called this addiction to unlimited growth *la civilisation de toujours plus*. According to de Jouvenel, mankind nowadays lives in a society of more and more. Our institutions are becoming more and more adapted to growth, and less suited to a stationary state. Our social system rests on the incessant development of new needs. If the ever increasing demand for goods and services would cease, Bertrand de Jouvenel argues that the economy would collapse.

Max Weber (1958) called this attitude of more and more *the spirit of capitalism*. According to Weber, man is dominated by money-making, by acquisition as the ultimate purpose in life. This continued accumulation of wealth has become a goal for its own sake, rather than a means to an end. Economic growth is no longer used by man as a means for the satisfaction of his material needs. According to Weber, capitalism is identical with the pursuit of profit, and forever renewed profit. This profit making in a capitalistic system is essential, since in a capitalistic order of society, an individual enterprise which does not take advantage of its opportunities for profit-making will soon bankrupt. According to Weber, the drive towards the accumulation of wealth can be found in the Protestant ethic. Protestantism supplies the moral energy for the capitalistic entrepreneur in the economic system to keep growing.

Although the call for economic growth is omnipresent in today's society, in ancient times the desirability of an ever expanding economy was questioned. According to Weisskopf, " the concept of growth reflects the value-attitude system of early capitalism before and during the Industrial Revolution. In distinction from previous societies where the pursuit of wealth and hard work were considered as inferior activities and as a curse, left to slaves, women, and inferior social groups, industrial society made the acquisition of wealth morally acceptable and considered it as a moral obligation. Economic thought justified this attitude by assuming that acquisitiveness and the propensity to truck, barter, and exchange in order to increase one's wealth is a basic human propensity. Here, a unique historical phenomenon, the acquisitive attitude, was interpreted as a universal human inclination (1973, p. 242)". Perhaps the attitude of more and more was necessary in the beginning of the Industrial Revolution, when the quality of life was rather low. Today, however, most people in the Western World are rather well-off and much of the economic growth is for luxury items, not for necessities. Moreover, the accompanying excessive demand this growth places on the earth, leads to phenomena such as desertification, acidification, the extinction of plant and animal species, and the greatly accelerated exhaustion of our natural resources. Also controversial topics such as the depletion of the atmospheric ozone layer and the greenhouse effect are related to unlimited economic expansion. All these phenomena are warnings that man needs to pay greater attention to the impact of his activities on the environment. Man can no longer ignore the interaction between the economy and the environment, and must stop the delusion that there are no limits to the growth of the economic system.

2. THE ENERGY-ECONOMY-ENVIRONMENT INTERACTION

All flesh is grass.
Prophet Isaiah.

2.1 Introduction

At the end of the previous chapter, the desirability of taking into account the negative effects of economic activity on man's physical surroundings is discussed. These effects are the result of the existence of a continuous interaction between the energy system, the economy, and the environment. This 3-E (energy-economy-environment) interaction is the subject of this chapter. The chapter begins in paragraph 2.2 with an outline of the paradigm shift in economics that is required for the integration of the energy system, the economy, and the environment. In paragraph 2.3, the history of the 3-E interaction is described. Paragraph 2.4 deals with the scholars who argue that human history is energy-related. In paragraph 2.5, the energy theory of value is discussed.

2.2 A paradigm shift in economics

Since the beginning of this century, the relationship between the economy and the environment has fundamentally changed. At the beginning of this century, man was unable to radically change his physical surroundings. Today, the impact of human activity on the environment is much greater. According to the World Commission on Environment and Development, "the scale of our interventions in nature is increasing and the physical effects of our decisions cut across national frontiers. The growth in economic interaction between nations amplifies the wider consequences of national decisions. Many regions face risks of becoming irreversibly damaged, and this threatens the basis for human progress (1987, p. 27)".

Economics and the environment are thus becoming more and more intertwined. Standard economic thought sometimes ignores this interaction. The view of standard economics can be illustrated with the graph in which in almost every introductory textbook on economics the economic process is portrayed as a self-sustaining, circular flow between production and consumption. An important shortcoming of this model is that it represents the economy as a process that exists in complete isolation from the environment. The economic process however is not an isolated, self-sustaining process. The economy namely continuously alters the environment, and the environment in turn continuously alters the economy. Illustrative in this context are the words by which the French political philosopher Bertrand de Jouvenel characterized modern western man. According to de Jouvenel, "western man tends to count nothing as an expenditure, other than human effort; he does not seem to mind how much mineral matter he wastes and, far worse, how much living matter he destroys. He does not seem to realize at all that human life is a dependent part of an ecosystem of many different forms of life. Because the world is ruled from towns where men are cut off from any form of life other than human, the feeling of belonging to an ecosystem is not revived. This results in a harsh treatment of things upon which we ultimately depend, such as water and trees (1958, pp. 140-141)".

By ignoring the environment, the circular flow model cannot determine whether man's physical surroundings can keep up with an expanding economic system. The danger of this lies in the fact that the environment may become irreversibly affected at a certain point in time. What is needed is a model that will take into account the dependence of the economy on the environment and by doing so will protect us from the dangerous consequences of environmental degradation. In this model, the economy is located within the environment with which it can exchange energy and matter.

For the integration of economics in the environment, a paradigm shift in the economic science is needed. Such a reorientation is required according to Robert Costanza and Herman Daly, who state that "to effect a true synthesis of economics and ecology is the second most important task of our generation, next to avoiding a nuclear war. Without such an integration we will gradually despoil the capacity of the earth to support life (1987, p. 7)". The writers of the Brundtland report share the opinion of Costanza and Daly when they write that "the common theme throughout the strategy for sustainable development is the need to integrate economic and ecological considerations in decision making. They are, after all, integrated in the workings of the real world. This will require a change in attitudes and objectives and in institutional arrangements at every level (1987, p. 62)".
A change in the orientation of economics is also required to make the transition from the cowboy economy of the past to the spaceman economy of the future. In *The Economics of the Coming Spaceship Earth*, Kenneth Boulding (1973) pictures today's economic system as the cowboy economy, the cowboy being symbolic of the illimitable plains and also associated with reckless, exploitative, and violent behaviour. Boulding called the economy of the future the spaceman economy, in which the earth has become a single spaceship, without unlimited reservoirs for extraction and pollution. Boulding argues that the two types of economy can best be distinguished with respect to the value attached to consumption. According to Boulding, "in the cowboy economy, consumption is regarded as a good thing and production likewise; and the success of the economy is measured by the amount of throughput from the factors of production, a part of which, at any rate, is extracted from the reservoirs of raw materials and non-economic objects, and another part of which is output into the reservoirs of pollution (1973, p. 127)". Now one could argue that if the sources and sinks of the earth were infinite, throughput may be used as a means of quantifying the success of an economy. The Gross National Product is a rough measure of this throughput. The earth's surface is however limited. Therefore, Boulding argues that "in the spaceman economy, throughput is by no means a desideratum, and is indeed to be regarded as something to be minimized rather than maximized. The essential measure of the success of the economy is not production and consumption at all, but the nature, extent, quality, and complexity of the total capital stock, including in this the state of the human bodies and minds included in the system. In the spaceman economy, what we are primarily concerned with is stock maintenance, and any technological change which results in the maintenance of a given total stock with a lessened throughput (that is, less production and consumption) is clearly a gain. This idea that both production and consumption are bad things rather than good things is very strange to economists, who have been obsessed with the income-flow concepts to the exclusion, almost, of capital-stock concepts (1973, p. 127)".

2.3 History of the energy-economy-environment interaction

Although standard economic thought sometimes tends to disregard the interaction between man and the physical surroundings on which he is dependent in all his doings, in former days this interaction was not ignored. In 1662, Sir Willam Petty, the earliest and most important English economist who prepared the ground for the classical system, wrote *A Treatise of Taxes and Contributions*. In this work he said that "Labour is the Father and active principle of Wealth, as Lands are the Mother (1662, vol i p. 68)". In the 1750s there developed in France a body of economic theory to which the name physiocracy was given. The term physiocracy, derived from Greek and literally meaning rule of nature, was given to this stream of economic thought after Dupont de Nemours' publication *Physiocratie ou Constitutions essentielles du Gouvernement le plus avantageux au Genre Humain* (1761). The central point in the reasoning of the physiocrats was the search for the surplus which might be available for accumulation. This surplus was called the *produit net*. The physiocrats divided labour into productive and sterile labour. The former consisted only of labour which was capable of creating a surplus, i.e. something over and above the wealth which was consumed in order to be capable of producing. All other labour was sterile. According to the physiocrats, the produit net was a surplus of tangible wealth of physical goods. It was not an abstract term used as an exchange value. Because of this, the physiocrats selected one sector of the economy as the only really productive one. In agriculture, the difference between goods produced and goods consumed was most obvious. The produit net in agriculture namely was the difference between the yield of a piece of land minus the food consumed by the farmer and the amount of seed that was used. It was the most apparent kind of surplus. The physiocrats claimed that no surplus of value could arise in exchange. Industry too created no value, it only transformed objects. Agriculture alone could yield a surplus. This surplus created by agriculture was the basis for Quesnay's famous *Tableau Oeconomique* (1758), in which the circulation of the produit net between the different social classes of society was described. According to the physiocrats, humans had no control over nature and the highest wealth would be attained if economic behaviour was in accordance with nature.

This reliance on what is natural is also emphasized by the classical economists. Classical scholars such as Smith, Ricardo, and Malthus believed in the existence of an inherent natural order, which was superior to any man-made order. Adam Smith, for example, described the supremacy of the natural order and the imperfections of human institutions in his famous *Wealth of Nations* in the following way: "take away artificial preferences and restraints and the obvious and simple system of natural liberty will establish itself. Again that order of things which necessity imposes is promoted by the natural inclinations of man. Human institutions too often thwart these natural inclinations (1776, p. 385)". The classical school of economic thought claimed that society should be organized in harmony with this natural order in order to obtain the optimal conditions for a flourishing economic system.

In the 19th century, the physical basis of economics that was advocated by the physiocrats and classical economists was taken a step further with the discovery of the laws of thermodynamics. According to Gaggioli and Obert, "thermodynamics is the science which deals with energy and its transformations, and with the relationship between the properties of substances. The subject may also be called physical chemistry by the chemist or heat by the physicist (1963, p. 13)". Thermodynamics deals only with the macrostructure of matter and does not concern itself with events happening at the molecular level. Historically, thermodynamics was developed before an understanding of the internal structure of matter was achieved. The science of thermodynamics began with an analysis by the French engineer Sadi Carnot, on the problem of how to build the best and most efficient heat engine.

The way a steam engine ordinarily operates is that water is boiled by the heat from a fire, and the steam so formed expands and pushes a piston, which makes a wheel go around. After that, one could complete the cycle by letting the steam escape into the air. The drawback of this approach is that one has to keep supplying water. It is more efficient to condens the steam, and pump the water back into the boiler, so that it circulates continuously. Heat is thus supplied to the engine and converted into work. In *Reflections on the Motive Power of Heat and on Machines fitted to Develop that Power*, Carnot (1824) wondered what properties substances such as water or alcohol must have to make the best possible engine. This question to which Carnot addressed himself, constituted the beginning of thermodynamics.

The results of thermodynamics are all contained in certain apparently simple statements, called the laws of thermodynamics. The first law concerns the conservation of energy. It states that energy can be changed in form, but it can neither be created nor destroyed. This means that if one form of energy is changed to another form, the same total quantity, expressed in energy equivalents, remains after the transformation. This does not mean that also the quality of energy, i.e. the ability to do work, remains the same. Take for example a waterfall. The water of the Niagara river possesses potential energy. Potential energy is converted to kinetic energy when it is used to set a body in motion. So, when the water of the river starts falling, the potential energy is turned into kinetic energy. After that, this kinetic energy of the water is not lost when the water reaches the pool, but is converted into thermal energy. This is illustrated by the fact that the water at the bottom of the Niagara Falls is one-eight of a degree Celsius warmer than at the top (Thirring, 1958). But although the loss of the kinetic energy of the falling water is exactly compensated by the increase in the thermal energy of the water, the quality of the energy is altered. The ordered motion of the flowing water can be used to do work on the blades of a turbine. With the random motion of the molecules of the water in the pool, the ability to do work is much less. Consequently, the ability to do work has diminished. Another example is a rotating wheel. When a brake is applied to such a wheel, the mechanical energy is converted into thermal energy. So, when work is done against friction, the lost work equals to the heat produced. The reverse however is not possible. It would be very convenient to be able to convert heat into work merely by reversing a process like friction. This is however not possible as is described by the second law of thermodynamics. The second law states that heat cannot completely be transformed into work. Another formulation of this law is that one cannot make heat spontaneously flow from a body of low temperature to one of high temperature.

Since the second law defines quality differences between types of energy, it places distinct restrictions on energy conversions. Although high-quality work can always be completely transformed into low-quality heat, this heat can never be fully reconverted into work. Besides this, the second law pervades a 100% efficient energy transformation, because some of the high-quality energy will be degraded into heat. The warming up of an electric motor when it runs is an example of this.

The economic relevance that thermodynamics brought to light is that man can only use a particular form of energy. The second law teils us that all kinds of energy are gradually transformed into heat, and that this heat becomes so dissipated in the end that man can no longer use it. Energy thus can be divided into available (or free) energy, which can be transformed into work, and unavailable (or bound) energy, which cannot be so transformed.

Although thermodynamics started with the study of the economy of the heat engine, standard economics did not pay much attention to this physics of economic value. Physical and chemical scientists and biologists, however, did realize the relevance of thermodynamics as a basis for the economic process. The biologist and philosopher Herbert Spencer linked the evolutionary process to the laws of thermodynamics, because he thought that the struggle for existence was a struggle for available energy and resources. Spencer stated that "evolution is a change from a less coherent form to a more coherent form, as a result of the dissipation of energy and the integration of matter (1880, p. 337)".

In 1883, Sergei Podolinsky wrote *Menschliche Arbeit und Einheit der Kraft*. In this essay, this Ukranian biologist of Marxist persuasion considered whether a thermodynamic energy analysis could be fitted into the socialistic framework. His aim was to link the labour theory of value with the thermodynamic analysis of the economic process. Podolinsky was quite aware of the importance of thermodynamics for economics. According to Podolinsky, the limits to growth of the economy are not only to be sought in the organization of production, but also and perhaps mainly in the physical laws of thermodynamics.

The German chemist and Nobel Prize winner Wilhelm Ostwald (1907, 1911) argued that the concept and the laws of thermodynamics possess the power to unify and clarify all branches of science. According to Ostwald, "energy is the sole universal generalization (1907, p. 488)". And therefore, Ostwald argues that everything must be expressed in properties and relations of energy. Also matter must be defined in terms of energy. According to Ostwald, "there is no other universal condition among the different domains of scientific phenomena than that of energy. That is to say that whatever may happen physically, it is possible to state an equation every time between the energies that have disappeared and those that newly arrived. There is no other physical quantity to which such a generalization would apply (1907, p. 502)". For this reason, Ostwald argues that the laws of thermodynamics should be the basis for science as well as for everyday life.

In the early 20th century, the radiochemist and Nobel laureate Frederick Soddy (1922,1926) applied the laws of thermodynamics to the economic system. Soddy spent a considerable portion of his career examining the role of energy in the economic system and developing alternative economic theories. According to Soddy, "life derives the whole of its physical energy or power, not from anything self-contained in living matter, and still less from an external deity, but solely from the inanimate world. It is dependent for all the necessities of its physical continuance primarily upon the principles of the steam-engine. The principles and ethics of human law and convention must not run counter to those of thermodynamics (1922, p. 9)"

Soddy argues that the main failure of economics is the confusion of wealth, which is a physical concept, with debt, which is an imaginary concept: "debts are subject to the laws of mathematics rather than physics. Unlike wealth, which is subject to the laws of thermodynamics, debts do not rot with old age and are not consumed in the process of life. On the contrary, they grow at so much per annum, by the well-known mathematical laws of interest (1926, p. 70)". Soddy thus argues that debt grows at compound interest and as a purely mathematical quantity encounters no limits. Wealth grows for a while, but having a physical dimension, its growth eventually reaches a limit. Because the growth rate of wealth is lower than the growth rate of debt, the relationship between the two will cease to exist, and the banking system will collapse. According to Soddy, the economic system could be restored by a 100% reserve requirements system, a policy of maintaining a constant price-level, and freely fluctuating exchange rates.

2.4 Human history is energy-related

Because they have acknowledged the fact that physical laws govern the economic process, some non-conformistic scientists have tried to explain the history of mankind by looking at the environment in general and the energy provided by the environment in particular.

Regarding the relationship between man's history and the environment in general, Georgescu-Roegen (1973,1975A) pointed out that, for instance, the peoples from the steppes of Asia, whose primary economic activity was sheep-raising, began their Great Migration over Europe at the beginning of the first millennium as an ultimate response to the exhaustion of the soil of Central Asia, following a long period of grazing. Also unique civilizations, such as the Maya, vanished from the earth's surface because their people were unable to cope with the degradation of their environment by adequate technical progress. Besides this, Georgescu-Roegen argues that all conflicts between the great powers were not caused by conflicting ideologies. The conflicts rather were a result of the unequal distribution of natural resources.

One of the first to emphasize the role of energy for the development of society was Wilhelm Ostwald (1907,1911). According to Ostwald, all events can be defined as transformations of energy. As a result of this, human civilization can be described by the increasing control of man over energy. Ostwald argues that "the progress of society is characterized by the fact that more and more energy is utilized for human purpose, and that the transformation of the raw energies is attended by an ever-increasing efficiency (1911, p. 870)".

Like Ostwald, Frederick Soddy (1912A,1922,1926) believed that economic progress was made possible because of mankind's increasing use of energy. According to Soddy, "some conception of the part played by energy in human history began to take shape, and progress in the material sphere appeared not so much as a successive mastery over the materials employed for the making of weapons -as the succession of ages of stone, bronze and iron, honoured by tradition- but rather as a successive mastery over the sources of energy in nature, and their subjugation to meet the requirements of life. The whole of the achievements of our civilization -in which it is differentiated from the slow, uncertain progress recorded by history- appeared as due to the mastery over the energy of fire reached with the advent of the steam engine (1926, pp. 27-28)". Soddy thus argues that the progress of our society is a result of the invention of the steam engine. Because of this invention, the slow progress of human development was dramatically speeded up. According to Soddy, "the fact remains that if the supply of energy failed, modern civilization would come to an end as abruptly as does the music of an organ deprived of wind (1912A, p. 251)".

The big Depression of the 1930s was a solid basis for the re-emergence of a movement which started in 1918 as a group called the Technical Alliance. The Alliance conducted surveys of North America in which the economic system was described in joules rather than in monetary terms. The technocracy movement, led by Howard Scott, believed that the depressed economic conditions were a result of the inability of politicians and businessmen to manage the rapidly changing new world. The technocrats proposed to replace the traditional leaders of society by engineers, who had the technical expertise to make the right decisions. The technocrats used energy as a unifying concept for social, political and economic analysis because they assumed that energy was the main determinant with respect to economic and social development. The Technical Alliance measured social change in physical terms: the average number of kilocalories used per capita per day.

Two lucid analyses of the role of energy in human progress were written by W. Fred Cottrell. In 1955, this professor of sociology and government at Miami University wrote *Energy and Society*, and in 1972 he published *Technology, Man, and Progress.* Cottrell argues that there is a relationship between the energy that mankind uses and the kind of society it builds. According to Cottrell, "the amounts and types of energy employed condition man's way of life materially and set somewhat predictable limits on what he can do and on how society will be organized (1955, p. vii)". This thought can be clarified with the example of the Industrial Revolution. Cottrell argues that the Industrial Revolution was caused by the increasing use of the inanimate power of fossil fuels, which enormously increased labour productivity. The result of the Industrial Revolution was an enormous improvement in human civilization. According to Cottrell, an important condition for civilization is the aggregation of large populations in cities, and the differentiation of the inhabitants of these cities in specialized professions. Cottrell asserts that this kind of civilization can only been attained when there exist considerable quantities of surplus energy. The concept of surplus energy refers to the energy available to man in excess of that expended to make the energy available.

Another analyst of the role of energy in human history was the geologist Earl Cook. According to Cook, human progress has depended upon the increasing control of energy for human purpose. In *Man, Energy, Society* (1976), he set forth that centuries ago, the maritime nations Spain and Holland used the energy provided by the wind to achieve world dominance. Cook also argues that the main reason for the remarkably fast resurrection of Europe after the second World War was the utilization of very large quantities of abundantly available and cheap energy.

With the thought that the history of man is energy-related, the current concern that the energy supply system, which is largely based on non-renewable fossil fuels, cannot meet the demands of future generations, can be explained. According to Georgescu-Roegen (1981,1986), history can be considered a sustained series of technical innovations. They took mankind from the cave to the Moon in a few thousand years. But, as curiously as it may seem, only two innovations can be classified as fundamental breakthroughs. The first such invention was the mastery of fire. Georgescu-Roegen argues that "we may now regard fire as one of the most ordinary phenomena, yet that discovery was momentous. For fire is a qualitative energy conversion, namely the conversion of the chemical energy of combustible materials into caloric power. Moreover, fire creates a chain reaction: with just a small flame we can cause a whole forest to burn (1981, p. 71)". Man's control over fire enabled him to warm his home and cook his food. Besides this, it enabled man to smelt metals and bake ceramics. According to Georgescu-Roegen, it is therefore not surprising that the Ancient Greek attributed the bringing of fire to man to the immortal demigod Prometheus. To emphasize the importance of the mastery of fire for human history, Georgescu-Roegen calls it the Promethean Technology 1. The wood age was the result of this Promethean Technology 1.

As a result of the mastery of fire, wood was the main energy carrier for many centuries. The beginning of the Industrial Revolution in Western Europe however marked the end of the wood age. The problem with the Promethean Technology 1 namely was that because of the industrial growth the annual number of trees cut down quickly increased. According to Georgescu-Roegen, this was only natural since any Promethean Technology speeds up the depletion of the fuel which supports it. The result of this cutting down trees was that by the second half of the seventeenth century, forest conservation measures had to be imposed by almost every Western European government. The Promethean Technology 1 was thus running out of its energy carrier.

According to Georgescu-Roegen, an alternative energy carrier, namely coal, was known in Europe since the thirteenth century, but there were two problems associated with the substitution of wood with coal. The first difficulty was that coal burned dirty. The second and most important difficulty was the fact that a mine became quickly flooded when it was exploited, whereas the power sources at that time were not forceful enough to drain the mine. The solution to this problem came from the invention of the heat engine by Thomas Savery and Thomas Newcomen. Georgescu-Roegen calls this invention the Promethean Technology 2. According to Georgescu-Roegen, "the heat engine, exactly like fire, enabled man to perform a new qualitative heat conversion: the conversion of caloric power into motor power. Moreover, also like fire, the heat engine leads to a chain reaction. With just a little coal and a heat engine, more coal and also other minerals can be mined from which several heat engines can be made, which in turn leads to more and more heat engines (1981, P. 72)". The invention of the heat engine thus was a milestone in the history of mankind. This Promethean Technology 2 namely enabled man to switch from an energy supply system based on wood to an energy system based on the much more powerful energy carriers of mineral origin.

According to Georgescu-Roegen, mankind to a large extent still lives in the Promethean Technology 2. But, like all Promethean Technologies, the invention of the heat engine led to an expansion which speeded up the depletion of the fuel which supported the Promethean Technology. And whenever the supporting fuel of any Promethean Technology is almost exhausted, mankind's future depends on whether or not a new Promethean Technology is discovered. Now Georgescu-Roegen argues that there is not yet a new Promethean Technology 3, that will solve the present crisis, as the invention of the heat engine solved that of the wood age. Solar energy, for example, is not yet a viable technology. For solar energy to become the Promethean technology 3, one must be able to produce the convertors of solar radiation with the aid of only the energy converted by them and this is not the case. According to Georgescu-Roegen, the result of all this is that mankind is rapidly approaching an energy crisis, due to the fact that the new Promethean Technology is not yet found.

Weissmahr (1993) shares Georgescu-Roegen's view. He argues that new energy technologies were of major importance in the four waves of economic expansion over the last two centuries. Each expansion, which lasted about thirty years, was based on a new energy technology and was accompanied by a new infrastructure and new industries necessary for the application and diffusion of these new technologies. From 1790 till 1820, this energy technology was the power of running water and from 1845 till 1873 it was steam power. The third wave from 1895 till 1929 can be associated with electricity and during the fourth wave from 1945 till 1973 oil was the dominant energy technology. Weissmahr believes that, at present, the end of the fourth wave is approaching and there still is no new viable energy technology in sight.

2.5 An energy theory of value

From claiming that human history is energy-related, it is a relatively small step to claiming that the value of a good is determined by the amount of energy that is contained in it. One of the first advocates of the energy is value theory is L. Winiarski, who stated that "gold is the incarnation of socio-biological energy (1900, p. 256)". Winiarski suggests that gold is a standard for the amount of energy that is dissipate in an economic system. Ernest Solvay (1902) was a contemporary of Winiarski. Solvay argued that there is an equivalence between the value of an object and the amount of energy that it represents. Frederick Soddy (1912B,1922,1926) agreed with Solvay. According to Soddy, "as far as human affairs go, wealth and available energy are synonymous, and the poverty or affluence of this planet are primarily measured only by the death or abundance of the supply of energy available for its life and work (1912B, p. 187)". Soddy argues that wealth has its origin in useful or available energy. This implies that every time an amount of wealth is created, an amount of energy is dissipated. According to Soddy, this seems reasonable, since wealth cannot be created out of nothing.

More recently, Howard T. Odum (1971,1974,1976,1977) argued that flows of energy are the source of all economic value. According to Odum, "human economic systems can bring in materials and fuels to support populations and cultures. However, human beings are only a small part of the great biosphere of oceans, atmosphere, mountains, valleys, land, rivers, forests, and ecological components. Ultimately, it is not just human beings and their money that determine what is important; it is all the world's energy. It is therefore a mistake to measure everything in money. Instead, energy should be used as the measure, since only in this way we can account for the contribution of nature (1976, p. 42)". According to Odum, there is a relationship between energy and money which is called the counter-current systems relationship. This relationship implies that in money-based societies, money flows proportionate but in opposite direction to the energy required to produce the purchased goods and services. Odum also argues that our society is very sensitive to changes in inflowing energies: "if all energy sources are cut off from the economic system, the dollar loses value until it buys nothing, since there is no energy inflowing to produce goods and services once storages in the system have been exhausted (1977, p. 182)".

Support for Odum's theory was given by Robert Costanza (1980,1981). According to Costanza, energy flows are the main concern of energy analysis, and an important part of this energy analysis is the quantification of the embodied energy of goods and services. For example, the energy embodied in a dishwasher is the sum of the energy used to manufacture the dishwasher and all the energy consumed indirectly to produce the other inputs of manufacturing, such as the steel and plastic needed for this commodity. A systematic procedure to calculate the energy requirements, is the input-output (I-O) analysis. For his investigation, Costanza (1981) used a 90 sector energy input-output model maintained by the Energy Research Group at the University of Illinois. According to Costanza, the regression analysis results for total (direct plus indirect) energy consumption versus total dollar output per sector indicate that a significant (r^2 value of 0.99) relationship exists between embodied energy and dollar output. The only exceptions to this rule are the primary input sectors. According to Costanza, the energy theory of value is rejected by mainstream economists, because of the fact that energy is only one of a number of primary inputs to the production process. But Costanza argues that "from a physical perspective, the earth has only one principal net input, namely solar radiation. Although very small amounts of meteoric matter also enter the earth's atmosphere, and deep residual heat may continue to drive crustal movements, there is no stream of spacecraft carrying workers, government mandates, and capital structures onto the planet. Thus, practically everything on the earth can be considered to be a direct or indirect product of past and present solar energy. The same cannot be said for the other primary factors (1980, p. 1219)". According to Costanza, an energy theory of value is really a production theory with all production factors costs carried back to the solar energy input.

3. THE ENTROPY LAW AND THE ECONOMIC PROCESS

Thermodynamics is the only physical theory of universal content that will never be overthrown. That is, heat will never pass by itself from the colder condenser to the hotter boiler. If a refrigerator moves heat to hotter spaces, it is only because far more heat passes from some boiler to a condenser elsewhere.
Albert Einstein.

3.1 Introduction

In the preceding chapter, the energy-economy-environment interaction has been outlined. An important aspect of this interaction is the possibly negative impact of human activity on the environment. When taking into account this negative effect, limits emerge on the rate at which the economic system can expand. The concept of entropy can be used to clarify this finiteness. Therefore, the relationship between the entropy law and the economic process is the subject of this chapter. In paragraph 3.2, the mechanical foundation of the economic discipline is discussed. In paragraph 3.3, the second law of thermodynamics (the entropy law) is described. The similarities between entropy and order are discussed in paragraph 3.4. Paragraph 3.5 deals with the earth's finite amount of low entropy. Paragraph 3.6 focuses on the limited substitution possibilities between the production factors in an economy. Finally, paragraph 3.7 is concerned with the fact that the economic process cannot be reduced to thermodynamic equations.

