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Great transformations: Social revolutions erupted during energy transitions around the world, 1500–2013

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ABSTRACT

Over the past 500 years, the transition to fossil fuels has been accompanied by sociopolitical upheaval, revolution, and counterrevolution in countries around the world. Previous research found that social revolutions occurred during energy transitions in a limited sample of 38 countries. This research expanded the investigation to examine the relationship between shifts in the energy base of societies and transformative sociopolitical change in 66 countries since 1500, and to address new questions about these transitions. We found that two-thirds of all 52 identified revolutions occurred during the initial phase of the transition to fossil energy use (between 0.7 and 7.2 GJ/cap/year), a "critical energy transition phase" that lasted 42 years on average. This "critical energy transition phase" can be understood as an arena where social and economic adversaries met to contest past and future relations, a contest that resulted in turmoil, violence, and transformative social change. We also assess the impact of revolutions and counterrevolutions on the speed of energy transitions, finding that revolutions might accelerate transitions and repressions might slow them down. We also find that, in our sample, colonial rule slowed the pace of energy transitions for colonized subjects. These findings are significant because similar sociopolitical developments may be associated with the current energy transition in response to catastrophic climate change, a product of the previous transition.

1. Introduction

1.1. Research questions and basic assumptions

From a socio-ecological perspective, we expect that when humans change their core natural resource base, they also change their social organization [1–4]. As humans transitioned from hunting and gathering to agriculture, they created new social structures. In this process, people adopted a sedentary lifestyle and land tenure systems, constructed fortifications to defend against incursions, developed hierarchical political structures and began to worship all-powerful gods. This happened at different times and places around the world] [5,6].

Similar far-reaching social changes occurred during the past five centuries with the transition from the land-based energy system of agrarian societies tapping flows of solar energy to an energy system based on large geological deposits of fossil energy, triggering the transition to industrial societies.

The early 16th century can be considered a dividing line, when fossil fuels start to become an important source of energy in some regions of Europe. Studies on the energy history of the Netherlands [7,8] provide quantitative evidence on the use of peat as energy source; peat use in the Netherlands 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 [9–11]. Next in line is the United Kingdom, where the use of coal rapidly expanded in the middle of the 16th century. Studies have shown that by 1600 coal already amounted to 17 % of primary energy supply in the UK [12]. Coinciding with the beginning exploitation of the 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

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of a new economic regime: capitalism.[1] What was novel about it, was the need for economic growth, as the investments had to deliver financial gains in the future [13,14]. The opportunity of acquiring raw materials (such as spices, sugar, and in particular cotton and silk to complement domestic wool in manufacture) from overseas allowed for the increase of urban manufacture and the growth of an urban working class — long before the key fossil fuel-based technologies for industrial development, such as the steam engine, were in place.[2]

We hypothesize that the gradual shift to fossil fuels, as kicked off in the Netherlands and the United Kingdom in the early 16th century, and in many other countries thereafter, could shake up countries' internal political power relations, to the degree of triggering social revolutions. Our reasoning is the following: In agrarian states, the landed gentry traditionally constitutes the pillars of dynastic governance. The privileged position of the gentry depends on the size of the land they own, and the amount of the products of photosynthesis appropriated through land use, including food and feed for human and animal labor [17,18]. How much biomass can be harnessed depends on the amount of this labor invested in making use of the land [19,20]. In turn, providing this labor power and its biological reproduction requires most of the energy harvested. The energy return on investment [21] of traditional agro-ecosystems is positive, but low, and does hardly grow across time [19,22]. The situation is aggravated by population growth.[3] In contrast, fossil fuels accessible to urban and industrial centers of demand provide combustion materials with a higher energy density and at lower labor hours per unit energy. In contrast to biomass, they occur in large deposits and their transportation does not require dendritic structures (like the transport of grain or fuel wood) but can be accomplished by efficient linear facilities such as shipment across channels, or later, railways and pipelines [18]. Fossil fuels yield a higher energy surplus and liberate human labor power for other activities.

