On the Mutual Historical Dynamics of Societies' Political Governance Systems and their Sources of Energy: The Approach of the Vienna School of Social Ecology

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Marina Fischer-Kowalski *

Abstract: *»Zur wechselseitigen historischen Dynamik der politischen Steuerungssysteme von Gesellschaften und ihrer Energiequellen. Der Ansatz der Vienna School of Social Ecology«.* This article combines a brief overview of the theoretical approach of the Vienna School of Social Ecology with a report on the results of a long-term study on the coincidence of countries' first access to fossil fuels with social revolutions. The theoretical approach views societies in a system-theoretical perspective as hybrids of materiality and meaning, with "social metabolism" and "colonization of nature" as key links. Historical changes in the energy metabolism of societies are viewed as key drivers of change in social organization, distinguishing broadly between foraging and agrarian societies, both solar based energetically, but distinct by the latter applying elaborate colonization technologies that allow for higher energy returns at the price of a higher labor burden, the emergence of cities, and land-based steep social hierarchies. Finally, we report on a series of studies on the coincidence of countries' access to fossil fuels as allowing a transition to industrial societies, again on a much higher energy level. The very early transition phase ("critical energy transition period"), as we show empirically for a large number of countries worldwide across the past 500 years, was typically marked by what we characterize as social revolutions. Finally, we ask what societal changes a next energy transition, required to avoid catastrophic climate change, will bring about.

Keywords: Social Ecology Vienna School, systemic society-nature interactions, socio-metabolic regimes, fossil fuels, transition to industrial society, revolutions.

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1. Theoretical Underpinning: Social Metabolism and Colonization of Nature

We approach an understanding of society-nature interactions by proposing an epistemological framework encompassing both natural and social sciences. The framework focuses on the mutual dependencies of symbolic/cultural and biophysical processes that are relevant for societal dynamics, thus linking social and economic development to environmental change.

In this social ecology approach, societies are conceptualized as *hybrids of materiality and meaning*. Societies are conceived as the structural coupling between a communication system (Luhmann 1984) and biophysical elements (Fischer-Kowalski and Weisz 1999). The latter – i.e., the material portion of societies, their "biophysical structures" – encompass the human population, infrastructures such as buildings, machines, artifacts, and the domesticated animals exploited for societal use (livestock).

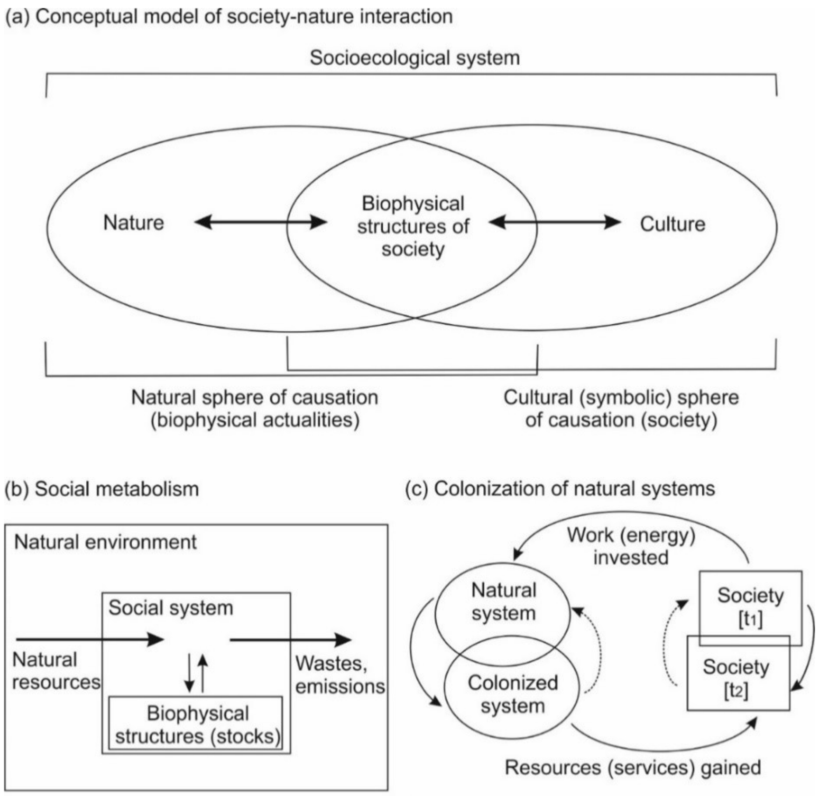
Briefly speaking, the term "communication system" refers to cultural heritage and meaning, social norms and institutions, and property relations as well as to ongoing processes such as information exchanges, social control, and monetary flows.