3.2 Economics and mechanics

Just like any other scientist in the first half of the nineteenth century, the leaders of the economic discipline of that time were impressed by the spectacular successes of the science of mechanics in astronomy. The aim of these leaders therefore was to build an economic science "after the mechanics of utility and self-interest (1879, p. 23)", as W. Stanley Jevons called it. And although the economic science has undergone profound changes since, the mechanistic view is still at the basis of economic thought. According to Georgescu-Roegen, "modern economists have developed, without a thought, their discipline on the mechanistic tracks laid out by their forefathers, fiercely fighting any suggestion that economics may be conceived otherwise than as a sister science of mechanics (1975A, pp. 347-348)". The reason for this worship of mechanics is that economists wanted to be able to predict the future state of the economy, just like Urbain Leverrier and John Couch Adams discovered Neptune. Leverrier and Adams discovered this planet, not by searching the sky, but by determining its position by calculations on a piece of paper.

The three key concepts in mechanics are mass, speed, and position. With these concepts, any process can be described. In mechanics, no qualitative but only quantitative differences in the total (kinetic plus potential) amount of energy resulting from a process are considered. According to Georgescu-Roegen, the viewing of the economic process as a sister science of mechanics results in the thought that a constant flow can arise from an unchanging structure. This thought was clearly expressed by A. C. Pigou, who stated that "in a stationary state, factors of production are stocks, unchanging in amount, out of which emerges a continuous flow of real income (1935, p. 19)".

Because mechanics recognizes no qualitative change but only quantitative change, Georgescu-Roegen (1975A) argues that any economic activity modeled after a mechanical process may be reversed, just like a pendulum. Also, no laws of mechanics would have been violated if the direction of time was reversed and the earth was set in motion in the opposite direction. According to Georgescu-Roegen, actual phenomena in the real world, however, do not follow this story. Actual phenomena move in a definite direction and involve qualitative change. Even the money in the circular flow model cannot circulate back and forth within the economic process, because coins and banknotes ultimately become worn out and their stock must be replenished from external sources. This is the lesson of the second law of thermodynamics, the entropy law. Thermodynamics has changed the mechanical outlook of traditional physics. Now, it should also alter mainstream modern economics that is still based on the laws of mechanics.

3.3 The entropy law

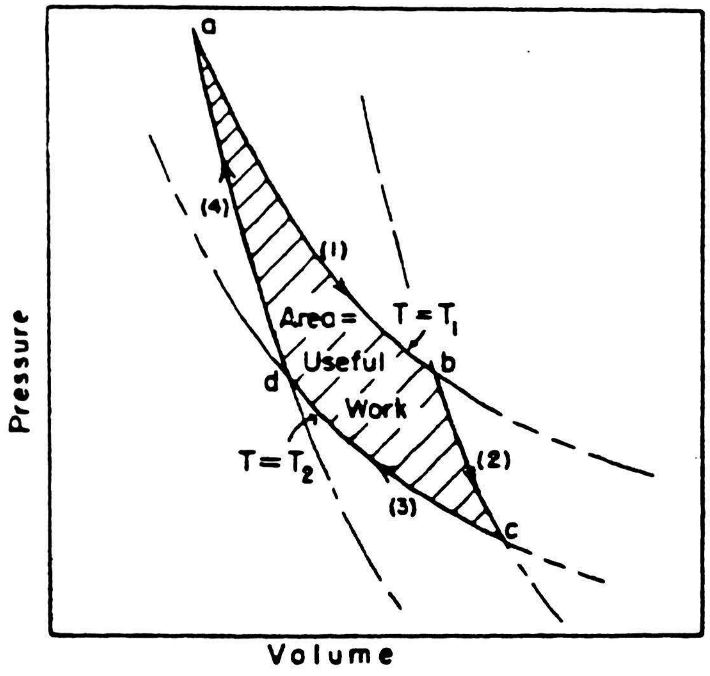

Figure 3.1 *The Carnot cycle (Feynman, 1966)*

The second law of thermodynamics states that a process whose only net result is to take heat from a reservoir and convert it into work is impossible, or equivalently, that one cannot make heat flow by itself from a cold to a hot object. It is also possible to state this law in another way. To illustrate this alternative formulation, consider a heat engine that has a boiler at temperature T_1. A certain heat Q_1 is taken from this boiler, the heat engine does some work W, and it then delivers some heat Q_2 into a condenser at another temperature T_2. And suppose this heat engine is an ideal heat engine, a so called reversible heat engine. In such a reversible heat engine every process is reversible, which means that, by infinitesimal changes, we can make the engine go in the opposite direction. This is only achieved when nowhere in the engine there is friction and nowhere in the engine there is a place where the heat of the reservoirs is in direct contact with something definitely cooler or warmer. An example of an engine cycle in which all processes are reversible, is the Carnot cycle. This cycle is illustrated in figure 3.1.

In the first step of the Carnot cycle, a gas in a cylinder with a frictionless piston expands isothermally at temperature T_1, absorbing the heat Q_1. The second step involves an adiabatic expansion, in which the temperature drops from T_1 to T_2. In step three, the gas is isothermally compressed at temperature T_2, delivering the heat Q_2. The cycle is completed in step 4, the adiabatic compression. During this compression, the temperature rises from T_2 back to T_1. So, the gas is carried around a complete cycle, and during this cycle the heat Q_1 is put in the engine at temperature T_1 and the heat Q_2 is removed from the engine at temperature T_2. Now, according to Carnot, the quotient of Q_1 and T_1 is equal to the quotient of Q_2 and T_2.

$$\frac{Q_1}{T_1} = \frac{Q_2}{T_2} \tag{3.1}$$

This means that if there is a single engine running between T_1 and T_2, then the result of an analysis is that Q_1 is to T_1 as Q_2 is to T_2, if the engine absorbs the energy Q_1 at temperature T_1, and delivers the energy Q_2 at temperature T_2. Whenever the engine is reversible, this relationship must follow. All this implies that in any reversible process as much Q/T is absorbed as is liberated. There is no gain or loss of Q/T. In classical thermodynamics this Q/T is called entropy, and we can say that there is no net change in entropy in a reversible cycle. The term entropy comes from Rudolf Clausius, who derived it from a Greek word meaning transformation or evolution. The symbol that usually represents entropy is S, and it is numerically equal to the heat Q delivered to a 1-degree reservoir. The entropy S is measured in joules per degree. So, if we have a reversible cycle, the total entropy of everything is not changed, because the heat Q_1 absorbed at temperature T_1 and the heat Q_2 delivered at temperature T_2 correspond to equal but opposite changes in entropy. And therefore the net change in entropy in zero. This law may look like the law of the conservation of energy, but it is not, because the rule only applies to reversible cycles.

If irreversible events are included, there is no law of conservation of entropy. An example of an irreversible event is this: If two objects with different temperatures T_1 and T_2 are put together, a certain amount of heat will flow from one to the other by itself. Suppose, for example, a hot stone is put in cold water. Then a certain heat ΔQ is transferred from the stone to the water. As a result of this, the entropy of the hot stone decreases by $\Delta Q/T_1$ and the entropy of the cold water increases by $\Delta Q/T_2$. Because the term **ΔQ** is positive and T1 is greater than T2, the change in entropy of the whole world is positive and equals the difference of the two fractions:

$$\Delta S = \frac{\Delta Q}{T_2} - \frac{\Delta Q}{T_1} \qquad (3.2)$$

This example can be generalized into the following proposition: in any process that is irreversible, the entropy of the whole world is increased. Only in reversible processes does the entropy remain constant. Since no process is absolutely reversible, there is always a gain in entropy.
With this foreknowledge, the two laws of thermodynamics can be stated as:

> First law of thermodynamics: the energy of the universe is always constant.
>
> Second law of thermodynamics: the entropy of the universe is always increasing.

Because the second law, which is often referred to as the entropy law, states that the entropy continuously increases, it governs the irreversibility of processes. The concept of irreversibility can be explained with a log of wood. When this log is burned, it can never be "unburned". The burning of a log of wood is thus an irreversible process. The increase in the entropy of the universe is irreversible as well.

3.4 Entropy and order

In the classical thermodynamics of Carnot and Clausius, the entropy concept is used to describe systems on a macroscopic level. Because of the abstract definition of entropy in the classical thermodynamics, the entropy concept has no real meaning. Everybody knows what is meant by the physical variables of mass, speed, and temperature. The entropy concept, however, only possesses a purely theoretical meaning. However useful entropy may be for thermodynamics, it has no real descriptive meaning.

This changed with the statistical mechanics approach to thermodynamics. This approach describes the behaviour of ideal gases on the microscopic level of atoms and molecules based on probability considerations. Take for example the diffusion of two gases. For this purpose, a container filled with an ideal gas 1 is considered. This container is connected to another container filled with an ideal gas 2 via a closed valve. Let the volume of the first container be V_1 and the volume of the second container be V_2. Also let the two containers be isolated. If the valve is opened, the gases diffuse and the result is a mixture of these two gases. The entropy change resulting from this process can be calculated with the following formula:

$$\Delta S = R \cdot \left(N_1 \cdot \ln \frac{V_1 + V_2}{V_1} + N_2 \cdot \ln \frac{V_1 + V_2}{V_2} \right) > 0 \qquad (3.3)$$

In this formula, the number of mols of the gas of type 1 and 2 are denoted by N_1 and N_2. The universal gas constant is denoted by R, and the volumes of the containers 1 and 2 are represented by V_1 and V_2. This formula shows that the diffusion of gases is accompanied by an increase in entropy. In the initial state of the process, in which both of the gases are separated by the valve between the two containers, there is a higher degree of order than in the final state, in which the two gases are mixed. The increase in entropy is thus accompanied by an increase in the disorder of the system. Therefore Ludwig Boltzmann argued that the concept of entropy can be used to describe the order of a system. According to Boltzmann, the statistical definition of entropy can be expressed by the following equation:

$$S = k \cdot \log D \tag{3.4}$$

In this equation, the symbol k represents the so-called Boltzmann constant ($1.38 * 10^{-23}$ Joule per Kelvin), and D represents a quantitative measure of the disorder of a system. Equation (3.4) can be illustrated with a lump of sugar that is put in a cup of tea. The spreading out of the sugar over the water in the cup results in an increase in disorder, and hence in an increase in entropy.

This way of looking at entropy was taken a step further by the information theory approach to thermodynamics. In this approach, entropy is a measure of the information contained in a message. The initiator of this movement was Claude Shannon. In his research on the capacity of communication channels, Shannon (1949) showed that one can define a general measure of the information contained in a message consisting of symbols Ei. According to Shannon, the following namely holds true:

$$I = - \sum P_i \cdot \log P_i \tag{3.5}$$

In this equation, i denotes the number of symbols and Pi denotes the inherent probability of recording symbol Ei. According to Shannon, this amount of information I can be linked to entropy by the following equation:

$$S = - k \cdot I \tag{3.6}$$

Consequently, the negative of entropy and information are equivalents. Besides Shannon, the equivalence between information and the entropy concept was also expressed by Brillouin (1956) and Jaynes (1957).

The statistical mechanics and information concepts of entropy thus clarify the implications of the second law of thermodynamics. The entropy of a system is a measure of the randomness of the system. The greater the degree of disorder, the higher is the entropy of the system. A briquette of coal contains an amount of ordered resources of low entropy. When this coal is burned, a part of the energy content of this energy carrier is converted into work, and the rest is converted into disordered waste heat. This heat no longer has the capability to do work because of its low temperature.

3.5 A finite amount of low entropy

Especially after the enormous progress of the past decades, standard neoclassical economists' faith in science and technology to refute any known law has become a widespread belief. And it is true that economics apparently eludes the entropy law because living organisms, machines, and banknotes remain almost unchanged over short periods of time. Entropic degradation, however, pertains to long-run forces. Because these forces act extremely slowly, they are often ignored. Man is only interested in today and tomorrow, not in what happens a thousand of years from now. Yet it is the slow-acting forces of entropic decay that are the most harmful in general. According to Nicholas Georgescu-Roegen, the entropy law is the major link between the economy and the environment. The main idea of his book *The Entropy Law and the Economic Process* is that the entropy concept is at the basis of all economic life. Georgescu-Roegen states that "whatever the economic expertise of other scientists, economists could not fare continuously well in their own field without some solid understanding of the entropy law and its consequences (1971, p. 352)".

Another explicit treatment of the importance of the concept of entropy for man was formulated by Erwin Schrödinger. In his famous writing *What is Life ?*, Schrödinger (1955) wondered what keeps mankind from death. Schrödinger argues that the obvious answer is by eating and drinking. The technical term for this is metabolism, which literally means change or exchange. So, organisms exchange something through which decay is postponed. After dismissing materials and energy, Schrödinger argues that low entropy is what keeps us from death: "every process that is going on in nature means an increase of the entropy of that part of the world where it is going on. A living organism continually increases its entropy and consequently tends to approach the dangerous state of maximum entropy, which is death. It can only keep aloof from it, i.e. alive, by continuously drawing from its environment negative (= low) entropy (1955, p. 72)".

Erwin Schrödinger thus points out that an organism needs low entropy which it sucks from the environment and degrades into high entropy. In this context, also the economic process can be described as a system in which inputs enter in a condition of low entropy (their potential usefulness is at a high level) and outputs pass out in a condition of high entropy (a low level of potential usefulness). Besides our biological life, also our whole economic life thus feeds on low entropy. The second law of thermodynamics states that any irreversible process is accompanied by an increase in entropy. Because of this entropy law, the irreversible economic processes transform low entropy inputs into high entropy wastes. This makes the entropy law, for example, the source behind the economic scarcity of energy. Were it not for this law, the energy of a barrel of oil could be used over and over again, by first transforming the energy content of this energy carrier into heat, and after that transforming this heat into work, and finally transforming the work back into heat.

Low entropy matter and energy cannot be created and can only be used once. Consequently, the sources of low entropy that mankind has at its disposal are continuously used up. According to Georgescu-Roegen (1971,1975A), there are three sources of low entropy that man can use. These sources are the energy that can be liberated from our fossil fuel reserves, the free energy received from the sun, and the material structures stored in the bowels of the earth. Now, one could argue that the technologies of the exploration and extraction of fossil fuels have continuously improved over the past 200 years. Besides this, one could say that the sun will continue to shine for millions of years. So, there is no need to worry about the supply of low entropy energy. A similar optimism can be displayed for the supply of low entropy materials. One could argue that it is foolish to think that we can run out of matter, since the whole earth is made out of matter.

The problem, however, is that the high-quality fossil fuel resources have mostly been extracted already, and that new discoveries tend to be smaller, deeper, less accessible, and therefore generally more difficult to recover. As a result of this, further technological improvements in exploration and extraction will ultimately become more costly to achieve. Moreover, at a certain point in time, the amount of energy required to mine a ton of fossil fuels will become larger than the energy content of that ton of fossil fuels. Besides this, also the direct utilization of solar energy for human purpose is not free of troubles. The reason for this is that there not yet exists an energetically viable technology for using direct solar energy. The drawback of solar energy in comparison with energy contained in energy carriers, such as oil and natural gas, is that the last are available in a concentrated form. Solar radiation, however, reaches the earth with an extreme low intensity. As a result of this, the direct use of solar energy in some appreciable amount would require a disproportionate amount of matter and energy. In addition to the critical remarks regarding the unlimited supply of low entropy energy, one can also make objection to the thought that the supply of low entropy matter is infinite. Although the earth is made of matter, this matter is not all of the kind that can be used by man to produce commodities, such as cars and dishwashers. The reason for this is that for the production of those commodities, both accessible and available matter is needed. In theory, it would be possible to manufacture commodities out of the metals that are dispersed in low concentrations in the water of the oceans. To collect these metals, however, would require so much low entropy resources that this is not a realistic option. So, besides the amount of low entropy energy, also the amount of low entropy matter is finite.

3.6 Limits to substitution

Although there is only a limited amount of low entropy matter-energy, the thought that the economy can maintain its historical growth rates is omnipresent. The mechanism by which unlimited growth with a limited supply of low entropy matter and energy can continue is the permanent substitution of low entropy matter-energy with capital and labour. This thought can be illustrated with figure 3.2. In this figure, the substitution possibilities between a capital-labour aggregate and energy are shown.

The isoquant in figure 3.2 represents alternative combinations of capital, labour, and energy to produce the same output. Consider for example a heat engine with a certain efficiency η_1. With some capital expenditure, the efficiency of this engine can be increased from η_1 to η_2. As a result of this capital expenditure, the energy required to deliver the same amount of service is decreased. This substitution of energy with capital can be represented in figure 3.2 by a shift from point 1 to point 2. The same shift is also obtained if the economic output is produced with more labour and less energy.

In figure 3.2, the substitution of energy with capital or labour can continue until the energy required for the production of the output approaches to zero. In reality, however, this is impossible. The reason for this is that the second law of thermodynamics precludes the continued substitution between energy and other inputs.

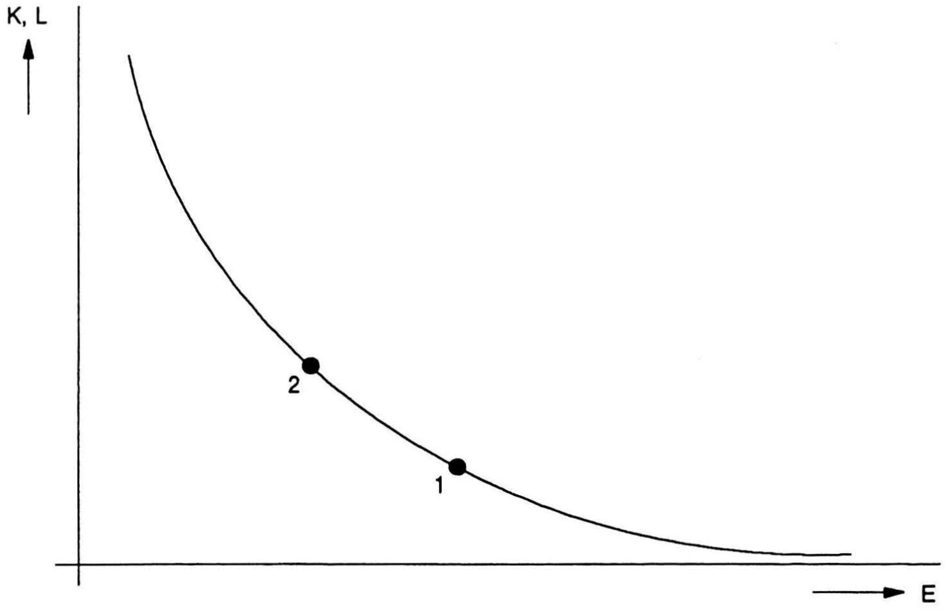

Figure 3.2 *Substitution graph*

The energy efficiency of an engine can be defined as the quotient of the useful work delivered by the engine and the total energy input supplied to the engine. Now Carnot argues that the maximum energy efficiency of work that can be obtained by a heat engine from a temperature difference is proportionate only to the ratio between the temperatures. It can be shown that the theoretical maximum efficiency Emax of a heat engine can be calculated with the temperature of the heat source T_1 (the boiler temperature) and the temperature of the heat sink T_2 in the following way:

$$E_{max} = \frac{(T_1 - T_2)}{T_1} \tag{3.7}$$

In this formula, the temperatures T_1 and T_2 are in degrees Kelvin. Emax is known as the Carnot efficiency of an energy transformation process. Also other cycles such as the Rankine cycle have theoretical maximum efficiencies. The maximum efficiency of a fossil fuel electric power plant, for example, is around 75%. The second law of thermodynamics thus sets upper limits to the efficiency of economic processes such as power generation. Therefore, besides the exact sciences, the entropy law also influences everyday economic life. To include the entropy law in the substitution graph, the isoquant of figure 3.2 must be shifted to the right. This is illustrated in figure 3.3.

In this figure, Emin represents the energy requirement in the situation in which the process operates with a thermodynamically theoretical maximum efficiency η_{max}.

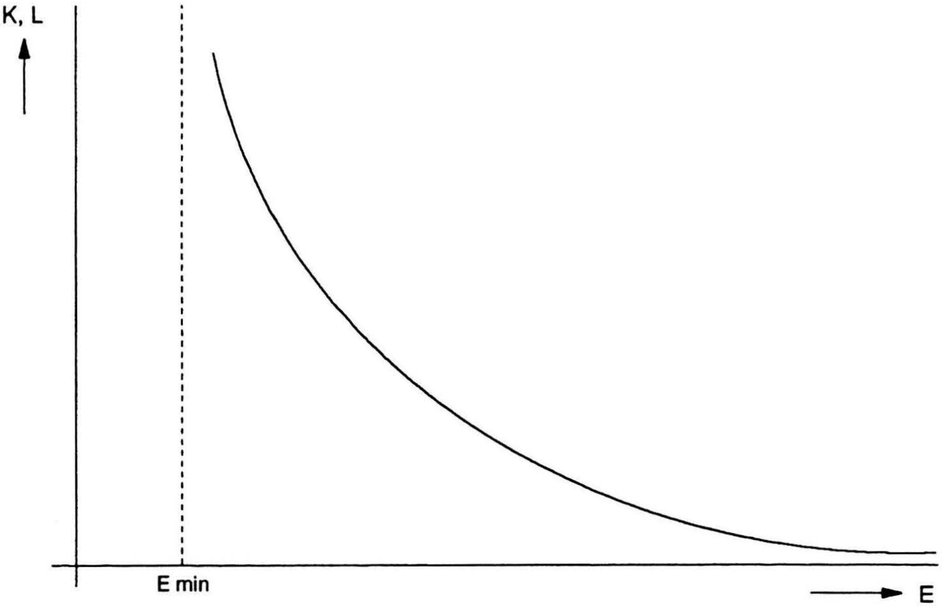

Figure 3.3 *Substitution graph and thermodynamics*

Because of the entropy law, there are upper limits to the substitution possibilities between low entropy resources and the labour-capital aggregate. But suppose that the continued substitution of low entropy energy and matter with capital and labour were possible, this would however not necessarily imply that as a result of this substitution, the total amount of energy and matter were proportionately diminished. The substitution strategy assumes that capital, labour, energy, and matter are independent inputs to production, which means that the availability of capital and labour does not depend on the supply of low entropy energy and matter. In reality, however, the factors of production are not independent of each other. Consider for example the factor labour. An employee not only needs the energy that is contained in his food. He also needs clothes and a home. Besides the energy needed for subsistence, an employee in today's society also has a need for an automobile to visit customers and magazine subscriptions to keep up with the developments in his profession. Consequently, the energy contained in cars and magazines is also necessary to enable the worker to perform well.

This also applies to the production factor capital. There is an energy component to the factor capital as well, as can be clarified with the example of a heat recovery system. In such a system, the supply air from the outside is heated by the exhaust air from the inside. This process takes place in a heat exchanger. The efficiency of such a heat exchanger can be defined as the ratio of the heat actually transferred and the theoretically attainable maximum heat transfer. When capital is expended to increase the surface of such a heat exchanger, a larger fraction of the available heat can be recovered. Consequently, the energy efficiency has improved. However, this process of minimizing the amount of energy by means of increasing the heat exchanging surface cannot go on forever. The reason for this is that a heat exchanger must be manufactured. When the size of the heat exchanger is increased, the amount of energy and matter required to produce the piece of equipment increases proportionately. At a certain point, the amount of energy required to enlarge the heat exchanger by a certain amount becomes greater than the additional energy that can be recovered by the increase in surface. Therefore, increasing the surface of a heat exchanger beyond some point will not reduce but rather increase the total amount of energy.

Another example concerns insulation. Increasing the insulation level of a dwelling leads to a lower annual energy demand for space heating. However, the insulation materials required for this purpose must be manufactured. In this manufacturing process, an amount of energy is used. From the trade-off between the energy used during the manufacturing process and saved during the use of the insulation, an optimal environmental thickness (Bowdidge, 1990) can be determined. This optimal environmental insulation thickness can be defined as the thickness of insulation beyond which no further reduction in the total amount of energy required for space heating and manufacturing of the insulation material can be achieved. The optimal environmental insulation thickness thus denotes the maximum potential for energy savings through insulation regardless of the amount of capital expenditure. This implies that expending capital to increase the insulation level of a building beyond the optimal environmental insulation thickness will have counterproductive effects.

3.7 No analogy between economics and thermodynamics

The concept of entropy thus can be used to explain the fact that the economic system is subject to certain laws of physics. This however does not imply that all economic processes can be reduced to thermodynamics. It is wrong to degrade the economic science to a system of physical formulae. An example of such an approach is given by John Bryant, who developed a formal analogy between thermodynamic equations and economic phenomena. According to Bryant (1985), the economic system can be defined in terms of thermodynamic and other physical laws. He argues that it is possible to find equivalent properties in the economy for the thermodynamic concepts of temperature and entropy. Bryant further argues that the trade cycles in the economy can be related in some way to the cycles used by physicists and engineers to describe the working of heat engines. Bryant also claims that physical equivalents to the concept of inflation can be determined.

The problem with Bryant's thermodynamic approach to economics is that it is an abstract exercise which has no real meaning. The economic science namely has properties that cannot be explained by natural laws. The same criticism applies to the energy theory of value. Although energy is a very important component in the production of goods and services, an incomplete picture of the economic process is drawn if economic value is equated with the energy content of a good or service. Commodities are more than embodied energy. Also the thought that human progress is merely a result of the increasing use of energy for human purpose is too one-sided. Energy is not the only factor in the evolution of mankind.

Because human conduct is unpredictable, no law of physics can ever accurately explain economic processes. No physical law, for example, can explain why a particular individual purchases brand X instead of brand Y. The laws of physics, however, do set limits to our economic possibilities. Economics is to a more or less extent constrained by the energy laws.

4. SOLUTIONS TO THE PROBLEM OF ECONOMIC GROWTH IN A FINITE ENVIRONMENT

Ideas are everywhere, but knowledge is rare.
T. Sowell.

4.1 Introduction

In chapter 3, the entropy law has been used to clarify the finiteness of man's physical surroundings. When this finiteness is taken into account, three ways of thinking about economic growth can be distinguished. In paragraph 4.2, an optimistic view is given by the World Commission on Environment and Development, the writers of the well-known Brundtland report. They advocate a forceful economic growth, that does however consider the effects of this continued expansion on the ecosystem. A less optimistic picture is sketched by Herman Daly in paragraph 4.3. Daly argues that economic growth must cease in order to prevent it to cause irreversible damage to the environment. In paragraph 4.4, a rather pessimistic view is given by Nicholas Georgescu-Roegen, who states that the termination of economic growth is not sufficient. Georgescu-Roegen claims that the current growth trend must be reversed into a negative growth trend.

4.2 The solution of the World Commission on Environment and Development

What is needed is a new era of economic growth; growth that is forceful and at the same time socially and environmentally sustainable.
Gro Harlem Brundtland.

Since the beginning of the 1950s, economic growth has vastly improved human conditions in large parts of the world. In those parts, infant mortality has been falling, human life expectancy has been increasing, the proportion of illiterates has been declining, and new food production techniques have caused annual yields to increase. To achieve this improved quality of life, industrial production has grown enormously over the past decades. According to Rostow (1978), the annual increase in industrial production today is as large as the total industrial production in Europe in the 1930s. And because of this growth in production, also the use of natural resources has grown tremendously. The earth is thus changing profoundly. And this growth has not ended yet. Population will probably more than double before stabilizing, thereby increasing economic activity even further.

This expansion has a fundamental impact upon the environment, because many of the goods and services that have caused the economy to grow are material- and energy-intensive. The negative effect of human economic activity on the environment can be illustrated by the emergence of phenomena, such as acid rain, the depletion of the ozone layer, and the greenhouse effect. But despite this explosive economic growth, the number of people without food, clothes, and a decent home is increasing. The least developed countries are becoming poorer and poorer. This also leads to environmental degradation. An illustration of the way in which economics and ecology act as antagonists is the fact that especially the poor African nations overexploit the environment in order to pay their Western World creditors. So, economic growth increasingly disrupts ecological processes, but the differences between rich and poor nations are becoming bigger, not smaller. To reverse this process, governments must realize that economic development issues cannot be decoupled from environmental issues. The only possible solution to the economic development problem and the environmental problem is to treat them integrative.

This thought was behind the establishment in 1983 of the World Commission on Environment and Development by the General Assembly of the United Nations. The World Commission was connected with, but independent of the UN and national governments. The objectives of the Commission, presided by Gro Harlem Brundtland, were "to examine the critical environment and development issues and to formulate realistic proposals for dealing with them, to propose new forms of international co-operation on these issues that will influence policies and events in the direction of needed changes, and to raise the levels of understanding and commitment to actions of individuals, voluntary organizations, businesses, institutes, and governments (1987, pp. 3-4)". The results and recommendations of the Commission were formulated in *Our Common Future* (1987). According to the writers of this so-called Brundtland report, the destructive interaction of poverty and environmental degradation is a waste of opportunities and resources. As a solution to this problem, the writers advocate a new era of economic growth, in order to avert global catastrophes. But although the Commission's overall assessment is that the international growth must be speeded up, they stress that the environmental constraints must be respected.

Economic growth is of course accompanied by changes in the environment. A forest, for example, may be lost in one part of the ecosystem and gained elsewhere. The writers of the Brundtland report argue that this is not necessarily wrong if system-wide effects such as soil erosion have been considered. When the rate of use of renewable resources like forests is within the limits of regeneration, the consumption of these resources causes no problems. For non-renewable resources such as fossil fuels and minerals, the story lies different because their use reduces the stock. This means that the use of these elements could lead to the process of industrial growth running into material resource constraints. But, according to the World Commission, this does not imply that these resources should not be used. Although non-renewable resources are by definition exhaustible, studies such as those made by Barnett and Morse (1963), Goeller and Weinberg (1978), and the OECD (1979) suggest that few minerals are likely to run out in the near future and that substitutes are available. Therefore, the World Commission argues that the use of non-renewable resources will not become a problem now and in the future if the scarcity of a resource, the availability of technologies for minimizing depletion, and the possibilities for substitution are taken into account.