As soon as fossil fuels (and other forms of modern energy) become available, creating urban jobs, the gentry's privileged position, and its income, becomes threatened. Thus, fossil fuels become a challenge to the established social hierarchy. At the same time, they enable and drive growth of urban centers,[4] technological development, and rising income from manufacture and trade empowers an evolving class of entrepreneurs, who employ a growing labor force, often at poor conditions [6]. These socio-political impacts apparently occur already at a stage when the quantitative share of the new energy resource is still relatively low. In Europe, the gradual transition to fossil fuels happens within a long period of lessening availability of land based solar energy per head of population, which had declined by about 25 % in the period 1500–1800, and by 15 % from 1750 to 1820, due to population growth and aggravated by climatic change [16,24]. The access to coal opened a pathway to economic growth in Western Europe, Russia and the United States, from the 19th century onward (in Britain already before), and led to a global divergence of energy regimes, with other world regions lagging far behind [16].

In a recent study, focusing mainly on Europe and the U.S., we actually found historical social revolutions to have occurred particularly in countries' early phase of the take off to fossil fuel use [1]. Here, we extend our inquiry further into the 21st century, and investigate this link under very different economic and technological conditions, with a considerably larger sample of nations from all continents, often (previous) colonies of the earlier accessors to fossil fuels. We also analyze suppressive events and impacts of colonialism. Specifically, we try to answer the following research questions:

1. Can we confirm the findings of our previous study that there is an early critical energy transition phase (CEP) before a country's full take-off of fossil fuel use (and the use of other modern energy including hydro and nuclear power), in which social revolutions are particularly likely, also for countries that underwent this transition more recently?
2. What role did colonialism and the attainment of independence play in countries' transition to modern energy?
3. Do revolutions (REV) and suppressive events (SUP) in turn have an influence on the speed of the take-off of modern energy use?

1.2. Identification of revolutions, revolutionary events, and suppressive events

There is no standard global source that focuses specifically on social revolutions [25]. Political and social science scholars do not agree about what events qualify as such. Tilly [26] and Goldstone [27,28] identify hundreds of events in the past centuries as revolutionary in character, while Zimmermann [29] lists just 16 cases after 1600. Skocpol [30] views revolutions as rare bottom-up events, and includes only those events that successfully changed state and class structures. Trimberger [31] includes "revolutions from above", Jansson et al. [32] and Osterhammel [33] focus on transitions to democracy. Hobsbawm [34] describes the period 1789–1848 as the "age of revolutions".

Table 1 outlines the criteria we used to identify revolutions (REV), revolutionary events (REE), and suppressive events (SUP). The classification of events follows the intentions of their principal actors; it does not take into account the degree to which these activities were successful or unsuccessful in the short term. Thus, by definition, REV and REE pursued, first and foremost, political objectives on a nation state level, namely the liberation of the people from the dominance of existing rulers[5]; secondly, they sought to achieve social objectives, such as land reform or religious freedom; and thirdly, they mobilized mass action from the people. SUP, on the other hand, aimed at defending existing power relations or to install a different elite fraction in power, while restricting civil freedoms; they did not advance a program of social reform and they sought to prevent revolutionary mass movement, frequently by violent means (Table 1).

It is important to note that in our analysis we only assess the occurrence of revolutionary or suppressive efforts at a particular time, but not if these events were successful in accomplishing their objectives. We think that the success (or failure) of such events depends on a large number of factors unrelated to the energy transition. Thus, we are solely concerned with the drive and capacity to create new political and social

[1] See https://www.history.com/news/east-india-company-england-trade; https://en.wikipedia.org/wiki/Dutch_East_India_Company; [6].

[2] 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 [15]; the steam engine became the key technology for industrial development, but was not widely in use before the last quarter of the 19th century [16].

[3] Population doubled in Europe 1500–1750, with most growth occurring before 1625; after 1750, there was a new cycle of expansion [23]. UK was a special case with its "enclosures" driving people from the land into cities. For the rest of Europe, population growth apparently played a role and led to a fall of land based solar energy availability per capita [16], putting pressure on peasants and landlords.

