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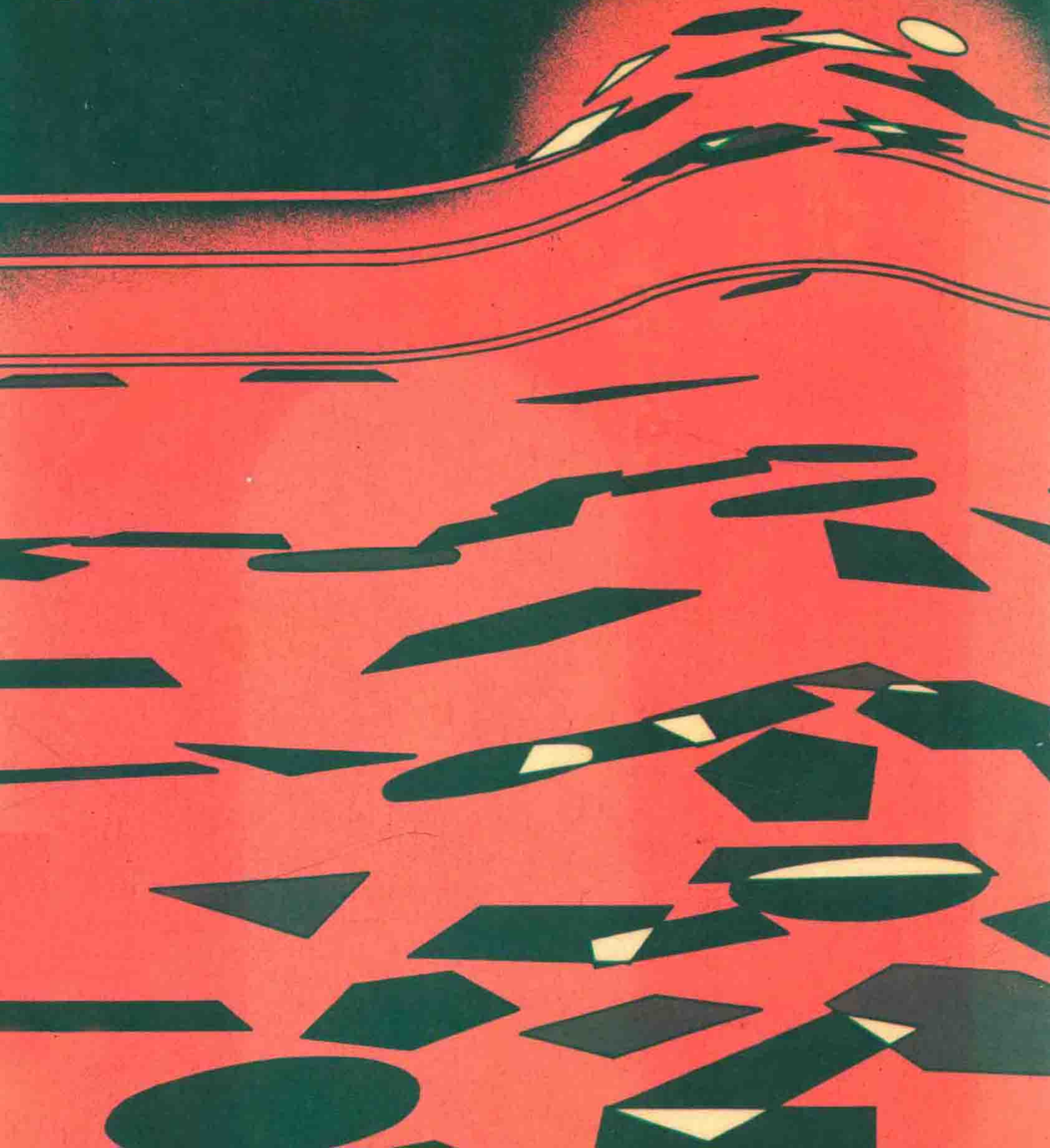
BIO-ENERGY

technology, thermodynamics and costs

DAVID BOYLES



BIO-ENERGY: Technology, Thermodynamics and Costs

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Table of Contents

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Preface

This book arose from an evaluation in industry of the merits and problems of bio-energy. Although it was conceived from within an oil company there was nonetheless a real interest in establishing whether bio-energy could succeed and a substantial research effort was undertaken in this area. The author was not aware of any interest in hastening the demise of a possible competitor to oil.

Proposals for processing biological materials to fuels have been made repeatedly in the last hundred years. Similar causes may have directed thoughts each time towards this area. At various times fears grew regarding the supply of liquid hydrocarbons. There has also been the problem of recurring agricultural surpluses. The use of ethanol and vegetable oils as fuels for internal combustion engines was promoted at the end of the last century, during the 1930s and in the last ten or so years. It is ironic that in each case subsequent events have resulted in a relative oil abundance which has made the proposals less relevant.