The most important conclusion of the World Commission on Environment and Development is that a forceful growth that does take into account nature's carrying capacity is needed. This growth must be "a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional changes are all in harmony and enhance both current and future potential to meet human aspirations (1987, p. 46)". This process is called sustainable development. Sustainable development can be defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs (1987, p. 43)".

An important part of this definition is the concept of needs, especially the needs of those who are not so well of. According to the World Commission, priority in the development process should be given to the needs of the world's poor: "the essential needs of vast numbers of people in developing countries for food, clothing, shelter, and jobs are not being met and beyond these basic needs these people have legitimate aspirations for an improved quality of life. A world in which poverty and inequity are endemic will always be prone to ecological and other crises. Sustainable development requires meeting the basic needs of all and giving everyone the opportunity to satisfy their aspirations for a better life (1987, pp. 43-44)". Meeting human needs and aspirations depends upon a forceful economic development, particularly in the third world. This development must be sustainable. The writers of the Brundtland report argue that sustainable development implies that there are limits to the expansion of the economic system. These limits are a result of the way in which society is organized and the state of science and technology. However, these limits are not fixed, so that economic growth remains possible.

When the limits that are imposed by the sustainable development concept are respected, future generations will also be able to satisfy their needs. Besides the concern for the needs of the now living indigent humans, this concern for future generations is the second key concept in the definition of sustainable development. According to the World Commission, "many present efforts to guard and maintain human progress, to meet human needs, and to realize human ambitions are simply unsustainable in both the rich and poor nations. They draw too heavily, too quickly on already overdrawn environmental resource accounts to be affordable far into the future without bankrupting those accounts These efforts may show profits on the balance sheets of our generation, but our children will inherit the losses. We borrow environmental capital from future generations with no intention or prospect of repaying. They may damn us for our spendthrift ways, but they can never collect our debt to them. We act as we do because we can get away with it: future generations do not vote; they have no political or financial power; they cannot challenge our decisions (1987, p. 8)". Therefore, the writers of the Brundtland report advocate a sustainable development, so that the opportunities for future generations will not be lost.

As already mentioned, a central point in the reasoning of the World Commission on Environment and Development is that growth must be revived in order to break through the negative spiral of poverty and environmental degradation. According to UNIDO (1985), world industrial output must be increased by a factor 2.6 when the standard of living in developing countries is raised to the level of the industrialized countries. Given the projected population growth trends, a five- to tenfold increase in world production will become necessary by the time world population ceases to grow. To achieve this, rapid economic growth is required. According to the writers of the Brundland report, this growth has major consequences for the environment. Therefore, sustainable development implies more than just economic growth. If development is to be sustainable, it must change fundamentally in order to diminish the burden that mankind places on his physical surroundings.

According to the writers of the Brundtland report, especially a reliable energy supply system that does not overpressure the environment is of major importance to the concept of sustainable development. The Commission argues that the growth in annual world energy use has diminished over the past years. However, rapidly growing populations and increasing standards of living in the developing countries will be accompanied with an increased energy demand. An average inhabitant of an African country, for example, uses tens of times less energy than a citizen of a Western World country. To raise the quality of life of the poor will require an enormous energy use, which cannot be drawn by the environment. This argument is especially valid when the demand for energy is met by fossil-fuel energy carriers.

As a solution to this problem, the World Commission on Environment and Development argues that the economic growth in the future can be made less energy-intensive by means of energy efficiency improvements. According to the World Commission, "energy efficiency policies must be the cutting edge of national energy strategies for sustainable development, and there is much scope for improvement in this direction. Modern appliances can be redesigned to deliver the same amounts of energy-services with only two-thirds or even one-half of the primary inputs needed to run traditional equipment. And energy efficient solutions are often cost-effective (1987, p. 14)". A future with a diminishing energy to GDP ratio is needed. This can only be achieved if the world invests in energy efficiency instead of building more primary supply sources. The World Commission argues that "by using the most energy efficient technologies and processes now available in all sectors of the economy, annual global per capita GDP growth rates of around 3% can be achieved without a growing energy use. These growth rates are as least as great as can be regarded as a minimum for reasonable development. This path requires huge structural changes to allow market penetration of efficient technologies, and it seems unlikely to be fully realizable by most governments during the next 40 years (1987, p. 173)". But, according to the World Commission, "the crucial point about these lower, energy efficient futures is not whether they are perfectly realizable in their proposed time frames. Fundamental political and institutional shifts are required to restructure investment potential in order to move along these lower, more energy-efficient paths (1987, p.173)". The Commission thus argues that the energy efficient scenario is the only option for the future. This scenario is however not impossible. In many countries, the energy to GDP ratio has fallen significantly over the last years as a result of the introduction of energy efficient technologies. According to the World Commission, "if properly managed, efficiency measures could allow industrial nations to stabilize their primary energy consumption by the turn of the century. They would also enable developing countries to achieve higher levels of growth with much reduced levels of investment, foreign debt, and environmental damage (1987, p. 174)".

4.3 The solution of Herman Daly

Anyone who believes that exponential growth can go on forever in a finite world is either a madman or an economist.
Kenneth Boulding

Although they stress that economic growth must take into account the ecosystem's carrying capacity, the writers of the Brundtland report advocate a forceful economic growth, as a means of alleviating poverty and solving all other economic ills. They argue that economic output is a good thing, as long as the environment is not overpressured. According to Herman Daly (1973A,1973B,1977,1979), however, an ever increasing economic output is not desirable at all. Daly argues that "the growth paradigm has outlived its usefulness. It is a senile ideology that should be retired into the history of economic doctrines (1973B, p. 152)". According to Daly, a new paradigm in the economic science is required. This new paradigm must correspond with the finiteness of our planet. This means that unlimited economic expansion is unwarranted. Herman Daly calls the new paradigm the steady state economy. The steady state can be defined as "an economy in which the total population and the total stock of physical wealth are maintained constant at some desired level by a minimal rate of maintenance throughput, i.e. by birth and death rates that are at the lowest feasible level, and by physical production and consumption rates that are equally at the lowest feasible level (1973B, p. 152)".

The first part of the definition of the steady state economy (constant stock) can be traced back to John Stuart Mill, and the originator of the second part (minimal flow of throughput) is Kenneth Boulding. In 1857, J. S. Mill wrote *Principles of Political Economy*. In this book, Mill wrote about the stationary state in a way that is even more relevant today than in his own time. According to Mill, "it must always have been seen by political economists, that the increase in wealth is not boundless. They must have seen that at the end of what they term the progressive state lies the stationary state, that all progress in wealth is but a postponement of this, and that each step in advance is an approach to it (1857, p. 320)". Mill argues that the stationary state is on the whole a better state than the progressive state in which growth is dominantly present. An egoistic ideal of life, which is characteristic for the social situation in the progressive state, is namely not the most appealing future for mankind. Mill argues that there is no reason for the fact that people who are already richer than necessary should become even more rich. Only in the developing nations is an increase in economic output still an important policy goal. Besides this, Mill argues that although much more people can be accommodated on the earth's surface, there is no reason for desiring this: "the density of population necessary to enable mankind to obtain, in the greatest degree, all the advantages both of cooperation and social intercourse has, in all the most populous countries, been attained. A population may be too crowded, though all be amply supplied with food and raiment. It is not good for a man to be kept perforce at all times in the presence of his species. Nor is there much satisfaction in contemplating the world with nothing left to the spontaneous activity of nature; with every rood of land brought into cultivation, which is capable of growing food for human beings; every flowery waste or natural pasture plowed up, all quadrupeds or birds which are not domesticated for man's use exterminated as his rivals for food, every hedgerow or superfluous tree rooted out, and scarcely a place left where a wild shrub of flower could grow without being eradicated as a weed in the name of improved agriculture (1857, p. 324)". Because of the negative effects of economic growth, John Stuart Mill hopes that his descendants will be satisfied with a stationary state, before they are forced to accept it when the earth can no longer cope with a growing economy. According to Mill, such a stationary state however does not mean a stationary development. Mill states that "a stationary condition of capital and population implies no stationary state of human improvement. There would be as much scope as ever for all kinds of mental culture, and moral and social progress; as much room for improving the art of living and much more likelihood of its being improved, when minds cease to be engrossed by the art of getting on (1857, p. 326)".

Although he thought that political economists must have always seen that the increase in wealth is not boundless, mainstream economists have certainly not taken the words of Mill at heart. While admiring many of his other publications, Mill's thoughts on the steady state did not struck root with most of his colleagues. In *Economic Theory in Retrospective*, Mark Blaug (1968), for example, rejects the stationary state concept of Mill as strongly coloured by his social views and hopelessly dated. According to Herman Daly, however, Mill's pleading for the stationary state is even more relevant today than in the 19th century.

For the second part of the steady state definition, the thoughts of Kenneth Boulding (1949,1973) emerge. As already mentioned in chapter 2, Boulding's closed economy of the future requires an organization of the economic science which differs from the open economy of today. Boulding argues that in the spaceman economy, the main task is not throughput but stock maintenance, and any technology which makes it possible to maintain a certain stock with less throughput is an improvement. In this respect, increasing consumption rates are negative, instead of positive. According to Boulding, "if we had clothes that would not wear out, houses that did not depreciate, and even if we could maintain our bodily condition without eating, we would clearly be much better of (1973, p. 128)".

Now the origin of the steady state is traced back, the meaning of the steady state economy can be clarified. According to Daly, the first part of the definition states that the steady state is a state with a constant stock of physical wealth and a constant stock of people. These stocks of capital and labour cannot remain constant by themselves. Humans pass away and resources are used up. For this reason, Daly argues that the stocks of capital and labour can only remain constant if the rate of outflow (death and consumption) is compensated by an equally large rate of inflow (birth and production). This equilibrium to maintain total stock constant can be obtained either with a high rate of throughput (equal to both the rate of inflow and outflow) or with a low rate. Now Daly argues that the second part of the definition of the steady state economy implies that the rate of throughput should be as low as possible. According to Daly, "for an equilibrium stock the average age at death of its members is the reciprocal of the rate of throughput. The faster the water flows through the tank, the less time an average drop spends in the tank. For the population, a low rate of throughput (a low birth rate and equally low death rate), means a high life expectancy, and this is desirable for that reason alone. For the stock of wealth. For the stock of wealth, a low rate of throughput (low production and equally low consumption) means greater life expectancy and durability of goods and less time sacrificed to production. This means more leisure or non-job time, to be divided into consumption time, personal and household maintenance time, culture time, and idleness. This too seems socially desirable, at least within limits (1973A, p. 14)".

To minimize the flow of throughput, Daly argues that two variables can be used, namely the size of the stocks and the durability and the stocks. Given the fact that the size of the stocks remains constant in the steady state economy, the durability of the stocks must be maximized so that the depletion of resources is minimized. According to Daly, the concept of durability goes beyond the life expectancy of a commodity. Also what happens to a commodity after its use ought to be a matter of thought. For example, the possibility for recycling must be investigated, when talking of durability. Daly further argues that the economy's use of resources must be modeled after the cycles in nature. According to Daly, "the best use of resources would imitate the model that nature has furnished: a closed-loop system of material cycles powered by the sun. In such an economy, durability is maximized, and the resources on earth could presumably last as long as the sun continues to radiate the energy to turn the closed material cycles (1973A, p. 15)". Daly thus asserts that an economic system must be created in which all waste is recycled.

It is frequently urged that a state of non-growth will ultimately become necessary because of an ever increasing scarcity of natural resources on the depletion side of the economy. Herman Daly, however, argues that mainly the pollution side provides the limits to a growing economy. The laws of the conservation of mass and energy state that matter and energy cannot be destroyed. Consequently, depletion ultimately leads to pollution. Therefore, pollution provides another foundation for the steady state economy. According to Daly, this pollution side has been less studied than the depletion side. The reason for this is that a large part of the input side is divided into pieces of private ownership. The output side, however, is not partitioned. Therefore, the waste absorbing capacity of the environment can, to some extent, be used by everyone. This results in a overexploitation of the environment. Garrett Hardin (1968) calls this the *Tragedy of the Commons*. Herman Daly tends to call it the invisible foot: "Adam Smith's invisible hand leads private self-interest to unwittingly serve the common good. The invisible foot leads private self-interest to kick the common good to pieces. Private ownership and private use under a competitive market give rise to the invisible hand. Public ownership with unrestrained private use give rise to the invisible foot. Public ownership with public restraints on use give rise to the visible hand (and foot) of the planner. Depletion has been partially retrained by the invisible hand, while pollution has been encouraged by the invisible foot (1973A, pp. 17-18)". Daly argues that it is therefore not surprising to find limits occurring mainly on the pollution side.

Now the necessity of the steady state has been clarified, the question of how it should be attained emerges. According to Herman Daly, a stationary state can be obtained with the right technology and the right social institutions of control for keeping the stocks of physical wealth and people constant and for distributing the stock of wealth among the people. The first means of assuring the future is an appropriate technology. Daly argues that production technology in the steady state ought to be aimed at improving the durability of commodities. According to Daly, "maximum durability means maximizing the time matter spends as wealth and minimizing the time it spends as garbage. Our current technology does not aim at maximizing durability. It comes closer to minimizing it, in order not to spoil the market for replacement demand (1973B, p. 157)". According to Daly, technological progress should be aimed at minimizing the negative environmental effects of production.

The second means of assuring the future are the social institutions of control and distribution. Daly argues that "the guiding design principle for social institutions is to provide the necessary control with a minimum sacrifice of personal freedom, to provide macrostability while allowing for microvariability, and to combine the macrostatic with the microdynamic (1973B, pp. 157-158)". An example of this thought are the freely tradeable birth certificates to be used for maintaining a constant population level. The idea behind these certificates is to give each person a licence to have an number of children corresponding to the replacement fertility. These certificates could be traded on a free market. In this way, there could be stability on the macro-level and variability on the micro-level.

Herman Daly closes his outline of the steady state economy by remarking that this state is not unrealistic. According to Daly, "the steady state is in broad characteristics the only realistic possibility. The present economy is literally unrealistic because in its disregard for nature it is attempting the impossible. The steady-state paradigm, unlike the growth paradigm, is realistic because it takes the physical laws of nature as its first premise (1973B, p. 170)".

4.4 The solution of Nicholas Georgescu-Roegen

The economic process is entropic in all its material fibres.
Nicholas Georgescu-Roegen.

Mankind has been fascinated by myths for centuries. Many myths deal with man's foolish thought that he is superior to everything else in the universe and that his powers are unlimited. Once, man believed that the earth was the centre of the universe. At another time, man thought that he could move an object without using energy or that he could use the same energy over and over again. According to Georgescu-Roegen (1971,1973,1975A, 1980,1981) another myth is proposed by mainstream economists. It is the myth that man will always discover new sources of energy and new ways of exploiting them. The thought is that man, with his unlimited technological possibilities, will always find a solution to a problem when the situation becomes critical. According to Georgescu-Roegen, it is true that up to now almost every generation was better of than the preceding one. But it is also true that each generation has used up a greater amount of natural resources. Georgescu-Roegen argues that the great mineral bonanza of the past two hundred years enabled mankind to achieve a great economic growth. Especially after the second world war, an abundance of cheap crude oil made the increase in the welfare in most parts of the world possible. Although technological change was essential for economic growth, this growth was only possible with the incredible amounts of low entropy provided by the mineral bonanza. Because of the existence of enormous amounts of natural resources of low entropy, Georgescu-Roegen asserts that mainstream economists think that the entropy law does not apply to the economic discipline. According to Georgescu-Roegen, "the most natural rallying idea is that mankind's entropic dowry is virtually inexhaustible, primarily because of man's inherent power to defeat the entropy law in some way or another. The thought is that just as has happened with many other natural laws, the laws on which the finiteness of accessible resources rests will be refuted in turn (1975A, p. 359)". But, as Georgescu-Roegen argues, "the difficulty of this historical argument is that history proves with even greater force, first, that in a finite space there can only be a finite amount of low entropy and, second, that low entropy continuously and irreversibly dwindles away (1975A, p. 359)" Georgecu-Roegen further argues that substitution offers no solution to this problem, because energy in its abstract form cannot be substituted, whatever the market price.

Although he states that thermodynamics is the physics of economic value, Georgescu-Roegen is not completely satisfied with the way in which Carnot, Clausius and their descendants formulated the laws of thermodynamics. Georgescu-Roegen argues that "thermodynamics has remained a science concerned only with what happens to energy. It has completely ignored what happens to matter, without which there can be no piston and cylinder performing transformations of thermal energy into mechanical work and conversely. To be sure, thermodynamics recognizes that because friction is inherent in any natural production of mechanical work, part of the energy initially available for this effect is wasted into dissipated heat, without producing any work. No actual engine, therefore, can convert all available energy into useful work. Thermodynamics however only gives formulae for energy transformations, but nothing is said about the changes undergone by the matter of the piston, the cylinder, the wires, the chemical solutions, or the gases themselves (1981, p. 54)". The reason for ignoring what friction does to matter lies in the fact that friction is a very difficult and controversial phenomenon. In this context, Ernest Rabinowicz (1965) remarked that there are very few statements that can be made in the field of friction which are not controversial.

Thermodynamics thus acknowledges the fact that because of friction an amount of available energy is lost. But it does not consider the fact that friction influences matter as well. According to Georgescu-Roegen, this leads to the modern energetic dogma, which states that only energy matters. Georgescu-Roegen argues that the energetic dogma is "the notion that with a sufficient supply of energy we can mine any rock regardless of its mineral content and also recycle completely any material substance (1980, p. 79)". The energetic dogma can be clarified with the statement of Harrison Brown (1957), who claims that all that needs to be done to obtain whatever material man desires is to add sufficient energy to a system. The modern energetic dogma is also supported by Einstein's equivalence $E = MC^2$. Georgescu-Roegen however argues that "despite the Einsteinian equivalence of mass and energy, there is no reason to believe that we can convert energy into matter except at the atomic scale in a laboratory and only for some special elements. The point is that even the formation of an atom of carbon from three atoms of helium, for example, requires such a sharp timing that its probability is astonishingly small, and hence the event may occur on a large scale only within astronomically huge masses. We cannot produce a copper sheet, for example, from energy alone. All the copper in that sheet must exist as copper (in pure form or in some chemical compound) beforehand. Therefore, the statement that energy is convertible into most of the other requirements of life is, in this unqualified form, apt to mislead (1975A, pp. 355-356)".

The second law of thermodynamics states that every irreversible process is accompanied by a decrease in the quality of energy. According to Georgescu-Roegen, just like energy, matter is subject to an irreversible degradation as well: "ever since my first thoughts on the entropic nature of the economic process, my position has been that in any system that performs work of any kind not only free energy but also matter arranged in some definite structure continuously and irrevocably dissipates (1981, pp. 58-59)". The fact that matter is important as well, inspired Georgescu-Roegen to formulate a new law, which he calls the fourth law of thermodynamics. The first law (total energy is constant) and the second law (the entropy steadily increases) were already mentioned. The third law of thermodynamics states that the absolute temperature of zero degrees cannot be reached, or equivalently, that the entropy becomes zero at the absolute zero of temperature. According to Georgescu-Roegen, the new fourth law of thermodynamics completes the old laws of classical thermodynamics and is formulated as:

> Fourth law of thermodynamics: a closed system cannot perform work indefinitely at a constant rate.

Just like the other laws of thermodynamics, the fourth law can be stated in other, but equivalent, formulations. One of these formulations and probably the most important one for economics is that complete recycling is impossible.

Now one could object to this formulation of the fourth law that it would be possible to recycle all the small particles released from a worn out automobile tire, just as it would be possible to reassemble all the pearls of a broken necklace in a room. But Georgescu-Roegen argues that to reunite all these tire particles would require an immense effort spread over a very long time, during which the objects that are used in this collection effort will become worn out as well and will therefore have to be reassembled in turn. This leads to an infinite regress. Materials thus wear out in such a way that the molecules originally belonging to these materials are gradually dissipated beyond the possibility of being reassembled. This means that once dissipated, matter cannot be completely recycled. Only matter that is that is no longer in a desired form can be recycled. For this reason, Georgescu-Roegen argues that only what is found in garbage and junk yards, the so-called garbojunk such as broken glass, old newspapers and worn out motors, can be recycled. So, just like energy, matter also exists in two different states, namely available and unavailable.

Because of his firm belief in the four laws of thermodynamics, Georgescu-Roegen argues that "what goes into the economic process represents valuable natural resources and what is thrown out of it is valueless waste. From the viewpoint of thermodynamics, matter and energy enter the economic process in a state of low entropy and come out of it in a state of high entropy (1973, p. 37)". Georgescu-Roegen further argues that the economic process neither produces nor consumes matter and energy; it only absorbs matter and energy and throws it out continuously. This may lead to the notion that the economy only changes valuable inputs of low entropy into valueless waste of high entropy. Georgescu-Roegen however objects to this thought, when he argues that "it compels us to recognize that the real output of the economic process (or of any life process, for that matter) is not the material flow of waste, but the still mysterious flux of the enjoyment of life. Without recognizing this fact, we cannot be in the domain of life phenomena (1975A, p. 353)".

The fact that the economic process transforms valuable inputs of natural resources to valueless outputs of waste can be explained by a thermodynamic hourglass. Georgescu-Roegen portrays the economic process by an hourglass in which the stuff of the upper half stands for available low entropy matter-energy. By pouring this stuff down into the lower half it becomes unavailable high entropy waste. But unlike the normal ones, this thermodynamic hourglass cannot be turned upside down. With this hourglass, Georgescu-Roegen explains that "in the context of entropy, every action, of man or of an organism, nay any process in nature, must result in a deficit for the entire system (1975A, p. 354)". Every time, for example, a car is driven from point A to point B, the entropy of the universe increases. Another example is the mining of some copper ore. Although the entropy of the ore decreases every time a copper sheet is produced, this result can only be achieved at the expense of a much greater increase in entropy somewhere else.

When the upper half of the thermodynamic hourglass was replenished again and again, the transformation from low entropy inputs to high entropy waste would not be a reason for concern. Georgescu-Roegen however argues that in a finite world, there can only be a finite amount of low entropy. Because of this finiteness of the amount of low entropy matter-energy, Georgescu-Roegen points out that "the truth, however unpleasant, is that the most we can do is to prevent any unnecessary depletion of resources and any unnecessary deterioration of the environment (1975A, p. 363)". This is the reason why Georgescu-Roegen emphasizes that "every time we produce a Cadillac, we irrevocably destroy an amount of low entropy that could also be used for producing a plough or a spade. In other words, every time we produce a Cadillac, we do it at the cost of decreasing the number of human lives in the future. Economic development through industrial abundance may be a blessing for us now and for those who will enjoy it in the near future, but it is definitely against the interest of the human species as a whole if its interest is to have a lifespan as long as is compatible with its dowry of low entropy (1973, pp. 46-47)".

Moreover, besides the problem of the finiteness of low entropy matter-energy, continued economic growth must lead to more waste. Because of the laws of thermodynamics, Georgescu-Roegen argues that "we cannot produce better and bigger refrigerators, automobiles, or jet planes without producing also better and bigger waste (1973, p. 44)". Numerous natural scientists and economists think that the industrial processes of the future will produce a negligible amount of waste and that this negligible amount of waste can be recycled permanently. Georgescu-Roegen however argues that recycling requires an amount of low entropy resources much greater than the decrease in the entropy of what is recycled. So, there is no industrial activity free from a considerable amount of pollution, just as there is no costless disposal of pollution in terms of low entropy.

Another problem that Georgescu-Roegen outlines is that of thermal pollution. The second law of thermodynamics states that it is impossible to achieve an efficiency of 100% and that eventually all energy ends up as waste heat. An implication of this second law is that continued economic growth leads to an increase in the use of energy and this in turn leads to an increase in the amount of dissipated heat. Because this waste heat is an important aspect in maintaining the thermodynamic equilibrium between the earth and the rest of the universe at a favourable temperature, an increase in the amount of dissipated heat per unit of time can alter this balance. This can have serious effects on the environment. Therefore, Georgescu-Roegen argues that "since the entropy law allows no way to cool a continuously heated planet, thermal pollution could prove to be an even more crucial obstacle to growth than finiteness of accessible resources (1975A, p. 358)".

Given all these problems, Georgescu-Roegen concludes that the only reasonable path for the future would be to economize as much as possible. Therefore, the most desirable state is not a growing one, not even a stationary one, but a declining state. According to Georgescu-Roegen, the current growth must cease, and must be reversed to achieve a negative growth. To reverse the current growth trend, Georgescu-Roegen proposes quantitative regulations that must result in the termination of squandering activities, such as overlighting, overheating, overcooling, and overspeeding. Also the production of superfluous commodities must be stopped. Besides this, fashion must be banned and durable goods must be made more durable. Although these regulations will lead to less comfort, Georgescu-Roegen does not want man to return to the cave. But he does want to reverse the current growth trend. Georgescu-Roegen is however sceptic of man's willingness to cope with a negative economic growth. According to Georgescu-Roegen, "there is neither cynism nor pessimism in believing that even if made aware of the entropic problem of the human species, mankind would not be willing to give up its present luxurious life in order to ease the life of those humans who will life ten thousand or even one thousand years from now. It is as if the human species were determined to have a short but exciting life. Let the less ambitious species have a long but uneventful existence (1973, p. 47)".

5. THE REBOUND-EFFECT: AN INTRODUCTION

5.1 Introduction

In the previous chapter, three ways of thinking about economic growth in a finite environment have been presented. These views were positive growth (The World Commission on Environment and Development), zero-growth (Herman Daly), and negative growth (Nicholas Georgescu-Roegen). Of these three options, the thoughts of Gro Harlem Brundtland and her confederated are of course the most attractive. The writers of *Our Common Future* advocate continued economic growth in combination with efficiency improvements in the use of energy and materials. The underlying thought behind this approach is that energy efficiency improvements make it possible to have increasing economic growth rates without increasing demands for energy carriers, such as oil and gas. The problem with this energy efficiency approach to solving all energy-related problems however is that it is not certain that using energy more efficiently reduces the demand for it proportionately. The rebound-effect is a means of quantifying this effect. The rebound-effect can be defined as that part of the initially expected energy savings, resulting from energy efficiency improvements, that is lost because of the 3-E interaction. In this chapter, an introduction into this rebound-effect is given. Paragraph 5.2 contains the thoughts of the famous 19th century economist W. Stanley Jevons on the subject of using energy more efficiently. In paragraph 5.3, the polemic with respect to the rebound-effect in the international journal *Energy Policy* is outlined. Paragraph 5.4 describes a case study of the rebound-effect.

5.2 The thoughts of W. Stanley Jevons

The thoughts behind the rebound-effect are not new. Already in 1865 it was made clear that using energy more efficiently does not necessarily reduce the demand for it. In that year, W. Stanley Jevons published *The Coal Question, an Inquiry Concerning the Progress of the Nation and the Probable Exhaustion of our Coal-Mines.* According to Jevons, it was possible to divide the history of British industry and trade into two periods. Before the middle of the 18th century, Britain was a rude and half-cultivated country, with an abundance of resources that were exported, such as corn, wool, meat, and timber. The British people were unskilled. They were learners rather than teachers compared with other cultures. But after 1750, all that changed. Instead of exporters of raw materials, the British became importers; instead of importers of manufactured goods, they became exporters; instead of learners, they became teachers. According to Jevons, this progress in the civilization of Britain was not due to any general intellectual superiority of the British inhabitants, but to the availability of natural resources.

In 1850, the British export of iron was scarcely inferior to the total production of iron of the rest of the world. W. Stanley Jevons argued that this was not a result of the quality of the British iron. Compared to the iron produced in Sweden, Belgium, or Austria, the British iron was of a very poor quality because of the sulphur, phosphorus, and other impurities of the British ore. The reason for the British dominance was the cheapness of their products. According to Jevons, this cheapness depended upon extracting coal from the British mines at very low costs. Coal thus was a very important resource. Or as Jevons put it: "day by day it becomes more obvious that the coal we so happily possess in excellent quality and abundance is the mainspring of modern material civilization. And as the source especially of steam and iron, coal is all-powerful. This age has been called the Iron Age, and it is true that iron is the material of greatest novelty. By its strength, endurance, and wide range of qualities, it is fitted to the fulcrum and lever of great works, while steam is the motive power. But coal alone can command in sufficient abundance either the iron or the steam; and coal therefore commands this age: the age of coal. Coal, in truth, stands not besides but entirely above all commodities. It is the material energy of the country, the universal aid, the factor in everything we do. With coal almost any feat is possible. Without coal we are thrown back into the laborious poverty of earlier times (1865, pp. vii-viii)". With this in mind, W. Stanley Jevons argued that it was not surprising that every year the amount of coal that was extracted from the British mines became larger and larger.

Britain was thus growing rich upon an apparently infinite supply of coal. Jevons however argued that this was a fallacy because coal in itself was limited in quantity. This could be seen in the increasing difficulty to gain the needed supplies each year. According to Jevons, "in the increasing depth and difficulty of coal mining we shall meet the vague but inevitable boundaries that will stop our progress. And while other countries mostly subsist upon the annual and ceaseless income of the harvest, Britain is drawing more and more upon a source which yields no annual interest, but once turned to light and heat and force is gone forever into space (1865, p. 307)".