[4] We analysed the degree of urbanization in the countries investigated, before and after the early phase of transition to modern energy (CEP). The common pattern is a steep rise in urban population during CEP, with the only exception of China (which is known for its effort to encourage coal use among rural villages). The share of urban population before the country's transition to modern energy varied between <10 % and 30 %, and had either remained relatively constant, increased slightly, decreased in some cases, or oscillated (Figs. S4 and S5 in the supplementary information). Thus, not urban growth as such, but only in conjunction with a rise of modern energy raises the probability of revolutions.

[5] Historically, many revolutions fought to abolish dynastic rule and establish republican forms of governance [35]. Later, it was more often about liberation from colonial rule [8].

Table 1
The three main criteria for categorizing socio-politically turbulent events as revolutions (REV) or revolutionary events (REE), and suppressive events (SUP) and their characteristics. An event was classified as a revolution (REV) if all three of the criteria in Table 1 were met: political goals, social goals, and mass movement. It was classified as a revolutionary event (REE), if only two of the three criteria were met. A suppressive event (SUP) was coded if at least two of the three suppression criteria were met.

Revolutions (REV) and revolutionary events (REE)	Suppressive events (SUP)
1. Political goals: an effort at turning over political power/authority, such as …	
• Abolish absolute monarchy, reduce rulers by heritage to constitutional monarchs or introduce republican rule	• (Re)create monarchy, restore monarchy
• Overthrow ruler/government	• Military coup, establish dictatorship, junta, or one-party rule
• Independence from foreign masters	• (Re-)establish foreign control
• Establish civil rights and popular sovereignty (elections)	• Restrict civil rights, popular sovereignty, cancel elections, nullify their results
• Formulate a new constitution, expanding citizen rights within it	• Abolishing constitutional government; abolish term limits for leaders
2. Social goals: propagation of a fundamental social transformation, such as …	
• Abolish feudal privileges and serfdom	• Dismantle liberal mass media and other outlets for free expression of opinion
• Abolish slavery	• Reintroduce forms of slavery (forced work for prisoners or on tribal/gender grounds)
• Expand the franchise, human and civil rights	• Restrict franchise and/or civil rights for all citizens, minorities or particular groups
• Land reform and/or tax reform in favor of those who actually work the land	• Disappropriate small landholders, expulsion of tenants („land grabbing“)
• Separate church and state	• (Re)establish state religion
3. Mass movement: major mass mobilization and non-institutionalized actions, such as …	
• Widespread riots, uprisings and violent conflict	• Violent suppression of mass movements
• Widespread non-violent demonstrations, mass strikes and/or persistent acts of disobedience	• Declarations of martial law or emergency rule; delegation of authority to the military
• Armed attacks on leaders, assassination of authoritative figures upon mass demand	• Imprisonment of dissidents, death squads, internment camps, shooting demonstrators, delegating authority to non-state actors to use violence

visions of a desirable future, as well as the ability to mobilize a large number of individuals to pursue them (revolutions). Suppressive events represent the motive and ability of powerful state actors to thwart or reverse the realization of such visions.

The remainder of the paper is structured as follows: In Section 2 we describe the sources and methods used in generating time series data reaching back before the onset of modern fuel use and up to 2013; how we identified politically and socially turbulent events (revolutions, revolutionary events and suppressive events) and classified them (Section 2.1); the indicators and data sets for modern energy use (Section 2.2); and how we combined the datasets used for the analysis (Section 2.3). In Section 3 we present the findings of our analysis, structured by the above research questions. We discuss these findings in Section 4 and offer some reflections on their possible implications for the current situation and the future ahead: a shift away from fossil fuels, and possibly into an energy-constrained future.

