Lecture Notes in Energy 36

Charles A.S. Hall

Energy Return on Investment

A Unifying Principle for Biology, Economics, and Sustainability

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Preface

Most earlier civilizations, and many today, attributed their existence, well-being and rules for proper behavior to a powerful God or gods. Our civilization, and indeed earlier ones, has a new god, energy, rarely acknowledged but increasingly understood by a relative few, that allows our existence and determines many aspects of our material well-being. Energy is the master determinant of most that happens on Earth. As such it has determined, and will continue to determine, directly and indirectly, the major events of civilization. But this view is not well understood, principally because most analysts, economists and prognosticators, not to mention college freshmen, have not been taught the fundamentals of energy, which is too often presented, if at all, in a dispersed highly technical way that cannot reach most of the potential readers. I have spent my adult life studying energy and systems science, first as an ecologist and subsequently as something like an economist. I was trained by many but especially my Ph.D. advisor, Howard Odum, who opened a world of understanding and explanation to me that allowed me to understand nature as much more systems and process rather than the disparate hodgepodge of differing activities and species that I had been previously trained to see. This book is meant as a straightforward and relatively non-technical introduction to energy and its role in nature and in human-dominated systems, including economics. It is a primer on how the world works, emphasizing commonalities in structures and processes obvious to one trained in systems science but to relatively few others. My modest claim to scientific fame has come from the development of the concept Energy Return On Investment (EROI, sometimes EROEI) which I first elaborated while studying why fish migrate but later applied to many things, including especially our search for new energy. My goal is to present the needed information as a story in our understanding of life, evolution and human society in relatively few pages.

I found it surprising that others did not see things from this energy perspective, as it seemed to me so clear, so general and so powerful in explanation. When later I worked in some thirty different countries around the world, I was often asked how, after a day or two of introduction, I could bring such useful insight to the problems of that country I was visiting? I would respond: "But I have seen it before, many times, often with different actors but common processes, all with energy as a basis." For energy is ubiquitous, even if our understanding of it is not. Energy is not something that can be observed only in the physics lab or with expensive instruments but is part of everything we do. Take the kitchen: we may think of energy when we boil water or turn on the oven, but who thinks of a sharp knife as energy, as a force concentrating device, of cooking as a means of giving the human gut access to plants whose cell walls made most plants inaccessible to humans before the human use of fire, or the sunlight and food chains that made the food available in the first place? Nor do we usually think of the energy investments made by farmers and the entire industrial system to get the food to us in convenient and (relative to historical conditions) inexpensive form at the local supermarket.

This story focuses on energy investments and the return on those investments as a kind of underlying super process that guides essentially all that life, including humans, do. This is a story about what we have learned, and what we need to know, to understand our place in the universe and the future of human civilization.

Syracuse, USA — Charles A.S. Hall

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Contents

Part I
Energy and Investments

Economists usually consider that there are two things we do with the resources at our disposal, consumption (using them now, often for our own pleasure) or investments (defering their use and using them in some way to generate more resources in the future). They, and people more generally, usually think of such resources and investments in terms of money or time. But in essentially all cases investments must be made in terms of energy. This section introduces the concepts of resources and energy, starting with an historical approach.

Chapter 1
Investments

Our story starts with investments. The concept of investment, of using resources already in hand to attempt to get more in the future, is familiar and essential to the human condition, indeed to all of life. It can explain a tremendous amount of our behavior. At the level of ourselves, our families, our communities, our nation or our world everything, in a sense, is about investments and return on those investments. The resources required for the generation of our food, for such wealth as we are able to garner, indeed for life itself do not appear for free but usually must be sought through investments, large or small. This is most obvious as we grow from children to young adults and observe the adult roles we might take on for ourselves. Farmers, bankers, entrepreneurs, most business people, musicians, and even academics are well aware that if they are to do well in their chosen field very large investments in time, effort, money, study, practice, and so on are necessary. The concept of return on investments is also very familiar to us as we examine financial returns on stocks or savings or houses or family. Each partner in a relationship must invest in various ways time, energy, thoughtfulness, and love or at least care if the relationship is to be successful. Various professional or charitable institutions emphasize the importance of investing in children, good government, science, or many other things for society's well-being. The list is almost endless because the concept of investment is crucial for nearly all that we do. Clearly, investments and return on investment underlies most of what we do and can do in life. Most of us know people who are obsessed with trying to get some kind of high return on their own investment. An investment implies something to be invested, which necessarily must be a surplus from the past. This book is about how we can generalize on the concept of return on investment and how we can understand nearly all investments much better by understanding them in terms of energy.