Around the middle of the 19th century, three different solutions to the problem of supplying Britain with coal in the future were considered. As a first solution, it was suggested by many scholars that when the coal was used up in Britain, it could be imported. But W. Stanley Jevons argued that the principles of trade denied such a thought: "if coal, as well as other raw materials, were found abroad, in Pennsylvania, Prussia, New South Wales, or Brasil, the whole cost of freight would be a premium upon establishing a system of coal-supported industry on the spot (1865, p. 223)". Therefore, foreign coal could not be expected to be the foundation of a prosperous British industry. According to Jevons, the fact that Britain exported coal, instead of proving an eventual possibility for a reversal of this current, proved its impossibility.

As a second option, it was argued that substitutes for coal could be found. After investigating the alternative sources of power of that time, Jevons however concluded that coal would probably never be replaced by anything better. According to Jevons, "coal is the naturally best source of power as air and water and gold and iron are, each for its own purpose, the most useful of substances, and as such will never be superseded (1865, p. 142)". Jevons acknowledged that if the coal mines would become exhausted, other sources of power such as tidal mills would be useful substitutes for it. But this would only be on the principle that something is better than nothing. And it would certainly enfeeble Britain's industrial position, compared with nations that would still possess large quantities of coal.

As a third solution, it was urged that the failing supply of coal could be met by using it more efficiently. It was supposed that with efficiency improvements the problem of scarce and costly fuel could be solved. With the aid of thermodynamics, it was possible to show that the efficiency of a good engine in Jevons time was less than 20%. In furnaces too, only a small portion of the energy content of the coal was actually used. Also in the domestic use of coal, a large part the heat escaped up the chimney unused. W. Stanley Jevons however argued that efficiency improvements in the use of coal are not a solution: "it is however a confusion of ideas to suppose that the more economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth (1865, p. 103)". According to Jevons, "it is the very economy of use of coal which leads to its extensive consumption. It has been so in the past, and it will be so in the future. Nor is it difficult to see how this paradox arises. The number of tons of coal used in any branch of industry is the product of the number of separate works and the average number of tons consumed in each. Now, if the quantity of coal used in a blast-furnace, for instance, be diminished in comparison with the yield, the profits of the trade will increase, new capital will be attracted, the price of pig-iron will fall, and the demand for it will increase. And eventually, the greater number of furnaces will more than make up for the diminished consumption of each. And if such is not always the result within a single branch, it must be remembered that the progress of any branch of manufacture excites a new activity in most other branches, and leads indirectly, if not directly, to increased inroads upon our seams of coal (1865, pp. 104-105)" Jevons thus argues that the more energy efficient the economic system becomes, the more will the economy thrive, and the higher will the annual coal consumption be.

For almost any use of coal, the energy efficiency can be increased. As an example of the many possibilities for saving coal, Jevons mentioned the utilization of the spare heat from waste gases of a blast-furnace by passing it through a steam-boiler. But, according to Jevons, "no one must suppose that the coal thus saved is spared; it is only saved from one use to be employed in others, and the profits gained soon lead to extended employment in many new forms. The several branches of industry are closely interdependent, and the progress of any one would lead to the progress of nearly all. And if the economy of use in the past has been the main source of progress and growing consumption of coal, the same effect will follow from the same cause in the future (1865, p. 115)".

According to W. Stanley Jevons, the exhaustion of the British mines would be accompanied by price rises of coal, compared with the prices of coal in other countries. As a result of this, Britain's industry and trade would perish. So, the increasing cost of coal would be an obstacle to further progress. In a response to this problem, Jevons argued that a policy of restrictions to limit the extraction of coal must be imposed. According to W. Stanley Jevons, "we have to make the momentous choice between brief greatness and longer continued mediocracy (1865, p. 349)".

5.3 The Energy Policy polemic

Although already in 1865 it was argued by W. Stanley Jevons that energy efficiency improvements do not necessarily lead to equal reductions in the demand for energy, there is still no consensus regarding the magnitude of the rebound-effect today. This can be illustrated by means of a description of the polemic in *Energy Policy*, an international journal addressing the economic, environmental, and social aspects of energy supply and utilization.

The discussion in *Energy Policy* regarding the rebound-effect started with an article by Bill Keepin and Gregory Kats (1988), entitled *Greenhouse Warming, Comparative Analysis of Nuclear and Efficiency Abatement Strategies*. In this article, Keepin and Kats argue that there are two possible policy responses to the problem of the greenhouse-effect, namely the adaptation response and the amelioration response. The adaptation philosophy says that greenhouse warming is inevitable and that man should therefore begin to adapt to it. The amelioration response states that the problem can be counteracted by reducing the dependence on fossil fuels in the future. Keepin and Kats are advocates of the latter option, and in their paper they examine two of the most popular strategies for ameliorating greenhouse warming through substantially reducing the use of fossil fuels in the future. The first of these strategies to fight the greenhouse-effect is by displacing fossil fuels with nuclear power. The second strategy to minimize the combustion of fossil fuels in the future is by energy efficiency improvements. Regarding the revitalization of nuclear power, Keepin and Kats conclude after analyzing various scenarios that "even a massive worldwide nuclear power programme sustained over a period of several decades could not solve the greenhouse problem. And even if it could, the Third World cannot support a major expansion of nuclear power on the scale that would be required in an attempted nuclear solution to greenhouse warming (1988, p. 539)". With respect to energy efficiency, Keepin and Kats conclude that "energy efficiency offers the greatest promise to reduce global CO_2 emissions substantially, while also ameliorating other problems, such as acid rain and economic inefficiency. Energy efficiency is the single most important technological factor determining future CO_2 emissions. Moreover, rather than being just a theory, this efficiency potential has also been demonstrated in practice. Since 1973, the energy used per unit world economic output has declined by 12%, primarily in response to increased oil prices. This has occurred in the absence of vigorous efforts to promote increased efficiency in most nations, and only gives a hint of what would be possible in the event of a concentrated effort to implement improved energy efficiency worldwide (1988, p. 550)". According to Keepin and Kats, "in the USA, the world's largest producer of CO_2, each dollar invested in electric efficiency displaces nearly seven times as much CO_2 as a dollar invested in nuclear power. Even if the most optimistic aspirations for the future economics of nuclear power were realized today, efficiency would still displace between 2.5 and 10 times more CO_2 per unit investment (1988, p. 554)". Therefore, Keepin and Kats conclude that improvements in energy efficiency constitute an effective and inexpensive response to the greenhouse warming problem, whereas nuclear power is an ineffective and expensive response. Opportunities for energy efficiency must be the cutting edge of energy policy throughout the world.

In a response to the Keepin and Kats paper, Len Brookes (1990) wrote *The Geenhouse Effect: The Fallacies in the Energy Efficiency Solution*. According to Brookes, energy efficiency improvements cannot by themselves solve the greenhouse-effect. Brookes argues that "what most advocates of the energy efficiency route to salvation overlook, is that there is no evidence that using energy more efficiently reduces the demand for it. The efficiency of conversion of fuel to useful heat or mechanical energy has improved by an order of magnitude in the last 100 years. Also the average thermal efficiency of power stations in the UK has improved from less than 10% in the 1920s to more than 40% today. Yet we now consume more energy both in total and on a per capita basis than we did then (1990, p. 199)". According to Brookes, the reason for this is the fact that efficiency improvements lead to price decreases, which in turn lead to demand increases.

To clarify the issue, Brookes considers two scenarios, one in which energy constitutes a constraint on the level of economic activity, and one in which it does not. Regarding scenario 1, Brookes argues that if the price of energy becomes a serious economic obstacle (as it did in 1973 and again in 1979), there are two possible courses of action. The consuming country can either do nothing and accept a reduction in the level of economic activity or it can adjust by substituting capital and labour for energy. Now Brookes argues that "compared with the option of taking no remedial action, the option of accommodating to the price rise results in the balance between energy supply and demand being struck at a higher price, hence a higher level of production and consumption of energy than if there had been no energy efficiency response. In other words, in the case where energy price is a constraint, responding by using energy more efficiently results in a higher level of energy consumption than if there had been no such response, and this is true whatever the motive (1990, p. 200)". Regarding scenario 2, Brookes refers to the research done by Sam Schurr and Dale Jorgenson. In this case where the energy price is not a constraint on economic activity, two phenomena are taking place. These phenomena are the substitution of energy for labour and capital with the consequent improvement in their economic productivity, and a parallel improvement in the productivity of energy, i.e. a falling energy consumption per unit of economic output. Unfortunately for the advocates of energy efficiency, Brookes argues that "these phenomena are accompanied by increases in total energy consumption. The reason for this is that the substitution of energy for capital and labour has such a beneficial effect on the productivity of those two inputs that their combined rate of productivity improvement exceeds the rate of improvement of energy productivity. And it is a truism that if multifactor productivity growth exceeds energy productivity growth while inputs of labour and capital are not falling, the net effect is for total energy consumption to increase, even though energy consumption per unit of output may be falling (1990, p. 200)". So, Brookes argues that in both scenarios energy efficiency leads to an increase in energy consumption, rather than a decrease, compared with the situation without the energy efficiency improvements. Besides this, Brookes states that in investigating the residential sector, he found a very high correlation between income and energy use. According to Brookes, "domestic consumers tend to spend a constant proportion of their income on fuel and electrical energy, implying that higher efficiencies of appliances lead to higher levels of use and increases in the number of appliances. More generally, purchasing power released by lower expenditure on existing uses of fuel finds an outlet somewhere, and in modern industrial societies it is almost bound to be in the purchase of goods and services, that require energy in their production if not on other uses of fuel itself (1990, p. 201)". From all this, Len Brookes concludes that the claims of conservationists such as Keepin and Kats are not true. As history proves, the enormous improvements in energy efficiency that have taken place in the course of time have been accompanied by increases in energy consumption, not decreases, and this is to be expected in the future as well. According to Len Brookes, "the present high profile of the topic of global warming and energy efficiency seems to owe more to the current tide of green fervour than to sober consideration of the facts and the validity and cost of solutions (1990, p. 201)".

Len Brookes' paper evoked various responses in the next editions of Energy Policy. Support for Brookes view was given by Geoffrey Greenhalgh (1990) in his paper *Energy Conservation Policies.* According to Greenhalgh, the oil price rises of 1973 and 1979 ended an era of cheap energy and also made clear to public and governments the vital role of energy in the economy. As a result of these price rises, a whole range of programmes, such as energy audits, financial incentives, and the adoption of energy efficiency regulations and standards were introduced by national governments in order to save energy. The success of these measures was usually measured in terms of improved energy intensity, seen as a reduction in the energy to GDP ratio. But, according to Geoffrey Greenhalgh, "it is a fundamental misconception to think that a change in the energy to GDP ratio gives an indication of the efficiency of energy use. It does not. The ratio merely illustrates changes in the use in which energy is put in a society, and these uses can change quite independently of any change in the actual efficiency with which energy is used (1990, p. 294)". Greenhalgh namely argues that there are a number of factors that could affect the energy to GDP ratio. One of these factors is the structural change within society from industrial production to the service sector. Another factor is the shift from bulk products with a low added value to more specialized products with a high added value. Besides the misconception that the energy to GDP ratio is an indicator of the energy efficiency of an economy, Greenhalgh argues that the introduction of more energy efficient appliances leads to a reduction in the running costs and this in turn will lead to a greater usage. There is of course nothing wrong with that. The use of these appliances satisfies the needs of consumers. Greenhalgh however argues that the aim of conservationists such as Keepin and Kats is not consumer benefit but a reduction in the consumption of energy carriers. According to Greenhalgh, "the incentive to improve the efficiency of energy use is ever present, driven by both technical advance and economic gain. Artificial attempts to promote energy conservation as a policy in its own right, deliberately aimed at reducing consumption, may only distort the energy economy. Insofar as they are successful they will only accelerate the natural rate of progress, which leads to reduced costs of using energy. This can only tend to increase the eventual consumption. The end result may then be quite different to what the conservationists intend (1990, p. 298)".

Opposition to Brookes' thoughts was given by three authors. One of them was Dave Toke (1990) in *Increasing Energy Supply not Inevitable.* According to Toke, there does exist historical evidence that using energy more efficiently reduces the demand for it. The primary energy consumption in the United Kingdom in 1988 namely was 3% lower than in 1973, whereas GDP was about 31% higher. According to Toke, this was a result of energy efficiency improvements in the economy as a whole over that time period and precisely contradicts Brookes' assertion. Toke further argues that it is wrong to claim that there is a constant relationship between people's income and their spending on energy. To clarify his opinion, Toke uses the example of a consumer who decides to purchase a new television: "if efficiency standards produce TV's that use only half the amount of electricity, it does not mean that people will watch TV any longer, never mind twice as long. Sure, the money released by savings on energy bills will be respent on other goods and services, but only a small portion of this will be for the energy content of such goods and services (1990, p. 673)". To end his objections to Brookes' thoughts, Toke argues that Brookes pays too much attention to respending-effects and too little attention to analyzing the possible effectiveness of political intervention efforts to reduce the energy consumption. Brookes dismisses energy efficiency standards as a solution. According to Dave Toke, however, energy efficiency standards can dramatically improve the level of energy efficiency, thereby eliminating market imbalances and misallocations of resources. Toke claims that it is not unrealistic to think that with strong political intervention measures large reductions in the energy to GDP ratio can be achieved. Toke further argues that "although technical and economic considerations do set limits to what can be done, such limits are stricter in the short term than in the long term and at the end of the day there are a number of possible energy paths which can produce continuing increases in GDP figures but which incur rather different levels of external costs and impacts on the quality of life. We can make a political decision to adopt an energy efficient path that is more effective in combatting the greenhouse problem than the conventional nostrums of ever increasing energy supplies based more and more on nuclear energy (1990, p. 673)".

In a response to Dave Toke's critical remarks on Len Brookes' paper, Brookes (1991) wrote *Confusing the Issue on Energy Efficiency*. According to Brookes, the fact that the energy consumption in the UK fell by 3% between 1973 and 1988 while economic output increased by 31% does not contradict his conclusions. These results are namely entirely consistent with his claims. The period from 1973 to 1988 contained both of the oil crises. It was therefore an excellent example of scenario 1, in which energy supply and price were constraints on economic activity. Besides this, Brookes claims that the data that Toke quotes are not well chosen. For example, 19 of the 23 OECD used more primary energy in 1988 than in 1973. Brookes also argues that Toke deliberately selected 1973 as the base year in order to prove his point. The year 1973 namely was a peak year for UK energy consumption. Moreover, UK economic performance between 1973 and 1988 was highly atypical because much of the economic growth then was due to the exploitation of the oil and gas reserves from the North Sea. Brookes summarizes his critique by stating that "Toke has attempted to refute a general case, supported by scholarly research, by appealing to a very special case of an atypical country in a brief atypical period in its economic history (1991, p. 185)". Brookes further argues that it is wrong of Toke to think that a very high correlation between domestic energy consumption and personal disposable income cannot be found. And it is equally wrong to clarify this thought with a single hypothetical example of energy efficient TV's. According to Brookes, the high correlation was a statistically derived fact. To conclude his reply, Brookes again emphasizes that "there is no economic, environmental, or any other kind of purpose that is best served by maximizing energy efficiency and therefore Toke's energy efficient Utopia is a seriously flawed goal (1991, p. 186)".

To counteract Brookes' comments, Dave Toke (1991) wrote *Energy Efficiency*. In this piece, Toke again expresses the thought that Len Brookes' statement that after an oil crisis energy demand is higher in the situation with energy efficiency improvements than if there were no efficiency improvements is absurd. During the oil crisis, the majority of industries namely invested more in energy efficiency improvements than they would otherwise have done. The results of these investments was that the demand for energy ended up below what it would otherwise have been, not above. Moreover, these efficiency gains even influenced the energy economy long after the oil crisis ended. According to Toke, "Brookes' analysis is completely dominated by supply-side considerations, a stance which leads to bizarre analyses in an effort to prove that demand-side energy measures are always ineffective in reducing energy demand. The issue of market imbalances is completely ignored by Brookes who lives in his own world where the demand-side of the entire energy sector can be represented by a single demand curve with perverse movements (1991, p. 815)". One of the central points in Toke's reasoning is that the market imbalances which prevent a successful introduction of energy efficiency measures can be solved by government regulations. Dave Toke argues that essentially all that Brookes' claims say is that a combination of energy taxes and energy efficiency standards is needed to solve the problem.

Critical notes regarding Len Brookes' thoughts on the fallacy of the energy efficiency solution to the greenhouse warming problem were also expressed by Horace Herring and Mike Elliott (1990) in a *Letter to the Editor*. According to Herring and Elliott, Len Brookes does not grasp the central issue in the discussion. This issue namely is whether or not energy efficiency improvements are the best means of meeting the increased energy demand. Brookes argues that in the situation where energy is a constraint on economic activity, responding by increasing the energy efficiency results in a higher level of energy demand than if there had been no response. Herring and Elliott however argue that "this is not true in the short term nor under conditions of steadily rising energy prices. For elementary production theory implies that lower energy consumption can be achieved in the long run even with improving energy efficiency provided that the real price of energy rises at a steady rate over time. It is also possible to lower energy consumption without price rises or reducing output by improving energy efficiency, but only at the expense of moving to a sub-optimal economy. That is that the same level of output is achieved but at a higher cost than necessary (1990, p. 786)". Len Brookes grounds his thoughts on the concept of multifactor productivity growth. But, according to Herring and Elliott, "while the concept of multifactor productivity is usefully applied in industry, it must be remembered that industry in the UK accounts for only 28% of total delivered energy use. The concept is of less relevance to the other energy using sectors (1990, p. 786)". Moreover, Herring and Elliott argue that there is another inaccuracy in Brookes' reasoning, namely the fact that Brookes claims that an increase in income leads to an equal increase in the demand for energy. Herring and Elliott argue that the energy use in the domestic sector has not significantly changed since 1940, despite the yearly increases in income. According to Herring and Elliott, energy efficiency improvements were responsible for this. Horace Herring and Mike Elliott conclude by stating that "conservationists are on firmer ground than Len Brookes imagines. For increased energy efficiency, brought about under conditions of steadily rising prices, has the merits of saving energy, stimulating production, and buying time (perhaps 10-15 years) for us to carefully consider what energy sources are needed to replace fossil fuels in the 21st century (1990, p. 786)".

In a *Letter to the Editor*, Len Brookes (1991) responded to the critical remarks made by Horace Herring and Mike Elliott. According to Brookes, Herring and Elliott attempt to reject his conclusions expressed in *The Greenhouse Effect: The Fallacies in the Energy Efficiency Solution* with the point that economically unjustified energy efficiency improvements can reduce total energy demand. Brookes argues that this point is irrelevant since he explicitly mentions that economically justified improvements in energy efficiency do not contribute to reducing the demand for energy. Furthermore, Herring and Elliott use the fact that steadily rising energy prices can result in a reduction in total energy demand to prove Brookes' wrong. According to Len Brookes, however, also this fact does not enfeeble his argument. Another point by which Herring and Elliott try to reject Brookes' opinion, is that energy efficiency improvements may result in short-term reductions in the total demand for energy. Brookes replies to this critical remark by arguing that the greenhouse effect is surely not a short-term problem. Brookes ends his letter to the editor by remarking that "it is truly astonishing how tenaciously the faithful stick to their belief in energy efficiency as a cure for all ills. Herring and Elliott's letter is no analysis worth the name: it is simply a series of affirmations of belief by the faithful (1991, p. 187)".

A third opponent to Brookes' thoughts was Michael Grubb (1990). In *Energy Efficiency and Economic Fallacies*, Grubb agrees with Brookes that if energy becomes a serious economic obstacle (scenario 1), improving energy efficiency will not reduce the demand for it. In the much more usual situation where energy is not an obstacle to economic activity (scenario 2), historical data at least up to 1973 indicate that although energy productivity improved, the labour and capital productivity improved much faster. As a result of this, efficiency improvements were more than offset by the new uses for energy. From this, Brookes concludes that energy efficiency improvements have and will always increase the attractiveness of energy for new uses. Consequently, improvements in energy efficiency cannot reduce energy demand. In a response to Brookes' thoughts on scenario 2, Grubb writes that "while the historical analysis is fine, the final step in Brookes' arguments contains at least two major flaws. The first flaw is to assume that future economic reactions will parallel those of the past. The last decades have shown great changes in the pattern of energy and economic development. A long era of steadily declining fossil fuel prices will never return, and there is much evidence that some important end-uses of energy are approaching saturation. Also the pattern of economic development is shifting towards less material- and energy-intensive goods. Therefore, general statements about the energy foundation of future economic growth, largely based on pre-1973 data, are questionable (1990, p. 783)". With respect to the second shortcoming in Brookes' analysis, Brookes writes that "a more serious flaw is to confuse the role of naturally-occurring efficiency improvements with the effects of deliberate attempts to minimize energy consumption when price and availability are not constraints. In all the period up to 1973, improved energy efficiency was primarily a consequence of other pursuits, for example the drive to colonize new markets, by introducing automated processes in which the energy costs were lower than the labour costs. It is not surprising that this led to demand growth. But if energy efficiency is the goal, rather than the means, then the driving force is entirely different, and so are the macroeconomic implications. Consider for example a sector where the energy-using activity is relatively unresponsive to price. In the course of natural developments there may be little incentive for efficiency to improve, irrespective of technical potential. Yet these are precisely the sectors which are likely to offer the greatest energy savings. Conservation policy can choose to focus upon such areas, including those dominated by market failures, where the implicit price falls from increased efficiency have little impact on activity levels (1990, p. 783)". Grubb thus argues that there are many areas in the economy in which energy efficiency improvements can save energy because the price of energy is of minor importance. But there is more. Brookes argues that energy efficiency improvements lead to a higher purchasing power because of lower expenditures on existing uses of energy. This purchase power finds an outlet somewhere in the purchase of goods and services that require energy. But, according to Michael Grubb, total energy costs are generally a few per cent of GDP and this respending effect will also be of this order. Moreover, Grubb disagrees with Brookes' thought that domestic consumers tend to spend a constant proportion of their income on gas and electricity. According to Michael Grubb, a UK

Family Expenditure Survey namely showed that poor households spend a greater portion of their income on energy than average households even in absolute terms, because poor people do not have the financial means to insulate their homes and buy energy efficient appliances. Grubb argues that the major problem of the energy efficient solution is not the rebound-effect but the fact that with respect to energy efficiency serious market imperfections exist. These market failures result in an inefficient use of resources and higher than needed costs to society. As reasons for this inefficiency, Grubb mentions lack of knowledge, knowhow, and technical skills, separation of expenditure and benefit, limited capital often arising from external restrictions on capital budgets, rapid payback requirements, lack of interest in peripheral operating costs, and legal and administrative obstacles. According to Michael Grubb, "the result of all these factors is to create a pervasive imbalance between investments in supply and investments in end-use efficiency. Therefore, policies aimed at removing or circumventing these market obstacles and installing efficient and cost-effective technologies, will save energy and bring both environmental and economic benefits. This is not wishful thinking but the almost universal conclusion from those who have studied the realities of the economic imbalance between supply and demand (1990, p. 785)".

Len Brookes (1992) responded to Michael Grubb's criticism by writing *Energy Efficiency and Economic Fallacies: a Reply*. Brookes starts his response by stating that he will confine himself to scenario 2 (when energy is not a constraint) since Grubb agrees with him on scenario 1. Regarding the second scenario, Grubb states that Brookes' conclusions are wrong if improved energy efficiency is itself the goal, rather than the means to some end. Grubb claims that in such circumstances real energy savings and economic benefits will accrue at the macroeconomic level. Brookes rejects this thought because microeconomic measures cannot simply be extended to macroeconomic results. According to Len Brookes, "comparing the economics of different options for reducing economy-wide or even worldwide emissions of greenhouse gases due to fuel-using activities is a macroeconomic exercise that calls for macroeconomic treatment. The results of adopting an energy efficiency solution can only be judged at the macroeconomic level (1990, p. 390)". Furthermore, Brookes dismisses Grubb's claims because of the fact that Grubb is reversing the debate, by setting the maximization of energy efficiency as a goal in its own right. According to Brookes, it is wrong to state that the starting point of the discussion should be the acceptance of maximum energy efficiency as the goal. Brookes argues that "it would be reasonable to set the maximization of economic output as a goal; or the minimization of environmental damage; or the maximization of output subject to there being improvements at a given rate in defined environmental parameters. The maximization of energy efficiency does not result in any of these admirable goals and it would bias options in a damaging way to pretend otherwise. It would also divert attention from truly useful subsidiary goals, like setting targets for reductions in greenhouse gas emissions (1992, p. 392)". Besides this, Brookes also argues that when Grubb's goal is maximizing energy efficiency per se, energy becomes a scarce resource. This implies that Grubb's version of scenario 2 is in fact an example of scenario 1, with energy efficiency taking the place of the OPEC. Another point of controversy is the statement by Brookes that a high correlation exists between personal disposable income and residential energy expenditure, which means that people respend the money that is saved by efficiency improvements on energy. Michael Grubb argues that this is not true because poor people spend a larger proportion of their income on energy than rich people. According to Len Brookes, this fact is invalid for this discussion. The research by Brookes was a time series regression of total residential expenditure on energy upon total UK disposable income, while Grubb's argument merely illustrates behaviour changes across socioeconomic groups at a certain point in time. Brookes ends his response by agreeing with Grubb that a lack of knowledge on the part of the consumer is a source of economic inefficiency. Brookes argues that "if consumers are to make the right choices when faced with a constraint, say a form of carboniferous fuel rationing or taxation, it is important that they should be informed ones. A comprehensive approach to labelling in all its manifestations (showing the consumption level of appliances for example) is an important means to that end (1990, p. 392)".

In his *Reply to Brookes*, Michael Grubb (1992) put aside Len Brookes' comments. A large part of Brookes' paper is about the accusation that Grubb promotes energy efficiency as a goal rather than as a means to some end. According to Grubb, this is a strange accusation since a large part of the paper *Energy Efficiency and Economic Fallacies* is concerned with the conditions under which efficiency improvements become economically attractive. To clarify his point of view again, Grubb argues that "policies for promoting energy efficiency should be pursued until the marginal cost of squeezing more out of efficiency equates to that of new supply (1992, p. 393)". Another matter of dispute is whether the rebound-effect should be viewed in a microeconomic or macroeconomic context. According to Michael Grubb, the macroeconomic context is important but Brookes is using generalized macroeconomic results in ways that are irrelevant in the context of this discussion. Take for example a fridge. According to Grubb, competent microeconomic analysis will prove that the price-elasticity of fridge use is rather low. This means that if I buy a much more efficient fridge, I will not react to the decreased operating costs by leaving the fridge door open more often. So, according to Grubb, this effect is negligible. Grubb further argues that competent economic analysis can also prove that of the money that is saved in this way, only a small fraction will be respent on energy, implying that this effect is small as well. Grubb closes his reply by asserting that "Brookes neglects the central issue, namely the extent to which the measures intended to help close the efficiency gap will result in realized energy savings. That is not a question that can be answered by attempting to raise macroeconomic generalizations to the status of precluding microeconomic realities or by misrepresenting those who are trying to clarify the issues involved (1992, p. 393)".

In *Energy Efficiency Fallacies: the Debate Concluded*, L. G. Brookes (1993) responded to Grubb's reply to Brookes' reply to Grubb's reply to Brookes' paper *The Greenhouse Effect, The Fallacies in the Energy Efficiency Solution*. According to Len Brookes, Grubb has not mentioned new arguments which support his claims. In the first place, Grubb denies that he thinks that energy efficiency is an end, instead of a means to an end. But, according to Len Brookes, in his reply Michael Grubb states that energy efficiency should be improved until the marginal cost of efficiency equates to that of new supply. This thought proves Grubb's prepossession. According to Brookes, "if we are looking at the issue economically, the objective function to be maximized is not the energy efficiency but the efficiency of the economy as a whole. If consumption of certain types of fuel, for example, is causing problems, the most direct and economically soundest solution is to constrain consumption of that fuel by some form of rationing or by taxing it, and than reoptimize the objective function of the economic efficiency as a whole subject to the new constraint. Neither Grubb nor any other like minded writer has put forward cogent arguments to show why it is right to concentrate all the adjustment on energy-efficiency improvements (1993, p. 346)". Besides this, Brookes argues that Grubb offers no support in his reply for his claim that Brookes' macroeconomic approach to examining the problem is invalid. It is not sufficient to mention a single anecdotical microeconomic example of the purchase of a refrigerator to counter a serious macroeconomic argument. To end his reply, Len Brookes asserts that he does not want to condemn the followers of the energy efficiency movement. Brookes is not opposed to energy efficiency improvements and he enjoys the benefits of them at both the microeconomic and macroeconomic level. Brookes admits that he likes having appliances with lower operating costs and he welcomes the higher levels of national income that follow from the economy-wide improvements in energy productivity. But, according to Len Brookes, all this does not imply that improvements in energy efficiency can be seen as a means to reducing total energy consumption and as a solution to the greenhouse warming problem.