2. Description of methods

2.1. The selection of countries and time period for analysis

Following from our core research question on the temporal link between the onset of modern energy use and the occurrence of social revolutions, our sample was limited to those countries for which long-term data on modern energy use could be stablished (see Section 2.2). For each of these countries, we systematically searched the literature for events that might qualify as revolutionary or suppressive, starting approximately 100 years before the beginning of fossil fuel use. This inquiry extended back to the 15th century for the United Kingdom and the Netherlands. For several European countries, the United States, and some Latin American countries, we searched as far back as 1700; for the majority of other countries, we began our research at the turn to the 19th century.[6] Two coders based their classification of events on short narratives derived from historical databases and encyclopedias [37–39], applying the criteria listed in Table 1.

This information was shared among the coders and, in an iterative process, cross-checked by a third coder who paid special attention to a similar "granularity" across countries and between coders. If the coders disagreed about the significance or nature of an event, they engaged in multiple rounds of discussion and addressed the issue with the aid of additional literature research and expert consultation. We limited ourselves to events on the national level; thus, we did not pay attention to, e.g., internal conflicts with and between indigenous groups, local political conflicts or military conflicts with other nation states.

2.2. Data for our key indicator: modern energy use

The core energy indicator used in this study is *modern energy use* per capita *and year* [GJ/cap/yr] which measures primary energy use in gross calorific values per capita and year from fossil energy carriers and in later years also other modern energy forms, such as electricity from hydropower or nuclear energy [40].[7] A major limiting factor for the selection of countries was the availability of data on the long-term development of modern energy use from its very beginning up to 2013. We used data from the "core data set" [1] that provides long-term time series of modern energy use per capita for 17 countries (Argentina, Australia, Austria, Chile, China, France, Germany, India, Italy, Japan, Netherlands, Portugal, Russia/USSR, Sweden, Turkey, Great Britain/United Kingdom, USA). Additionally, we included data on the use of fossil fuels and other modern energy forms for 49 countries for which we sourced data from [41] for 1929, 1937 and 1949, [42] for 1950–1970 and [43] for 1971–2013. For Latin American countries we also used data on fossil fuel consumption from [44] for 1890, 1900, 1913 and 1925. For Indonesia, Iran and Brazil we used data from the Podobnik energy data collection [45] and for Spain from [46]. Population data to calculate modern energy use per capita was sourced from the Maddison Project database [47]. Note that we excluded countries that served as mayor suppliers of petroleum to the rest of the world (such as Bahrain, Saudi Arabia, the Oman, the Arab Emirates and Venezuela), because we assumed them to have been subject to very different dynamics [15].

[6] Recently, there was set up a database with similar intentions (denoting events as „campaigns") within the "Harvard Dataverse" [36]. Unfortunately, it covers only the 20th and 21st century.

[7] These modern forms of (exosomatic) energy, at least at the beginning of the energy transition, made up only a very small share of total energy use of agrarian societies, which includes food for humans and working animals (endosomatic energy) and fuel wood as well as early uses of wind and water power (exosomatic energy) and which amounted to roughly 40–50 GJ/cap/yr in Europe in the early 19th century [40]. The additional small share of fossil fuels, nevertheless, has an over proportional impact as it requires less labour power, and therefore, the energy return on energy investment is much higher.

For the majority of countries, the modern energy time series available from sources began well below 1–2 GJ/cap/year. In cases where the onset of modern energy use happened before the beginning of available time series data, we linearly extrapolated the beginning of modern energy use. The historical data fit a linear trend reasonably well ($r^2 >$ 0.70), and the extrapolations produced plausible results.

An overview of the development of modern energy use for all 66 countries included in the sample can be found in the Supplementary Information in Figs. S1, S2 and S3.

2.3. Combined datasets

Combining the time series on modern energy use and the revolutions database yields our full data set. The full dataset covers 66 countries and 276 events (52 REV, 140 REE, and 84 SUP) from 1500 to 2013, with modern energy use levels ranging from 0 to 384 GJ/cap/yr. As stated above, the duration of accessible historical periods varies by country. The full data set covers on average of 216 years of history per country, with an average of 90 years preceding the use of fossil fuels and other modern energy forms. Fig. 1 provides a summary of the various time series pertaining to country history, modern energy use, and history before the onset of modern energy use. A complete overview of the evolution of modern energy use and the dates of all identified events may be found in the supplementary information (Figs. S1–S3 and the accessible data file).