The two systems interact through society's *biophysical structures*: population, livestock, and physical infrastructure draw on nature (for food, energy, and materials), a process we term *social metabolism*; this process is secured by (culturally guided) interventions into nature in the form of physical labor. In return, nature responds by what we call "events" (food, energy, and materials are available in specific forms, or maybe not, their extraction changes their availability; the climate may vary, earthquakes or epidemics may occur, etc.). These "events" in turn get represented culturally through the lens the respective culture provides (e.g., as mal- or benevolence of the gods, failing or successful technology, rising or falling costs, or unintended consequences of human action) and evoke responses from the cultural system. These responses may be short-term (*live communication* to re-direct action and monetary expenses as analogue to metabolism) and/or take the form of developing *new programs* for dealing with nature (exploring new territories, technological developments, new capital investments, etc.). The cultural responses then translate into changes in biophysical interventions (Fischer-Kowalski and Weisz 1999).

This interaction model may seem overly complex; its complexity, though, is necessary to allow application to very different phases of history, and for making aware of the range of degrees of freedom in these feedbacks between social and natural systems.

One key term linking the biophysical elements of society to nature is "*social metabolism,"* the process of extracting resources from the environment; using them as sources of energy, commodities, and infrastructure; and transforming them finally into stocks, wastes, and emissions. A second, more complex process we term is "*colonization.*" Colonizing nature means to planfully intervene in its mechanisms to make them more suitable for society's needs and wants. Classical examples are deforestation and transformation of the land to produce edible biomass, breeding of animals to foster desired features, or regulating rivers; they happen on the level of ecosystems, organisms, cells/tissues, or the genome (Fischer-Kowalski and Erb 2016, 46f). As a rule, they require societal knowledge and labor, and they always have unintended side effects.

Figure 1 Systemic Interaction Model



Note: Socioecological concepts for analyzing society-nature interaction. (a) Overall heuristic model of society-nature interaction; society is seen as a "hybrid" of biophysical and cultural realms of causation. (b) Social metabolism, i.e., the stocks and flows forming the material basis of society. (c) Colonization of natural systems as a dynamic sequence of work or energy investments aiming at provision of services or resources. Figure reproduced from Haberl, Fischer-Kowalski, and Schmid 2023, forthcoming.

2. Theory Applied to History: Socio-Metabolic Regimes

Modes of subsistence of human societies can be distinguished; we term them *socio-metabolic regimes* (cf. Goudsblom 2002, 33-4, who speaks of "socio-ecological regimes"),

> that share, at whatever point in time and irrespective of biogeographical conditions, certain fundamental systemic characteristics derived from the way they utilize and thereby modify nature. [They are] above all distinguished by their type of energy system and [...] the main technologies of energy conversion [... and] can be characterized by their socio-metabolic profile and the associated modifications in natural systems that occur either as an unintended consequence (pollution, soil erosion) or as an intentional change induced by society. (Krausmann, Weisz, and Eisenmenger 2016, 64ff)

The main distinctions we draw are *foraging societies* (or hunter-gatherers), *agrarian societies*, and *industrial societies. Foraging societies* rely on an *uncontrolled solar energy system*, in the sense that they live from the land (or the sea) by extracting edible biomass, much like other large mammals; with one special exception: the use of fire and the corresponding amount of fuel wood for the provision of heat and for cooking, and in some places also for hunting (Goudsblom 1992; Sieferle 2001). Foraging or predatory societies were energetically limited by the density of prey animals within the distance they could be transported to the home; thus, their group size was also limited.[1] Sahlins (1972) describes them as leisure cultures. It made no sense to increase labor intensity: this would only lead to overexploitation of their food sources. Equally, there was no premium on population growth – quite to the contrary. *Agrarian societies*, by contrast, subsist by a *controlled solar-based energy system*: they actively manage (in our terms: colonize) terrestrial ecosystems by techniques of substituting forests with fields and plants for farming, and by domesticating animals for food and work. The agricultural techniques of breeding plants, regulating water bodies and drilling wells, farming, and domesticating animals support a much higher level of useful energy per unit area compared to hunter gatherers.[2] The amount of primary energy available at a given level of agricultural technology depends mainly on the size of cultivated land and on the labor input into this land. Thus, agrarian societies

1 Debeir, Deléage, and Hémery (1991, 17) estimate a maximum area of 1,500 km^2 and a group size of 50 persons.

2 Although the major source of energy is still biomass and therefore the energy system remains a land-based, low energy system, agricultural techniques and higher labor time per capita increase the proportion of usable energy per unit of land, i.e., the output of edible or otherwise useful biomass (such as feed for animal power to perform work and fibers for clothes) by two or three orders of magnitude. See Krausmann, Weisz, and Eisenmenger (2016, 70, esp. table 3.2, 74).

