Lecture Notes in Energy

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# Energy Storage and Civilization

## A Systems Approach

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# 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.

practically possible before—accumulate, transport and control the dispersal of energy at large scale. Control implies the capability of using energy *when* and *where* required—regulating the availability of energy in *time* and *space*. The distinction between regulating temporal and spatial availability, and how it relates to energy storage will be drawn out in later chapters.

The four strategies laid out earlier by Halstead and O'Shea (1989), including diversification, mobility, and exchange also contributed to large-scale control over the temporal and spatial availability of energy. However stored energy, in the form of non-perishable and transportable food, went further than simply supporting survival during periods of low food production. It made possible human evolutionary pathways, and particular forms of social organization, cultural norms and technological suites, that were unavailable prior to the Neolithic transition.

A popular view here holds that the availability of surplus food enabled humans to pursue, as desirable ends in their own right, ways of life characterized by increasingly elaborate forms of social and political organization, larger population, expanded territorial scale, more diverse material possessions and so on. Tainter (2011) argues that this view of how large-scale, socio-politically complex societies emerge and grow is misguided. He proposes instead that these forms of organization emerge in the course of solving immediate existential problems. More importantly though, they remain viable only to the extent that their resource costs—most prominently, their *energetic* costs—can be met on an ongoing basis. Tainter (1988) defines socio-political complexity in terms such as the diversification of specialist social roles, and just as importantly, elaboration of the means for *coordinating* the diversified roles. This is characterized by features such as increasingly hierarchical structures of organization and people occupying leadership positions of extended duration. Central to his thesis is the insight that humans will implement solutions involving greater socio-political complexity, and seek to maintain such complexity, only if the benefits entailed are perceived to outweigh the costs of funding those arrangements. This always entails a trade-off.

Human existence, though, is characterized by the encounter of new problems. We understand our places in the world in relation to individual and collective histories, and plan and act in the context of envisaged futures. This necessarily brings us into contact with countervailing currents of natural and other human origin. Where such currents are perceived to conflict with collective and individual desires, our situations take on a problematical character. As such, our responses to problematical situations, however necessary they may be, are always of short-term efficacy. The responses themselves help to establish the contexts for future problematical situations. According to Tainter's (1988) central thesis, wherever humans choose to implement collective responses to collective problems, socio-political complexity will proliferate, providing that there is also collective willingness to meet the energetic costs entailed.

The availability of ready means to accumulate and store surplus energy has profound implications here, for it weights the problem solving cost-benefit equation in favor of increased *potential* for socio-political complexity. By removing a prior

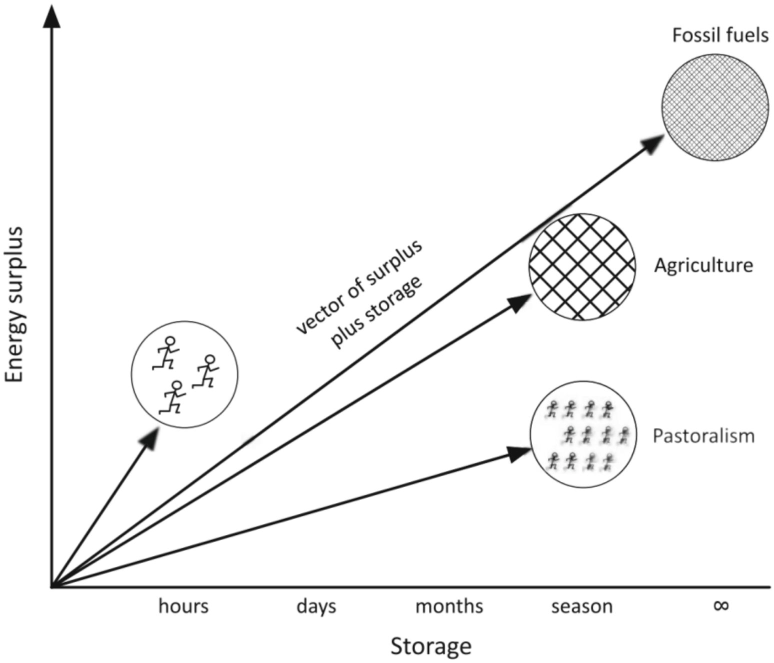

**Fig. 1.1** Stylized graph of energy surplus ($y$-axis) versus storage ($x$-axis). The value of energy supply is determined not just by the surplus (or net) energy, but by the capacity to store that energy. In this vector-based depiction, coupling a source of surplus energy with a means of storage adds to its underlying value

constraint to exploring certain areas of socio-political ‘state-space’, evolutionary pathways that would not be viable in the absence of such storage are now on the table.

## *1.3.2 Surplus Energy and Energy Storage*

Figure 1.1 qualitatively depicts the magnitude of the ‘state-space’ opened in this way in terms of the vector of energy *surplus* potential and energy *storage* potential. Energy surpluses were necessary, but not sufficient, for supporting Neolithic socio-political complexification.

