Ownership, technology, and resource depletion: what comes first?

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Abstract

We are on the brink of the fourth grand energy transition in human history. Each previous transition - to hunting large animals, to agriculture, and to fossil fuels - has brought epochal civilisational transformations in economic and political power. In this working paper, I provide a brief overview of how property practices, in particular, have changed during these first three energy transitions. Debates surrounding property recur in the specialist literature for each of these transitions, but are only rarely brought together into a framework allowing comparison between them, and only very rarely compared in terms of energy transition. A key debate across all specialist literatures is the question of why these transitions take place where and when they do. In this working paper, I present classify these debates in terms of being about whether technological innovation, changes in property practices, or resource depletion take place first, before the other changes occur. My preliminary findings appear to support a 'depletion first' hypothesis across the first three energy transitions. Though I do not reach any conclusions whatsoever about the current transition in this working paper, this research may nevertheless aid understanding of some of the causes and effects that may accompany this fourth grand energy transition, the transition away from fossil fuels.

Introduction

In a sense, the main purpose of this working paper is to clarify what is meant by 'grand energy transition', and then to work out how best to describe the different property practices that accompany these transitions. Once these clarifications are in place, the remainder of the paper picks out some important events in each grand energy transition and tries to see if a general framework might apply across all three previous energy transitions.

The paper is organised as follows. First, I set out the four main energy systems that have characterised human history so far, and briefly describe the grand energy transitions that have taken place between them. In the second section, I set out how property practices relate to energy systems, setting out the main property practices that emerge with the adoption of each new energy system. In the third section, I set out the different hypotheses of what causes energy transition, categorising them as the 'technology first', 'property first', and 'depletion first' hypotheses across the different specialist literatures. In the fourth section I discuss the method for distinguishing between causes and consequences, and describe the kinds of evidence that is available. In the fifth section, I use this evidence to set out some rough timelines for the sequence of events during each of the first three transitions. A short conclusion summarises these preliminary findings.

1. The grand energy transitions

'*Main energy systems*' are those energy systems that provide the majority of the energy that humans use, whether hunted meat, domesticated plants and animals, or fossil fuels. They may be supported by additional energy systems representing a smaller proportion of the energy that humans use, for example the use of whale oil or kerosene for lighting, which are called '*auxiliary energy systems*' (Debeir et al 1991). There have, so far, been four main energy systems, each characterising a societal epoch: the energy systems of a non-tool-using pre-human ancestor; the energy system of hunter-gatherer societies; the energy system of agricultural societies; and the energy system of fossil fuelled societies.

Each energy system has a number of comparable components. The '*initial source*' is the origin of the energy. In physical terms, this is where mass becomes converted into energy, for example in the process of nuclear fusion in the sun, from which most energy on Earth derives. '*Entropy slowing converters*' are the means by which energy is converted into mass on Earth, such as during photosynthesis, and through the processes that transfer energy to other parts of the system, for example through the cellular respiration of animals which consume the biomass of plants or other animals. '*How mass is captured*' refers to the way in which humans obtain that mass; this can be endosomatically, for example by using their hands to capture berries or small animals, or exosomatically, for example using tools to dig up pieces of coal. '*How mass is stored and transported*' refers to the way in which the captured mass is moved to where the mass will be converted into energy, for example endosomatically carrying meat to where it will be eaten, or exosomatically shipping coal to where it will be burned. '*Prime movers*' are the technologies that convert the mass from these energy resources into energy for human use. They are called 'prime movers' since they are used to convert the mass from an energy resource into kinetic energy; for example, digestion converts food into muscular movement in animate prime movers such as draft animals, whereas inanimate prime movers use machinery to convert mass into movement, such as when nuclear power plants use heat produced by radioactive fusion to turn steam turbines (adapted from Debeir et al 1991:18 and Smil 2010).

Transitions between energy systems can be characterised as the adoption of new technologies that play a role in the process of making energy resources available for human use. The energy analyst Vaclav Smil describes the transitions between the four main energy systems as the 'grand energy transitions' (Smil 2010). The first three grand transitions involved the development of hunting and scavenging tools to allow the capture of meat from animals in the savanna, the development of agricultural technologies to allow the capture of energy using domesticated plants and animals, and the adoption of inanimate 'prime mover' technologies such as the steam and internal combustion engines which allowed the large scale use of energy from fossil fuels (adapted from Smil 2010; see also Hall and Klitgaard 2012). Below, I briefly outline the four main energy systems that have been used in human history, and sketch the grand transitions that have taken place between them.

Table 1: the first grand energy system: pre-tool human ancestors

Initial source (where mass -> energy)	Solar energy
Entropy slowing converters (energy -> mass)	Photosynthesis (plants), cellular respiration (animals)

How mass is captured	Endosomatically (by hand or mouth)
How mass is stored and transported	Endosomatically (by hand or mouth, or as body fat)
Prime movers (mass -> kinetic energy)	Cellular respiration

The energy system of the last human ancestor that used neither tools nor fire is very similar to the energy system of virtually every other animal on earth. Solar energy is converted to mass by plant photosynthesis, some of which may be transferred to other animals before being captured, is then carried about by the capturer, and then digested and converted into muscular movement. This system would have been the main energy system for a non-tool using primate ancestor and, except for the direct use of energy from solar light and solar heat used for seeing and keeping warm, would have accounted for virtually all of the energy used in these prehuman societies.

The first grand energy transition is the transition from eating the foods of the forest to eating animals and plants of the savanna, particularly the meat from larger game animals. Previously, the main energy sources had been the fruits, berries, and invertebrates that are found in the forest. These dietary changes were accompanied by morphological changes to teeth, jaws, and digestive tracts, and by technological changes including stone tools, spears, and the control of fire (Stahl et al 1984, Hall and Klitgaard 2012: 46). Over time, hunting technologies improved and larger animals became more frequently captured (Mann 2007, Hall and Klitgaard 2012: 45).