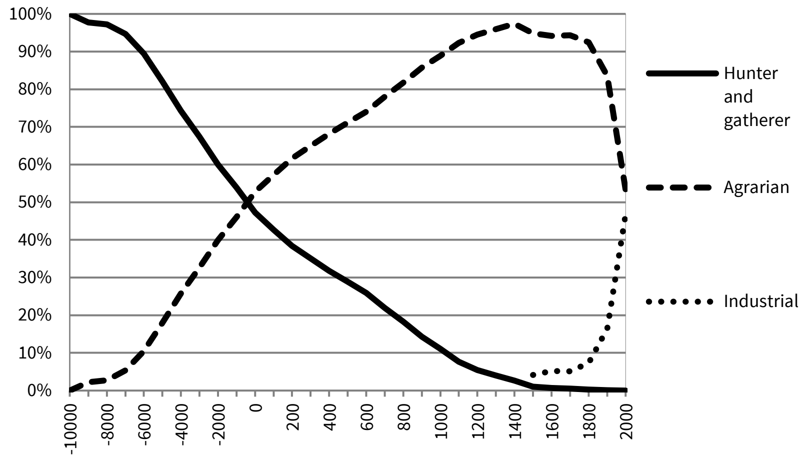
develop sedentary lifestyles of high labor intensity and welcome potential workers of low food demand (such as slaves or children).

The transition from hunting and gathering to agriculture, commonly termed as "Neolithic Revolution," was not a revolution in the common sense of the term. During the time it was occurring in most parts of the world, climatic change (global warming), population growth, and a new socio-metabolic technology (agriculture) coincided. Higher population density in some favorable areas may have stimulated the evolution of agricultural techniques, as well as the development of property and power relations that replace traditional kinship relations. In the competition with close-by hunter-gatherer tribes, agricultural groups were superior, which forced the hunter-gatherers to withdraw to less favorable areas. If population density in an area exceeds a certain point, the path towards agriculture is a path of no return. The asymmetry that farmers, once they establish themselves in an area, cannot return to foraging in the same area, but foragers may become farmers, seems to have been the evolutionary mechanism that made the agrarian regime succeed, through centuries and millennia, all across the world more or less independently (Cohen 1977) – without the mode of living as farmers necessarily providing better nourishment or quality of life than that of hunter-gatherers (see Sieferle 1997, 2001; Scott 2017). The expansion of agricultural land into less favorable areas, the intensified use of this land, and, thus, the need for child labor (Boserup 1965; Ringhofer, Singh, and Fischer-Kowalski 2014) generate what ecological economics calls a "rebound effect," feeding population growth and annihilating (or reversing) gains in affluence for the individual.

There are three interrelated factors burdening the quality of life for ordinary people within the agrarian regime, all three related to the mode of cultivating land and creating – at least seasonally – a surplus of energy. *Factor number one* is the sedentary way of life and the need to maintain possession of the land and the livestock associated as well as of the products of the land: the harvest. This does not only require extra work for infrastructures providing storage and protection, but also provides the opportunity for the development of groups of specialists in violence, prepared to fight against intruders, and to be rewarded by agricultural surplus and extra labor. *Factor number two* is the labor intensity of agricultural work (as compared to hunting and gathering, see Sahlins 1972). It drives toward a patriarchic family organization, the need for child labor (as children can work but need less food), and, in consequence, population growth, which feeds back on intensifying labor requirements (Boserup 1965). *Factor number three*: intensive agriculture, first in particularly fertile river areas (such as around the Nile, the Euphrat and Tigris, and the Indus), leads to the emergence of agrarian states with a steep social hierarchy and elaborate edifices like temples, pyramids, or cathedrals, drawing again on additional labor power (Smil 2008). These states regularly enter into military conflicts with one another (see also Haberl et al. 2023, forthcoming). From the late Middle Ages, peat (the Netherlands) and coal (England) were welcomed as alternative sources of energy to be used as supplements for wood from forests already overexploited in the vicinity of population centers (Sieferle 1997). This marked the beginning of a new era: the industrial socio-metabolic regime.

The – very gradual – transition between socio-metabolic regimes occurred worldwide at very different points in time. Based on estimated differential population growth rates (Fischer-Kowalski et al. 2014), and taking the rise of city populations (Klein Goldewijk, Beusen, and Janssen 2010) as a reference point for the emergence of the agrarian regime, we arrived at the estimates pictured in Fig. 2. According to these estimates, the world had been populated once by a maximum of about 90 million hunter gatherers around 500 BC, then their numbers began to decline; in the last century BC, hunter gatherers had been overtaken by agrarian populations that rose to about 450 million by 1500 AD and kept rising until 2000 AD to three billion people. The rise of the industrial population started around 1500 AD and continued to a population of also 3 billion by AD 2000, just matching the agrarian world population (see Fig. 2).