Nothing happens without energy. This applies to economic activity and investments just as truly as to moving a soccer ball. But energy does not come for free, for many resources, including energy, must be invested to get energy for a later date. Gardeners know this: one has to till and fertilize the soil, plant the seed, water the little plant carefully and wait patiently for the plant to mature, usually while

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investing in various means to protect your investment from other species (or your own) eager to exploit your own work. Natural history, and human history, usually can be viewed as various species or groups of people making investments in an attempt to get more resources. Much of the human history of the world is about making investments, of necessity energy investments, in resource exploitation, trade and shipping, military campaigns, and so on in an attempt to secure more. But, importantly, throughout most of history, indeed for most of human civilization, energy was expensive, as it is expensive too for other organisms. A recent paper by King et al. (2015) found that for many centuries in England nearly half of all GDP was required to get the energy required to run the other half of the national economy.

Thus this book is about the importance of energy as the world's master resource and also how all life, including humans, have to invest a lot and then get a good return on their investment. Plants, animals and humans themselves who do not invest energy wisely in getting more energy are dead, extinct or exist only as "collapsed" societies.

Therefore investments need to be understood within a broader context, including biological, economic, and energetic. Biologists understand that an organism must meet its own energy requirements for maintenance and generate a surplus before it can invest in reproduction. Likewise economists usually divide what we do with the wealth we have or, especially, produce (i.e., GDP) into two broad categories: consumption and investments. Investments cannot be made into new enterprises until maintenance requirements are met. Hence we, meaning ourselves personally but also a business or a nation, can either spend our wealth or invest it. Basically, it is a matter of time: do we want to enjoy our wealth now or potentially more in the future. As such it is a "zero sum game," meaning that there is an *opportunity cost* to spending your money now: if you spend it now you cannot invest it for the future. For the average person this represents a dilemma, as anyone who has saved to go to college knows.

For monetary investments it seems like a good deal: a wise investment gives you more total money than if you simply spent it now. But from the energy perspective it is a little different, for when you spend money you are also spending energy. The money can be printed indefinitely, but most of the energy cannot, since by definition fossil fuels, which supply about 85 % of the energy we use and are mostly responsible for our great wealth, are not renewable; once used they are gone forever. And energy is essential to give money meaning. Once we thought that gold was a backing for money. Until 1972 one could, in theory, take in your dollars to the U.S. Government and get in exchange gold (the gold standard). But it was not gold that gave meaning to the dollar, it was the goods and services you could trade it for. And those goods and services required energy to produce, about 6 MJ (megajoules; see Table 3.1) per dollar in 2016. If you print or otherwise generate money without energy to back it up the money loses value. Hence we can think of money as lien (a promissory note) on energy. Thus if we are talking about monetary investments we are talking simultaneously about energy investments. Therefore opportunity costs also applies to energy opportunity costs; energy used for one activity or investment cannot be used for another.

Thus the concept of Energy Return On Investment (EROI). For any "progress," indeed simply sustaining any life process requires a continual influx of energy. This concept, often termed "maintenance metabolism", applies to fish in the sea, yourself and your civilization. The reason for this, developed more fully in Chaps. 3 and 6, is that there is a relentless tendency for the molecules that make up an organism (or a city) to degrade to a more random state. Organisms (and governments and private entities) must continually invest energy in keeping molecules in the very specific structures that life requires if it is to continue in its present form. And only after those investments have been met is it possible to have some kind of surplus—whether that is reproduction, evolution or growth or "progress" of a civilization.

