Lecture Notes in Energy

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Energy Storage and Civilization

A Systems Approach

Springer

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Preface

This is a book about energy storage in modern civilization, beginning from the Neolithic through the early modern and contemporary periods. The origin of the book traces back several years to exchanges about the inclusion of storage in net-energy analysis of renewable energy systems. At its simplest, net-energy analysis is the field of research that seeks to evaluate how much energy an energy supply process, such as crude oil production, returns after taking into account the energy needed to extract, process, upgrade, and deliver that energy. By definition, an energy supply system, whether it includes storage or not, that uses more energy than it delivers is energetically unviable—it is not worth implementing. The basis of what we present in this book is directly, or indirectly, tied in with net-energy analysis.

Before starting the book, we set ourselves the goal of answering several questions–What role does energy storage play in economic systems and the ways of life they enable? How do we value the benefits and costs of storage? Is it sufficient to consider storage solely in technological terms? And can storage technologies substitute for the unique performance characteristics of petroleum fuels, with their large inherent storage built-in, at large scale?

There are already many texts on the technical, engineering, and market-based aspects of energy storage. But most of these place storage within the domain of technology and assess the value of storage from a techno-economic "micro" perspective. Although this is important, we argue that a macroscale assessment of the role of storage needs to be undertaken from a biophysical economic perspective—price dynamics and market behavior alone are insufficient for understanding the roles and limits of storage at the macroscale.

The book starts from fundamentals and aims to provide a foundation for a deeper understanding of the role of storage in economic systems and the societies that they support. We begin the exploration with a historical perspective, starting with an anthropological overview. How did energy storage enable particular human evolutionary pathways and forms of social organisation, and what is its relationship with the cultural norms that emerged?

The focus shifts forward to the beginning of industrialisation, where we seek to provide a multidisciplinary perspective that identifies various questions for subsequent exploration. This includes questions relating to biophysical economics, the chemistry of fossil fuel combustion, electrical engineering concepts, and life-cycle concepts. Our objective is to encourage a broader appreciation of energy storage in scenario analyses, EROI studies, and energy-economic modelling. But more importantly, we seek to challenge the dominant frame of reference that storage can be understood in technological terms alone, with its value defined solely by techno-economic analysis.

We thank David Packer from Springer, and especially Charlie Hall, for encouraging us to write this book, editing the manuscript, and the valuable contributions. We are very grateful to the community of researchers and participants in the International Society of Biophysical Economics (ISBPE) and researchers from the University of Melbourne, including the Melbourne Sustainable Society Institute (MSSI) and Energy Transition Hub, for the many conversations that have influenced our thinking. Graham would especially like to thank Josh for helping to bring to life many of the ideas explored in this book through his clear writing style and capability of bridging a deep historical perspective with insights from futures research. Josh in turn wishes to express his appreciation to Graham for his generosity in inviting him along on the inquiry and learning process that lies at the heart of an endeavour such as this. Graham would also like to give special thanks to Kylie, Lachlan, and Sarah for their unwavering support and Sarah for her reviews and important feedback.

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Introduction

Fossil fuels are derived from the accumulation and storage of prehistoric biomass. The energy embedded in biomass comprises a small portion of ancient sunlight that was initially captured by green plants, which were subsequently protected from oxidation by anaerobic conditions and sedimentation, and concentrated by Earth system dynamics. Less than 0.1% of the total organic activity was eventually converted to oil and gas. Fossil fuels can be conceptualized as stored energy stocks that can be readily processed, transported, and converted to power flows on demand.

However, there are two strong drivers of a long-run transition away from fossil fuels. Firstly, the release of millions of years of stored carbon within a short time is perturbing the earth's natural carbon cycle and enhancing the greenhouse effect with probably severe adverse climate impacts. Secondly, although significant resources remain in place, fossil fuels are of course nonrenewable and finite. The era of easily accessible oil has passed, and all fossil resources, excepting perhaps unconventional oil and gas, are near or past their peak production rates.

Pre-industrial societies lived within the natural cycle, governed by the seasons, the sun's rising and setting, and the constraints of organic agriculture. In industrialized societies, the last few generations have become accustomed to copious power on demand regardless of the season.

A post-fossil fuel society will need to rely on energy released by nuclear fusion and/or fission, either directly or indirectly. By far, the most important primary energy source on a planetary scale is solar, derived ultimately from hydrogen and helium fusion reactions within the Sun. Much of the focus of this book is on how humans can utilize solar fusion indirectly, via Earth-based solar power technologies and wind power, to replicate the roles of fossil fuels. Direct use of fission, as nuclear power, is introduced but is not the main focus of this book, primarily because nuclear is not widely projected to expand significantly for the foreseeable future.