In relation to Palaeolithic societies, surplus energy implied the availability of food to support the band or tribe in excess of the energy costs of hunting and gathering. The emergence and persistence of early agricultural societies demonstrates that the benefits of greater control over energy use outweighed the short-run costs of accumulating and storing surpluses.

### 1.3.3 Counter-Examples

Numerous examples of societies that did not adopt sedentary agriculture provide counter examples. The role of potatoes also provides an interesting contrast between nutritional and storage properties.

The !Kung of the African Kalahari Desert were readily able to produce food surpluses, but lacked the means and motivation for food storage; nearly all food was consumed within two days of acquisition (Lee 1969). Instead, the !Kung 'spent' their surplus on rest, social life, and visiting other groups.

Similarly, many Aboriginal Australians lived an abundant nomadic life, and practiced an advanced form of what Gammage (2011, p. 281) termed 'farming without fences'. Gammage collated a staggering list of farming and conservation methods including burning, herding, hunting, weir construction, seeding, and other activities that would now be recognized as natural resource management. But none of these 'farming' activities were conducted as part of a tradition of sedentary agriculture.

The American anthropologist Marshall Sahlins studied both the Kalahari !Kung and Aboriginal Australians, and noted that they were easily able to satisfy all basic needs and enjoyed a great deal of leisure time (Sahlins 1974; Harlan 1992). Sahlins' anthropological studies led him to coin the phrase 'the original affluent society', referring to healthy and well nourished hunter-gatherers.

Interestingly, Aboriginal Australians cooked a type of bush bread known as damper, but collected the grains as part of a foraging tradition (Roth 2015). A variety of native seeds, and sometimes nuts and roots, were collected and crushed, and made into a dough that was baked in the coals of a fire. Seeds varied depending on the time of year and the particular area.

Despite a surplus exceeding basic needs and a rich cultural life, Aboriginal culture didn't replicate the complex city-state cultures of classical Europe, Asia or Central and South America. Aboriginal Australians relied more on Halstead and O'Shea's strategy of diversification and mobility, rather than seasonal storage. One reason for not adopting sedentary agriculture is that the long occupation of Australia had given Aboriginal Australians a profound understanding of the El Niño climate phenomenon (Clarke 2002). El Niño is notoriously difficult to forecast and delivers multi-year droughts, which would have spelled disaster for pre-industrial societies overly dependent on cropping.

The role of potatoes as a later staple crop provides another counter-example. Potatoes belong to the root vegetable group, including carrots, parsnips and turnips. They are nutritionally superior and are much easier to prepare for consumption than grains, but they have inferior storage characteristics. Root vegetables were traditionally stored in root cellars or storage rooms, where they could be preserved in cool, dry, dark places, insulated from winter frosts and summer heat. Stored properly, they can have a shelf life of several months (Nourian et al. 2003). From a nutritional standpoint, potatoes are generally better than wheat and other grains because they are richer in vitamins and nutrients. The two vitamins that are lacking, vitamins A and D, can be provided by dairy products. Historically, they also provided more calories per unit of land than grains (Nunn and Qian 2011). But potatoes can be stored only for a period of months after harvesting. They are also more fragile than grains, and not as amenable to bulk handling.

## 1.4 The Relation Between Energy Storage and Currencies

### *1.4.1 Salt as Food Preservative and Commodity Money*

The earliest forms of planned energy storage involved reserving surplus grain and cereal production for later consumption. Initially this provided societies that mastered food storage techniques with a survival advantage relative to other groups. In time though, food storage took on a more strategic role in the planning and management of social organization. This included the facilitation of exchange and trade. With the emergence of trade in surplus food between social groups, grains and cereals came to be used also as forms of commodity money—that is, money consisting of material that has value in its own right.

A biophysical perspective may help to shed light on why grains, which are perishable and therefore subject to decline in value with time, could nonetheless perform effectively as a form of money. Consider here the proposition that money represents a claim on future work (Hagens 2014). That is, money that I hold today may be exchanged at some point in the future for goods or services, the production of which requires physical work and hence energy use. From a biophysical perspective, the current value of the money that I hold relates to the expected claim that I can make on future work. Considered in this light, grains and cereals may have been recognized by sellers of goods and services as having monetary value due not only to their direct nutritional value for 'funding' physical work, but also for what we now know as their embodied energy value. That is, a quantity of grain or cereal 'in the hand' also represents a quantity of past labor investment. When grain is paid to me in exchange for my labor in some other area of economic activity, I am in effect acquiring the benefit of the labor that went into the grain's production. A notable feature of food-based commodity money comes to light here: it constitutes an abstract representation of the past work required to produce it, and, as digestible and nutritious organic matter, a concrete representation of future work potential. In accepting grain or cereal as a form of money, I am taking on the risk that its future value may decline due to spoilage. But I am also gaining, in an immediate and direct manner as a result of the exchange, effective control over a quantity of past agricultural labor that can now be directed towards ends of my choosing, including work that does not itself need necessarily to be nutritionally productive.

Perhaps the most important early preservation method was salting. Salt can be used for curing foods such as beef, pork, fish, and butter. In meats, salt acts as an inhibitor of spoiling by drawing water out of the microbial cells via the process of