Figure 2 Estimated Shares in Global Human Population by Socio-Metabolic Regimes



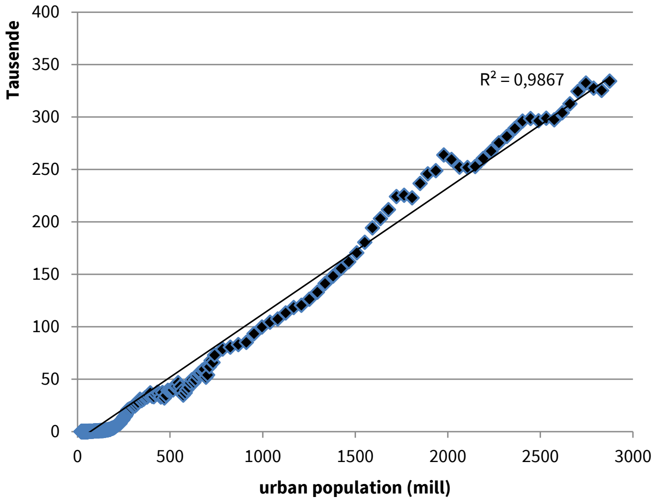
Note: Time axis is not to scale for different periods: 10k BC to AD 0: 1000-year intervals; AD 0-1900: 100-year intervals; 1950-2010: 10-year intervals. Reprinted with permission from Anthropocene Review (Fischer-Kowalski, Krausmann, and Pallua 2014).

The year 1500 AD can be considered a dividing line, as around that year fossil fuels start to become important sources of energy in some regions. Recent research (Gales et al. 2007; Gerding 1995) provides quantitative data on the use of peat as an energy source in the Netherlands; it started slowly in the late

Middle Ages, but by 1550 peat already amounted to 10% of primary energy supply and helped the Netherlands to its "Golden Age" at an energy level per inhabitant above any other European country – and also to the highest urbanization level in Europe (Centre for Global Economic History 2013; De Zeeuw 1978; Livi-Bacci 2006). Next in line is the case of coal in the United Kingdom. According to recent estimates, by 1550 coal amounted to 3% of its primary energy supply. While the Netherlands ran gradually out of peat in the next centuries, the UK could steadily increase its use of coal, export coal to other European countries, and move along a learning track towards industrial technologies while substantially increasing its urban population.

Based upon these forerunners, it makes sense to date the onset of the human use of fossil fuels rather precisely at the beginning of the modern era; from a socio-metabolic perspective we would argue that the control of the new energy source with an hitherto unknown power (Smil 2003) that allows expanding social energy use much beyond previous levels is highly relevant – even if the technologies to make efficient and diverse use of this energy evolve and spread only gradually. The functional inter-linkage with urban growth is apparent from the beginning: without a source providing heat for a rapidly increasing number of urban households and trades, no proto-industrialization would have taken place. But even more so, on the global level, there is a near perfect fit between urban population numbers and the amounts of fossil fuels used globally, across the next 500 years (see Figure 3).

Figure 3 Global Urban Population Numbers and Global Modern Energy Use 1500-2000 AD



Sources: from Fischer-Kowalski et al. 2014; urban population from Klein Goldewijk, Beusen, and Janssen 2010 (settlements with 2,500 inhabitants or more); Modern (primary) energy use includes fossil energy carriers such as peat, coal, petroleum and natural gas, hydropower, and nuclear. Time series based on data compiled in Krausmann and Fischer-Kowalski 2013; Fischer-Kowalski, Krausmann, and Pallua 2014; Podobnik 2005.

Coinciding with the onset of this new energy source, both the Netherlands and England established private global trading companies (with granted monopoly and military support): The East Indian Company (under Queen Elisabeth, founded in 1600), and the Dutch East India Company (established in 1602). They were the first joint stock companies of the world and marked the onset of a new economic regime: capitalism.[3] What was novel about it was the need for economic growth (or else: crash), as the investments had to deliver financial gains in the future, well measurable in financial terms (Binswanger 2019; Herrmann 2022).[4]

The opportunity of acquiring raw materials (such as spices, sugar, and in particular cotton and silk to complement home-grown wool in manufacture) from overseas weakened the local feudal elites and allowed for the increase of urban manufacture and the growth of an urban working class – long before

[3] See https://www.history.com/news/east-india-company-england-trade (Accessed 20 November 2022); https://en.wikipedia.org/wiki/Dutch_East_India_Company (Accessed 20 November 2022).

[4] As compared to, e.g., the military expansionism of the Roman empire, driven rather by political interests, where payoffs were much less calculable and limited physically by available land.

the key technologies for industrial development, such as the steam engine, were in place.[5] This is why we claim that not technological innovations, but the utilization of a new natural resource, fossil energy, marked the beginning of a new socio-metabolic, namely the industrial (or capitalist), regime. In contrast to the Neolithic Revolution, which had occurred across the world independently in different places at different points in time, the transformation of the agrarian to the industrial regime gradually spread from its early forerunners in Europe, England, and the Netherlands (Gerding 2010; Fischer-Kowalski et al. 2014).