After Brookes' piece, it is said in an editorial note that this was the final piece in the debate on the rebound-effect. It is namely clear that the various authors cannot come to an understanding on the issue. This is at the same time the most apparent conclusion that can be drawn from this polemic. Those who believe in a large rebound-effect are of opinion that, for instance, increased car efficiency will lead to an increased demand for travelling and an increased demand for other goods and services, which contain a considerable amount of energy. Those who do not believe in the existence of a large rebound-effect think that increased car efficiency will not lead to more travelling and an increased energy demand resulting from the respending of the money that is saved by the increased car efficiency. The whole question thus remains unsolved and highly speculative. The reason for this is the fact that no real attempts are undertaken to calculate the magnitude of the rebound-effect. The only way to reach agreement on the issue of whether or not a large rebound-effect exists is by means of a quantitative analysis.

5.4 The effectiveness of energy efficiency improvements: a case study

The energy required for domestic use represents an important part of the total energy consumption of a country. A considerable amount of this domestic energy consumption is used for the heating of dwellings. According to van Rossum (1991A,1991B), space heating accounted for 65% of the total Dutch residential energy consumption in 1985. It is therefore not surprising that governments see energy conservation by means of reducing the energy required for space heating as an important means in meeting their environmental policy goals. For example, in the National Environmental Policy Plan of the Netherlands which appeared in 1989, energy conservation through increasing the thermal efficiency of dwellings is one of the main options to reduce the emissions of carbon dioxide. Insulation is the most important means of changing the thermal efficiency of homes. For this reason, the increase in the thermal efficiency of an existing home (retrofitting) by means of insulating the cavity walls is the subject of this case study.

In any dwelling, heat transfer between the inside and the outside takes place by three separate agencies. These agencies are conduction, convection, and radiation. When heat goes through solid materials, the term conduction is used. A measure of the rate at which conduction happens is the coefficient of thermal conductivity. The thermal conductivity of metals is very high. The conductivity of aluminum for example amounts to 210 W/mK at 0°C (van Buuren and de Jong, 1990). Non-metals have much lower thermal conductivities. The lowest thermal conductivities are measured by materials that contain a considerable proportion of voids. These voids are small bubbles of gas or air. Examples of such materials are mineral wool and plastic foams.

Now consider the walls of a dwelling. In the case of heat transfer by means of conduction, the heat that passes from one area of the wall to the other can be described by the following equation:

$$Q_{cond} = \frac{\lambda}{d} \cdot \Delta T \qquad (5.1)$$

This empirical relation is only valid in a steady state situation, in which the heat capacity of the wall is neglected. In equation (5.1), the symbol Qcond denotes the heat in W/m^2 that passes through the material, the symbol d denotes the thickness of the material in metres, and **ΔT** represents the temperature difference between the two surfaces in degrees Kelvin. The symbol λ in equation (5.1) denotes the coefficient of thermal conductivity. The dimension of this coefficient is in W/mK. In English speaking countries, the symbol k instead of λ is used to indicate the thermal conductivity coefficient.

The thermal conductivity of air is very low, namely 0.020 W/mK at 0·C (van Buuren and de Jong, 1990). When a layer of air has an appreciable thickness, this λ-value however only has a purely theoretical meaning. The reason for this is a process called convection. Convection is the transfer of heat by the movement of the molecules of a liquid or a gas. An example of convection is the transmission of heat from the inside air to the internal wall of a dwelling and from the external wall to the outside air. The movement of the liquid or gas molecules can be caused by an external agency, such as a pump in the case of liquids or the wind in the case of gases. This is called forced convection. The movement of the molecules can also take place simply because a part of the liquid or gas is warmed up. This warming up results in a change in the density of the gas or liquid. As a result of this, the heated molecules start moving. This is called free convection.

Convection can only occur through a medium. For radiation, no medium is required. In fact, heat transfer by means of radiation is most favourable across a vacuum. Radiation heat transfer appears whenever there are two surfaces at different temperatures facing each other, or if there is a single surface facing an open space. Radiation proceeds at the speed of light, which is about 300,000 kilometres per second. Radiant heat is a form of electromagnetic radiation. This means that it is related to phenomena such as infra-red light, visible light, and X-rays. An example of radiation is the heating up of the external walls of dwellings during day-time when the sun falls upon them. Another example is that of the heat which is radiated from a fireplace on to the internal walls of a house.

Although complex equations are derived for the heat transfer by means of convection and radiation, within the building industry the two are frequently lumped together in the following empirical relation:

$$Q_{conv/rad} = \alpha \cdot \Delta T \tag{5.2}$$

Just like equation (5.1), this equation is only valid in a steady state. In equation (5.2), Qconv/rad denotes the heat in W/m^2 that is transferred, and ΔT represents the temperature difference. The symbol α denotes the heat transfer coefficient, which is expressed in W/m^{2}K. This heat transfer coefficient is composed of two components, namely a convective term α_{conv} and a radiative term α_{rad}. The magnitude of α_{conv} depends on the speed of the air flow. According to Boeke and van de Kraaij (1977), a value for α_{conv} of 2 W/m^{2}K can be used inside a building. Outdoors, the following approximate relation holds:

$$\alpha_{conv} = 6.2 + 4.2 \cdot v \tag{5.3}$$

In this equation, the symbol v denotes the air velocity in metres per second. Equation (5.3) illustrates that an air flow with a velocity of, for example, 3 metres per second corresponds with a value for α_{conv} of around 19 W/m^{2}K. Regarding the radiative term, it can be said that a value of 5 W/m^{2}K (Jaeckel and Okken, 1978) can be used for normal temperatures.

Now consider the heat transfer from a heated dwelling to the environment. The total heat flow through a wall can be expressed by the following equation:

$$Q_{tot} = \frac{1}{\frac{1}{\alpha_i} + \sum \frac{d}{\lambda} + \frac{1}{\alpha_e}} \cdot \Delta T \tag{5.4}$$

Equation (5.4) can also be written as:

$$Q_{tot} = k \cdot \Delta T \tag{5.5}$$

In this equation, the so-called k-value is expressed in W/ m^{2}K.

To quantify the effect of cavity wall insulation on the demand for natural gas, first the k-values of the walls of a dwelling in the situation without insulation and with insulation must be determined. After that, the difference in the k-values of these two situations can be used to determine the annual gas savings. For the calculation of the k-values, a traditional double brick wall, consisting of two layers of 105 mm thick brickwork with a λ-value of 0.7 W/mK (Jaeckel and Okken, 1978) is considered. In between the two brick layers, there is an air cavity of 60 mm that can be filled with insulation materials. On the inside, the wall is covered with 15 mm of gypsum plaster with a thermal conductivity of 0.9 W/mK (Jaeckel and Okken, 1978). For the inside of the room, a heat transfer coefficient α_i of 7 (= 2 + 5) W/m^{2}K can be used. When there is a wind of 3 metres per second blowing against the walls, the heat transfer coefficient for the outside α_e becomes 24 (= 19 + 5) W/m^{2}K.

When the air cavity is not filled with insulation materials, the k-value of the wall becomes:

$$k = \frac{1}{\frac{1}{\alpha_i} + \sum \frac{d}{\lambda} + \frac{1}{\alpha_e}} = \frac{1}{\frac{1}{7} + \frac{0.105}{0.7} + 0.10 + \frac{0.105}{0.7} + \frac{0.015}{0.9} + \frac{1}{24}}$$

$$k = 1.663 \tag{5.6}$$

In this equation, the 0.10 m^2K/W (Jaeckel and Okken, 1978) represents the total resistance of the air cavity.
Now the air cavity is filled with mineral wool with a coefficient of thermal conductivity of 0.035 W/mK (Bowdidge, 1990). The k-value in this situation becomes:

$$k = \frac{1}{\frac{1}{\alpha_i} + \sum \frac{d}{\lambda} + \frac{1}{\alpha_e}} = \frac{1}{\frac{1}{7} + \frac{0.105}{0.7} + \frac{0.06}{0.035} + \frac{0.105}{0.7} + \frac{0.015}{0.9} + \frac{1}{24}}$$

$$k = 0.451 \tag{5.7}$$

The difference in the k-values without and with insulation then becomes 1.212 (= 1.663 - 0.451) W/m^2K. This difference can be used to calculate the annual gas savings in the following way:

$$\Delta G = \frac{A \cdot 24 \cdot 3600 \cdot DD}{H \cdot \eta} \cdot \Delta k \tag{5.8}$$

In this equation, A denotes the inside measurement of the wall surface, DD denotes the average annual degree day value, H denotes the lower heating value of a normal cubic meter of natural gas, and η denotes the boiler efficiency.

For the average amount of degree days, a value of 3000 degree days per year (Macdaniel, 1980; Jaeckel and Okken, 1978) can be used when the inside temperature is set at 18·C. The lower heating value of a cubic meter of gas amounts to 31.65 MJ. When the interior surface of the dwelling is 120 m^2, and the boiler efficiency is 0.85, the annual gas savings become:

$$\Delta G = \frac{A \cdot 24 \cdot 3600 \cdot DD}{H \cdot \eta} \cdot \Delta k = \frac{120 \cdot 24 \cdot 3600 \cdot 3000}{31.65 \cdot 10^6 \cdot 0.85} \cdot 1.212$$

$$\Delta G = 1401.28 \ Nm^3 \ per \ year \tag{5.9}$$

The insulation of the cavity walls of this dwelling thus leads to annual savings of around 1400 Nm^3 gas. These savings agree well with other calculations of the natural gas savings resulting from cavity wall insulation, such as the studies by Jaeckel and Okken (1978) and Macdaniel (1980).

According to the Consumers Association (1990), the lifetime of the mineral wool that is used for the insulation of the cavity walls can be set at 20 years. This means that 28,000 (= 20 * 1,400) Nm^3 of natural gas will be saved over the lifetime of the insulation material. This is also the traditional engineering estimate of the energy savings resulting from cavity wall insulation. In reality, however, the total energy savings will not amount to

28,000 Nm^3 of natural gas or equivalently to 886,200 Megajoules (= 28,000 * 31.65 MJ), because a part of the energy savings is lost. The reason for this is the fact that cavity wall insulation is a very profitable energy conservation option.

According to the Consumers Association (1990) and Ybema and Okken (1992), the costs per square metre of cavity wall insulation amounts to 21 guilders. The costs of insulating the whole dwelling thus become 2,520 (= 120 * 21) guilders. The annual gas savings resulting from these insulation measures are 1,400 Nm^3. When the price per Nm^3 of natural gas is set at 0.50 guilders (Krachtkroniek, 1994), the annual amount of money that is saved becomes 700 (= 1,400 * 0.50) guilders. This money will be respent on various goods and services. All of these goods and services contain an amount of energy. Consequently, respending the money saved by the insulation measures results in a part of the energy savings being lost. De Paauw and Perrels (1993) studied the energy content of goods and services on a fairly detailed level. The results of their analysis indicate that the average energy content of goods and services amounts to 6.5 Megajoules per guilder spent. Now assume that the money that is saved by the insulation measures is respent on the average good or service with an energy content of 6.5 MJ/guilder, and assume that this average energy content will not change over the next 20 years. Further assume that the price changes over time of this average good or service are the same as the price rises of natural gas. Then the rebound-effect in this particular situation can be determined.

The annual gas savings are 1400 Nm^3. This corresponds with 700 guilders. When the house-owner pays the 2520 guilders for the insulation measures at the beginning of the 20-year lifetime of the insulation materials, the monetary savings in the first year will become -1820 (= 700 - 2520) guilders. This implies that besides saving 700 Nm^3 of natural gas, the house-owner will not be able to spend 1820 guilders on goods and services, containing an amount of energy. From this, the gas savings in the first year can be calculated. These savings namely amount to 56,140 MJ. This number is the addition of 44,310 (= 1400 * 31.65) MJ for the annual gas savings and 11,830 (= 1820 * 6.5) MJ for not being able to spend 1820 guilders on the average good or service. In the other 19 years, the house-owner will save 1400 Nm^3 gas and 700 guilders. The annual energy saving then become 39,760 MJ. This is an addition of 44,310 (= 1400 * 31.65) MJ for the annual gas savings and -4550 (= -700 * 6.5) MJ for respending the money saved by the insulation measures on the average good or service. The total energy savings over the lifetime of the insulation material of 20 years then become 811,580 (= 1 * 56,140 + 19 * 39,760) MJ.

The installation of cavity wall insulation will thus lead to energy savings that amount to 811,580 MJ. The engineering estimate of these energy savings higher, namely 886,200 MJ. The difference in the calculation of the energy savings between the engineering estimate and the real energy savings is caused by the rebound-effect. This feedback-effect can be defined as that part of the initially expected energy savings that is lost because of the energy-economy-environment interaction. In formula:

$$\text{rebound-effect} = \frac{\text{lost energy savings}}{\text{expected energy savings}} \qquad (5.10)$$

In this equation, the expected energy savings represent the traditional engineering estimate of the energy savings, resulting from energy efficiency improvements. This engineering approach does not take into account the fact that energy efficiency improvements lead to respending effects. As a result of this, the engineering approach tends to overestimate the net energy savings resulting from improvements in energy efficiency. In this particular case of cavity wall insulation, the engineering estimate of the energy savings is 886,200 MJ. Because of the respending of the money that is saved by the insulation measures, in reality only 811,580 MJ of energy is saved. The lost energy savings thus amount to 74,620 (= 886,200 - 811,580) MJ. With these lost energy savings and the expected energy savings, the rebound-effect can be calculated in the following way:

$$\textit{rebound-effect} = \frac{\textit{lost energy savings}}{\textit{expected energy savings}} = \frac{74{,}620}{886{,}200} = 0.084 \qquad (5.11)$$

This means that more than 8% of the expected energy savings is lost because of the feedback from the engineering measures to the economy.

Besides the fact that a part of the initially expected energy savings is lost because of respending effects, the net energy savings resulting from cavity wall insulation are in reality even smaller. The reason for this is the fact that the mineral wool that is used for the insulation purpose must be manufactured. Also the raw materials that are needed to produce the insulation material must be mined and transported to the factory. Moreover, the insulation material must be distributed from the factory floor to the location where it will be used. All of these steps require an amount of energy. In addition to this direct energy requirement, there is an indirect energy requirement in the production of the mineral wool. This indirect energy requirement, for example, involves the energy needed for the construction of the plant and the production processes. According to Boustead and Hancock (1979), the energy involved in the direct manufacture of the mineral wool insulation material amounts to 14 MJ/kg. Now assume that another 14 MJ/kg is required, either directly or indirectly, in the rest of the entire process. Then the total energy requirement for the mineral wool becomes 28 MJ/kg. In this case study, a traditional double brick wall with an air cavity of 60 mm is considered. It is assumed that the total surface of the walls amounts to 120 m^2. This means that 7.2 (= 120 * 0.06) m^3 of mineral wool is needed to insulate the cavity walls in this particular case. According to Bowdidge (1990), a characteristic density of 28 kg/m^3 can be used for the mineral wool that is used for cavity wall insulation. The 7.2 m^3 mineral wool that is used in this case thus corresponds with 201.6 (= 7.2 * 28) kg insulation material. Now recall that the energy content of 1 kg of mineral wool amounts to 28 MJ. Then, the amount of insulation material that is used to fill the air cavity in this particular case represents an energy content of 5645 (= 28 * 201.6) MJ. So, when besides the energy that is lost because of the respending of the money that is saved by the insulation measures, also the energy content of the insulation material is taken into account, the lost energy savings become 80,265 (= 74,620 + 5,645) MJ instead of 74,620 MJ. This in turn implies that the magnitude of the rebound-effect also changes:

$$\textit{rebound-effect} = \frac{\textit{lost energy savings}}{\textit{expected energysavings}} = \frac{80{,}265}{886{,}200} = 0.091 \qquad (5.12)$$

The rebound-effect thus becomes somewhat larger than in the situation in which the energy content of the insulation material is not considered.

Now one could argue that the price increases of natural gas and the average good or service will probably not remain the same. And one could also argue that the average energy intensity of goods and services will probably not remain constant at 6.5 MJ/guilder in the course of time. This however does not change the idea behind the quantification of the rebound-effect. Besides this, it is very difficult to predict the price of a Nm^3 of natural gas and the average energy intensity of goods and services in the future. It is, for example, frequently urged by numerous authors that the average energy intensity per guilder spent will decline in the future, as a result of the shift from the energy-intensive industrial society to the society in which the energy-extensive service sector is dominant. Other authors, such as Gilmer (1977) and Gershuny (1977,1978), however argue that the service sector itself is rather energy-intensive and that the energy to GDP ratio will not decline in the future. Therefore, a constant average energy intensity of 6.5 MJ/guilder is used throughout the planning horizon in the calculation of the rebound-effect in this case study.

6. THE REBOUND-EFFECT AND THE CONSUMER

6.1 Introduction

In the preceding chapter, an introduction into the rebound-effect has been given. In this chapter, the rebound-effect is outlined for the consumption-side of the economy. This rebound-effect results from improvements in the energy efficiency of appliances. In the context of the rebound-effect, the term appliance should be interpreted in a generic sense, in order to include all energy-using durables. This means that besides appliances such as TV's and dishwashers, also durables such as cars and central heating systems must be considered. Paragraph 6.2 discusses the shortcomings of the traditional engineering estimation of the effect of energy efficiency improvements of appliances on the demand for energy. In paragraph 6.3, the substitution and income effect are explained. Paragraph 6.4 contains a simple consumer behaviour model.

6.2 Mechanical determination of energy efficiency

The discussion of the consumption-side of the rebound-effect starts with the energy demand models of the late 1960s and early 1970s. After the oil crisis of 1973, serious doubts were expressed regarding the accuracy with which these models predicted the consumer demand for energy. An important shortcoming of the then existing models namely was that they were unable to quantify the effects of energy efficiency improvements of appliances on the total demand for energy. The oil price hike resulted in an awareness of the importance of energy conservation. The pre-oil crisis models were only capable of predicting demand under business-as-usual conditions, in which energy efficiency trends were extrapolated from historical patterns. During and after the oil price hike, however, the historical pattern regarding energy efficiency was fundamentally altered.

As a solution to the dissatisfaction with the energy demand models that existed before the oil crisis, models were developed that could capture the effects of energy efficiency improvements on the total demand for energy. Because a large part of the efficiency improvements were a result of changes in the engineering characteristics of appliances, it was argued that only so-called engineering models could accurately predict the impact of conservation measures on the energy demand. Examples of these engineering models are the ORNL (Oak Ridge National Laboratory) Residential Model of Energy Use (Hirst and Carney, 1978) and the REEPS (Residential End-use Energy Policy System) Model developed by Cambridge Systematics (Goett, McFadden, and Earl, 1982).

But also the engineering approach does not correctly quantify the impact of conservation measures on the demand for energy. The reason for this is that the determination of the impact of energy conservation on total energy demand by engineering models is essentially, as J. Daniel Khazzoom (1980,1986,1987,1989) calls it, mechanical. This means that with an improvement of appliance efficiency by some percentage, engineering models predict that the energy demand of that appliance will drop by an equal amount. So, when the average appliance efficiency increases by 1%, engineering models predict that as a result of this, energy demand will drop to 99.01% (=1/1.01) of its original level; when the average efficiency goes up by 2%, demand is predicted to drop to 98.04% (=1/1.02) of its original level; and so on.

At first sight, this thought appears to be plausible. And for an engineer in a research institute, a change in energy efficiency should lead to an equal but opposite change in the demand for energy. The engineer namely assumes that the same amount of service will be provided by a more efficient appliance. But while this thought may be true in an isolated research environment, it cannot simply be extended to society. One cannot ignore the impact of engineering measures to improve the energy efficiency on society, as if these conservation measures live a life of their own.

The reason for this is that besides the engineering side, there is also an economic side to the problem. The purchase of a more energy efficient appliance namely has implications for the price per unit of service that the appliance delivers. For example, investing in energy-efficient lighting will have consequences for the price per unit of illumination. Also buying a more efficient air-conditioner will lead to a change in the price per unit of cooling. Another example is the fact that the purchase of a more fuel-efficient car will lead to a change in the price per vehicle-kilometre. Because of these changes in the price per unit of service, consumers will react by changing the way in which they spend their money.

Since traditional engineering models neglect the fact that changes in appliance efficiency also have an economic component to them, the traditional engineering approach exaggerates the energy savings that result from improvements in energy efficiency. More realistic models should take into account the fact that energy efficiency influences demand in the same way as, for instance, income or the price of fuel. To achieve this, an economic component must be added to the engineering models to allow for a feedback effect (the rebound-effect). When this effect is taken into consideration, economic forces that are the result of efficiency improvements can be determined. These economic forces result in a modification of the initially predicted energy savings.

6.3 The substitution and income effect

Consumers will react to changes in the energy efficiency of appliances. This can be clarified by means of an example, concerning the purchase of a more efficient appliance, such as an air-conditioner. It is assumed that the purchase of this appliance will result in a decrease in the price per unit of cooling, which includes both the energy costs and capital costs. This means that besides an amount of energy, the consumer will also save an amount of money.

When the price per unit of service of an appliance decreases, the appliance will become less expensive relative to other goods and services. This may lead to an increased demand for the service that this appliance delivers. In economic theory, this type of rebound-effect is called the price or substitution effect. Empirical evidence for the fact that efficiency improvements lead to demand increases seems to be provided by Clifton T. Jones (1993), who studied the effect of increased motor vehicle efficiency on the demand for travelling. The results of Jones' investigation namely indicate that about 30% of the energy-saving benefits associated with fuel efficiency improvements of cars are offset by an increased travelling demand, which is initiated by these efficiency improvements. Other evidence of this type of rebound-effect was given by Adams and Rockwood (1983), who conclude from monitoring house-owners who insulated their dwellings that a 20% increase in the thermal efficiency of residential buildings only yields 8% energy savings in gas-heated homes and 14% savings in electrically-heated homes. This feedback-effect is a result of increases in the temperature setting and other behavioural changes. Similar results are also obtained by Hirst and White (1985). After analyzing specific electricity and gas billing data for several years, they conclude that between 5% and 25% of the energy savings due to retrofitting is taken back in terms of increased comfort.

The substitution effect however does not tell the whole story. A decrease in the price per unit of service of an appliance namely not only increases the service demand of that appliance, but it may also lead to an increased demand for other goods and services. This type of rebound-effect is called the income effect in economic theory. The income effect stems from the fact that the purchase of a more efficient appliance leads to an amount of money being saved. This money, which can be seen as additional income, will ultimately be respent on various goods and services, all containing an amount of energy. An example of this type of rebound-effect is the fact that the money that is saved by the lower running costs of the air-conditioner is respent on increased car use. Also the case study of chapter 5, in which the money that is saved by cavity wall insulation is respent on average goods and services, is an example of the income effect. According to de Paauw and Perrels (1993), the average amount of energy per guilder expenditure amounts to 6.5 MJ/guilder. Therefore, this type of rebound-effect is not of a negligible magnitude.

Besides these two causes, there may also exist another possible cause for the rebound-effect. This cause refers to the fact that energy efficiency improvements may lead to a reduction in the demand for energy carriers, such as oil and gas. As a result of this, the pressure on energy supply may fall and the prices of oil and gas may drop, thereby inducing an increased demand for these energy carriers. The problem with this rebound-effect is that the effect of a decreased demand for oil and gas on the price of these energy carriers is difficult to predict. Therefore, this type of rebound-effect will not be considered in this study.

6.4 A simple consumer behaviour model

As a result of the substitution and income effect, energy efficiency improvements do not lead to proportionate reductions in the demand for energy. The underlying reason for this rebound-effect is the fact that consumers do not want to minimize energy costs but rather want to maximize utility. This can be illustrated with the following consumer behaviour model. In this model, the purchase and utilization of an energy-using appliance such as an air-conditioner is described for a consumer who must replace his old appliance which has gone out of order.

When an air-conditioner is purchased or replaced, a consumer has the option of choosing from a number of different types of air-conditioning. In this consumer behaviour model, two types of air-conditioning which both deliver the same amount of service are considered. Generally, a consumer who is well informed about the purchase price, energy efficiency, and service level of different types of appliances will choose the appliance type which best balances the added purchase costs of higher efficiency against the reduction in operating costs. Therefore, the two types of air-conditioners that are considered are a less energy efficient air-conditioner with a lower purchase price (air-conditioner 1) and a more efficient air-conditioner with a higher purchase price (air-conditioner 2). This tradeoff between the lower operating costs for the more efficient appliance and the lower capital costs for the less efficient appliance is an important element in the model.

In the model, the following notation will be used:

SU = service units.
MU = money units.
EU = energy units.

X = flow of service provided by the appliance (air-conditioner) in [SU].
Y = flow of service provided by all other goods in [SU].

P_X = price per unit of service of the appliance in [MU / SU].
P_Y = price per unit of service of all other goods in [MU / SU].

M = total income of the consumer in [MU].
Q = purchase price of the appliance in [MU].

P_e = price of energy in [MU / EU].
e = efficiency, measured in units of delivered service per unit of energy consumed in [SU / EU].

A consumer desires the services provided by the air-conditioner X and all other goods Y, which can be summarized in the utility function U (X, Y). These services cannot be consumed infinitely, since the consumer has a limited amount of money at his disposal. The budget constraint that the consumer faces is that the purchase price of the appliance plus the price of the service delivered by the appliance and all other goods may not exceed the consumer's income:

$$P_X \cdot X + P_Y \cdot Y + Q \leq M \tag{6.1}$$

A rational consumer will choose that combination of X and Y which yields the highest utility under the given budget constraint. The amount of service of X and Y that is demanded in the optimal situation depends on the type of utility function that is used. In this model, a CES (Constant Elasticity of Substitution) utility function is utilized. The CES utility function is given by:

$$U(X, Y) = [\, \alpha \cdot X^{-\rho} + (1-\alpha) \cdot Y^{-\rho} \,]^{-\frac{1}{\rho}} \tag{6.2}$$

To calculate the demand for the service of X and Y, consider the Lagrangian with multiplier λ:

$$L = (\alpha \cdot X^{-\rho} + (1-\alpha) \cdot Y^{-\rho})^{-\frac{1}{\rho}} + \lambda \cdot (M - Q - P_X \cdot X - P_Y \cdot Y) \tag{6.3}$$

With this Lagrangian, the first-order conditions can be derived:

$$L_X = -\frac{1}{\rho} \cdot (\alpha \cdot X^{-\rho} + (1-\alpha) \cdot Y^{-\rho})^{-\frac{1}{\rho}-1} \cdot -\rho \cdot \alpha \cdot X^{-\rho-1} - \lambda \cdot P_X = 0$$

or:

$$-\frac{1}{\rho} \cdot (\alpha \cdot X^{-\rho} + (1-\alpha) \cdot Y^{-\rho})^{-\frac{1}{\rho}-1} \cdot -\rho \cdot \alpha \cdot X^{-\rho-1} = \lambda \cdot P_X \tag{6.4}$$

and:

$$L_Y = -\frac{1}{\rho} \cdot (\alpha \cdot X^{-\rho} + (1-\alpha) \cdot Y^{-\rho})^{-\frac{1}{\rho}-1} \cdot -\rho \cdot (1-\alpha) \cdot Y^{-\rho-1} - \lambda \cdot P_Y = 0$$

or:

$$-\frac{1}{\rho} \cdot (\alpha \cdot X^{-\rho} + (1-\alpha) \cdot Y^{-\rho})^{-\frac{1}{\rho}-1} \cdot -\rho \cdot (1-\alpha) \cdot Y^{-\rho-1} = \lambda \cdot P_Y \tag{6.5}$$

Now divide the first-order condition (6.4) by the first-order condition (6.5). This results in:

$$\frac{\alpha \cdot X^{-\rho-1}}{(1-\alpha) \cdot Y^{-\rho-1}} = \frac{P_X}{P_Y} \tag{6.6}$$

This equation can also be written as:

$$X^{-\rho-1} = \frac{P_X}{P_Y} \cdot \frac{(1-\alpha)}{\alpha} \cdot Y^{-\rho-1} \tag{6.7}$$

or:

$$X = \left(\frac{P_X}{P_Y} \cdot \frac{(1-\alpha)}{\alpha} \right)^{-\frac{1}{1+\rho}} \cdot Y \tag{6.8}$$

Now substitute the X from equation (6.8) into the budget constraint (6.1) to obtain the demand for Y:

$$M = Q + P_X \cdot \left(\frac{1-\alpha}{\alpha} \cdot \frac{P_X}{P_Y} \right)^{-\frac{1}{1+\rho}} \cdot Y + P_Y \cdot Y \tag{6.9}$$

or:

$$M - Q = Y \cdot \left(P_X \cdot \left(\frac{1-\alpha}{\alpha} \cdot \frac{P_X}{P_Y} \right)^{-\frac{1}{1+\rho}} + P_Y \right) \tag{6.10}$$

$$Y = \frac{M - Q}{P_X \cdot \left(\frac{1-\alpha}{\alpha} \cdot \frac{P_X}{P_Y} \right)^{-\frac{1}{1+\rho}} + P_Y} \tag{6.11}$$

In a similar manner, the demand for X can be derived. Recall equation (6.6). This equation can be rewritten as:

$$Y^{-\rho-1} = \frac{P_Y}{P_X} \cdot \frac{\alpha}{1-\alpha} \cdot X^{-\rho-1} \tag{6.12}$$

or:

$$Y = \left(\frac{P_Y}{P_X} \cdot \frac{\alpha}{1 - \alpha} \right)^{-\frac{1}{1+\rho}} \cdot X \tag{6.13}$$

Now substitute the Y from equation (6.13) into the budget constraint to obtain the demand for X:

$$M = Q + P_X \cdot X + P_Y \cdot \left(\frac{P_Y}{P_X} \cdot \frac{\alpha}{1 - \alpha} \right)^{-\frac{1}{1+\rho}} \cdot X \tag{6.14}$$

or:

$$M - Q = X \cdot \left(P_X + P_Y \cdot \left(\frac{P_Y}{P_X} \cdot \frac{\alpha}{1 - \alpha} \right)^{-\frac{1}{1+\rho}} \right) \tag{6.15}$$

$$X = \frac{M - Q}{P_X + P_Y \cdot \left(\frac{P_Y}{P_X} \cdot \frac{\alpha}{1 - \alpha} \right)^{-\frac{1}{1+\rho}}} \tag{6.16}$$

To determine the rebound-effect in this consumer behaviour model, recall the two air-conditioners. Air-conditioner 1 represents the less efficient appliance with the lower purchase price. This piece of equipment is a new version of the old appliance which has gone out of order. Air-conditioner 2 represents the more efficient appliance with the higher purchase price. The following values are chosen for the parameters in this model:

α = 0.1 in [-].
ρ = 0.5 in [-].
P_e = 15 in [MU / EU].
Q_1 = 1000 in [MU].
Q_2 = 1200 in [MU].
M = 10000 [MU].
e_1 = 0.5 in [SU / EU].
e_2 = 0.75 in [SU / EU].