Not surprisingly there is a premium on a positive return on investment and especially a high return. If one takes a broad view of evolution any time a new technology with a high energy return happens along in the evolution of life there will be an explosion of life forms using this technology. For example, before some 500 million years ago there was no free oxygen in the atmosphere or the seas. Life was abundant and diverse, but none of it used oxygen (as we do) as a terminal electron acceptor because there was no oxygen available. Life operated on fermentation, generating energy-rich alcohol as an unusable by-product. But once land plants evolved and generated free oxygen as a by-product of photosynthesis, other organisms were able to utilize this oxygen and increase their own utilization of their own food (such as plant sugars) by about a factor of 4. Hence, once the technology of using oxygen was "worked out" through the development of mitochondria, it spread very rapidly throughout the animal kingdom, and also to plants and many microbes. This greater ability to use energy by animals in turn led to much more active and mobile lifestyles, investing existing energy into obtaining much more. Likewise as human societies evolved new energy-capturing technologies (such as agriculture, wind powered sailing ships, and fossil fuels) the technology spread rapidly. Those species and humans who understood or happened upon the new energy-rich opportunities tend to be those (or their descendants) who are with us now.

Humans have always invested their own energy into the requirements for life, originally through hunting and gathering, then through agriculture, then through various industrial processes, and always through conquest and exploitation. Today, this investment process has been institutionalized in Western civilizations through capitalism, including industrial development, colonialization, war and "free trade." This is a very powerful process because, in part, it has so closely combined the expansion of the exploitation of fossil fuels with the economic interests of many of its participants at every level, but especially the top, of the economic ladder. It allows enormous concentrations of wealth and power that in turn reinforce the wealth and power of its participants. There are many in the world today who wish to decrease the power of this process which we examine in Chap. 12.

I find it curious that the generality of this relation—energy as master enabler and EROI as a key determinant—throughout much of the living world has not received more attention and emphasis. But for this it to be understood and appreciated humans need first to understand what energy is and how energy works. This is developed in the next chapter.

Reference

King, C.W., J.P. Maxwell, and A. Donovan. (2015). *Comparing world economic and net energy metrics*, Part 1: Single Technology and Commodity Perspective. Energies 2015:12949–12974.

Chapter 2
The Development of the Laws of Thermodynamics

In order to understand what energy is, it is necessary to understand the laws of thermodynamics. The most important step in this process is unraveling the relation of heat to other forms of energy. Thus we start with an historical perspective of how the human understanding of heat and energy evolved from mystical to increasingly scientific. Much of the interest in heat and energy was initiated by the astonishing success of James Watt's steam engine in the middle of the eighteenth century. While it was obvious that the engine could translate heat from coal into very powerful and useful mechanical work, the underlying reasons as to how were mysterious to many.

2.1 The History of Our Understanding of Energy[1]

In 1750, humans had essentially no clue as to what energy was, how it operated, how it was transformed, and how it was related to work or investments. But in the following century a series of remarkable discoveries and experiments, mostly from Scottish, French, and English scientists, uncovered the essentials of energy and its relation to investments. First were the remarkable discoveries of Isaac Newton—which actually took place 100 years earlier. Newton discovered the three laws of motion (every object remains in its state of motion unless acted upon by an outside force; accleration is force divided by mass; for every action there is an equal and opposite reaction) and in the more than 350 years since then no fourth law has been discovered! Newton showed that the behavior of matter, which earlier had appeared as chaotic and unpredictable, actually followed a very few mathematically predictable rules. And they were universally applicable, that is they could be repeated again and again by different people in different countries and expanded to other

[1]For a much more detailed historical and physical development see: Ayres, Robert. 2016. Thermodynamics, wealth production, complexity. Springer, New York.

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