3. Social Conflicts Marking the Transformation from the Agrarian to the Industrial Regime

From a socio-metabolic perspective, we expect the shift of society's core energy base to be associated with a major transformation in social organization. The biomass-based agrarian systems are highly energy-constrained. How much biomass can be harnessed depends, besides various biogeographical factors, mainly on the extent of the territory and on the amount of human labor invested in making use of the land (Boserup 1965; Krausmann, Weisz, and Eisenmenger 2016). Providing this labor power and its biological reproduction in turn requires most of the energy harvested from the land.[6] Moreover, an energy constraint for transportation across land is also a limiting factor for urbanization (Boserup 1965; Wrigley 2016). Thus, in agrarian societies, typically more than 85% of the population live in rural settlements and have to work the land to provide for food and other basic needs of the population (Fischer-Kowalski et al. 2014). The surplus that can be extracted and used by the people not working the land, such as kings, their courts and military ranks, landlords, religious authorities, and urban residents, is tightly constrained.

Fossil fuels, which are concentrated at geological deposits and have a higher energy density than biomass, make it possible to break out of this

[5] Newcomen's atmospheric-pressure steam engine overcame the limits of deeper coal mines filling with groundwater and pumping this out with animals; this was introduced in 1712 (Mitchell 2011); the steam engine became a key technology for industrial development but was not widely applied before the mid-18th century.

[6] Technically speaking, the energy return on investment (Hall, Cleveland, and Kaufmann 1986) of traditional agro-ecosystems is positive, but typically low (Galán et al. 2016; Krausmann, Weisz, and Eisenmenger 2016). Coal (and in some regions also peat) accessible to centers of demand could provide combustion materials at fewer labor hours per unit energy. Their transportation did not require dendritic structures (like the transport of firewood) but could be accomplished by much more efficient linear facilities such as shipment across sea and channels or, later, by railways and pipelines (Wrigley 2016). They yielded a higher energy surplus and liberated human labor power for other activities.

stalemate – already long before the development of specific fossil fuel related energy conversion technologies. Coal provided, among other things, a cheap and readily available energy source for heating urban houses, allowing urban centers to grow quickly (Wrigley 2016; Allen 2012). We contend that this change in the energy base, the (at first very small) increase in energy availability, combined with the rapid influx of new landless poor classes into urban centers, created a sort of "anteroom" prior to the start of industrial development proper, where traditional, agrarian, land-based social hierarchies clash with novel ideas and aspirations that find widespread resonance in the diverse public spaces of developing cities and may lead to social revolutions. We followed this hypothesis by investigating the onset of fossil fuel use, and the occurrence of social revolutions, for as many countries as we could reconstruct their energy history long enough, across the past 500 years (Fischer-Kowalski et al. 2014, 2019).

Table 1 Criteria of Classification of Revolutions and Revolutionary Events

(1)	A serious effort at turning over political power (PT) and the justification for political authority, such as:
•	abolishment of absolute monarchy;
•	overthrow of the king/prime minister/ruler in favor of a new type of government;
•	national independence/autonomy;
•	achieving rights to be politically represented for a larger part of the constituency (general assembly, parliament, soviets, etc.);
•	abolition of political privileges of the ruling class;
•	formulating a new constitution.
(2)	Propagation of a program of fundamental social transformation (ST), such as:
•	abolition of feudal tenures and serfdom;
•	abolition of slavery
•	program of human and/or civil rights (equality before the law, freedom of expression, inviolability of property, freedom of movement, right to resist oppression, etc.);
•	land reform, tax reform;
•	dismantlement of religious monopolies.
(3)	Major mass mobilization (MM) and non-institutionalized actions that undermine existing authorities, such as:
•	violent uprisings and armed conflict (across the country in several localities and regions);
•	non-violent demonstrations and effective, persistent acts of disobedience (across the country in several localities and regions).

One issue we had to resolve was to base our records on a definition of "revolution" that was applicable across time and could be identified unambiguously.[7] In our first effort (Fischer-Kowalski et al. 2014), we followed a

[7] There is no standard global source that focuses specifically on social revolutions (Colgan 2012). Political and social science scholars do not agree about what events qualify as social revolutions. Tilly (1993) and Goldstone (1980, 2001) identify hundreds of events in the past centuries

classification of historical events across 17 countries according to the following criteria, with reference to Goldstone (2001).

These criteria are similar to those used by Colgan (2012), except that we do not necessarily require a successful turnover in government. As there is no standard cross-national time-series dataset for revolutionary events (Colgan 2012), we based our classification on descriptions from widely accepted comparative sources (such as the World History Net and the Encyclopedia Britannica), starting from a net search (country name, "revolution," and "revolt"). Events that were coded positive on all three criteria were classified as "revolutions" (R); if they were coded positive only on one or two of the criteria, they were classified as "revolutionary events" (RE). The coding was done by three coders first independently, and in case of disagreement a deeper search into the event ensued until the coders could find agreement. There was some incongruence across sources concerning the timing of revolutions. Often, these events are embedded in or follow international wars, which makes it difficult to identify the precise year when the event as such starts. Aware of these uncertainties, we sought to code events by their starting year.