A cool, hard look at the facts of bio-energy processes was felt necessary. The proponents of these processes have predicted an age of abundant, cheap energy which would be obtained in a relatively non-polluting manner and which would avoid the dangers of nucelar power. Even if these processes are expensive at the moment, they say, research and increasing real prices for fossil fuels will eventually make them competitive. How much truth is there in these assertions? Can one quantify how abundant, how cheap, how clean, bio-energy would be and when it will become commercially viable? In addition there is the nagging question of whether more primary energy is really made available or does bio-energy merely translate fossil materials into alternative fuels? Hidden energy subsidies may mean that the net result is an energy sink for remaining fossil fuels.

An attempt is made to answer these questions. However, although an enormous literature has appeared in recent years, relevant data are sparse. The commercial viability of the processes is obscured in the literature by a plethora of technical detail. Although some of the biofuels are claimed to be economic, there has been no general move to exploit them on a large scale. Where the processes have been adopted, this is in practice often been due to government subsidies provided for social and political rather than economic reasons. Energy and economic costs are compiled in different ways by different reviewers, often according to their bias towards or against the project. Unrealistic credits are sometimes allowed for the by-products of bio-energy. The result is, to say the least, confusing and leaves the general reader in uncertainty as to whether biofuels are currently being developed on a massive scale or whether they are the wishful hopes of the anti-nuclear lobby. This study was written to provide at least the questions which should be asked when bio-energy proposals are discussed. In addition to competent technical descriptions, cost breakdowns, cost sensitivities and longer-term social and environmental costs are required. The answers should be presented in the perspective and terminology of current world economic activities. Some reference must be made to current or past processes which use similar feedstocks or similar reaction pathways. It is important to know for those other processes what is economically viable and what is not. Bio-energy is a subject where what is and what might be in the future are often confused.

Although the results of the present study are not on the whole optimisitc for the future of bio-energy as a major component of world energy supplies, there are some factors which could conceivably change bio-energy prospects. These are examined. Research, the author's own area of interest, is one of these and the sensitivities of the total costs of bio-energy to specific innovations are highlighted. In some areas of the world, bio-energy is the only energy available and just as in the past this sufficed for our energy needs it may suffice in undeveloped countries for some time to come. It has been suggested that it would be preferable for such countries to improve this route rather than follow the path trodden by the industrialised societies in developing fossil and nuclear fuels. Whether the peoples depending on bio-energy would in the long term agree is debatable.

1

The need for abundant and cheap energy

1.1 ENERGY, ENTROPY AND USEFUL WORK

The Role of Energy

The world currently uses the equivalent of seven thousand million tonnes of oil every year for energy purposes. In volume the energy trade exceeds all others. The importance of this trade needs no emphasis, since no human activity can proceed without expenditure of some form of energy. Any threat to the continuing availability of energy is viewed with alarm. In recent years such threats have taken the form of price rises, embargos, and the predicted absolute scarcity of raw energy in the future. Part of the response to these threats has been an increased interest in developing new sources and forms of energy.

Before considering one of these new energies, bio-energy, the fundamental role of energy in human affairs should be examined. In essence energy, in the form of fuels, is used to establish and maintain order in the material world. Transport, house construction, consumer goods etc. all represent a re-ordering of raw and manufactured materials and allow the building-up of the patterns desired by members of human societies. The ultimate cost is not in energy, which is neither made nor destroyed (First Law of Thermodynamics), but in entropy which for the total system inexorably increases (Second Law). In the many processes for introducing order, energy-dense fuel is degraded and its energy is converted to low-grade heat.

Whether in nature or in man's many activities, energy is needed to fuel the processes of creative change. Organisation and growth are entropically unfavourable processes and are only possible by coupling them to total entropy production during energy degradation. The result is useful work, which either creates other energy-dense materials or arranges material components to the benefit of the organism, whether it is a life-form or a human society. Both types of organism need the consumption of specific fuels in their construction and in their maintenance.

Growth and Complexity

The most obvious way in which living organisms differ from other entities in the physical world is in their complexity. The fossil record and the history of human societies reveal patterns of ever-increasing complexity. The more complex the structure and function of an organised body, the more the energy seen to be needed in its construction and maintenance. For growth, an energy greater than a minimum maintenance requirement must be made available. Where less than maintenance needs are supplied the body must adapt or die. Where energy is supplied above maintenance rate but less than excess, a limitation is placed on the rate at which the organism can grow. For maximum growth, energy and other materials must be in excess.

These restraints may be demonstrated in a much more satisfactory way in natural organisms than in human economies. Growth limited by energy in the latter would be difficult to demonstrate. There are many other uncontrolled factors which may limit growth. Also human economies are not bound by a relatively unchanging genetic code; they can, although they do not always, adapt rapidly in terms of their doubling times. Nevertheless, human activities also depend on the available energy and any threatened limitation is seen with concern.