The price P_X per unit of service for the air-conditioners is determined by the energy costs:

$$P_X = \frac{P_e}{e} \tag{6.17}$$

For air-conditioner 1, the efficiency amounts to 0.5 units of service per unit of energy. The efficiency of air-conditioner 2 is 50% higher, namely 0.75 [SU / EU]. With these efficiencies and a price per unit of energy of 15 Money Units, the price per unit of service for the air-conditioners can be calculated:

$$P_{X_1} = \frac{P_e}{e_1} = \frac{15}{0.5} = 30 \quad [MU / SU] \tag{6.18}$$

$$P_{X_2} = \frac{P_e}{e_2} = \frac{15}{0.75} = 20 \quad [MU\ /\ SU] \tag{6.19}$$

The efficiency of all other goods Y is 3 [SU / EU]. This means that one unit of energy is required for three service units of all other goods. The price per unit of Y is partially determined by energy costs and partially by non-energy costs. The price P_Y is:

$$P_Y = \frac{P_e}{e_Y} + P_{non-energy} = \frac{15}{3} + 5 = 10 \quad [MU\ /\ SU] \tag{6.20}$$

With these numbers, the demand for X and Y can be calculated for situation 1 in which the less energy efficient air-conditioner 1 is purchased and for situation 2 in which the more efficient air-conditioner 2 is purchased:

$$X_1 = \frac{M - Q_1}{P_{X_1} + P_Y \cdot \left(\frac{\alpha}{1-\alpha} \cdot \frac{P_Y}{P_{X_1}} \right)^{-\frac{1}{1+\rho}}} = \frac{10000 - 1000}{30 + 10 \cdot \left(\frac{0.1}{0.9} \cdot \frac{10}{30} \right)^{-\frac{1}{1+0.5}}}$$

$$X_1 = 75 \tag{6.21}$$

$$Y_1 = \frac{M - Q_1}{P_Y + P_{X_1} \cdot \left(\frac{1-\alpha}{\alpha} \cdot \frac{P_{X_1}}{P_Y} \right)^{-\frac{1}{1+\rho}}} = \frac{10000 - 1000}{10 + 30 \cdot \left(\frac{0.9}{0.1} \cdot \frac{30}{10} \right)^{-\frac{1}{1+0.5}}}$$

$$Y_1 = 675 \tag{6.22}$$

$$X_2 = \frac{M - Q_2}{P_{X_2} + P_Y \cdot \left(\frac{\alpha}{1-\alpha} \cdot \frac{P_Y}{P_{X_2}} \right)^{-\frac{1}{1+\rho}}} = \frac{10000 - 1200}{20 + 10 \cdot \left(\frac{0.1}{0.9} \cdot \frac{10}{20} \right)^{-\frac{1}{1+0.5}}}$$

$$X_2 = 99.23 \tag{6.23}$$

$$Y_2 = \frac{M - Q_2}{P_Y + P_{X_2} \cdot \left(\frac{1-\alpha}{\alpha} \cdot \frac{P_{X_2}}{P_Y} \right)^{-\frac{1}{1+\rho}}} = \frac{10000 - 1200}{10 + 20 \cdot \left(\frac{0.9}{0.1} \cdot \frac{20}{10} \right)^{-\frac{1}{1+0.5}}}$$

$$Y_2 = 681.54 \tag{6.24}$$

With these demands, the energy use can be calculated for the two situations:

$$\textit{energy use for X in situation 1} = \frac{X_1}{e_1} = \frac{75}{0.5} = 150\ EU \tag{6.25}$$

$$\textit{energy use for Y in situation 1} = \frac{Y_1}{e_Y} = \frac{675}{3} = 225 \; EU \tag{6.26}$$

$$\textit{total energy use in situation 1} = 150 + 225 = 375 \; EU \tag{6.27}$$

$$\textit{energy use for X in situation 2} = \frac{X_2}{e_2} = \frac{99.23}{0.75} = 132.31 \; EU \tag{6.28}$$

$$\textit{energy use for Y in situation 2} = \frac{Y_2}{e_Y} = \frac{681.54}{3} = 227.18 \; EU \tag{6.29}$$

$$\textit{total energy use in situation 2} = 132.31 + 227.18 = 359.49 \; EU \tag{6.30}$$

Now recall that the air-conditioner which has gone out of order was of the less energy efficient type 1. This air-conditioner must be replaced with either a new type 1 (less efficient, lower purchase price) or a type 2 (more efficient, higher purchase price) appliance. To determine the preference for air-conditioner 1 or air-conditioner 2, the demands X_1, Y_1, X_2, and Y_2 must be substituted in the CES utility function:

$$U_1 = (\alpha \cdot X_1^{-\rho} + (1-\alpha) \cdot Y_1^{-\rho})^{-\frac{1}{\rho}} = (0.1 \cdot 75^{-0.5} + 0.9 \cdot 675^{-0.5})^{-\frac{1}{0.5}}$$

$$U_1 = 468.75 \tag{6.31}$$

$$U_2 = (\alpha \cdot X_2^{-\rho} + (1-\alpha) \cdot Y_2^{-\rho})^{-\frac{1}{\rho}} = (0.1 \cdot 99.23^{-0.5} + 0.9 \cdot 681.54^{-0.5})^{-\frac{1}{0.5}}$$

$$U_2 = 504.69 \tag{6.32}$$

Since U_2 is greater than U_1, the more efficient air-conditioner 2 is preferred.

In situation 1, the demand for air-conditioning amounts to 75 units of service. To deliver this amount of service, 150 (= 75 / 0.5) Energy Units are required. Because the total amount of energy required for all other goods Y amounts to 225 Energy Units, the total energy use in situation 1 is 375 (= 150 + 225) Energy Units. In situation 2, the efficiency of the air-conditioner has increased by 50% from 0.5 to 0.75, compared with air-conditioner 1. The traditional engineering approach now assumes that as a result of this energy efficiency improvement, the energy use for air-conditioning in situation 2 will drop from 150 Energy Units to 100 (= 75 / 0.75) Energy Units. Because the traditional engineering approach also assumes that the energy use for all other goods remains 225 Energy Units, the engineering prediction of the consumer's energy use in situation 2 is 325 (= 100 + 225) Energy Units and the expected energy savings amount to 50 (= 375 - 325) Energy Units.

In reality, however, the energy use in situation 2 amounts to 359.49 Energy Units. The reason for the fact that the engineering estimate of the energy savings is higher than the actual energy savings is that the traditional engineering approach does not consider the interaction between the energy system and the economic system in its analysis. More energy efficient appliances reduce the price per units of service they deliver. As a result of this, an amount of money is saved. This money will be respent on an increased demand for air-conditioning and all other goods. This results in energy savings which are smaller than those projected by the traditional engineering approach. In this particular case, the lost energy savings amount to 34.49 (= 359.49 - 325) Energy Units.

With these lost energy savings of 34.49 Energy Units and the expected energy savings of 50 energy units, the rebound-effect can be calculated:

$$\textit{rebound-effect} = \frac{\textit{lost energy savings}}{\textit{expected energy savings}} = \frac{34.49}{50} = 0.690 \qquad (6.33)$$

The rebound-effect in this particular case thus amounts to 69%. This means that almost 70% of the engineering estimate of the energy savings is lost because of the feedback from the engineering measures to the economy. No real meaning must however be attached to the magnitude of the rebound-effect in this consumer behaviour model, since the values adopted for the parameters in the model are not estimated by empirical research. The consumer behaviour model has merely been used to clarify the underlying thought behind the calculation of this feedback-effect. A more realistic determination of the rebound-effect can be obtained with the aid of the MARKAL-MACRO model.

7. QUANTIFICATION OF THE REBOUND-EFFECT WITH MARKAL-MACRO

7.1 Introduction

In chapter 6, the rebound-effect and the consumer has been described. In this chapter, an attempt is made to determine the magnitude of this rebound-effect on the consumption-side of the economy. An estimation of the effect of energy efficiency improvements on the demand for energy can be obtained with the aid of the MARKAL-MACRO model. Paragraph 7.2 contains a description of this MARKAL-MACRO computer model. Paragraph 7.3 presents the calculation of the rebound-effect.

7.2 Description of the MARKAL-MACRO model

Since the rebound-effect is a result of the energy-economy-environment interaction, it can only be determined with a model that integrates these three aspects. The MARKAL-MACRO model is such an integrated model. In MARKAL-MACRO, two models are formally linked together. These models are the systems engineering model MARKAL and the long-term macroeconomic growth model MACRO.

7.2.1 The MARKAL model

The MARKAL (acronym for MARKet ALlocation) model was developed between 1976 and 1981 by the members of the Energy Technology Systems Analysis Programme (ETSAP) under the auspices of the International Energy Agency (IEA) (Fishbone, 1983; Rowe and Hill, 1989). ETSAP was initiated in order to provide the IEA with an analytical tool for evaluating energy technologies within the context of national energy systems. The MARKAL model has been used for assessments of the national energy systems for most IEA countries. It has also been used as an aid for energy planners in developing nations such as Brasil, China, and Indonesia. At a lower level of aggregation, MARKAL has been used to analyze regional energy systems in Canada and community energy systems in Sweden.

MARKAL is a technologically oriented linear programming model of an energy system. In any energy system, primary energy sources are first extracted and then transformed by various supply technologies into a number of energy carriers, such as oil and gas. These energy carriers in turn are ultimately used by a vast number of end-use technologies for the purpose of satisfying human demands for particular energy services. In order to accurately represent such an energy system, the MARKAL model is built on the concept of a RES (Reference Energy System). The RES is a flowchart indicating all possible routes from each source of primary energy through various conversion processes to all service demands for energy. The flowchart can also incorporate the emissions resulting from activities in which energy is transported or converted. With the aid of the Reference Energy System, the MARKAL model can identify those routes and technologies that best satisfy the stated policy goals.

Since MARKAL is a data-driven model, the results of the MARKAL runs depend heavily on the quality of the input data. To build the model, the following four broad categories of data are required:

- Technologies and their characteristics. In MARKAL, a technology is described by technical and economic data, such as the efficiency of a process, the useful lifetime of the technology, the investment costs per unit of capacity, the operating and maintenance costs of the technology, and the datum of availability of a new technology. The scale of the technologies incorporated in the model may be either large or small. An integrated coal-gasification combined-cycle electricity generation station is an example of a large technology. Energy-efficient lighting and electric cars are examples of small-scale technologies. Technologies and their characteristics represent most of the input data in a MARKAL data-base.
- Primary energy sources. Primary energy may be expressed as oil and gas wells, coal and uranium mines, and biomass raw material. A source of primary energy is normally represented by a graph indicating the potential for extraction and the associated extraction costs. The MARKAL model also incorporates import and export of primary energy sources.
- Useful energy demands. The demands for useful energy do not refer to specific fuels. They rather refer to the service that a fuel renders. Examples of useful energy demands are automobile passenger-kilometres, units of thermal comfort of dwellings, and tons of steel. The service demands for energy are divided into several sectors, such as industry, transportation, and residential. These sectors may in turn be further disaggregated into subsectors.
- Environmental constraints. Since the negative effects of human activity on the environment are more and more acknowledged, emission reduction strategies are becoming increasingly important. Therefore, environmental constraints that limit the emissions of carbon dioxide, sulphur dioxide, and nitrogen oxides may be incorporated in MARKAL.

In any computer model, the values for the parameters are either supplied as input data (exogenous) or calculated by the model (endogenous). In MARKAL, exogenous quantities are for instance prices of specific fuels, useful energy demands per sector and subsector, and the unit costs of technologies. Examples of endogenous parameters are the quantity of each specific fuel that is used in each time period, and the utilized capacity of each technology in each time period. The endogenous parameters are called variables. In the MARKAL model, these variables are tied together by a number of logical relationships, which are called the constraints of the model. The most important constraints refer to the satisfaction of useful energy demands, the limits of the capacity of technologies, and the maximum allowable emissions.

MARKAL is solved by means of dynamic linear programming. This implies that in MARKAL the values of all model variables are determined simultaneously in such a way that the constraints are satisfied and the objective function in minimized. The objective function in MARKAL is the total net present value of the energy system's costs throughout the planning horizon.

7.2.2 The MACRO model

The MACRO model is a neoclassical macroeconomic growth model, which takes an aggregate view of long-term economic developments (Manne and Richels, 1992). MACRO incorporates one economy-wide production function. The factors of production for the model are capital, labour, and individual demands for useful energy. These input factors enter into the production function, which is a nested CES function. The nesting scheme of the production function is [(K,L), E]. This particular nesting has capital and labour combining Cobb-Douglas fashion and the two together combining CES fashion with energy. Because the production function has a nested nonlinear form, the MACRO model is characterized by smooth substitution. With its nonlinearity, a small price change of one of the input factors leads to a small change in the mix of inputs. This outcome could not be obtained by linear programming models, such as MARKAL. With these models, a so-called penny-switching effect is namely often encountered. This means that a small change in a variable will either lead to almost no effect or else to a very large effect.

The economy's output in MACRO is used for investment, consumption, and inter-industry payments for the cost of energy. Investment is used for capital accumulation. In each period, the net increase in the stock of capital is determined by investment minus depreciation. The long-term growth rate of the economy in MACRO is determined primarily by the value adopted for the growth of the labour force and its productivity. The combination of these two factors is expressed in labour efficiency units.

MACRO is solved by means of dynamic nonlinear optimization. In each time period, the MACRO model selects among the possible combinations of investment, consumption, and energy cost payments in order to maximize the objective function of maximum discounted utility of consumption. MACRO is dynamic in the same sense as MARKAL, which means that MACRO uses lookahead features for optimizing the objective function over the entire planning horizon. This is called perfect foresight.

7.2.3 The limitations of the stand-alone versions of MARKAL and MACRO

There are two different approaches towards the modeling of the energy-economy-environment interaction. These competing modeling techniques, which are called the top-down approach and the bottom-up approach, reach very different conclusions and recommendations on subjects which concern the 3-E interaction (Krause, 1993; Wilson and Swisher, 1993). This can be illustrated by means of the answer to the fundamental question in the greenhouse debate of how much it would cost to reduce greenhouse gas emissions. Both in the top-down and bottom-up approach, the costs of reducing carbon dioxide emissions are determined by comparing scenarios in which there is an upper-bound set on greenhouse gas emissions with a business-as-usual scenario. The difference between the two competing views is that in the top-down approach carbon dioxide reduction measures will increase the costs with which the energy supply system delivers the needed energy services. In the bottom-up approach, on the other hand, carbon dioxide reduction measures result in energy costs that are lower than in the business-as-usual situation. As a result of this, very different policy measures are being put forward by the two approaches.

In the top-down approach, the relations between the energy system, the economy, and the environment are mainly studied from a macroeconomic perspective. Examples of top-down analyses are the studies by Manne and Richels (1990) and Nordhaus (1990). Also the MACRO model has a macroeconomic orientation. The name top-down refers to the high aggregation level of this approach. The most important input assumptions for top-down models are projections of GNP growth rates; price forecasts for capital, labour, and energy; the elasticity of price-induced substitution between the three input factors; and the rate of non-price-induced changes in the energy intensity per unit of economic output.

The strength of the top-down approach is that the interactions between the energy system and the economic system are fairly accurately represented. Doubts however can be expressed regarding the accuracy with which the energy sector itself is described. Because of the macroeconomic orientation of top-down assessments, the energy sector is namely modeled by only a few equations. This implies that most of the energy technologies are not incorporated. Another important shortcoming of the top-down approach is its empirical foundation. In top-down models, for example, the future demand for energy is forecasted on the basis of historic relationships between energy use, energy prices, and economic output. This is a backward-looking approach. The problem with such an approach is the fact that historic relationships do not explain how things work. For this reason, the extrapolation of historical data into the future is only reliable if the system from which the data are obtained does not change too much over time. In the changing world of today, using historical data to predict future developments in the energy system is not very reliable. By assuming that everything will be the same in the future as it was in the past, new energy technologies that can provide the same service with less energy are not included. Also saturation effects in the demand for energy services are not taken into account in top-down assessments.

Because of the highly simplified description of the energy sector and the backward-looking approach, top-down models tend to systematically overestimate future demands for energy. Another implication of the shortcomings of the top-down approach concerns the estimation of the cost of carbon dioxide reduction strategies. The models that are utilized in top-down assessments determine the impact of carbon dioxide reduction strategies by calculating the effects of carbon taxes on overall economic performance. This means that carbon dioxide reduction measures are seen as opportunity costs. As a result of the overestimation of future energy demands and the limited technological options for reducing carbon dioxide emissions, macroeconomic models tend to overestimate the costs of carbon emission reductions.

In the bottom-up approach, the relations between the energy system, the economy, and the environment are analyzed from an engineering perspective. Examples of bottom-up approaches are the studies by Lovins and Lovins (1991) and Williams (1990). Also the MARKAL model has an engineering orientation. The name bottom-up refers to the fact that this approach begins its analysis with the consumer demands for energy services, such as heating, cooling, and lighting. The focus is thus on technologies that provide energy services, rather than on energy carriers, such as oil and gas. In bottom-up models, energy technologies that can provide the desired energy services are included. Also alternative state-of-the-art technologies that deliver the same amount of service with lower energy requirements are incorporated. The thought behind this is that the existing energy technologies have finite lifetimes, and that energy efficient state-of-the-art technologies can replace these existing technologies when they are written of. The most important input assumptions for bottom-up models are the costs and energy consumption of existing technologies and their state-of-the-art alternatives; the penetration rate of alternative technologies; the prices of specific fuels; and the consumer demands for various energy services.

The main strength of bottom-up models is that a very accurate and extensive representation of existing and alternative technologies in the energy system is used. A very important shortcoming of the bottom-up approach is that the economic feedback effects resulting from changes in the energy system are not included. For example, the effect of the introduction of more energy efficient technologies on the demand for energy services is not taken into account. The models used in the bottom-up approach thus only deal with demands for energy services and technologies that can deliver these services. They are not capable of quantifying the effect of changes in the energy sector on the other sectors of the economy or on economic output.

With respect to carbon dioxide reduction strategies, the bottom-up approach only calculates the costs of carbon dioxide emission reductions as energy expenditures, and not as opportunity costs. In fact, many top-down modellers argue that these energy expenditures are negative because a large part of the more energy efficient technologies are profitable. This in turn implies that it is the business-as-usual scenarios that entail the opportunity costs. When carbon dioxide reduction strategies save money, not carrying out these strategies will result in a lower than possible overall economic performance. The bottom-up approach thus reaches very favourable conclusions on the ability of energy technologies to mitigate the global warming problem. The problem with bottom-up assessments however is that by neglecting economic feedback-effects, the bottom-up approach underestimates the costs of carbon dioxide reduction strategies.

7.2.4 The MARKAL-MACRO model

It is thus difficult to compare the outcomes of top-down and bottom-up analyses. The reason for this is that the language of the two approaches is rather different. This problem is partially caused by the fact that the two modeling techniques originate from different academic disciplines. Another part of the problem is caused by the fact that the two modeling approaches are not asking the same question. The models were namely developed for different purposes. Because the two approaches were designed for different reasons, each of them possesses certain distinguishable qualities. However, both top-down and bottom-up models also suffer from serious shortcomings. To overcome these limitations of the stand-alone versions of top-down models such as the MACRO model and bottom-up models such as the MARKAL model, the MARKAL-MACRO model has been developed (Hamilton, 1992; Kypreos, 1992). With MARKAL-MACRO, an attempt is made to reconcile the macroeconomic and the systems engineering approach. The integrated model unites MACRO's aggregate economic view together with MARKAL's detailed description of the different technologies in the energy system.

With MARKAL-MACRO, the interaction between economic activity, the energy demands associated with this activity, and the energy system that must supply these demands can be investigated. As a result of this, MARKAL-MACRO can be seen as a tool to enhance the understanding between the engineer, the economist, and the policy maker. In figure 7.1, an overview of the MARKAL-MACRO model is given.

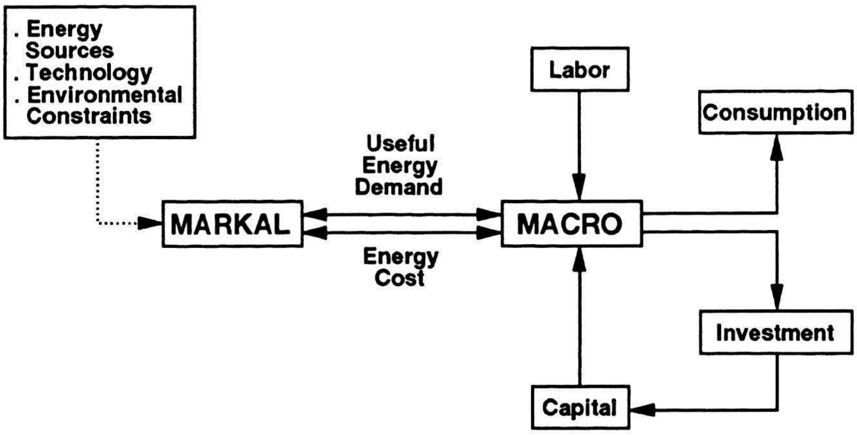

Figure 7.1 *The MARKAL-MACRO model*

In order to keep the need for structural changes in the two original models to a minimum, only two types of linkage are introduced. These are the representation of flows of energy from MARKAL into MACRO, and payments for these flows from MACRO into MARKAL.

The stand-alone version of MARKAL is demand-driven. This means that in MARKAL the demands for useful energy are specified exogenously. In the linked model, energy supplies, energy costs, and useful energy demands are interdependent. They are determined endogenously within MARKAL-MACRO.

Aggregate energy costs are generated in MARKAL. Besides fuel costs, these energy costs are composed of capital costs and operating and maintenance costs for all supply and conversion technologies. Together with consumption and investment, the energy costs represent claims upon the gross output generated by the MACRO production function.

MARKAL-MACRO is written in GAMS (a Generalized Algebraic Modeling System). GAMS is a high level modeling language used to build computer models and support the development of these models. Besides this, GAMS also increases the reliability and flexibility associated with the use of the models. The modeling language has been developed by the Analytic Support Unit of the World Bank (Brooks, 1988). GAMS has been especially designed to handle both linear and nonlinear complicated computer models. The syntax of GAMS closely resembles the row-oriented style of the constraint equations formulated in MARKAL-MACRO. GAMS provides a convenient interface to nonlinear optimizers. The MARKAL-MACRO model is solved using the optimizer MINOS (Model Incore Nonlinear Optimization System). MARKAL-MACRO operates in a processing environment which is centred around an integrated analysis support tool. This tool is called MUSS (Markal User Support System). MUSS is a user-friendly interface incorporating the features of a relational database, spreadsheet, file management, and graphics presentation system.

7.2.5 The basic relations in MARKAL-MACRO

MARKAL-MACRO is a model which is created by coupling the MARKAL model and the MACRO model. This integration of MARKAL and MACRO is based upon the concept of one economy-wide production function. The main advantage of this approach is that a direct link can be established between a physical process analysis and a macroeconomic growth model. The main disadvantage is that the representation of the whole economy by only one production function is a gross simplification of reality. In MARKAL-MACRO, aggregate output during period t is determined by one nested CES (Constant Elasticity of Substitution) production function. This production function is of the following specific form:

$$Y_t = [\ a \cdot {K_t}^{\rho \cdot \alpha} \cdot {L_t}^{\rho \cdot (1-\alpha)} + \sum b_i \cdot D^{\rho}_{i,t}\ ]^{\frac{1}{\rho}} \tag{7.1}$$

In this function, the symbol Kt denotes the capital stock in period t, the symbol Lt denotes the labour force in period t, and the symbol Di,t denotes the demand for useful energy type i in period t. Aggregate output in period t is represented by the symbol Yt. This particular CES production function contains a capital-labour aggregate and an aggregate of useful energy demands. At the top level, the capital-labour aggregate may be substituted for the energy aggregate. At the bottom level, there is a unity elasticity of substitution between capital and labour. This structure implies that capital and labour may be directly substituted for each other, for example, through the automation of labour-intensive tasks. The higher the wages become, the more attractive it becomes for employers to switch over to automated production. At the bottom level, also each category of useful energy demand may be substituted for the other.

The ease or difficulty of substitution between the capital-labour aggregate and the energy aggregate in MARKAL-MACRO is determined by the value adopted for the ESUB (Elasticity of SUBstitution) parameter. This parameter is related to the exponent ρ of the production function through the following equation:

$$ESUB = \sigma = \frac{1}{1-\rho} \tag{7.2}$$

Aggregate output in MARKAL-MACRO is thus a function of capital, labour, and different types of useful energy demand. This aggregate output is used for three purposes, namely for consumption, for building up the stock of capital, and for inter-industry payments for energy costs. This relation can be specified through the following equation:

$$Y_t = C_t + IV_t + EC_t \tag{7.3}$$

In this equation, Ct denotes consumption in period t, IVt denotes investment in period t, and the energy cost payments in period t are denoted by ECt.

In MARKAL-MACRO, the energy sector is defined as an intermediate sector. Therefore, the Gross Domestic Product equals consumption plus investment. In formula:

$$GDP_t = C_t + IV_t \tag{7.4}$$

MARKAL-MACRO is a non-linear computer model. It uses the criterion of the maximum sum of the discounted logarithm of aggregate consumption to obtain the optimal solution.

7.3 Calculation of the rebound-effect

Energy efficiency improvements do not necessarily lead to proportionate decreases in the demand for energy. The rebound-effect is a means of quantifying this effect. The rebound-effect can be defined as that part of the initially expected energy savings, resulting from energy efficiency improvements, that is lost because of the energy-economy-environment interaction:

$$rebound\text{-}effect = \frac{lost\ energy\ savings}{expected\ energy\ savings} \tag{7.5}$$

Because feedbacks from the energy system to the economy are incorporated in the MARKAL-MACRO model, the effect of energy efficiency improvements on the demand for energy can be estimated with this linked energy-economy-environment model. But first consider the example of figure 7.2.

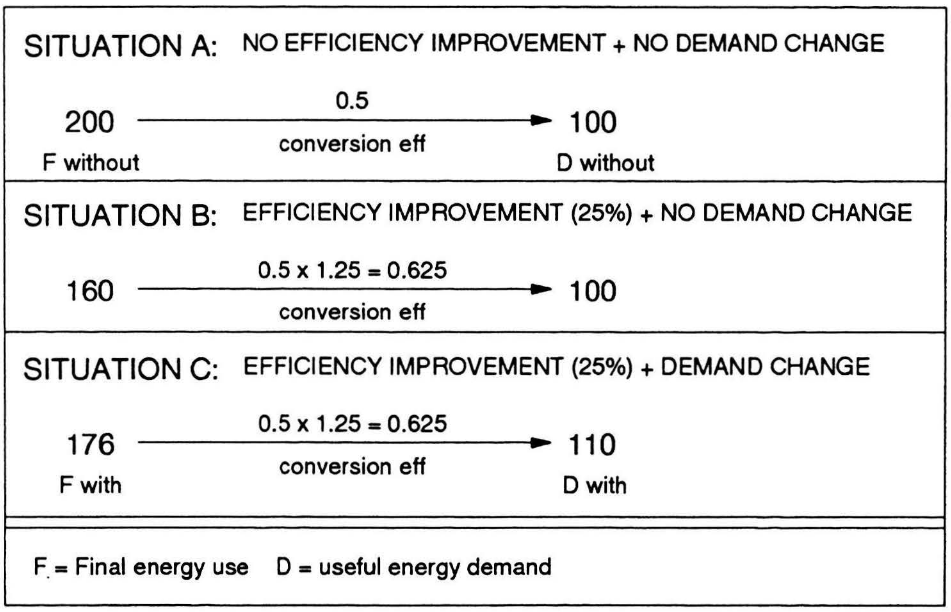

Figure 7.2 *Example*

In this figure, the conversion from final energy use F to useful energy demand D is shown for three different cases. Situation A of figure 7.2 describes the base case. In this base case, there is a useful energy demand of 100 energy units. The conversion efficiency in situation A is 0.5. Since the final energy use is the quotient of the useful energy demand and the conversion efficiency, the final energy use in situation A becomes 200 (= 100 / 0.5) energy units.