Our ambition was to reconstruct each country's energy system in a timeline that starts a few decades before the onset of fossil fuel use. With the exception of the Netherlands, where there was wide-spread use of peat already in the 13th and 14th centuries (Gerding 1995), the first fossil fuel used by countries is coal. Coal mining was recorded very early on, so that researchers like Podobnik (2011) were able to compile databases of extraction and use of fossil energy carriers and other modern energy sources (hydropower for electricity generation, nuclear heat) of reasonable accuracy, which we made liberal use of. To calculate the indicator "share of fossil fuels in the total of primary energy use," we also required data on total energy use: that is, we had to add biomass to modern energy types. Data on biomass consumption were derived from a global database of biomass flows (Krausmann and Fischer-Kowalski 2013), which provides national data on biomass use for the period 1910–2005. For earlier periods we extrapolated total biomass use on the basis of constant per capita values of 1910 and population estimates. This relies on the assumption that biomass use is growing largely with population and changes in per capita biomass flows are comparatively small.

as revolutionary in character, while Zimmermann (1983) lists just 16 cases after 1600. Skocpol (1994) views revolutions as rare bottom-up events and includes only those events that successfully changed state and class structures. Trimberger (1978) includes "revolutions from above," and Eisenstadt (1978) identifies many cases across history. Jansson, Lindenfors, and Sandberg (2013) and Osterhammel (2009) focus on transitions to democracy. Hobsbawm (1962) describes the period 1789–1848 as the "age of revolutions."

Table 2 Sample of Countries (N=17) with Revolutions or Revolutionary Events before WWII

Country, year	Event (name)	Criteria fulfilled[8]			Classification
		PT	ST	MM	
Argentina 1810	May revolution	+	-	-	RE
Australia 1901	Referendum	-	-	-	-
Austria 1848	March, May, Sept. Rev	+	+	+	R
Chile 1851	Mapuche Rev.	+	-	-	RE
China 1911	Xinhai Rev.	+	-	-	RE
China 1949	Communist Rev.	+	+	+	R
England 1642	Civil Wars, Cromwell	+	+	+	R
England 1688	Glorious Revolution	+	-	-	RE
France 1789	French Revolution	+	+	+	R
France 1830	July Revolution	+	+	+	R
France 1848	February Revol.	+	-	-	RE
France 1871	Commune de Paris	+	-	+	RE
Germany 1848	March Revolution	+	+	+	R
India 1900	Inde Movement	+	-	+	RE
India 1930	Ghandi civ. disobedience	+	-	+	RE
India 1942	Quit movement	+	-	-	RE
Italy 1848	Garibaldi insurrection	+	-	+	RE
Japan 1868	Meiji restoration	+	+	-	RE
Netherlands 1568	Dutch Revolt	+	-	-	RE
Netherlands 1787	Batavian Revolution	+	-	+	RE
Portugal 1820	Liberal Revolution	-	-	-	-
Portugal 1910	Milit. Coup d’etat	+	+	-	RE
Portugal 1974	Carnation Rev.	+	+	-	RE
Russia 1905	Rev. Const. Monarchy	+	-	+	RE
Russia 1917	Socialist Rev.	+	+	+	R
Sweden		-	-	-	
Turkey 1923	Atatürk: Republic	+	+	+	R
USA 1776	Decl. of Independence	+	-	+	RE
USA 1861	Civil War	-	+	+	RE

Source: Fischer-Kowalski et al. 2019, SI Table S2. For the classification of countries with turbulent events in the post WWII sample (N=34) see Table S3 (ibid.).

We succeeded in reconstructing long term energy use for those 17 countries; in most cases, we managed to cover a time period starting at least 50 years before fossil fuel use took off (we chose the cutting point of a share of 4% fossil fuels) and ending fairly close to the present. The countries are

8 PT=political transformation; ST=social transformation; MM=mass mobilization.

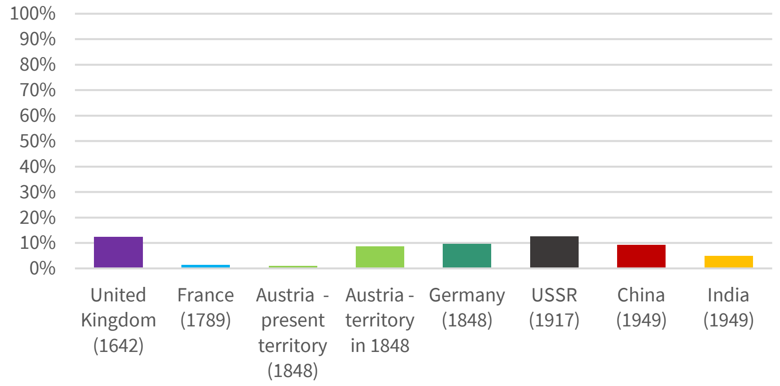
described according to their present territory as far as possible; in the case of Austria, we also calculated the energy indicators for the country at the time of the transition.