A feature of even the humblest microbial cells is that the bulk of energy used in growth is used not in the synthesis of energy-dense products but for the correct placement of molecules within cells in organised groups and structures [1]. An example is that of the yeast, *Saccharomyces cerevisiae*, shown in Table 1.1. The enthalpy of metabolism is largly spent on an outflow of entropy and very little goes to the synthesis of calorific cell material. There is in fact enough energy, even allowing for the inefficiences in energy currency (ATP) production to form perhaps ten times the cell material made. The energy is, however, needed for cell organisation.

Table 1.1 – Energy degradation in anaerobic yeast growth.

	Enthalpy of catabolism	Free energy of ATP hydrolysis (2 moles)	Enthalpy of cell synthesis
Kcals/mole glucose consumed	−31	−14.6	+0.23

With human activities the bulk of the energy is similarly used, not for the production of high calorific materials or high energy states, but to introduce order and to establish structure and function. A myriad of irreversible processes are involved, causing large outflows of entropy.

Net Energy Analysis

The implications of these simple observations are far-reaching. For example, energy consumption is often seen as largely centred on the high calorific fuels used for heating and transport. Whilst it is true that considerable energy dissipation occurs at their point of use, a great deal of energy has been degraded in refining and transporting the fuels and in constructing the fuel-burning devices. Even seemingly non-energy intensive activities such as the provision of human services involve the allocation and the indirect expenditure of energy. For example wages paid for services are spent ultimately on energy expensive goods and other energy-consuming services.

The question of how much energy is used in the production of various goods and services has been asked in recent years. The answer is obtained with much difficulty and is found to be partly a matter of definition. One method, described by Wright [2], calculates from published government statistics on a number of industries the total energy used in producing different commodities. The types of input used by different authors are enlightening and illustrate the all-pervading influence of energy in developed economies.

In net energy analysis all fuel inputs in the production of an article or in the production of its component parts are traced back to primary energy consumption. The original energy inputs in the fabrication of imported materials may also be taken into account, since these represent a primary energy input. Capital may or may not be treated as an energy input; however, a simple relationship exists for doing this. The energies represented by human labour, profits and solar radiation (e.g. in agriculture) may be and are sometimes included. The primary energy needed to produce all the goods and services that man enjoys as a reward for his labours is not usually a component of energy analyses although a case can also be made for doing this [3]. Some feedstocks for manufactured products are themselves high energy materials. These are usually included and can lead to unusually high values for total energy inputs to these goods. Typical values using input–output statistics and not including capital, labour, solar or profits inputs are included in Table 1.2 [2]. The calorific value of the commodities themselves are included for comparison. It is seen that the energy used in making an article may be much more than the heat of combustion of the product itself.

The subject of energy inputs will be returned to later since they must be taken into account when assessing the efficiency of the processes for preparing fuels. If we are concerned about the ultimate reserves of energy, these processes should yield more usable fuel than the usable fuels consumed. Bio-energy processes, for example, whilst dealing with substantial amounts of energy are complex and may embody hidden energy costs derived from the total matrix of national energy-consuming activities. Their adoption should not mean that we cause a net depletion of other equally usable energies. Our strategy should be to obtain the economically maximum useful work from the fuels available.

Table 1.2 – Energy costs and calorific value of commodities.

Commodity	Energy cost, GJ/t	Calorific value, GJ/dry t
Sugar	21	16.5
Paper	61	17.5
Wood pulp	28	17.5
Soybean oil	18	42
Cotton	57	17.5
Fertilisers (mean required)	31	–
Synthetic rubber	129	40
Paint	144	40
Steel	12	–
Copper	80	–

1.2 SCALE, EFFICIENCY AND ENERGY DENSITY

Three basic physical considerations are involved in the use of energy in given tasks. The first is whether the energy resource is large enough. The second is how efficiently the available energy can be used. The third is the rate at which the energy can be supplied to effect the task. Productivity is a combination of the three factors.

Energy Abundance

Again living cells provide an analogy with economic systems. Cells use either inorganic molecules (the chemolithotrophs), preformed organic molecules (the heterotrophs), or the sun's radiation (photo-autotrophs) as fuel. However, the energy source is only one possible limitation among many others to the growth of organisms in the biosphere: temperature, nutrients, water and disease are often more important limiting factors. Attempts to demonstrate yearly variations in photosynthetic yield with insolation, for example, have generally failed [4]. Success in nature is perhaps less in finding a scarce energy supply than in adapting to exploit an abundantly available resource. There are still environments, for example the sea and deserts, where organisms have not adapted and very poor use is made of the considerable light energy flux received.

In a similar way man has been surrounded by abundant energy forms and has only learned slowly how to use them. First, energy was derived by the biochemical oxidation of preformed carbon compounds in animal and plant food. Later, dried plant biomass such as wood was combusted at higher temperatures in air. Subsequently the more concentrated remains of long-dead cells in the form of coal and oil were burned. Finally man learned how to exploit the