Now the conversion efficiency is increased by 25% from 0.5 to 0.625 (= 1.25 * 0.5). Situation B gives the traditional engineering response to this efficiency improvement. The engineering approach only takes into account the effect of the efficiency improvement on the final energy use. Since it does not take into account the effect of energy efficiency improvements on the demand for energy, the useful energy demand in situation B remains 100 energy units. With this useful demand of 100 energy units and a conversion efficiency of 0.625, the final energy use in situation B becomes 160 (= 100 / 0.625) energy units.

In situation C, also the impact of the price-induced energy efficiency improvement on the useful energy demand is considered. Price-induced efficiency improvements can be defined as efficiency improvements that reduce the price per unit of useful energy demand. For example, the purchase of a more fuel-efficient car will lead to a reduction in the price per automobile passenger-kilometre. As a result of this price reduction, the useful energy demand will very likely increase. In situation C, the useful demand increases from 100 to 110 energy units. Because the energy efficiency is 0.625, the final energy use in situation C becomes 176 (= 110 / 0.625) energy units.

Now the rebound-effect can be quantified. The expected energy savings can be calculated from the difference in the final energy use in the base case (situation A) and the situation in which no behavioural response is permitted (situation B). Therefore, the expected energy savings in this example amount to 40 (= 200 - 160) energy units. Since the real energy savings can be calculated from the difference in the final energy use in the base case (situation A) and the situation in which a behavioural response is permitted (situation C), the real energy savings are 24 (= 200 - 176) energy units. The lost energy savings can be calculated from the difference between the expected and the real energy savings. The lost energy savings in this situation become 16 (= 40 - 24) energy units. The rebound-effect is the quotient of the lost energy savings and the expected energy savings. The rebound-effect in this example thus becomes:

$$\textit{rebound-effect} = \frac{\textit{lost energy savings}}{\textit{expected energy savings}} = \frac{16}{40} = 0.40 \tag{7.6}$$

In order to quantify the rebound-effect with MARKAL-MACRO, two runs are to be carried out. These runs are identical except for one thing. In one of the two runs, there is a very low upper-bound set on price-induced energy efficiency improvements on the consumption-side of the economy, such as new cooling techniques, energy-efficient lighting, and improved thermal efficiency of dwellings. This means that no price-induced energy-efficiency improvements are possible in this particular run. This MARKAL-MACRO run without energy efficiency improvements corresponds with situation A of the example. In the other run, no upper bounds are set on efficiency improvements. This MARKAL-MACRO run with energy efficiency improvements corresponds with situation C of the example. The results of the two runs with the MARKAL-MACRO model for the Netherlands in the year 2020 are shown in figure 7.3.

	final energy use	useful energy demand
no efficiency improvement	2353.53 F without	2605.74 D without
with efficiency improvement	2340.00 F with	2613.10 D with

Figure 7.3 *MARKAL-MACRO results on the consumption-side*

In this figure, final energy use F is expressed in Petajoules. Useful energy demand D is a mix of various energy service demands expressed as an index number. The two runs of figure 7.3 are performed under a 50% CO_2 reduction constraint and with a value for the overall elasticity of substitution ESUB of 0.25. The CO_2 reduction constraint is used because without this constraint, very few energy efficiency improvements would be profitable. This means that practically no energy efficient technologies would be present in the MARKAL-MACRO run with the price-induced energy efficiency improvements. Consequently, the comparison of the runs with and without price-induced energy efficiency improvements would lead to a comparison of two nearly identical MARKAL-MACRO runs. With the data of figure 7.3, the rebound-effect can be calculated in a similar way as in the example. The results of this calculation are shown in figure 7.4.

SITUATION A: NO EFFICIENCY IMPROVEMENT + NO DEMAND CHANGE

$$\underset{\text{F without}}{2353.53} \xrightarrow[\text{conversion eff}]{1.107} \underset{\text{D without}}{2605.74}$$

SITUATION B: EFFICIENCY IMPROVEMENT + NO DEMAND CHANGE

$$2333.41 \xrightarrow[\text{conversion eff}]{1.117} 2605.74$$

SITUATION C: EFFICIENCY IMPROVEMENT + DEMAND CHANGE

$$\underset{\text{F with}}{2340.00} \xrightarrow[\text{conversion eff}]{1.117} \underset{\text{D with}}{2613.10}$$

F = final energy use D = useful energy demand

expected energy savings = 2353.53 - 2333.41 = 20.12
real energy savings = 2353.53 - 2340.00 = 13.53
lost energy savings = 20.12 - 13.53 = 6.59

$$\text{Rebound} = \frac{\text{lost energy savings}}{\text{expected energy savings}} = \frac{6.59}{20.12} = 32.8\ \%$$

Figure 7.4 *Calculation of the rebound-effect*

In this figure, the final energy use and useful energy demand of situation A are obtained from the MARKAL-MACRO run without energy efficiency improvements. The conversion efficiency of 1.107 in situation A is the quotient of useful energy demand (2605.74) and final energy use (2353.53) of that particular run.

The final energy use and useful energy demand of situation C are obtained from the MARKAL-MACRO run with energy efficiency improvements. The conversion efficiency from final energy use to useful energy demand in situation C is calculated in a similar way as in situation A.

For situation B, no MARKAL-MACRO run is carried out. The reason for this is the fact that the final energy use and the useful energy demand for this situation can be obtained from the two MARKAL-MACRO runs that are used for the situations A and C. Since in situation B no behavioural response is allowed, the useful energy demand of situation B equals the useful energy demand of situation A, namely 2605.74. The conversion efficiency of situation C is 1.117 (= 2613.10 / 2340.00). Because in both situation B and situation C price-induced efficiency improvements are included, the conversion efficiency of situation C can be used for situation B as well. Now the final energy use of situation B can be calculated by dividing the useful energy demand of 2605.74 by the conversion efficiency of 1.117. This results in a final energy use in situation B of 2333.41 Petajoules.

The final energy use and useful energy demand of situation B can also be derived following another path. Situation B represents the situation with price-induced efficiency improvements but without the behavioural response to these changes. Since the useful energy demands are specified exogenously in MARKAL, this stand-alone engineering version of the MARKAL-MACRO model exactly fits this description. To determine the final energy use and useful energy demand for situation B with the MARKAL model would however require a great effort. That is, in order to use the MARKAL model for situation B, the values for the useful energy demands that are determined endogenously in the MARKAL-MACRO run of situation

A must be fed into the MARKAL model for 39 types of useful energy demand and for 5 time periods.

With the data of figure 7.4, the expected energy savings, the real energy savings, and the lost energy savings can be calculated. These energy savings are of course not actual realizations but figures calculated by the MARKAL-MACRO model. The expected energy savings refer to the engineering estimate of the energy savings, in which no feedback effects are taken into account. The expected energy savings amount to 20.12 (= 2353.53 - 2333.41) Petajoules. The real energy savings refer to the situation in which there are feedback-effects from the energy efficiency improvements to the demand for energy. The real energy savings are 13.53 (= 2353.53 - 2340.00) Petajoules. From the difference between these two figures, the lost energy savings can be calculated. The lost energy savings amount to 6.59 (= 20.12 - 13.53) Petajoules. With the lost energy savings and the expected energy savings, the rebound-effect calculated by MARKAL-MACRO can be determined:

$$\textit{rebound-effect} = \frac{\textit{lost energy savings}}{\textit{expected energy savings}} = \frac{6.59}{20.12} = 0.328 \qquad (7.7)$$

The MARKAL-MACRO results thus indicate that there is a rebound-effect of 32.8 % in this particular case. This means that almost 33 % of the initially expected energy savings is lost because of the energy-economy linkage.

The rebound-effect results from price-induced energy efficiency improvements pulling up the useful energy demand. In MARKAL-MACRO, there are two reasons for the fact that the useful energy demand in the run with energy efficiency improvements exceeds the level of useful energy demand in the run without efficiency improvements. To clarify this, consider the aggregate production function that is used in the MARKAL-MACRO model:

$$Y_t = [\ a \cdot K_t^{\rho \cdot \alpha} \cdot L_t^{\rho \cdot (1-\alpha)} + \sum b_i \cdot D_{i,t}^{\rho}\ ]^{\frac{1}{\rho}} \qquad (7.8)$$

From this production function, the dual function which relates the price of output to the prices of capital, labour and useful energy demands can be derived:

$$P_Y = [\ a^{\sigma} \cdot (P_K^{\alpha} \cdot P_L^{(1-\alpha)})^{1-\sigma} + \sum (\frac{P_{D_i}}{b_i})^{1-\sigma}\ ]^{\frac{1}{1-\sigma}} \qquad (7.9)$$

With these equations, the demand for useful energy type i under profit maximization can be determined in the following way:

$$\text{max! } \textit{profit} = \text{max! } W = \text{max! } P_Y \cdot Y - P_K \cdot K - P_L \cdot L - \sum P_{D_i} \cdot D_i \qquad (7.10)$$

$$\frac{dW}{dD_i} = P_Y \cdot \frac{dY}{dD_i} - P_{D_i} = 0$$

$$P_Y \cdot \left(\frac{1}{\rho} \cdot \left(a \cdot K^{\rho\alpha} \cdot L^{\rho(1-\alpha)} + \Sigma b_i \cdot D_i^{\rho} \right)^{\frac{1}{\rho} - 1} \cdot \rho \cdot b_i \cdot D_i^{\rho - 1} \right) - P_{D_i} = 0$$

$$P_Y \cdot \left(Y^{\rho \cdot (\frac{1}{\rho} - 1)} \cdot b_i \cdot D_i^{\rho - 1} \right) - P_{D_i} = 0$$

$$Y^{1 - \rho} \cdot b_i \cdot D_i^{\rho - 1} = \frac{P_{D_i}}{P_Y}$$

$$D_i^{\rho - 1} = \frac{P_{D_i}}{Y^{1 - \rho} \cdot b_i \cdot P_Y}$$

$$D_i = \left(\frac{P_{D_i}}{Y^{1-\rho} \cdot b_i \cdot P_Y} \right)^{\frac{1}{\rho - 1}}$$

$$D_i = Y \cdot \left(\frac{P_{D_i}}{b_i \cdot P_Y} \right)^{-\sigma} \tag{7.11}$$

With this equation, the two causes for the increase in the demand for useful energy resulting from energy efficiency improvements can be explained. The first cause is the fact that price-induced energy efficiency improvements lead to a decrease in the price per unit of useful energy demand, relative to the price per unit of capital and labour. For instance, cavity wall insulation is a very profitable example of an energy efficiency improvement. Consequently, the installation of insulation will lead to a reduction in the price per unit of thermal comfort. When the relative price of one of the production factors changes, the production function allows us to adapt by substituting more of the cheaper production factor in place of the more expensive production factors. So, when useful energy becomes cheaper, capital and labour will be substituted for useful energy, and the useful energy demand will increase. This can be illustrated with equation (7.11). When the price P_{Di} per unit of useful energy demand of type i in this equation decreases, the demand Di for useful energy of that type will increase.

The second cause is the fact that price-induced efficiency improvements in the MARKAL-MACRO model lead to higher economic growth rates. Total production Y in the year 2020 in the run with the energy efficiency improvements amounts to 905.890 billion guilders. In the MARKAL-MACRO run without the energy efficiency improvements, total production is slightly lower, namely 904.094 billion guilders. A higher level of production is accompanied by a higher useful energy demand. This also can be illustrated with equation (7.11). When total production Y increases, the useful energy demand increases as well.

There also exists a third possible cause for the rebound-effect. This feedback-effect results from the fact that widespread energy efficiency improvements may depress the demand of energy, thereby reducing the prices of energy carriers, such as oil and gas. These price reductions in turn may increase the demand for the energy carriers. In MARKAL-MACRO, this rebound-effect is not considered, because for example the price of a barrel of oil is not endogenously determined in the model, but specified exogenously.

The rebound-effect calculated with the MARKAL-MACRO model thus indicates that almost 33 % of the expected energy savings is lost because of the economic feedback from engineering measures to increase the energy efficiency. Great care however must be taken when this result is extrapolated from the MARKAL-MACRO model to the real world. Just like any other model, MARKAL-MACRO is by definition a simplification of reality. Recall, for example, the aggregate production function of MARKAL-MACRO:

$$Y_t = [\ a \cdot K_t^{\rho \cdot \alpha} \cdot L_t^{\rho \cdot (1-\alpha)} + \sum b_i \cdot D_{i,t}^{\rho}\ ]^{\frac{1}{\rho}} \tag{7.12}$$

In this production function, there are substitution possibilities between the capital-labour aggregate and the aggregate of useful energy demands. These substitution possibilities are governed by an overall elasticity of substitution ESUB. In MARKAL-MACRO, energy is substituted for capital and labour when the price per unit of useful energy is decreased. Consider for example energy-efficient lighting. When the introduction of this type of lighting results in a reduction in the price per unit of illumination, the price per unit of the aggregate of useful energy demands is decreased as well. As a result of this price reduction of the energy aggregate, there will be substitution from the capital-labour aggregate to the useful energy aggregate. The increased demand for the useful energy aggregate is then decomposed into increased demands for the different types of useful energy in separate. This is a very crude way of describing the substitution possibilities between capital, labour, and energy in an economy. Besides this, the economy in the MARKAL-MACRO model is represented by only one sector, in which there are no possibilities for international trade. This is a gross simplification of reality as well. Therefore, the MARKAL-MACRO calculations of the rebound-effect must be carefully interpreted when they are used to estimate the magnitude of the rebound-effect in reality.

8. THE REBOUND-EFFECT IN PERSPECTIVE

8.1 Introduction

In the previous chapters, the rebound-effect has been carried out calculated with the MARKAL-MACRO model. In this chapter, the rebound-effect is placed in perspective. Paragraph 8.2 outlines the consequences of the existence of a rebound-effect for the so-called fifth fuel concept. Paragraph 8.3 deals with the question of how the rebound-effect can be reduced. In paragraph 8.4, the fact that the rebound-effect besides to energy also applies to the other production factors is discussed. The existence of the rebound-effect in other fields of research is outlined in this paragraph as well.

8.2 The fallacy of the fifth fuel concept

Over the past 20 years, the interest in energy efficiency has vastly improved. Energy efficiency is placed high on the societal agenda. The reason for this is the fact that many think that improvements in energy efficiency are the solution to all sorts problems. These problems range from reducing the dependence on imported fuels, through avoiding investment in new power plants, to combatting the threat of global warming. Also national governments believe that promoting energy efficiency is an important element in meeting their environmental policy goals.

An important advocate of energy efficiency is Klaus Meyer-Abich. In *Energieeinsparung als neue Energiequelle*, Meyer-Abich argues that energy efficiency improvements can be considered a new source of energy: "Energieeinsparung ist neben den fossilen Brennstoffen und den Kernenergieträgern eine der großen Energiequellen der Zukunft. Der in der Nachfrage nach Energie zum Ausdruck kommende Bedarf kann nicht nur durch Brennstoffe (fossil oder kernenergetisch), sondern in großem Umfang genauso gut oder besser durch Energieeinsparung gedeckt werden. Die Möglichkeiten zur Nutzung der Energiequelle Energieeinsparung treten deshalb immer mehr in den Vordergrund der energiepolitischen Diskussion (1979, p. 17)". And Meyer-Abich continues: "Man kann denselben Nutzen, der bisher durch den Einsatz bestimmter Mengen von Energieträgern erzielt oder gewährleistet wurde, auch durch einen geringeren Einsatz an Energieträgern hervorbringen, wenn zusätzliche Einsparungsmaßnahmen getroffen werden. Insoweit Energieträger durch Einsparungsmaßnahmen substituiert werden können, ist die Einsparung von Energie funktional eine Energiequelle. Daß Energieeinsparung im Rahmen von Energieversorgungssystemen funktional eine Energiequelle ist und als solche verstärkt genutzt werden kann, ist energiewirtschaftlich und energiepolitisch auch in der Öffentlichkeit eine der erfreulicheren Perspektiven der letzten Jahre. Der Anteil der nicht durch Verzichte erkauften und unter dem Gesichtspunkt des gleichen Nutzens mit dem Energieträgerangebot konkurrierenden Energiequelle Energieeinsparung an der Energieversorgung der Bundesrepublik kann in den achtziger und neunziger Jahren durchaus die Größenordnung des Einsatzes von Kernenergie und Steinkohle erreichen und den der Braunkohle übersteigen (1979, p. 28)".

T. Anderson agrees with Meyer-Abich. In *Letting Conservation Compete for Energy Dollars: a Policy Imperative*, Anderson (1990) argues that energy efficiency improvements are becoming increasingly attractive as an alternative to meet the growing world energy demand. According to Anderson, "energy conservation should be analyzed as both an energy resource in its own right and a means of reducing costly uncertainty about future energy needs. Conservation should be offered the opportunity to compete on equal terms with more conventional options for the capital that authorities allocate specifically for energy investments (1990, p. 343). Anderson argues that a new approach to energy planning is required. This new approach should explicitly treat energy efficiency as a new energy supply source.

Similar thoughts are also expressed by Steward Boyle (1989) in *More Work for Less Energy*. According to Boyle, energy efficiency works: "adding up the advantages of energy efficiency invariably leads to the conclusion that spending money on efficiency measures, rather than on new sources of supply, is much more cost-effective (1989, p. 40)". Boyle asserts that the reason that not all options for efficiency improvements are utilized is that utilities have an inertia with respect to energy efficiency improvements. Utilities namely never had to consider the possibility of energy savings as an alternative to the increased energy supply from new power stations.

Also the Association for the Conservation of Energy sees in energy conservation a new supply source. The director of this association Andrew Warren (1987) namely argues that besides oil, gas, coal, and uranium, energy efficiency improvements can be regarded as the new fifth fuel. Warren explains this thought by the following reasoning: "customers do not require electricity or gas per se, but rather they require energy services, such as heat, light, and mechanical power. These services can be met by the combination of supply expansion or demand reduction, whichever meets their needs for energy at the lowest possible cost to society. This can come not only from new power supply sources but equally from energy efficiency investments (1987, p. 522)". And because Warren argues that investments in energy efficiency often provide very good rates of return, a situation must be created in which these energy efficiency investments are evaluated by the same criteria as those applied to investments in traditional energy supply sources. Warren further argues that in policy models that describe energy supply systems, energy efficiency should be explicitly introduced as a new fuel source.

Seeing energy efficiency improvements as a new source of energy obviously has policy implications. One of the most important implications is that the advocates of the fifth fuel concept argue that the energy needed during the time that is required to make the structural change from an energy supply system based largely on fossil fuels to an energy supply system based on renewables can be supplied by energy conservation. According to Weissmahr (1993), for example, the end of the fossil fuel era is approaching, but there is still no new economically viable energy technology based on renewables in sight. Confronted with this problem, some scholars have drawn the conclusion that the era of economic growth has ended. Weissmahr however argues that the contrary is the truth: "the future will be prosperous, precisely because so much energy has been wasted in the past. In the next 30 years about 70 per cent of the fuel used for heating and cooling houses, and 40 per cent of the oil used in transportation can be saved and redirected to industry for doing work. This programme will achieve two results at the same time. It will create new markets for all products used in well insulated housing and fuel efficient transportation, and at the same time hold the price of oil constant because total demand in industrial countries will remain stationary or decline (1993, p.43)". For this reason, Weissmahr argues that energy efficiency improvements will be the driving force behind the transition period from fossil fuels to renewables.

Similar thoughts are expressed by Klaus Meyer-Abich, who writes the following about the time provided by energy efficiency improvements to make the transition to an energy system based on renewables: "durch eine Einsparungspolitik kann das eigentliche, langfristig gleichwohl anstehende Problem -nämlich das der Zeit, die für einen Übergang auf praktisch nicht erschöpfbare Energiequellen zur Verfügung steht- erheblich entschärft werden. Denn eine Politik, die sich die Entwicklung energiesparender Technologien zum Ziel setzt, kann gerade diejenigen technischen Fortschritte induzieren, deren Möglichkeit gegen das Erschöpfungsargument und die daraus gezogenen Konsequenzen geltend gemacht wird, und kann dadurch die globalen Vorräte im Vergleich zu einer ungebrochenen Steigerung ihrer Ausbeutung strechen, wodurch wiederum die nötige Zeit für die Entwicklung und Erprobung der Technologien zur Nutzung von praktisch nicht erschöpfbaren Energiequellen gewonnen wird (1979, p. 39)". So, also Meyer-Abich argues that the time available to develop an energy system based on renewables can be extended by means of energy efficiency improvements.

Because of the slackening of our fossil fuel reserves, the viewing of energy efficiency improvements as a new fifth fuel is very appealing. The only problem of this fifth fuel concept, however, is that it is not true. As a result of the rebound-effect, energy efficiency improvements cannot be viewed as a new energy supply source. Recall for example Andrew Warren's (1987) pleading for energy efficiency as the new energy supply source. In *Saving Megabucks by Saving Megawatts*, Warren argues that investments in energy efficiency are often very profitable, and that therefore utilities must invest in energy conservation instead of energy supply capacity. Warren's assertion that energy efficiency improvements often provide attractive investment opportunities is true. For example, insulating the cavity walls is a very lucrative way of improving the energy efficiency of a dwelling. And it is also true that as a result of the insulation measures, a smaller annual amount of natural gas is needed to deliver the same amount of thermal comfort. But this does not necessarily imply that the speed with which our fossil fuel reserves are depleted is proportionately reduced. The reason for this is the feedback-effect from the efficiency measures to the economy. When energy efficiency improvements result in *Megabucks* being saved because less *Megawatts* are required, these *Megabucks* will be respent on goods and services, thereby creating a *Mega-rebound-effect.* This rebound-effect takes away part of the initially expected energy savings. Consequently, referring to energy efficiency as the fifth fuel is misleading. There is no such thing as a fifth fuel.

8.3 How can the rebound-effect be reduced?

Engineering measures to improve the efficiency of use of energy set in motion economic forces that may diminish the initially expected energy savings. This effect is called the rebound-effect. The rebound-effect can be defined as that part of the initially expected energy savings, resulting from energy efficiency improvements, that is lost because of the 3-E interaction. This definition implies that the bigger is the rebound-effect, the smaller are the energy savings resulting from the efficiency improvements. Therefore, the rebound-effect should be reduced.

One approach aimed at diminishing the magnitude of the rebound-effect, is by adopting energy efficiency measures that go beyond the economic optimum. This can be illustrated with the simple consumer behaviour model of chapter 6. In this model, the purchase and utilization of an air-conditioner was described for a consumer who had to replace his old air-conditioner which had gone out of order. The consumer had to choose between two appliances. Air-conditioner 1 represented a new appliance of the same type as the air-conditioner which had gone out of order. The purchase price of this appliance was 1000 Money Units and its efficiency was 0.5. Air-conditioner 2 represented a more efficient appliance with an efficiency of 0.75 and a purchase price of 1200 Money Units.

In the consumer behaviour model, appliance 2 was chosen because the combination of only a slightly higher purchase price and a much higher efficiency led to a decrease in the price per unit of cooling, compared with appliance 1. This price decrease per unit of cooling led to an amount of money being saved. In the model, this money was respent on an increased demand for air-conditioning and other services. As a result of this respending, 69% of the expected energy savings was lost.

Now consider an air-conditioner of type 3. This air-conditioner is a state-of-the-art appliance with an efficiency of 0.9. Because of the better materials and components used in their construction, state-of-the-art appliances are much more expensive to buy than comparable appliances with average efficiencies. The purchase price of air-conditioner 3, for example, amounts to 2000 Money Units. With the aid of the formulae derived in chapter 6, the demand for air-conditioning and other services can be determined for situation 3:

$$X_3 = \frac{M - Q_3}{P_{X_3} + P_Y \cdot \left(\frac{\alpha}{1-\alpha} \cdot \frac{P_Y}{P_{X_3}} \right)^{-\frac{1}{1+\rho}}} = \frac{10000 - 2000}{16.67 + 10 \cdot \left(\frac{0.1}{0.9} \cdot \frac{10}{16.67} \right)^{-\frac{1}{1+0.5}}}$$

$$X_3 = 103.24 \tag{8.1}$$

$$Y_3 = \frac{M - Q_3}{P_Y + P_{X_3} \cdot \left(\frac{1-\alpha}{\alpha} \cdot \frac{P_{X_3}}{P_Y} \right)^{-\frac{1}{1+\rho}}} = \frac{10000 - 2000}{10 + 16.67 \cdot \left(\frac{0.9}{0.1} \cdot \frac{16.67}{10} \right)^{-\frac{1}{1+0.5}}}$$

$$Y_3 = 627.93 \tag{8.2}$$

In these two equations, Px_3 represents the price per unit of service for air-conditioner 3. Px_3 is the quotient of the price per unit of energy of 15 Money Units and the efficiency of the air-conditioner of 0.9.
With these demands for air-conditioning and other services, the energy use in the situation when air-conditioner 3 is purchased can be calculated:

$$\textit{energy use for X in situation 3} = \frac{X_3}{e_3} = \frac{103.24}{0.9} = 114.71\ EU \tag{8.3}$$

$$\textit{energy use for Y in situation } 3 = \frac{Y_3}{e_Y} = \frac{627.93}{3} = 209.31 \; EU \tag{8.4}$$

$$\textit{total energy use in situation } 3 = 114.71 + 209.31 = 324.02 \; EU \tag{8.5}$$

In situation 1, the energy use for air-conditioning was 150 Energy Units and the energy use for other services was 225 Energy Units. The total energy use in that situation thus amounted to 375 Energy Units. In situation 3, the efficiency of the air-conditioner has increased by 80% from 0.5 to 0.9, compared with the air-conditioner in situation 1. The traditional engineering approach now assumes that as a result of this energy efficiency improvement, the energy use for air-conditioning will drop from 150 (= 75 / 0.5) Energy Units to 83.33 (= 75 / 0.9) Energy Units. Because the engineering approach also assumes that the demand for other services remains the same, the engineering prediction of the energy use in situation 3 becomes 308.33 (= 83.33 + 225) Energy Units. The expected energy savings can be calculated from the difference between the energy use in situation 1 and the engineering prediction of the energy use in situation 3. The expected energy savings become 66.67 (= 375 - 308.33) Energy Units.

In reality, the energy use in situation 3 is not 308.33 but 324.02 Energy Units. The difference between these two numbers, which is a representation of the lost energy savings, is caused by the feedback-effect resulting from the purchase of the state-of-the-art energy efficient air-conditioner 3. The lost energy savings in this case thus amount to 15.69 (= 324.02 - 308.33) Energy Units. Now the rebound-effect in situation 3 can be calculated with these lost energy savings of 15.69 Energy Units and the expected energy savings of 66.67 Energy Units:

$$\textit{rebound-effect} = \frac{\textit{lost energy savings}}{\textit{expected energy savings}} = \frac{15.69}{66.67} = 0.235 \tag{8.6}$$

So, the rebound-effect in this situation becomes 23.5%. This is considerably smaller than the rebound-effect in the case when air-conditioner 2 was purchased. The rebound-effect in situation 2 namely amounted to 69%. The reason for this is the fact that state-of-the-art appliances are so expensive to buy that the lower energy costs per unit of service cannot make up for the higher purchase price of these appliances. This means that less money will be saved than in the economically optimal situation. When less money is saved, less money will be respent, and the rebound-effect will be smaller.

The purchase of appliances with the highest energy efficiencies thus has very beneficial consequences. First, the higher is the efficiency of the appliance, the lower is the energy use per unit of service that the appliance delivers. Second, the higher is the efficiency of the appliance, the lower is the rebound-effect. There is however a problem with this state-of-the-art approach towards reducing the magnitude of the rebound-effect. The purchase of a very energy efficient appliance namely may lead to a sub-optimal economic decision. To illustrate this, recall the consumer behaviour model in which the two types of air-conditioners were compared on a utilitarian basis. Total utility U_1 in the situation when appliance 1 was purchased amounted to 468.75. Total utility U_2 in situation 2 was 504.69. Because U_2 was greater than U_1, the more energy efficient air-conditioner 2 was purchased. Now consider the state-of-the-art air-conditioner 3. With the demand for air-conditioning X_3 and other services Y_3, total utility in situation 3 can be determined:

$$U_3 = (\alpha \cdot X_3^{-\rho} + (1-\alpha) \cdot Y_3^{-\rho})^{-\frac{1}{\rho}} = (\ 0.1 \cdot 103.24^{-0.5} + 0.9 \cdot 627.93^{-0.5}\ )^{-\frac{1}{0.5}}$$

$$U_3 = 477.61 \tag{8.7}$$

Total utility in situation 3 thus amounts to 477.61, which is considerably smaller than total utility in the situation when an air-conditioner of type 2 is chosen. This implies that the purchase of an air-conditioner of type 3 leads to a lower than possible utility under the given budget constraint. More in general, it means that a reduction in the magnitude of the rebound-effect by adopting state-of-the-art energy efficiency measures can only be obtained at the expense of a more or less disruption of the economy.

8.4 The rebound-effect in a different context

Up to now, the rebound-effect has been examined for energy. In this final paragraph, the fact that the rebound-effect also applies to the other production factors will be clarified by means of an example concerning the production factor labour. Besides this, an illustration will be given of the existence of the rebound-effect in other fields of research.