Our original sample covered seven countries with and six countries without a revolution. We are liberal and fairly common sense in what we count as a "revolution." In the transitional phase between the agrarian and the industrial energy regime, we accept anything as a "revolution" that resembles an effort at a rapid social and political transformation of society by a bottom-up process aiming at overturning social and political power relations (see Table 1). This effort, in contrast to the conception of Skocpol (1979), need not be immediately successful – it may be largely defeated (like the Austrian or German revolutions in 1848). But that it is waged at all speaks in favor of a situation that major actors conceive of as a "revolutionary situation," like some authors (Eisenstadt 1978; Skocpol 1979) call it. Thus, in our analysis, we accept anything as a "revolution" where a serious and historically noted attempt is made to overthrow political power on a national level and introduce social reforms by a movement from below.

While it used to be quite common to study revolutions as important events in the course of transition to modernity (see the review by Goldstone 1980), this was to our knowledge never linked to the issue of energy sources and energy regimes. The transition to modernity is usually conceived of as a highly complex process, encompassing urbanization, population growth, technological change, value changes, economic changes (rise of capitalism), new ideologies and interest groups (see, e.g., Tilly 1978), and more. This complexity, as Goldstone (1980, 430) rightly criticizes, is very hard to break down to something measurable. A similar fate is shared by approaches focusing on technological change (e.g., Gruebler 1998, 2004). We suggest the share of fossil fuels in a country's domestic energy use to be a very simple, annually measurable, and highly valid indicator for the degree of transition to modernity, to industrial society. In particular, it indicates how far the transition to modernity is already progressed at a certain point in time. Fully mature industrial economies all have a share of modern energy carriers (mainly fossil fuels, but also nuclear energy and hydropower) between 70% and 80% (Haberl 2001), which they have achieved at different points in time. The advantage is that for the observed time period, the share of fossil fuels in domestic energy consumption (DEC) is a steady variable: for all countries investigated so far, it always rises with time and never declines for more than a few years during periods of major political and economic crisis.[9]

[9] Among our material, there is one exception to this rule: China's "Great Leap Forward" in 1959, an effort at boosting industrialization of the countryside, first led to a massive increase in coal consumption, but then to crisis and famine and a reduction of coal use for many years.

Figure 4 Share of Fossil Fuels in Primary Energy Use (DEC) in the Year of Revolution



Source: Fischer-Kowalski et al. 2014, 22.

Already at our first attempt, we found a very clear-cut result of our analysis: all seven cases of revolution found fall into a very early phase of the transition to fossil fuel use. There is no revolution occurring at a time the country does not use fossil fuels at all, and there is no case above a 12% share of fossil fuels. The average share of fossil fuels in the year of the revolution is 7.42% (or 1.89 GJ/cap/year according to the extended sample, Fischer-Kowalski et al. 2019), and the standard deviation for this value is very small (sd = 0.042).[10]

We feel we have arrived at quite a solid outcome: Revolutions are often part of the course of transition to modernity, and if they occur, they do so very early in the process, in what complex systems transition theory calls the "take-off phase" of transition (Fischer-Kowalski and Rotmans 2009).[11] This observation holds true for events spread across three hundred years of history. At the same time, a substantial share of countries manage this transition without a revolution.

In a next effort we extended our dataset with a supplementary set of 34 post WWII developing countries, in which we found 14 revolutions, and for both datasets we were able to identify statistically a "critical energy phase" in which revolutions were most likely to occur (Fischer-Kowalski et al. 2019): it ranged from 0.47 to 7.71 GJ/cap/year fossil fuel use for both sets of countries – thus again in the very early phase of the energy transition.

The transition of the energy system towards using fossil fuels provided countries with a huge competitive advantage. More energy and energy

[10] These values have been calculated using the data for the Austrian monarchy of the time.

[11] But of course, if we think of very different cases like the revolutions in Arab countries in 2009–2012, or anti-colonial uprisings in Latin America, or turns away from communist/soviet rule in 1989 ff, we might come up with different results.

carriers of higher density, and therefore so much easier to transport, allowed a fully new range of activities: infrastructure construction (roads, canals, mining, etc.). This was particularly relevant in the face of continuous territorial threats, as common throughout history, that required sustained military interventions. All enlightened governments seem to have been quite aware of this and made efforts to secure themselves areas containing coal mines and to promote their exploitation.[12]

A transition to the new energy regime, therefore, was a clearly downstream development enforced by interstate competition (at least within Europe). In the wake of the coal age, most state governments struck by enlightenment[13] indeed made efforts to accelerate modernization of their country (often prompted by external threats and competition). But these efforts (modernization of the military, introduction of schooling, coal mining with skilled workers freed from being subject to landlords and their jurisdiction, etc.) typically met with resistance from the part of the landed aristocracy, as they were clearly directed against their interests. They probably did not very much meet the interests of the peasants either.[14] In the absence of a revolutionary movement, it could be a very difficult and slow process to open the pathway towards modernity, even if the state government pressed in this direction, a process that could even be stalled altogether by opposing forces maintaining the status quo.[15]