Table 2: the second grand energy system: hunter-gatherer societies

Initial source (where mass -> energy)	Solar energy
Entropy slowing converters (energy -> mass)	Photosynthesis (plants), cellular respiration (animals)
How mass is captured	**Exosomatically (tools)**
How mass is stored and transported	Endosomatically (by hand or mouth, or as body fat)
Prime movers (mass -> kinetic energy)	Cellular respiration

Unlike the pre-tool human energy system where biomass is captured purely by hand, the energy system of the hunter-gatherer relies upon capturing biomass using tools such as hunting tools, grinding stones, and fire. Tools are used by nonhuman animals including ravens and beavers, and by nonhuman primates including chimpanzees, but only in humans is the largest proportion of energy captured using exosomatic tools. This system would have become the main energy system once hunted animals and processed plants provided the majority of the energy used (with the rest still provided by direct solar heat and light, those foods readily consumable without processing, and the burning of biomass in fires). There are periods in human history when hunted large game supplemented by processed plant foods would have accounted for the vast majority of the energy used by humans. This energy system still applies to every present day mobile hunter-gatherer society.

The second grand energy transition is the transition from hunter-gathering to agriculture. Following the control of fire and the use of hunting tools, the human population eventually grew and expanded beyond Africa, quickly followed by the extinction of large animals wherever humans settled (Prescott et al 2012, noting climate change as well as human hunting may have been factors). Plant husbandry, particularly, involved a shift to an abundant and reliable but more labour intensive food energy source (Cohen 1977, Barker 2009: 402). The new technologies of energy conversion were the tending, storage, and domestication of plants, and the corralling, husbanding, and domestication of animals. Interestingly, where an energy substitute to large animals was found in the intensive exploitation of harvests from coasts, lakes, or rivers, foragers lived largely sedentarily without much risk of depleting their source of food. In such places, for example north-western Europe, the Nile Valley, Japan, the Ganga Valley, the eastern Woodlands of North America, and coastal Peru, full agriculture was adopted much later (Barker 2009: 399), and only once agricultural techniques had been developed and introduced from elsewhere. In time, technologies like collar-harnessing and ploughs were developed which allowed draft animals to be used as animate energy converters to supplement the work done by human muscle (Smil 2010: 49-50).

Table 3: the third grand energy system: agricultural society

Initial source (where mass -> energy)	Solar energy
Entropy slowing converters (energy -> mass)	Photosynthesis (plants), cellular respiration (animals)
How mass is captured	Exosomatically (tools)
How mass is stored and transported	**Exosomatically**
Prime movers (mass -> kinetic energy)	Cellular respiration (humans and traction animals)

Whilst mobile hunter-gatherers do not store game or wild plants, and only transport them after they have captured them, domesticates are themselves a form of storage: grains are stored over winter and, most vividly, a herd of animals is ‘live stock’ and represents energy stored ‘on-the-hoof’. For several millennia, agriculture would have accounted for around ninety per cent of the energy used by humans, with the remainder mostly obtained directly as solar light and heat, through the burning of firewood, peat, and turf, and from inanimate prime movers such as sails, waterwheels, and windmills (Smil 2010).

The third grand energy transition was the transition to fossil fuels and to fossil fuelled prime movers. The use of fossil fuels dates at least as far back as to Roman Britain and Han dynasty China (Needham 1964 in Smil 2010: 28, 36), though until the sixteenth century coal was regularly burned only by the poor (Smil 2010: 28). The decline of forests, however, especially near to cities, led to the expansion of coal mining. At some point between 1650 and 1700, coal came to provide more than half of the UK's energy supply (Hatcher 1993:55; though there are various estimates and dates which may be important; see Kraussmann et al 2008; Smil 2010: 28-29). Similarly, before coal, though inanimate prime mover technologies like sails, water wheels, and windmills had been used for millennia, they had never supplied a significant proportion of energy when compared to animate prime movers such as human or animal muscle (Krausmann et al 2008, Smil 2010: 51).

Table 4: the fourth grand energy system: fossil fuelled society

Initial source (where mass -> energy)	Solar energy
Entropy slowing converters (energy -> mass)	Photosynthesis (plants) then fossilisation or coalification
How mass is captured	Exosomatically (tools)
How mass is stored and transported	Exosomatically
Prime movers (mass -> kinetic energy)	**Combustion in inanimate converters (e.g. steam turbine)**

The development of the steam engine at the start of the eighteenth century was the first inanimate prime mover driven by fossil fuels, and it allowed the expansion of coal extraction, initially by providing the means to drain deep coal mines that had penetrated the water table (Rhodes 2007: 4, Pomeranz 2001). Technological improvements in the steam engine around the middle of the eighteenth century gradually allowed coal to replace draft animals in transport which, combined with the development of coke-fuelled iron blast furnaces, led to further increases in coal use (Krausmann et al. 2008). In the late nineteenth century the internal combustion engine was developed, using fuels previously considered waste products from the refining of crude oil into kerosene for lighting. Technologies allowing the commercial generation of electricity, initially from hydro-power but soon overwhelmingly from coal and then fossil hydro-carbons, became increasingly widespread (Smil 2010: 41-42). Globally, by 1950, human labour supplied at most 5% of all work, animals about 10%, and inanimate converters such as the internal combustion engine and steam turbines at least 85% (Smil 2010).

2. The appearance of new property practices

Energy systems can be thought of as the flow of units of energy through an energy system. Within those systems, property practices describe how people behave towards to the units of flow that are possessed by others. Indeed, probably the simplest property practice of all is that of '*first possession*', whereby a unit of flow such as a berry, a piece of meat, an ear of corn, or a piece of coal is not taken if it is already possessed by another (see Krier and Serkin 2014). '*Communal property*' practices are where first possessors give units of flow to other group members; in other words, where communal property is practiced it is community membership, not first possession, that entitles an individual to flow units, even if those flow units are in the possession of somebody else (adapted from Boehm 2004). '*Stock property*' is where the flows from an energy stock, such as a berry bush, a herd of animals, a field of corn, or a colliery, are taken into the possession of whoever owns the stock, not whoever has first possession of the flow unit; for example, some of the flow units that a peasant first possesses comes under control of the lord who asserts property rights in that stock of land. (Note that this differs from 'group territoriality' which I do not include in the charts below as it remains roughly constant throughout the four energy systems and does not directly relate to the governing of energy flows to individuals; I do, however, mention group territoriality in my discussion, if it is particularly interesting or relevant.) I classify slavery as a form of ‘stock property’ practice where all the flow units which the slave first possesses immediately comes under control of the lord, but slavery could equivalently be considered as a property practice whereby the flow units first possessed by prime movers (the slaves) immediately becomes the property of the masters of those prime movers. '*Intellectual property*' is the practice by which people who patent new energy technologies are entitled to a share of the flow from the realisation of those ideas. For example, the patent holder of an improved kind of steam engine could prevent use of such machines unless they receive a share of the flow units from those who have used such an engine to become the first possessors of coal they would not otherwise have been able to mine (though for convenience, the patent holder may prefer payment in cash).