The rebound-effect for the production factor labour can be illustrated with the historical example of the change in labour productivity in the 19th century. Since the industrial revolution, there has been a labour-saving bias of technical change which was a result of the invention of new machines and processes which replaced labour with capital and energy. The consequence of this substitution was that the labour productivity, i.e. the output produced per employee or per worker-hour, increased. According to Sonenblum (1983), for example, the labour productivity in the U.S.A. increased by a factor 2200 in the course of the 19th century. This increased labour productivity worried many scholars of that time (Khazzoom; 1980,1986). They thought that a doubling of labour productivity would lead to an equal reduction in employment. Also Karl Marx drew this pessimistic conclusion. Marx thought that the diminished demand for labour would lead to mass unemployment. This unemployment in turn would cause the capitalistic system to collapse.

In reality, however, the massive unemployment and consequent destruction of capitalism did not occur. The reason for this was the fact that the increased labour productivity led to an increased economic growth at that time. In fact, Fabricant (1983) even argues that the increases in labour productivity have been the dominant source of economic growth in the U.S.A. over the past two centuries. The increased demand for goods and services associated with this economic growth led to an increase in the demand for labour which more than offset the decrease in labour demand associated with the improvements in labour productivity. And the net result was that employment increased, rather than decreased.

The same also applies to the increased utilization of computers and robots in today's manufacturing processes. These production aids enable production workers to achieve a higher productivity, thereby making some workers idle. The efficiency improvements however lead to an increased economic growth. This means that while some jobs may be lost, others are gained. And although the expert opinions on this subject are not exactly of the same tenor, the net result is probably positive.

The rebound-effect thus also applies to the factor labour. But, there is a difference with the rebound-effect that results from energy efficiency improvements. The labour rebound-effect namely has positive instead of negative consequences. The rebound-effect represents that part of the initially expected saving that is lost. The result of lost energy savings is an increased depletion of our fuel reserves (unless use is made of renewables). Lost labour savings result in less unemployment. So, the rebound-effect with respect to the factor labour should be maximized instead of minimized.

Besides the fact that there is a feedback-effect with respect to the production factors in an economic system, a rebound-effect is also encountered in other domains. This can be clarified by means of the example of the introduction of wide-bodied aircraft (Spare, 1990). In the middle of the 1960s, the predicted increase in air-transportation for the 1970s presented difficulties for this industry. The thought was that if the increased demand for air-transportation had to be met by a larger number of small planes such as the Boeing 707, there would not be enough airline space available and the airports would not be able to cope with the increased activity. In a response to this threat, a jumbo-type aircraft was designed. On 22 January 1970, Pan Am began service with its first wide-bodied Boeing 747 on the New York-London route. The introduction of these large airplanes thus was expected to lead to a decrease in the number of daily take-offs and landings at airports. In reality, however, quite the opposite occurred. The efficiency improvements that were a result of the introduction of the larger airplanes namely led, in a competitive market, to lower air fares. Because of these lower air fares, people started flying further and more often. And the decrease in the number of take-offs and landings resulting from the use of the bigger planes was more than offset by the increase in the number of take-offs and landings resulting from the increased demand for air-travelling.

9. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions can be derived from this study:

1. The rebound-effect exists. This implies that a part of the initially expected energy savings, resulting from energy efficiency improvements, is lost because of the energy-economy-environment interaction.

2. The rebound-effect is completely consistent with economic behaviour. Consumers do not want to minimize energy costs, they rather want to maximize utility.

3. The MARKAL-MACRO model is feasible to determine the magnitude of the rebound-effect. The MARKAL-MACRO estimation of the rebound-effect on the consumption-side of the economy amounts to 33 %. Care must however be taken when the MARKAL-MACRO results are extrapolated from the model to the real world.

4. The MARKAL-MACRO results indicate that the rebound-effect is larger than what the energy efficiency optimists assert, but smaller than what the energy efficiency pessimists claim.

5. The rebound-effect can be reduced by adopting energy efficiency measures that go beyond the economic optimum. This reduction can however only be obtained at the expense of a more or less distortion of the economic system.

6. There is no fifth fuel. Because of the existence of the rebound-effect, energy efficiency improvements cannot be viewed as a new energy supply source.

The following recommendations can be made:

1. Additional research is required on the rebound-effect. The focus of that research should be on a more accurate estimation of the magnitude of the rebound-effect and on measures to reduce the rebound-effect.

2. More research should also be carried out on the subject of the energy-economy-environment interaction in general. The entropy concept can be seen as a useful tool in this context.

3. The MACRO component of the MARKAL-MACRO model should be further developed as to allow for a better representation of the economy.

4. The economic feedback-effects resulting from profitable reductions in pollution (the Pollution Prevention Pays nostrum) should be examined.

REFERENCES AND LITERATURE

REFERENCES:

Adams, R. C., and A. D. Rockwood (1983). Impact of Improved Building Thermal Efficiency on Residential Energy Demand. Pacific Northwest Laboratory, Richand.

Anderson, T. (1990). Letting Conservation Compete for Energy Dollars: A Policy Imperative. Sustainable Energy Choices for the 90s, Conference Proceedings, 343-350.

Barnett, H. J., and C. Morse (1963). Scarcity and Growth. The Johns Hopkins Press, Baltimore.

Blaug, M. (1968). Economic Theory in Retrospect. Richard D. Irwin, Homewood.

Boeke, A. W., and P. A. van de Kraaij (1977). Climate Control. Delft University of Technology, Delft (in Dutch).

Boulding, K. E. (1949). Income or Welfare? Review of Economic Studies, 17, 77-86.

Boulding, K. E. (1973). The Economics of the Coming Spaceship Earth. In Daly, H. E. (Ed.), Toward a Steady-State Economy, Freeman, San Fransisco, 121-132.

Boustead, I. and G. Hancock (1979). Handbook of Industrial Energy Analysis. Ellis Horwood Publishers, Chichester.

Bowdidge, J. R. (1990). Environmental Insulation Thickness. Energy and the Environment, 1, 307-317.

Boyle, S. (1989). More Work for Less Energy. New Scientist, 5 August 1989, 37-40.

Brillouin, L. (1956). Science and Information Theory. Academic Press, New York.

Brookes, L. G. (1990). The Greenhouse Effect, The Fallacies in the Energy Efficiency Solution. Energy Policy, March 1990, 199-201.

Brookes, L. G. (1991). Confusing the Issue on Energy Efficiency. Energy Policy, March 1991, 184-186.

Brookes, L. G. (1991). Letter to the Editor. Energy Policy, March 1991, 187.

Brookes, L. G. (1992). Energy Efficiency and Economic Fallacies: A Reply. Energy Policy, May 1992, 390-392.

Brookes, L. G. (1993). Energy Efficiency Fallacies: The Debate Concluded. Energy Policy, April 1993, 346-347.

Brooks, A. (1988). GAMS: A User's Guide. The World Bank, Washington D. C.

Brown, H., J. Boner, and J. Weir (1957). The Next Hundred Years. Viking Press, New York.

Brundtland, G. H. (1987). Our Common Future: The World Commission on Environment and Development. Oxford University Press, Oxford.

Bryant, J. (1985). Economics, Equilibrium, and Thermodynamics. In Gool, W. van, and J. J. C. Bruggink (Eds.), Energy and Time in the Economic and Physical Sciences. North Holland, Amsterdam.

Buuren, B. van, and J. A. de Jong (1990). Physics. Educabook, Culemborg (in Dutch).

Carnot, S. (1824). Reflections on the Motive Power of Heat and on Machines fitted to Develop that Power. Macmillan, London.

Consumers Association (1990). Energy Conservation in her second Youth. Consumers Guide, September 1990, 510-523 (in Dutch).

Cook, E. F. (1976). Man, Energy, Society. Freeman, San Fransisco.

Costanza, R. (1980). Embodied Energy and Economic Valuation. Science, 210, 1219-1224.

Costanza, R. (1981). Embodied Energy, Energy Analysis, and Economics. In Daly, H. E., and A. F. Umana (Eds.), Energy, Economics, and the Environment, Westview Press, Boulder, 119-145.

Costanza, R., and H. E. Daly (1987). Towards an Ecological Economics. Ecological Modelling, 38, 1-7.

Cottrell, W. F. (1955). Energy and Society. McGraw-Hill, New York.

Cottrell, W. F. (1972). Technology, Man, and Progress. Merrill, Columbus.

Daly, H. E. (1973A). Introduction. In Daly, H. E. (Ed.), Toward a Steady-State Economy, Freeman, San Fransisco, 1-32.

Daly, H. E. (1973B). The Steady-State Economy: Toward a Political Economy of Biophysical Equilibrium and Moral Growth. In Daly, H. E. (Ed.), Toward a Steady-State Economy, Freeman, San Fransisco, 149-174.

Daly, H. E. (1977). Steady State Economics. Freeman, San Fransisco.

Daly, H. E. (1979). Entropy, Growth, and the Political Economy of Scarcity. In Smith, V. K. (Ed.), Scarcity and Growth Reconsidered. The Johns Hopkins University Press, Baltimore. 67-94.

Dupont de Nemours (1761). Physiocratie ou Constitutions essentielles du Gouvernement le plus avantageux au Genre Humain.

Fabricant, S. (1983). The Productivity-Growth Slowdown: A Review of the Facts. In Schurr, S. H., S. Sonenblum, and D. O. Wood (Eds.), Energy, Productivity, and Economic Growth. Oelenschlager, Gunn, and Hain, Cambridge, 47-70.

Feynman, R. P., R. B. Leighton, and M. Sands (1966). The Feynman Lecture on Physics: Mainly Mechanics, Radiation, and Heat. Addison-Wesley, Reading.

Fishbone, L. G., G. Giesen, G. Goldstein, H. A. Hymmen, K. J. Stocks, H. Vos, D. Wilde, R. Zolcher, C. Balzer, and H. Abilock (1983). User's Guide for MARKAL. Brookhaven National Laboratory, Upton.

Gaggioli, R. A., and E. F. Obert (1963). Thermodynamics. McGraw-Hill, New York.

Gershuny, J. I. (1977). Post Industrial Society: the Myth of the Service Economy. Futures, 2, 103-114.

Gershuny, J. I. (1978). After Industrial Society: The Emerging Self-Service Economy. Macmillan, London.

Georgescu-Roegen, N. (1971). The Entropy Law and the Economic Process. Harvard University Press, Cambridge.

Georgescu-Roegen, N. (1973). The Entropy Law and the Economic Problem. In Daly, H. E. (Ed.), Toward a Steady-State Economy. Freeman, San Fransisco, 37-49.

Georgescu-Roegen, N. (1975A). Energy and Economic Myths. Southern Economic Journal, 3, 347-381.

Georgescu-Roegen, N. (1975B). Dynamic Models and Economic Growth. World Development, 11, 765-783.

Georgescu-Roegen, N. (1979). Comments on the Papers by Daly and Stiglitz. In V. K. Smith (Ed.), Scarcity and Growth Reconsidered. The Johns Hopkins Press, Baltimore, 95-105.

Georgescu-Roegen, N. (1980). Matter: A Resource Ignored by Thermodynamics. In St-Pierre, L. E., and G. R. Brown (Ed.), Future Sources of Organic Raw Materials: CHEMRAWN I, Pergamon, New York, 79-87.

Georgescu-Roegen, N. (1981). Energy, Matter, and Economic Valuation: Where Do We Stand ? In Daly, H. E., and A. F. Umana (Eds.), Energy, Economics, and the Environment, Westview Press, Boulding, 43-79.

Georgescu-Roegen, N. (1986). The Entropy Law and the Economic Process in Retrospective. Eastern Economic Journal, 1, January/March, 3-25.

Gilmer, R. W. (1977). Services and Energy in US Economic Growth. Institute for Energy Analysis, Oak Ridge.

Goeller, H. E., and A. M. Weinberg (1978). The Age of Substitutability. American Economic Review, December, 1-11.

Goett, A. A., D. L. Mc Fadden, and G. L. Earl (1982). The Residential End-Use Energy Policy System. In End-Use Models and Conservation Analysis, Electric Power Research Institute, Palo Alto, 1-51.

Greenhalgh, G. (1990). Energy Conservation Policies. Energy Policy, April 1990, 293-299.

Grubb, M. J. (1990). Energy Efficiency and Economic Fallacies. Energy Policy, October 1990, 783-785.

Grubb, M. J. (1992). Reply to Brookes. Energy Policy, May 1992, 392-393.

Hamilton, L. D., G. Goldstein, J. Lee, A. Manne, W. Marcuse, S. Morris, and C.-O. Wene (1992). MARKAL-MACRO: An Overview. Brookhaven National Laboratory, Upton.

Hardin, G. (1968). The Tragedy of the Commons. Science, December 13, 1243-1248.

Herring, H. and M. Elliott (1990). Letter to the Editor. Energy Policy, October 1990, 786.

Hirst, E., and J. Carney (1978). The ORNL Engineering-Economic Model of Residential Energy Use. Oak Ridge National Laboratory, Oak Ridge.

Hirst, E., and D. White (1985). Indoor Temperature Changes After Retrofit: Inferences Based on Electricity Billing Data for Nonparticipants and Participants in the BPA Weatherization Program. Oak Ridge National Laboratory, Oak Ridge.

Jaeckel, G., and Okken, P. (1978). Economic Aspects of the Insulation of Dwellings. University of Groningen (in Dutch).

Jaynes, E. T. (1957). Physical Review 106, 620.

Jevons, W. S. (1865). The Coal Question. Macmillan, London.

Jevons, W. S. (1879). The Theory of Political Economy. Macmillan, London.

Jones, H. G. (1975). An Introduction to Modern Theories of Economic Growth. The Camelot Press, Southampton.

Jones, C. T. (1993). Another Look at US Passenger Vehicle Use and the Rebound-Effect from Improved Fuel Efficiency. The Energy Journal, 4, 99-110.

Jouvenel, B. de (1958). A Philosophy of Indian Economic Development. Navajibad Publishing House, Ahmedabad.

Jouvenel, B. de (1959). Organisation du Travail et l'Amenagement de l'Existence. Free University Quarterly, 7, 6.

Keepin, B., and G. Kats (1988). Greenhouse Warming: Comparative Analysis of Nuclear and Efficiency Abatement Strategies. Energy Policy, December 1988, 538-561.

Khazzoom, J. D. (1980). Economic Implications of Mandated Efficiency Standards for Household Appliances. The Energy Journal, 4, 21-40.

Khazzoom, J. D. (1986). An Econometric Model Integrating Conservation Measures in the Residential Demand for Electricity. JAI Press, Greenwich.

Khazzoom, J. D. (1987). Energy Savings Resulting from the Adoption of More Efficient Appliances. The Energy Journal, 4, 85-89.

Khazzoom, J. D. (1989). Energy Savings from More Efficient Appliances: A Rejoinder. The Energy Journal, 1, 157-166.

Krachtkroniek (1994). Prices of Energy. May 1994 (in Dutch).

Krause, F. (1993). Cutting Carbon Emissions: Burden or Benefit? International Project Sustainable Energy Paths, El Cerrito.

Kuhn, T. S. (1970). The Structure of Scientific Revolutions. University of Chicago Press, Chicago.

Kypreos, S. (1992). The MARKAL-MACRO Model, Links and Potential Extensions. PSI, Villigen.

Lovins, A. B., and H. L. Lovins (1991). Least-Cost Climatic Stabilization. Annual Review of Energy and the Environment, 16.

Macdaniel, T. D. (1980). Insulation Guide. Kluwer Technische Boeken, Deventer (in Dutch).

Malthus, T. R. (1798). Essay on the Principles of Population.

Manne, A., and R. Richels (1990). Carbon Dioxide Emission Limits: an Economic Cost Analysis for the U.S.A.. The Energy Journal, 2, 51-59.

Manne, A. S., and R. C. Richels (1992). Buying Greenhouse Insurance: The Economic Costs of Carbon Dioxide Emission Limits. MIT Press, Cambridge.

Meyer-Abich, K. M. (1979). Energieeinsparung als Neue Energiequelle. Carl Hanser Verlag. Munchen.

Mill, J. S. (1857). Principles of Political Economy, Vol 2. J. W. Parker and Son, London.

Mishan, E. J. (1967). The Costs of Economic Growth. Staples Press, New York.

Nordhaus, W. (1990). Count Before You Leap. The Economist, 7 July 1990, 19-22.

Odum, H. T. (1971). Environment, Power, and Society. Wiley-Interscience, New York.

Odum, H. T. (1974). Energy, Ecology, and Economics. Ambio, 6, 220-227.

Odum, H. T., and E. C. Odum (1976). Energy Basis for Man and Nature. McGraw-Hill, New York.

Odum, H. T. (1977). Energy, Value, and Money. In Hall, C. A. S., and J. W. Day (Eds.), Ecosystem Modelling in Theory and Practice, Wiley-Interscience, New York, 174-196.

OECD (1979). Interfutures: Facing the Future. Paris.

Ostwald, W. (1907). Modern Theory of Energetics. The Monist, 4, 481-515.

Ostwald, W. (1911). Efficiency. Independent, 71, 867-871.

Paauw, K. F. B. de, and A. H. Perrels (1993). The Energy Intensity of Consumption Packages. Netherlands Energy Research Foundation. ECN-C-93-043 (in Dutch).

Petty, W. (1662). A Treatise of Taxes and Contributions.

Pigou, A. C. (1935). The Economics of Stationary States. Macmillan, London.

Podolinski, S. (1883). Menschliche Arbeit und Einheit der Kraft. Die Neue Zeit, 1.

Quesnay, F. (1758). Tableau Oeconomique.

Rabinowicz, E. (1965). Friction and Wear of Materials. Wiley, New York.

Rees, J. (1990). Natural Resources. Routledge, London.

Ricardo, D. (1817). Principles of Political Economy and Taxation.

Rossum, T. F. M. van (1991A). Developments in the Electricity Consumption of Households. University of Utrecht, November 1991 (in Dutch).

Rossum, T. F. M. van (1991B). Developments in the Natural Gas Consumption of Households. University of Utrecht, November 1991 (in Dutch).

Rostow, W. W. (1978). The World Economy: History and Prospect. University of Texas Press, Austin.

Rowe, M. D., and D. Hill (1989). Estimating National Costs of Controlling Emissions from the Energy System, A Report of the ETSAP Project. Brookhaven National Laboratory, Upton.

Schrödinger, E. (1955). What is life? University Press, Cambridge.

Schurr, S. H. (1982). Energy Efficiency and Productive Efficiency: Some Thoughts based on American Experience. The Energy Journal, 3, 3-14.

Shannon, C. E., and W. Weaver (1949). The Mathematical Theory of Information. University of Illinois Press, Urbana.

Simon, J. L. (1981). The Ultimate Resource. Princeton University Press, Princeton.

Smith, A. (1776). An Inquiry into the Nature and Causes of the Wealth of Nations.

Soddy, F. (1912A). Matter and Energy. London.

Soddy, F. (1912B). Transmutations, the Vital Problem of the Future. Scientia, 11, 199.

Soddy, F. (1922). Cartesian Economics. Henderson, London.

Soddy, F. (1926). Wealth, Virtual Wealth, and Debt. George Allen and Unwin, London.

Solow, R. M. (1973). Is the End of the World at Hand? Challenge, March/April, 39-50.

Solow, R. M. (1974A). Intergenerational Equity and Exhaustible Resources. Review of Economic Studies, 29-45.

Solow, R. M. (1974B). The Economics of Resources or the Resources of Economics. American Economic Review, May, 1-14.

Solvay, E. (1902). Note sur des Formules d'Introduction a l'Energitique Physio- et Psycho-Sociologique. H. Lamartin, Bruxelles.

Sonenblum, S. (1983). Overview and Commentary. In Schurr, S. H., S. Sonenblum, and D. O. Wood (Eds.), Energy, Productivity, and Economic Growth, Oelgeschlager, Gunn, and Hain, Cambridge, 3-46.

Spare, P. H. (1990). The Fifth Fuel: The Debate Continues. Energy World, April 1990, 177.

Spencer, H. (1880). First Principles. Appleton, New York.

Thirring (1958). Energy for Man: from Windmills to Nuclear Power. Harper and Row.

Toke, D. (1990). Increasing Energy Supply not Inevitable. Energy Policy, September 1990, 671-673.

Toke, D. (1991). Energy Efficiency. Energy Policy, November 1991, 815.

Umana, A. F. (1981). Toward a Biophysical Foundation for Economics. In Daly, H. E., and A. F. Umana (Eds.), Energy, Economics, and the Environment, Westview Press, Boulding, 21-41.

UNIDO (1985). Industry in the 1980s: Structural Change and Interdependence. New York.

Ybema, J. R., and P. A. Okken (1992). Technology Characterizations 2000-2040. Netherlands Energy Research Foundation, ECN-C-92-063 (in Dutch).

Wallich, H. C. (1972). Zero-Growth. Newsweek, January 24, 62.

Warren, A. (1987). Saving Megabucks by Saving Megawatts. Energy Policy, December 1987, 522-528.

Weber, M. (1958). The Protestant Ethic and the Spirit of Capitalism. Harper Collins, London.

Weisskopf, W. A. (1973). Economic Growth versus Existential Balance. In Daly, H. E. (Ed.), Toward a Steady-State Economy, Freeman, San Fransisco, 240-251.

Weissmahr, J. A. (1993). An Evolutionary Economic Theory for a Sustainable Future. International Journal of Global Energy Issues, Special Issue on Energy Analysis, 1, 39-43.

Williams, R. H. (1990). Low-Cost Strategies for Coping with Carbon Dioxide Limits. The Energy Journal, 3, 35-59

Wilson, D., and J. Swisher (1993). Exploring the Gap: Top-Down versus Bottom-Up Analyses of the Cost of Mitigating Global Warming. Energy Policy, March 1993, 249-263.

Winiarski, L. (1900). Essai sur la Mechanique Sociale: l'Energie Sociale et les Mesurations. Revue Philosophique, 49, 256-287.

LITERATURE:

Arnoux, L. A. (1985). The Value of Energy/The Energy of Value. In Gool, W. van, and J. J. C. Bruggink (Eds.), Energy and Time in the Economic and Physical Sciences, North-Holland, Amsterdam, 343-379.

Ayres, R. U., and I. Nair (1984). Thermodynamics and Economics. Physics Tody, November 1984, 62-71.

Beckerman, W. (1972). Economists, Scientists, and Environmental Catastrophe. Oxford Economic Papers, May 1972, 327-344.

Boulding, K. E. (1976). Economics for Good or Evil. Technology Review, July/August 1976, 5.

Brookes, L. G. (1978). Energy Policy, the Energy Price Fallacy and the Role of Nuclear Energy in the UK. Energy Policy, June 1978, 94-106.

Bruggink, J. J. C. (1985). The Theory of Economic Growth and Thermodynamic Laws. In Gool, W. van, and J. J. C. Bruggink (Eds.), Energy and Time in the Economic and Physical Sciences, North-Holland, Amsterdam, 135-145.

Christensen, P. P. (1987). Classical Roots for a Modern Materials-Energy Analysis. Ecological Modelling, 38, 75-89.

Cleveland, C. J. (1987). Biophysical Economics: Historical Perspective and Current Research Trends. Ecological Modelling, 38, 47-73.

Daly, H. E. (1980). The Economic Thoughts of Frederick Soddy. History of Political Economy, 4, 469-488.

Dasgupta, P. S., and G. M. Heal (1979). Economic Theory and Exhaustible Resources. University Press, Cambridge.

Denison, E. F. (1979). Explanations of Declining Productivity Growth. Survey of Current Business, 8.

Diamant, R. M. E. (1986). Thermal and Acoustic Insulation. Butterworths, London.

Faber, M. , H. Niemes, and G. Stephan (1987). Entropy, Environment, and Resources. Springer-Verlag. Berlin.

Fast, J. D. (1954). Entropy in Science and Technology, Part 1: The Entropy Concept. Philips Technisch Tijdschrift, 7, 202-214 (in Dutch).

Fast, J. D. (1954). Entropy in Science and Technology, Part 2: Examples and Applications. Philips Technisch Tijdschrift, 9, 278-288 (in Dutch).

Fast, J. D. (1954). Entropy in Science and Technology, Part 3: Examples and Applications (continued). Philips Technisch Tijdschrift, 11, 336-348 (in Dutch).

Fast, J. D. (1956). Entropy in Science and Technology, Part 4: Entropy and Information. Philips Technisch Tijdschrift, 56, 170-182 (in Dutch).

Faucheux, S. (1993). The Role of Energy in Production Functions. International Journal of Global Energy Issues, 1, 41-55.

Franken, J. C. (1965). Thermodynamics. E.J. Brill, Leiden (in Dutch).

Fowler, K. J. V. (1985). Design of Thermal Loads for Building Structures. Bath Press, Avon.

Georgescu-Roegen, N. (1972). Process Analysis and the Neoclassical Theory of Production. American Journal of Agricultural economics, 54, 279-294.

Georgescu-Roegen, N. (1982). Energetic Dogma, Energetic Economics, and Viable Technologies. In Moroney, J. R. (Ed.), Advances in the Economics of Energy and Resources. Jai Press, Greenwich, 1-39.

Giampietro, M., and D. Pimentel (1991). Energy Efficiency: Assessing the Interaction between Humans and their Environment. Ecological Economics, 4, 117-144.

Gool, W. van (1982). Two-Factor and Multi-Factor Trade-Offs in Energy Conservation. In Economic Theory of Natural Resources, Physica-Verlag, Wurzburg-Wien, 515-531.

Gool, W. van (1985). Entropy and Exergy. In Gool, W. van, and J. J. C. Bruggink (Ed.), Energy and Time in the Economic and Physical Sciences, North-Holland, Amsterdam, 11-15.

Hall, C. A. S., C. J. Cleveland, and R. Kaufmann (1992). Energy and Resource Quality. University Press, Colorado.

Hannon, B. (1975). Energy Conservation and the Consumer. Science, 189, 95-102.

Hausman, J. A. (1979). Individual Discount Rates and the Purchase and Utilization of Energy-Using Durables. The Bell Journal of Economics, Spring 1979, 33-54.

Hausman, J. A., and P. L. Joskow (1982). Evaluting the Costs and Benefits of Appliance Efficiency Standards. AEA Papers and Proceedings, 2, 220-225.

Hertzmark, D. I. (1978). Economics, Thermodynamics, and the Allocation of Energy. University of Wisconsin, Madison.

Hogan, W. W., and A. S. Manne (1977). Energy-Economy Interactions: The Fable of the Elephant and the Rabbit. In C. J. Hitch (Ed.), Modelling Energy-Economy Interactions: Five Approaches, Resources for the Future, Washington D.C.

Hoogendijk, W. (1991). The Economic Revolution. Green Print/Jan van Arkel, Utrecht.

Hueting, R. (1974). New Scarcity and Economic Growth. Agon Elsevier, Amsterdam (in Dutch).

Hueting, R. (1987). An Economic Scenario that gives Top Priority to Saving the Environment. Ecological Modelling, 38, 123-140.

Hueting, R. (1990). The Brundtland Report: A Matter of Conflicting Goals. Ecological Economics, 2, 109-117.

Jorgenson, D. W. (1986). The Great Transition: Energy and Economic Change. The Energy Journal, 3, 1-13.

Kamenetzky, M., and R. H. Maybury (1989). Technical and Financial Rationality Concern for Human Needs and Ecosystems: A Conceptual Framework. Science and Public Policy, 2, 68-72.

Khazzoom, J. D., M. Shelby, and R. Wolcott (1990). The Conflict between Energy Conservation and Environmental Policy in the US Transportation Sector, Energy Policy, June 1990, 456-458.

Kram, T. (1993). National Energy Options for Reducing CO_2 Emissions, Volume I: The International Connection. Netherlands Energy Research Foundation, ECN-C-1993-101.

Martinez Alier, J., and J. M. Naredo (1982). A Marxist Precursor of Energy Economics: Podolinsky. The Journal of Peasant Studies, 9 , 207-224.

Munasinghe, M., and G. Schramm (1983). Energy Economics, Demand Management, and Conservation Policy. Van Nostrand Reinhold, New York.

Pindyck, R. (1979). The Structure of World Energy Demand. The MIT Press, Cambridge.

Proops, J. L. R. (1985). Thermodynamics and Economics: From Analogy to Physical Functioning. In Gool, W. van, and J. J. C. Bruggink (Eds.), Energy and Time in the Economic and Physical Sciences, North-Holland, Amsterdam, 155-174.

Richmond, B. (1980). A Dynamic Framework for Investigating Policies to Increase the Energy Efficiency of the Industrial Sector. Proceedings of the International Conference on Cybernetics and Society, 15-18.

Roll, E. (1973). A History of Economic Thought. Faber, London.

Routh, G. (1975). The Origin of Economic Ideas. Macmillan, London.

Schumacher, E. F. (1973). Buddhist Economics. In Daly, H. E. (Ed.), Toward a Steady-State Economy, Freeman, San Fransisco, 231-239.

Sweeney, J. L. (1984). The Response of Energy Demand to Higher Prices: What have we Learned? American Economic Review, 2, 31-37.

Webb, M., and M. Ricketts (1980). The Economics of Energy. Macmillan, London.

Weyman-Jones, T. (1986). The Economics of Energy Policy. Gower Publishing Company, Aldershot.

Zimmerman L. J. (1968). History of Economic Ideas. Albani, Den Haag (in Dutch).