The re-estimation of the critical energy phase (CEP) identified in a previous study [1] was based on the subgroup of countries that had reached energy maturity by 2013. In this context, "energy maturity" refers to the minimum rate of energy use necessary to accomplish a particular level of development. Based on the relationship between primary energy consumption and the human development index, this value has declined over time, making it difficult to pinpoint when the transition to modern energy use reaches maturity. Arto et al. [48] and Steckel et al. [49] reviewed numerous ways for determining these thresholds and discovered values ranging from 15 to 45 GJ/cap/year of primary energy use (including traditional energy sources). We set the maturity threshold at 35 GJ of modern energy use per capita, choosing a threshold at the higher end of this range to avoid excluding too many countries from our analysis. The main characteristics of the full and the maturity datasets are summarized in Table 2.

All figures and analyses were based on the full dataset, sometimes (if stated) excluding Great Britain and the Netherlands, where the usage of fossil fuels began significantly earlier (i.e., already in the 15th century, see Fig. 3) than in all other countries.

3. Findings

In this section we provide evidence that the empirical data are consistent with our three main assertions: First, it is justified and useful to speak of a critical energy transition phase (CEP) that we denote as an "anteroom" to industrialization, during which revolutions are especially frequent. Second, the CEPs of countries occur in different time periods and are a more reliable predictor of social turbulence than the historical era in which these events occur. Thirdly, and perhaps counterintuitively, despite technological progress, the duration of CEP has not decreased over time. Finally, we investigate the effects of colonization and suppressive events on the duration of the early energy transition of countries.

3.1. The critical energy phase as the revolutionary anteroom of industrial society

Prior research [1] identified a critical energy transition phase (CEP) at the take-off of the energy transition between 0.4 and 7.1 GJ/cap/yr (Table 3). One objective of this study was to determine if this revolutionary "anteroom" of the full energy transition is also observable in a larger sample encompassing more countries and a longer time period. We attempt to reproduce these results using our maturity subset (≥ 35 GJ/cap/yr, see Fig. 2), which consists of 29 countries and 21 revolutions, as opposed to seven revolutions in six countries in the previous study. The original study established the CEP as the 80 % prediction interval for modern energy use under the assumption that modern energy use of countries at the time of their revolutions followed a lognormal distribution. Fig. 2 shows that this assumption does not hold true for the maturity subset, which has a left skewed distribution. Several revolutions occurred at relatively high levels of modern energy use in Cuba (15 GJ/cap/year), Portugal (30 GJ/cap/year), and Tunisia (34 GJ/cap/year). However, the figure also reveals that the distribution has a well-defined peak in the early stages of modern energy use.

Simplifying the original study's methodology, we define the critical energy phase as the interval of fossil energy use that encompasses two-thirds (66 %) of the observed revolutions in the maturity subset. This results in a CEP ranging from 0.7 to 7.2 GJ/cap/yr, which is essentially identical to the one previously defined (Table 3). As validation for this approach, we apply the CEP to the full dataset, which also includes countries which have not yet reached energy maturity (66 countries, 52 revolutions). Close to two-thirds (33 of 52) of all REV fell within the CEP, indicating that the CEP generalizes to the full dataset. Only five revolutions occurred before the CEP, while nine occurred after (see Fig. 3a). These are the more recent revolutions in Iran, Argentina, and Egypt, in addition to the previously stated revolutions in Cuba, Portugal, and Tunisia. In light of these results, we believe it is legitimate to speak of a CEP in the early stages of modern energy use that is especially susceptible to the occurrence of revolutions throughout the past centuries.