It is worth emphasising that my focus here is on property practices surrounding the flow of units within energy systems. This is a shift in focus from many analyses, which often take land ownership to be the key property practice with which other practices are compared (for example North and Thomas 1977). The shift in focus onto examining the property practices surrounding units of energy flow has the advantage that the same kind of analysis can be applied to all energy systems. In other words, the question about how different kinds of property practice emerge can now be united by a single mode of analysis and by a single framing question: how do flow units get taken away from their first possessors and come, instead, under the control of people who are not the first possessors?

Table 5: the property practices in pre-tool human ancestors's energy system

First possession	Practiced over moveable flow units
Communal property	No
Stock property	No
Intellectual property	No

In the absence of archaeological evidence, inference from the behaviours of present day primates is the best indicator that a common ancestor between humans and various branches of the human-primate clade, living in analogous energetic circumstances, had similar property practices (Boehm 2004). For individual flow units, a first possession property practice is observed by many primates, in that moveable objects like a piece of fruit, a nut, or a small animal are rarely taken by others whilst still in the hands of their first possessor. However, taking does still occur and only occasionally will third parties intervene to prevent it; the reasons for third party intervention remain unclear. Though all primates in the homo-pan clade (after the branching of gorillas) exhibit group territoriality - that is, group defence of the resource stock - there is little evidence that such conflicts are governed by the practice of any property norms or rules between groups, and such conflicts are instead resolved through violence or displays of violence (Pryor 2003, Boehm 2004).

Table 6: the property practices in hunter-gatherer energy systems

Among pre humans the first possessor could expect to maintain possession of what they capture; among mobile hunter-gatherer societies, first possessors are expected to give up possession of high value foods such as meat and honey to other members of the group. This shift is profound: entitlement to such a unit of flow from an energy resource is no longer accorded due to being its possessor, but is accorded due to being a member of the community. Mobile hunter-gatherers continue to have no 'stock property', and group territoriality resembles pre-human societies, though usually conflicts are resolved with less violence and more negotiation. Whilst there may be 'intellectual property' in songs or spells, there are no intellectual property practices governing component processes of hunter-gatherer energy systems; hunter-gatherers do not, for example, expect to receive payment for inventing a better spear (Pryor 2003, Boehm 2004).

Table 7: the property practices in agricultural energy systems

There is a vast range of different agricultural societies. Almost universally, however, agricultural societies differ from hunter-gatherers in that they have a property practice whereby entitlement to possession of at least some flow units is granted to whoever holds 'stock property'. A large portion of a persons possessions is governed by these 'stock property' practices, whereby possessions accrue to the owner of the resources stock, not the first possessors; for example, all that a slave first possesses, and a sizeable portion of that which a serf or peasant first possesses, becomes the possession of their master. Of course, the actual practices governing the energy system of agricultural societies can range from the despotic dominion of a tyrant who claims to possess all, to a complex of community practices governing who may extract what from a common pool resource such as a fishery (e.g. Ostrom 1990). 'Communal property', where a person is entitled to units of flow simply by being a member of a community, persists in systems such as 'tithing' whereby a small portion of a person's possessions, often around a tenth, is donated for the consumption of those unable to provide for themselves (see, for example, Old Testament sources such as Deuteronomy 14:24-28). Group territoriality also persists in behaviour very similar to those

First possession	Practiced over some moveable flow units
Communal property	Practiced over some high value items, e.g. meat and honey
Stock property	No
Intellectual property	No

First possession	Practiced over some moveable flow units
Communal property	Practiced over a portion, e.g. tithing
Stock property	Practiced over land, e.g. kingdoms, common pool resources
Intellectual property	No

that occur in the two previous energy systems, though almost everywhere specialists begin to emerge, and agricultural societies develop systems where warriors and soldiers engaging in territorial defence receive flow units from those working on the stock of land (Moore 2003). 'Intellectual property' practices in energy technologies have not yet emerged.

Table 8: the property practices in fossil fuelled societies

Again, there are a great variety of fossil fuelled societies of great complexity, though throughout the nineteenth century, and certainly by the start of the twenty-first century, certain broad aspects of their property systems are virtually universal. 'Communal property' practices persist in the portion of taxation that is designated for welfare. 'Stock property' practices persist over land, and now apply to other energy resources such as collieries and oil wells. After the enclosure of land, however, the taking of unit flows from their first possessors is no longer governed by customary norms but by contract: the first possessors are employees who exchange the food, coal, or oil they extract according to contracts of employment, and cannot chose to keep hold of the flow units of which they are the first possessors (see Polanyi 1944). 'Intellectual property' practices governing energy technologies, such as steam engines, also appear at around the time of the fossil fuel era, which prevent the use of these technologies in harnessing energy flows unless the payment of a share of the gains from those flows is paid as a license for using that technology.

3. What comes first: property, technology, or energy resource depletion?

These, then, are the property practices accompanying the four grand systems of human history. Each new system is characterised by new property practices, new technologies, and new energy systems. There are a variety of ways in which property practices, technological innovations, and the adoption of new energy system might interrelate. Indeed, one immediate similarity across the different literatures on each of the transitions

First possession	Practiced over some moveable flow units
Communal property	Practiced over a portion, e.g. taxation for welfare
Stock property	Practiced over land and other resources, increasingly consolidated
Intellectual property	Practiced over energy technology, e.g. steam engine patent

is a tendency to avoid unicausal models (e.g. Gurven 2004, Cohen 2009; one notable exception that perhaps proves the rule is McCloskey 2010, for example p.176). A complex of causes are required to account for why transitions occur at one time and place, but not in others; indeed, technology, property practices, and energy systems do not change in isolation from each other, and they do all change with each transition. Nevertheless, debates about the underlying causes of each transition – or, more simplistically, which change comes first – have taken place in each of the literatures on the transitions to hunter-gathering, to agriculture, and to fossil fuelled society. I propose to divide these into three broad hypotheses:

1) property changes come first;

2) technological changes come first; or 3) energy resource depletion comes first.