A transition from energy sources comprising accumulated stocks of past sunlight to sources derived from present flows will require a replication of the energy storage services provided by geologically sequestered fossil fuels. Replicating these services has both economic and energetic costs. In light of these costs, human societies will very likely need to re-examine demand expectations, and indeed the wants and needs fulfilled by current energy demand, that have taken shape in the context of copious on-demand power.

Most analyses of energy storage adopt a relatively narrow technical or economic focus. This book broadens the scope of the study by placing it within broader historical and biophysical frameworks. The focus is on the underlying physical properties of storage rather than the role of energy markets and economics, which are treated in detail in other publications. Much of the discussion refers to electricity systems, but the scope includes the provision of energy services via liquid and gaseous fuels. The discussion is grounded in the principles of biophysical economics, which adopts various tools including net-energy analysis (NEA). NEA, including the energy return on investment (EROI) metric, has the potential to supplement conventional economic and environmental models by providing an energetic valuation of energy supply.

The layout of the chapters is as follows:

Chapter 1 begins by exploring the role and value of storage from first principles, taking into account lessons from the historical trajectories of human societies. We explore three key cultural transitions in human societies and argue that energy storage played a defining role in all three. We identify the transitions as (1) the Neolithic transition, manifesting in the shift from foraging and hunting to agriculture and settlement; (2) the first industrial revolution, manifesting in the rise of coal-fired steam power; and (3) the Age of Oil, manifesting in the emergence petroleum-fuelled mass mobility.

Chapter 2 examines the origin and role of fossil fuels and explores their importance in enabling contemporary forms of social organization. The focus is on the ways in which shifts from flow-based to stock-based energy sources supported economic changes previously unavailable.

Chapter 3 is a primer on energy and the fundamental forces of nature and an exploration of the implications for energy storage.

Chapter 4 introduces the net-energy concept and explains how net-energy analysis and the EROI metric can contribute insights that are not obvious from market-based economic analysis alone.

Chapter 5 reconceptualizes efficiency as it applies to storage. It introduces the concepts of direct and indirect efficiency in order to provide context for the importance of embodied energy and EROI.

Chapter 6 considers electricity supply from an electrical engineering perspective. Electricity faces storage limitations that are unusual compared with other energy carriers, and it warrants special attention due to the system-level implications of transitioning to high penetrations of variable renewable generation. The discussion draws attention to the role of existing electricity system services, with an emphasis on how these might be replicated with renewable generation and storage. It also discusses the functions of the most common forms of storage presently deployed in modern electrical grids.

Chapter 7 considers the strengths and limitations of scenario analyses reliant on quantitative modelling for investigating the storage magnitude that may be required in high penetration renewable energy futures.

Chapter 8 explores the role of hydrogen as an energy carrier and the concept of the “hydrogen economy.”

Finally, Chap. 9 synthesizes the various strands of inquiry pursued over the book’s course.

Contents

Chapter 1
History as a Guide to Understanding the Future of Storage

1.1 The Argument for the Primacy of Energy Storage

Human energy use is derived from sources that can be characterized as either stocks or flows. In this view, the solar energy reaching the earth is an energy flow, but the energy embodied in wood that was derived from solar energy, via photosynthesis, is an energy stock. Energy storage deals with the relationship between stocks and flows: storing energy, whether by natural or anthropic processes, involves the accumulation of flows as stocks; exploiting stored energy involves the conversion of stocks to flows.

The concepts of energy flows and energy stocks are important for understanding the pivotal roles that energy carriers play in enabling economic activity. An energy carrier is any physical phenomenon that can be harnessed to transfer energy from one time and place to another. Gasoline, run-of-mine coal, and electricity are all widely recognizable energy carriers. Depending on context, water flowing in a river, compressed air or hydraulic fluid can also play the roles of energy carriers. The energy associated with gasoline can be quantified in terms of a flow rate, for example the production of an oil refinery per some time period, distributed by truck, ship or pipeline. It can also be quantified in terms of a stock—for instance, the same time period's production from the refinery, now stored as part of a nation's strategic fuel reserve. In other cases, the energy flow associated with a carrier is not readily accumulated as a stock. This is exemplified most prominently by electricity, but in the early years of the seventeenth century industrial revolution in England, run-of-river mills faced a similar situation: available power, being the rate at which hydraulic energy could be put to mechanical use, fluctuated with rainfall and with the seasons. In the case of electricity, accumulation of energy flows as energy stocks can be achieved on a large scale only by first converting the energy to another form, associated with a physical phenomenon of different type. These ideas will be developed further as the book proceeds.