Revolutions mobilizing the masses in a bottom-up process are able to achieve breakthroughs of traditional barriers that go far beyond what orderly governance may achieve. At the same time, they may induce protracted violence, insecurity, and lack of governance, and thus a delay of a transition of

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[12] An interesting example of this kind is the War of Succession that involved most European Empires 1740–1748, in which Prussia demanded Silesia from Austria in return for accepting Maria Theresia as Habsburg heiress. This war between Prussia and Austria was exactly about coal, and Prussia's Frederick II immediately after his victory sought to promote legislation that would free coal miners from them being subject to landlords' rule. It could be that the military conflicts over the Netherlands of that time between France and Austria also had a background in the – now Belgian – coal mine areas. This might be worthwhile following up with historical data.

[13] Even in India, the 16th century saw an enlightened rule that very much resembles counterparts in Europe.

[14] We do not agree with Paige's (1975) conclusions about the key role of peasants in revolutions. According to our theory, peasants take a very ambivalent position towards the energy transition. On the one hand, they share a common enemy with the new urban classes: the landed gentry. This makes them prone to become partners in a revolutionary process. On the other hand, the direction of social change is likely to devalue, and in the end almost destroy the peasant's social position as monopoly suppliers of energy to society. They may gain from being relieved from personal dependency on the landlord and long accumulated debts; but they do not necessarily gain from the introduction of a free labor market, and in the long run they will suffer from the fact that labor productivity, and in effect wages, can progress so much faster under industrial (fossil fuel subsidized) conditions than it ever can progress in agriculture.

[15] Both Skocpol (1979) and Trimberger (1978) have emphasized in their detailed analyses of several cases (China, Russia, Turkey, and Japan) that the goals of the states towards modernization of the industrial base were in conflict with the elite class privileges of those societies.

the energy system. On the other hand, such periods of turmoil may extend over a few years at most, while social deadlocks and blockades of innovations may extend over several decades. Our findings indicate that the pace of countries' adoption of fossil fuels and other modern energy forms, and the industrial transformation, does not depend upon revolutions. It further does not, to the degree generally assumed, accelerate across time as technological innovations are in principle available (Gruebler 2012). Among the countries in the core dataset, the energy transition led into a successful industrial transformation within roughly two generations after takeoff. A screening of the countries in the post WWII supplementary sample shows that at least in the (as far as observable) first 50 years after their takeoff, the energy transition progresses more slowly than in the countries with an earlier transition, and in some countries, it seems not to happen at all.

4. What Can Be Learned from our Findings for the Socio-Metabolic Transformation Ahead?

It is definitely easier to understand past transitions than to learn from them for the future. And it is easier to learn from the past what to expect and what not to expect for the future than to learn what could be actively done about it. The approach we take in this article is situated very much on a "macro" level, and therefore lends itself for evolutionary interpretations of systemic processes rather than actor and action-oriented lessons. We assume the challenge ahead is a "great transformation" (Polanyi 1944) that industrial societies will undergo, willingly or not, within the coming decades, in the course of this century. This "great transformation" is part of an ongoing long-term process, and at the same time very different. While in the long course of human history, the energy intensity of human modes of subsistence has been rising exponentially (Sieferle 1997; Smil 2008; Fischer-Kowalski et al. 2014), a next mode of subsistence will not be positioned on that log-linear upward trajectory of human energy control but deviate from it downwards. The (pretty diplomatic) Global Energy Assessment (GEA 2012) a decade ago assumed a decline in global energy use, more likely to occur in high consumption industrial than in high population growth developing countries – this has not happened yet. At the same time, the high-energy-supply historical era of the industrial regime has provided humanity with unprecedented chances to learn and to technically manipulate natural and social processes – not all of this is energy-dependent, and lessons of the past may be used for new purposes. This is why we try to better understand these lessons from the past – even if humanity may never be expected to "manage history." In our view, if the geological history of the Earth had not provided such huge reserves of fossil energy as a "selection environment," human history of the past 500 years would have evolved very differently. Our contribution should be seen as an effort to bring this variable into the picture and empirically demonstrate its impact on socio-political change. But this "gift from nature" (fossil fuels) has allowed humanity to have an extremely destructive impact on the life conditions on the Earth, such as accelerating climate change and extinguishing a large proportion of non-human species. Now there are also very powerful stakeholders – political and economic – who fight for the continuation of the fossil fuel-based pathway, and – so far – much weaker and more heterogeneous forces to fight for fundamental change. Whether this again will involve some new kind of revolutions, or work in different ways or not at all, is hard to tell. The open time frame for making the fundamental changes needed to keep the Earth inhabitable for human civilizations is very short, indeed.

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