Though contemporary systems are often compared to each other (e.g. Boehm 2004, Pryor 2003, 2005), and historical comparisons are often made (e.g. Polanyi 1944, Braudel 1981), it is rare that a historical comparison is specifically framed as one between different energy systems (though see Passet 1979, Debeir et al 1991, Smil 2010). It is rarer still that the property practices of each of these energy systems are compared (Boehm 2004, a study of contemporary human and nonhuman primates, is the closest I have found). My project here, then, is to begin to make just such a comparison. Using the conception of property practices as they relate to units of flow in energy systems, as I have outlined above, allows for the kind of comparison that previous models have not been able to conduct. I also have the advantage of basing any conclusions on new archaeological evidence that I some cases has been uncovered only in the last decade or so. Note that the transition to large game and to fossil fuels each occurred independently only once, so these literatures I draw on focus on the transition to hunting large animals in Africa and the transitions to fossil fuels in England. The transition to agriculture, on the other hand, occurred independently in multiple centres across the world, so I have drawn on literature that discusses the transition to agriculture in general, but focused in particular on the literature on the transition to agriculture in Western Asia.

Below, I discuss some examples of the kinds of hypothesis advanced within the respective literatures. The next goal of this section, beyond simply establishing that similar discussions play out across these different literatures, is to see whether there is any indication that there are, in fact, generalisable trends among the causes and consequences of the first three grand energy transitions.

3.1 The 'property first' hypothesis

In the literature surrounding the transition to larger animals, the 'property first' hypothesis holds that sharing (Pruetzl in Gintis et al 2015, and Gintis et al 2015), or at least 'increased tolerance' for taking (Melis and Semman 2010: 2671), enabled early humans to make the transition to the hunting of larger game, since it allowed for cooperative hunting (Winterhalder and Smith 1992), or at least for communal feeding from scavenged carcasses (Melis and Semman 2010). One version of this hypothesis is that tolerance for other group members taking from first possessors formed the basis for the speciation of humans who could cooperate: "variation in tolerance around food among individuals of the last common ancestor to *Homo* and *Pan* might have served as the raw material on which natural selection worked on the way to a species that actively shared the spoils of collaboration" (Hare and Tomasello 2005 quoted in Tomasello et al 2012). Similarly, behavior-based versions of the 'property first' model suggest that "[o]nly with the evolution of reciprocity or exchange-based food transfers did it become economical for individual hunters to target large game. The effective value of a large mammal to a lone forager . . . probably was not great enough to justify the cost of attempting to pursue and capture it. . . . However, once effective systems of reciprocity or exchange augment the effective value of very large packages to the hunter, such prey items would be more likely to enter the optimal diet" (Winterhalder and Smith 1992:60).

In the transition to agricultural society, the 'property first' hypothesis holds that property practices in which the stock of land was held by individuals or families encouraged the tending of plants and animals which had not previously been worthwhile, since without property anybody could simply take them. Douglass North and Robert Thomas provide the classic statement of this hypothesis: “The key to our explanation (of the transition from foraging to farming) is that the development of exclusive property rights over the resource base provided a change in incentives sufficient to encourage the development of cultivation and domestication” (North and Thomas 1977: 230, parenthesis in original). In a more recent restatement of this thesis, Samuel Bowles and Jung-Kyoo Choi write that the transition to agriculture “was not sparked by a superior technology. It occurred because possession of the wealth of farmers – crops, dwellings, and animals – could be unambiguously demarcated and defended. This facilitated the spread of new property rights that were advantageous to the groups adopting them” (Bowles and Choi 2013: 8830).

In the transition to fossil fuelled society, it is fair to say that most scholars follow Robert Brenner (1982) in noting the importance of population decline and a decline in agricultural productivity in the centuries before the transition (the transition is often thought of as a change of property practices during the ‘transition to capitalism’, or as a technological transition during the Industrial Revolution). As such, most such scholars would fall under the ‘depletion first’ hypothesis below. Nevertheless, within this literature, the focus is not on whether depletion occurred first, but on why, once depletion took place, England made a transition to fossil fuels whilst places in similar situations, such as China, did not. So scholars such as Douglass North and Avner Grief might nevertheless be described as ‘property first’ theorists in the sense that they view the emergence of new property practices as the most important factor in the transition, emphasising the importance of “the spontaneous emergence of institutions that enforced contracts through better property rights, acceptable arbitration arrangements, and the kind of institutions that created strong incentives that overcame opportunistic behavior, rent- seeking, and reduce uncertainty” (Mokyr 2002: 28). According to this hypothesis, the outcome of these changed property practices are the adoption of more efficient agricultural techniques and the adoption of intellectual property practices that incentivised technological innovation and allowed the energy transition to fossil fuels to take place.

3.2 The ‘technology first’ hypothesis

In the transition to large game literature, I'm not aware of many explicitly formulated arguments that hunting or scavenging tools actually preceded the depletion of forests, but the argument that hunting tools, used as weapons, may bring about communal property by making it dangerous for an individual to refuse to share their possessions is put powerfully by James Woodburn: “the means to kill secretly anyone perceived as a threat to their own well-being . . . acts directly as a powerful leveling mechanism. Inequalities of wealth, power and prestige . . . can be dangerous for holders where means of effective protection are lacking” (Woodburn 1982:436; see also Gintis et al 2015 for a recent restatement). There is also evidence that hunting tools have been adopted by chimpanzees in the savanna at Fongoli, making that population of chimpanzees unique both in living in the savanna and in using hunting tools (Pruetz and Bartolani 2007). Combined with observations that chimpanzees do sometimes share meat, this has led Jill Pruetz to suggest that although the use of hunting tools as weapons may have been important in encouraging a change in property practices, “large-mammal hunting was not a prerequisite for behaviors that ultimately lead to the level of cooperation seen in our species” (Pruetz 2015 in Gintis et al 2015: 344). This is, in all fairness, not advanced as a fully developed argument, but nevertheless, the suggestion is that hunting tools may have preceded both forestry depletion and changes in property practices towards communal property.