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In energy research, energy storage is usually discussed with reference to technological devices such as batteries, or fuels such as gasoline. Energy storage is also essential in nature. In biology, adenosine triphosphate (ATP) production during photosynthesis can be viewed as an energy storage process. The role of ATP in energizing cellular function involves continuous processes of storage and discharge. Similarly in ecology, energy storage in the form of biomass is studied in terms of the differential energy flow rates between trophic levels. All energy flows in ecology are ultimately derived from sunlight via photosynthesis. Although there are many contexts for energy storage, we want to argue that energy storage, as both a technological and natural phenomenon, has been much more significant to the development of human civilizations than usually understood.

In this chapter, we will explore three key historical transitions in the ways that human societies have organized, and argue that energy storage was a defining factor of critical importance in all three. Energy storage need not have been the primary *causative* factor, but was an essential *enabling factor*. In other words, the emergence of a new energy storage process was necessary but not sufficient for allowing those transitions.

We identify the transitions as (1) the Neolithic transition, manifesting in the shift from foraging and hunting to agriculture and settlement; (2) the first industrial revolution, manifesting in the rise of coal-fired steam power; and (3) the Age of Oil, manifesting in the emergence petroleum-fueled mass mobility. Although all three transitions are some of the most important cultural events in human history, there is a remarkable divergence of causative explanations, especially for both the first and second. Even the role of petroleum is often underestimated in economic history—the key drivers of modernity are generally given as technological, cultural or institutional.

Given the declining fossil fuel base and adverse effects of global climate change, the aim of this book is to explore what energy storage strategies or technologies may come next. A post-fossil fuel society will need to rely on fusion and/or fission, either directly or indirectly. By far the most important primary energy source on a planetary scale is solar, derived ultimately from hydrogen and helium fusion reactions within the Sun.

But substituting solar energy for all the energy services currently provided by fossil fuels will require incorporating storage into energy systems, on a very large scale. This leads to two questions—what type of storage, and what is the economic and energetic cost?

We believe that starting from first principles reveals deeper insights about the past, present and future roles for energy storage. The aim of this chapter is to provide an introductory ‘macro’ perspective, before moving on to a more detailed ‘micro’ perspective on energy storage.

1.2 The Neolithic Transition

1.2.1 Human Evolution

The precise evolution of modern humans continues to be debated, especially the relationship between *Homo sapiens* and archaic hominin species (Galway-Witham and Stringer 2018). An ancient ancestor of modern humans, *Homo erectus* (or upright man) lived from about 2 million years ago. Following the adaption of tree dwelling anthropoids to walking on two feet in a drying, more open, grassland environment, it is believed that primitive stone tools were developed, fire was harnessed, along with early advances in social organization, art and perhaps religion (Diamond 2005). Anatomically modern humans appeared roughly 200,000 to 150,000 years ago (Galway-Witham and Stringer 2018; Scott 2017), and dispersed out of Africa somewhere between 100,000 and 60,000 years ago (Galway-Witham and Stringer 2018; Weaver 2015). There is no definitive answer as to when fire was harnessed for cooking, but Wrangham (2009) argues that it could have been as early as the emergence of *Homo erectus*. Fire increased the digestible organic matter in both vegetables and meat (increasing energy availability from a given food mass), and significantly reduced the time spent on chewing foods.

The Neolithic transition occurred at different times and in different places, and began roughly 10,000 years ago. It refers to the passage of human tribes from a nomadic life of foraging and hunting, to one of agriculture and settlement. Up until the transition, Palaeolithic societies lived a subsistence life of hunting and gathering, governed by the diurnal and seasonal cycles.

1.2.2 The Crucial Advantage of Grains and Cereals

In the Neolithic transition, humans began domesticating plants and animals. Competition for land increased as populations increased and bands were pushed to less productive land. At the beginning of this development, protocultivation was applied to wild plants, leading to domestic species. The same process was occurring with animal raising and breeding. Initially, domestication would have occurred alongside traditional foraging, hunting, and fishing. It gradually led to specialized crop cultivation, land clearing and basic irrigation (Mazoyer and Roudart 2006; Hibbs and Olsson 2004).

In the next stage of crop development, fruit and nut trees were cultivated, such as olives, figs and grapes. These reached maturity much more slowly and would have required settled village life but were a source of seasonal nutrition and variety. Further developments required advanced cultivation techniques, such as cross-pollination and grafting.