In the transition to agricultural societies, the 'technology first' hypothesis holds that the transition to agriculture occurred as soon as people had invented the technology by which plants and animals could be domesticated, a view that was widely held in the first half of the twentieth century. T. Douglas Price and Ofer Bar-Yosef write that "archaeologists and others generally considered that farming was a highly desirable and welcome invention providing security and leisure time for prehistoric peoples. Once human societies had recognized the possibilities of domestication, they should have immediately started farming" (Price and Bar-Yosef 2011: 166). Today, however, given the evidence that the transition to agriculture was not nearly as immediately desirable as had been previously assumed, most archaeologists and anthropologists follow some kind of 'depletion first' hypothesis, as described below. Nevertheless, one fairly recent suggestion (which is, again, not fully developed) put forward by Colin Tudge is that the development of agricultural technology may actually have led to the depletion of large animals since humans may have hunted large animals to extinction because they knew they could always fall back on farming (Tudge 1998).

In the transition to fossil fuelled societies, there are, again, few scholars who endorse the perhaps popular lay view that innovations such as the seed drill, the spinning jenny, and the steam engine spontaneously kick started the Industrial Revolution; however, a more nuanced 'technology first' view suggests that the adoption of a more scientific (e.g. Mokyr 2002) or a more 'bourgeois' (McCloskey 2010) worldview led to an improved epistemic and cultural basis for technological innovation which could otherwise not have occurred. Again, like in the 'property first' view of the transition to fossil fuels, whilst scholars may not dispute that a decline in population and agricultural productivity actually preceded the transition to fossil fuels, a 'technology first' hypothesis may suggest that the main reason that the transition to fossil fuels did not occur earlier or elsewhere is because the capacity to develop technologies that could make efficient use of those fuels had not previously existed (see Mokyr 2002 for an overview).

3.3 The 'depletion first' hypothesis

In the transition to hunter-gatherer societies, the 'depletion first' hypothesis suggests that the decline in forest foods would have increasingly pushed pre humans into the savanna to obtain foods. This 'savanna hypothesis' has been described as the theory that "human evolution... was triggered by a change in the environment, involving increasing openness of the landscape and decreasing feeding resources, forcing hominins to move longer distances across more diverse biotopes" (Dominguez-Rodrigo 2014: 69). The hypothesis is that the gradual shift into the savanna and the accompanying morphological and dietary changes later led to the development of improved hunting tools and to communal property practices over the high value foods of the savanna (Mann 2007: 102, Hall and Klitgaard 2012: 45).

In the transition to agricultural societies, the 'depletion first' hypothesis suggests that the depletion of larger game led to increased reliance on food that could be gathered or herded, incrementally causing the coevolution of domesticates, and to a change in the property practices over both energy flows and over the stock of land itself. Following the ethnographic work of Lewis Binford in 1968, most scholars now agree with his arguments that hunter-gatherers would not become farmers unless there was no other choice (see Price and Bar-Yosef 2011). Another classic statement is by Mark Cohen (1977) who suggests that agriculture emerged out of a dietary diversification strategy as the existing food base diminished; as restated in Cohen (2009): "the demonstrably diminishing labor efficiency foragers accepted as the price of making more efficient use of land (diet breadth) indicates that older and preferred strategies had to be supplemented in the face of an increasing demand/supply ratio prior to the adoption of domesticates" (Cohen 2009: 707).

In the transition to fossil fuelled society, the 'depletion first' hypothesis suggests that as agricultural land (Moore 2003 and references therein) and woodland (Nef 1932 in Smil 2010:28-30) became depleted, land became less productive and firewood ever more difficult to collect. This led to a change in property practices from an open field system in which many individuals had access to flows from the resource stock, to an enclosed system in which the lord controlled most if not all the flows from the land. The argument is that depletion led to changes in property practices, which then encouraged technologies to increase agricultural productivity. Brenner and Isset, for example, write that "having failed to reinstate serfdom, lords did succeed in asserting their absolute property rights to the greater part of the land... commercial landlords, unable, as the feudal lords had been, to take their rents by extra-economic coercion, were obliged to depend on rents determined by supply and demand... The emergent class of direct producers... were correspondingly obliged to maintain themselves through taking up commercial leases on a competitive land market. Compelled therefore to produce competitively to survive economically, these tenant farmers had to adopt an approach to their economic production that diverged sharply from that of England's medieval peasantry" (Brenner and Isset 2002: 618). This competitive production incentivised the adoption of new agricultural techniques and technologies, and combined with an increasing use of coal following forestry depletion (Pomeranz 2001), gave incentives for the development of new technologies to supplement or replace animal and human labour (Smil 2010).

4. Method: distinguishing causes from consequences

On the basis that causes precede effects, evidence from the archaeological and historical record should provide at least a crude indication of the order in which these changes occured. Broadly, four kinds of evidence can be used to date the approximate appearance of new property practices, of new technologies, and of resource depletion: firstly, direct archaeological or historical evidence; secondly, the existence of a trait across individuals or groups in the present suggesting the likely presence of that trait in their common ancestor (homology); thirdly, the existence of a trait in individuals or groups in analogous circumstances (homoplasy); and fourthly, subsequent changes in behaviour following changes in circumstance. A much more complete survey will form an important part of future work; one particular problem that will need further thought is that evidence for technological change and depletion often leaves fairly definite archaeological and historical traces, but that evidence for social changes like property practices may not survive as well and so may appear only later in the historical record. Nevertheless, for now, some preliminary findings are presented below as simple timelines with brief notes on the kinds of evidence available; dates in red correspond to evidence for changes in depletion, dates in blue correspond to evidence for changes in technology, and dates in green correspond to evidence for changes in property practices.

5. Preliminary findings
Timeline 1: The transition to larger animals

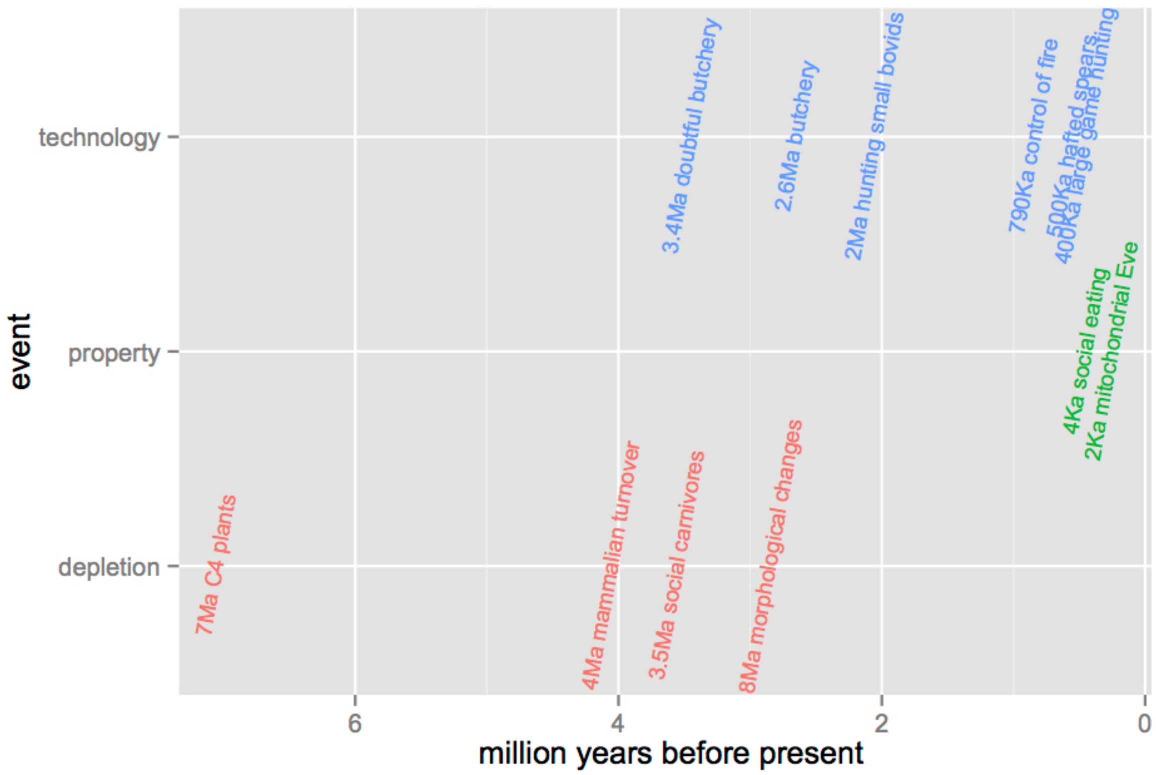
7 Ma: (million years ago): archaeological evidence of an increase in C4 plants that thrive in sunnier drier conditions (Edwards and Smith 2009).

4 Ma to 2.5 Ma: archaeological evidence of the start of a series of 'mammalian turnover pulses' in which mammals occupying a specialist niche went extinct and speciation into new species prompted by adaptation to new environments particularly between 4 Ma and 2.5 Ma, with a large mammalian turnover pulse at around 2.8Ma (Vrba et al 1989, Bobe and Behrensmeyer 2003, Dominguez-Rodrigo 2014).

3.4 Ma: archaeological evidence (taphonomic evidence) indicating possible butchery on bones (McPherron et al 2010, and doubts by Rodrigo-Dominguez 2010, both cited in Pobiner 2013: 3).

3.5 Ma: archaeological evidence that social carnivores including baboons and *Australopithecus afarensis* emerged (Macho 2013: 2).

2.8 Ma: archaeological evidence of morphological changes to Homo, especially Homo erectus, teeth, jaws, digestive system, and body and brain size, in adaptation to changing diets by around 2.8 Ma (Pobiner 2013 and references therein, Mann 2007 and references therein).



2.6 Ma: archaeological evidence that with some certainty dates butchery (Dominguez-Rodrigo et al 2005 in Pobiner 2013:2); also lithic technologies associated with bone assemblages become more common in the period 2.6-2 Ma (Ferraro et al 2013).

2 Ma: archaeological evidence for hunting of small bovids (and that medium bovids were scavenged for their brains) consistent with evidence that Oldowan hominins (2.6-1.7mya) acquired and consumed animal tissues, but it is not clear if it is occasional or more frequent (Ferraro et al 2013: 62174); persistent carnivory, whether from scavenging or hunting, also dated to around 2ma (Ferraro et al 2013: 62174, with further evidence from 1.5mya at Olduvai cited therein); supported by analogical evidence of hunting tool use by chimpanzees at Fongoli that have also been pushed to adapt to savanna environments by depletion of their forest environments (Pruetz and Bartolli 2007).

790,000 years ago: archaeological evidence for the control of fire (Goren-Inbar et al 2004; claims of earlier evidence of controlled fire (e.g., Gowlett et al. 1981; Brain and Sillen 1988; Bellomo 1994) are not widely accepted (e.g. James 1989, all cited in Goren- Inbar et al. 2004).

500,000 years ago: archaeological evidence of hafted stone spear points (Wilkins et al 2012 in Pobiner 2013: 3; also Foley and Gamble 2009); also around this time there are stone blades in East Africa (Blasco et al 2014).

400,000 - 200,000 years ago: archaeological evidence that large animal hunting took place at Qesem cave (Stiner et al 2009); also evidence of hunting including a Lavallois spear point found still lodged in a wild ass (Boeda et al 1999 in Waguespack et al 2009 and Gintis et al 2015; I am not clear on the date for the Lavallois spear point); note that actualistic evidence suggest that stone tips provide only very little advantage over fire hardened wooden points (see Waguespack et al 2009).

400,000-200,000 years ago: archaeological evidence for communal property consists of taphonomic evidence that bones were communally butchered (Gintis et al 2015 and references therein), and for meat sharing at Qesem cave (Stiner et al 2009). Besides cut marks, which are hard to interpret (Lupo and O'Connell 2002 in Gintis et al 2015), this partly relies on inference from analogy, since in the absence of norms governing the sharing of meat among members of the community, it is hard to conceive of a way in which a large animal carcass could be taken back to a communal area if there were a general scramble for meat at the site of the kill, like those which accompany hunts by chimpanzees after which meat is torn from the carcass by numerous individuals (Tomasello et al 2012: 675). However, this archaeological evidence is further supported by the inferences of homology and of homoplasy below.

200,000-100,000 years ago: inference of homology from the existence of communal property rules in all extant human groups that share a common ancestor, mitochondrial Eve (the date of 'Y-chromosomal Adam' might be later, 60-90,000 years ago, or a bit earlier, around 250,000 years ago (Karmin et al 2015). Since "there are no human groups who behave like other great apes in simply scrambling for food competitively in most situations" (Tomasello et al 2012: 675), this suggests the common ancestor of all humans would also have observed a kind of communal property rule with regard to food (inference of homology as a methodology is discussed in detail in Duda Zrzavy 2013 and Boehm 2004).