The crucial development was the adoption of grain and cereal farming. Cereal types differed between regions—in the Fertile Crescent, wheat and barley dominated; in China, millet and rice; in Mesoamerica, corn (Diamond 2005). The organized cultivation of grains and cereals enabled production surpluses, which in turn permitted inter-seasonal storage. In principle, inter-seasonal storage increases the food available for consumption during the leanest season. The implication of this is sometimes framed in terms of Liebig's 'law of the minimum'—in the absence of such inter-seasonal storage, the population level or survival capacity of a community is regulated not by the annual resources, but by the smallest quantity of food available during the leanest season (Testart et al. 1982).

But in the early stage of farming, the calorific return from consuming grains, relative to the overall calories expended for sowing, harvesting and preparing, was much less than traditional foraging and hunting and it is not obvious that farming would have been worth the effort. More precisely, the energy returned on (energy) investment (EROI) is the ratio of the calorific return to the calorific expenditure for food procurement. Agriculture requires intense effort over long periods, often with variable results. In contrast, the energy surplus of gathering (Lee 1969) and hunting was often very high—contemporary studies of basic hunters find an EROI of greater than 26:1 (Glaub and Hall 2017).

1.2.3 Why Farm?

Given that the returns on investment from foraging and hunting were probably greater than early agriculture, it is not obvious why early humans adopted and persisted with agriculture, and why those people survived while others were displaced. Indeed, the Neolithic transition is one of the defining events in human cultural history, yet the underlying cause is still the subject of intense debate.

The prevailing view until at least the twentieth century, was that 'agriculture was simply a practice waiting to be discovered' (Weisdorf 2005). Reflecting the orthodox nineteenth century view, Darwin (1868, p. 309) believed in the idea of the inevitability of agriculture, noting—

> The savage inhabitants of each land, having found out by many and hard trials what plants were useful, or could be rendered useful by various cooking processes, would after a time take the first step in cultivation by planting them near their usual abodes.

However, by the second half of the twentieth century, anthropologists found evidence that foragers and hunters may have been better fed and healthier than comparable agriculturists, eventually leading Harlan (1992, p. 27) to pose the question—

> Why farm? Why give up the 20 hour work week and the fun of hunting in order to toil in the sun? Why work harder for food less nutritious and a supply more capricious? Why invite famine, plague, pestilence and crowded living conditions? Why abandon the Golden Age and take up the burden?

Many hypotheses have been proposed for the adoption of agriculture, including population pressure, overkill of large fauna, environmental factors, climatic changes, the end of the last glaciation, and others, however no explanations have proven complete (Weisdorf 2005). Perhaps it is because barley could not be 'hunted out' as human populations increased.

Deevey (1960) compiled several population sources and plotted human population estimates over the last million years on a log-log graph. Log-log axes uncover changes that are significant in relative magnitude but may be insignificant in absolute magnitude. He argued that three population surges are evident in the historical record, as a result of: (1) tool-making; (2) agriculture; and (3) the scientific-industrial revolution. One explanation for increased population due to agriculture may have been that the end of nomadism meant less stress during pregnancy, although a grain-based diet also led to lower general health (Angel 1984).

The role of food storage as an explanation has been widely explored in the anthropological literature, including James Scott's (2017) recent book: *Against the grain: a deep history of the earliest states*. Where storage has been identified as an explanation for the Neolithic, it is usually identified as a straightforward response to gaps in food supply (Rowley-Conwy and Zvelebil 1989). Mumford (1967, p. 139–40) drew a connection between food and the means of storage, arguing that 'the radical Neolithic inventions were in the realm of containers', pointing to the development of baked clay vessels for the storage of grain, oil, wine and beer. Testart et al. (1982) connected the ideas of seasonal food supply, settlement and storage, arguing that 'whenever resources are highly seasonal, sedentism and large-scale storage imply each other: storage brings forth sedentism, and sedentism presupposes storage. Which historically precedes the other is a chicken-and-egg question.'

Halstead and O'Shea (1989) summarized the role of storage as one of four basic strategies for responding to food shortages due to either the seasonal cycle, short term scarcity, or other natural variability in the environment. The four strategies include:

1. **diversification**, as a strategy to counteract scarcity of one resource by sourcing others, especially through sourcing a wider range of plant and animal species;
2. **mobility**, as a strategy to even out spatial discrepancies in resource availability by movement between areas of resource abundance;
3. **storage**, as a strategy to even out temporal discrepancies in resource availability, by 'saving it for later'; and
4. **exchange, sharing and reciprocity**, as a group of strategies for playing off temporal variability in resource availability, against spatial variability in resource abundance. Exchange functions in a fashion similar to storage, in that present abundance is converted, via social transactions, into a future obligation in time of need. The idea of 'negative reciprocity', or theft, might also be treated as belonging in the same category as exchange.