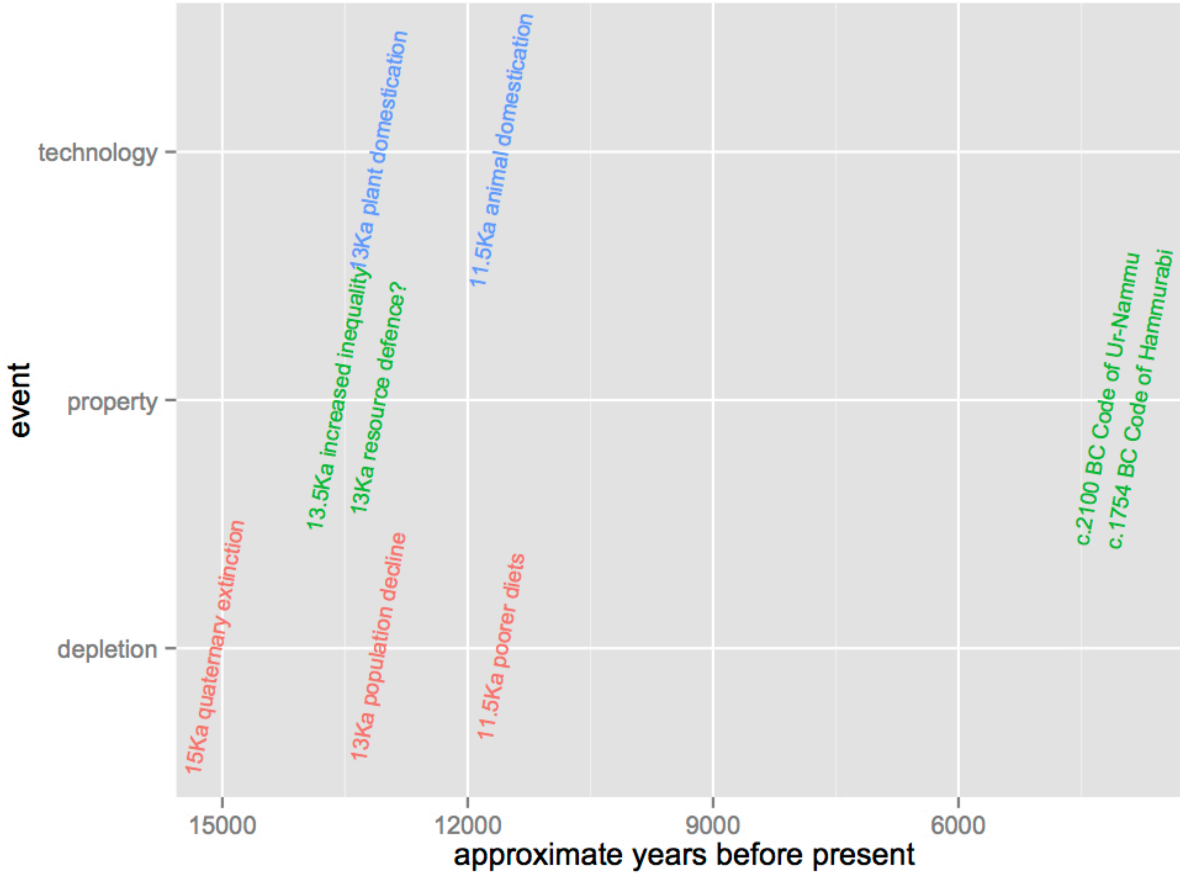
200,000 years ago: inference of homoplasy from the existence of communal property practices amongst extant hunter-gatherers in similar ecological niches to that occupied by early human ancestors at that time; note that where there is both homology and homoplasy, the model is inferentially very strong (this methodology discussed in detail in Moore 1996, also cited in Dominguez-Rodrigo 2014:74). There may be reason to extend this much further into the past if evidence of social carnivores, or perhaps particularly savanna chimpanzees and baboons, indicate that they have nascent communal property practices, as Jill Pruetz suggests may be the case (in Gintis et al 2015); I have not thoroughly reviewed this literature, but have yet to find any evidence of this.

Timeline 2: The transition to agriculture in Western Asia

15,000 years ago: archaeological evidence for the start of the 'quaternary extinction' of larger animals in Western Asia, and analogous evidence from wherever else humans settled (Brook and Barnowsky 2011 and refs therein).

13,500 years ago: analogous anthropological and archaeological evidence of an increase in inequality in small scale societies as they become more sedentary (for a review of this large literature, see Price and Feinman 1995 and 2012; also cited in Dow and Reed 2013: 636; but see Borgerhoff Mulder et al. 2009 cited in Gurven et al 2010 for a discussion of the view that there is a connection between sedentism, domestication, and inequality).

13,000 years ago: archaeological evidence of "the existence of corporate groups that controlled important resources", though I suggest that this may be no different from territoriality as found in other primates (Price and Bar-Yosef 2012:151; also cited with a summary of other evidence in Dow and Reed 2013: 629). Also archaeological evidence of mortuary practices suggesting social stratification and differentiation in accumulated wealth (Kuijt and Prentiss 2009 and Price and Bar-Yosef 2012, cited in Dow and Reed 2013); however, others argue that early farming societies were not necessarily more economically stratified than hunter-gatherer societies, but that this may have occurred in societies with limited, predictable and monopolisable resources (see Borgerhoff Mulder et al. 2009, also cited in Gintis et al 2015: 335; this needs further investigation).



13,000 years ago: archaeological evidence of a population decline (Price and Bar-Yosef 2011, also citing Belfer-Cohen and Goring-Morris 2011; Wang et al 2014:52 indicates analogous evidence in China is unclear).

13,000-11,500 years ago: archaeological evidence of increased consumption of low ranked foods including bone grease, smaller faster game, and juvenile animal indicate poorer diets and depletion of larger animals (Munro 2004, Stiner, Munro, and Surovell 2000; of juveniles in the Levant see Speth 2013). At the end of this period, known as the Younger Dryas, the climate briefly improved and evidence suggests that sedentary societies, even those with agricultural techniques, returned to more mobile hunting and gathering.

13,000-10,000 years ago: Putterman and Trainor 2006 collate archaeological evidence across the world; Putagganan and Fuller 2009 use phylogenetic evidence to date speciation of domesticated plants; Zeder 2008; Price & Bar-Yosef 2011 find evidence of domestication in animals. Towards the end of this period, populations again collapse (Shennan et al 2013; Karmin et al 2015).

2,100 BC: historical written evidence of property practices, the earliest surviving; the Sumerian Code of Ur-Nammu indicates property practices in livestock by individuals, temples, and palaces, and in slavery (Ellickson 2009).

1,700 BC: historical evidence, in the Code of Hammurabi, of property practices in livestock (Ellickson 2009).

1,550 BC: archaeological evidence of livestock branding irons (Ellickson 2009: 19n65;

Ellickson also refers to much older stone age paintings of branding but the source he cites is not clear and itself contains no citation).

Timeline 3: The transition to fossil fuels in England

1200 AD onwards: archaeological and historical evidence of population decline (Moore 2003: 157-158 and references therein; Moore also relates poorer soils to increased susceptibility to disease such as the plague, though further evidence for this is required).

1348-1516: historical evidence of early enclosures; 1489-1516 anti-enclosure acts attempt to prevent enclosures, including 1515 act making enclosure an offence (Beresford 1998:102).

1400 onwards: archaeological and historical evidence of poorer diets and famine (e.g Braudel 1981:73-74).

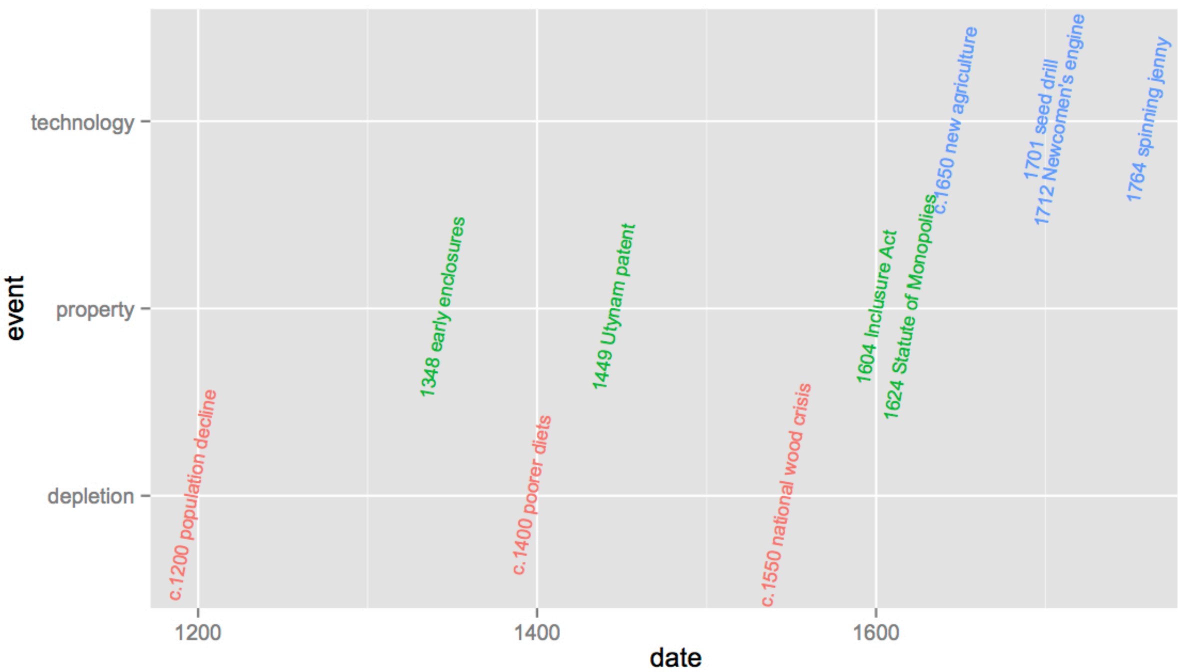
1449: historical evidence of John Utynam, a glassmaker, being granted the first full English patent (Edward II having offered 'letters of protection' to foreign workmen to encourage them to come to England during a prolonged economic slump).

1550: historical evidence of the approximate start of the national wood crisis (Nef 1932 in Smil 2010:28-30).

1604: historical evidence of changing property practices as the first of a series of Inclosure acts not only legalise but facilitate enclosures.

1624: historical evidence of the establishment of modern intellectual property practices through the Statute of Monopolies act.

1650: historical evidence of new agricultural techniques, including fertilisers, new crops, and crop rotation (Moore 1966: 23, suggesting that these technologies were adopted



because the rise in wool prices was at an end).

1701: historical evidence: Jethro Tull improves the horse drawn seed drill. **1712:** historical evidence: Newcomen patents the first useable steam engine.

1764: historical evidence: James Hargreaves invents the spinning jenny, which is patented in 1770 (Espinasse 1874: 322).

Conclusion

The main aim of this paper has been to clarify what is meant by 'grand energy transition', as well as describing how changes in property practices, in particular, have coincided with past transitions. Given the complexity and diversity of energy systems, energy technologies, and property practices, I hope that the fairly simplistic models I have used to describe them here are a plausible starting point. I very much welcome any suggestions as to how any of the models presented here may be refined.

As for the application of the models, I suggest that the preliminary survey of evidence provides some support for the hypothesis that a general trend does indeed exist across the transitions, and that a 'depletion first' hypothesis for each of the transitions may be supported; at the very least, in each transition, the depletion of the previous energy base does appear to precede changes in technology and property practices. As noted above, a ‘depletion first’ hypothesis is consistent with much of the more recent specialist literature on each transition (though it differs somewhat from the popular view that attributes much more to human insight and the desire to innovate than most scholars seem inclined to do).

The survey of evidence is far from complete, but it is already interesting to note some apparent commonalities between all three energy transitions. In addition to the apparent general applicability of a ‘depletion first’ hypothesis across all three transitions, during the second and third transition (I have as yet found no evidence either way for the first), there is also evidence that depletion is preceded by a fall in population or even a population collapse, and that the transitions are followed by a period of poorer living standards until technology later improves. This, again, further supports the idea that these transitions were brought about by resource depletion. These grand energy transitions, it seems, were not the consequence of spontaneous human innovation: people in the past have been pushed into energy transitions, only developing new technologies and new property practices in response to energy transitions that are already under way.

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