Extending the observation to revolutionary (REE) and suppressive (SUP) events reveals a similar pattern (Fig. 3 and Fig. 4). Both types of events are most prevalent in the CEP. In terms of fossil energy use at the time of the event, as well as the timing of a country entering the CEP, the distributions of all three types of events are remarkably similar (Fig. 3b). REEs, but particularly SUPs, appear to occur at slightly higher levels of fossil energy use and a little later in time. These differences are not statistically robust but it seems plausible that SUP events mostly happen after REV and REE events.

The years when countries enter their CEP span more than five centuries, with Great Britain passing the energy threshold in 1433 and Nepal only reaching it in 1985 (Fig. 4). However, during the late 19th century and the decades following World War II, the bulk of countries in our sample enter their CEP.

It is interesting to note that the duration of CEP is not systematically contracting historically (see Table 4), if we disregard the very slow forerunners Great Britain and The Netherlands. If it were mainly a matter of existence of suitable technologies, we should indeed expect a systematic acceleration of the transition process to modern energy use. But apparently, other factors play a major role, such as the continuous rise of SUPs per time period[8] (see Section 3.2). Socio-political processes prove to be very relevant for the speed of an energy transition — a finding well applicable to the world's current energy transition, away from fossil fuels (see Section 4).

Another issue is the thesis raised by Hobsbawm [34] that there is something like a "revolutionary era", which was located in the middle of the 19th century. Could we identify another revolutionary era in other parts of the world in the first half of the 20th century?

We created three simple statistical models (Table S4 in the supplementary information) to investigate the correlation structure between REVs, CEPs, and the historical era in which the events happened. Due to

[8] The shorter CEP duration among countries with CEP occurring after 1939 (8 countries) is relativized by the long duration of countries with incomplete CEP: out of these 17 countries, 15 started their CEP after 1939, and thus belong to this group of countries (see Fig. 4).

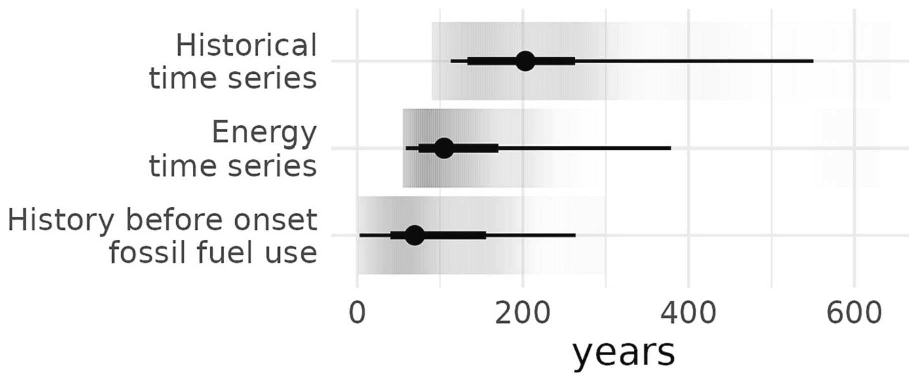

Fig. 1. Descriptive statistics of the time series data. Median years of history (203), energy use (105) and history before onset of modern energy use (70). Figure shows the median values (dots), the intervals containing 80 % (bold line) and 95 % (line) of the data, as well as the underlying density distribution (gradient).

Table 2
Dataset overview: the full dataset includes all countries with energy time series and coded events; the maturation dataset is the subset of countries that have reached the modern energy maturity threshold of 35 GJ/cap/yr by 2013.

Data	Countries	n years	Event type		
			REV	REE	SUP
Full	66	14,339	52	140	84
Maturation	29	3918	21	55	39

Table 3
Boundaries and mean of old [1] and new (this study) critical energy phase (CEP) (GJ/cap modern energy use) and median length of CEP duration.

Dataset	CEP start	CEP end	CEP mean	CEP duration
	Modern energy use (GJ/cap/year)			Median (years)
Fischer-Kowalski et al. [1]	0.4	7.1	1.7	49
This study	0.7	7.2	3.6	42

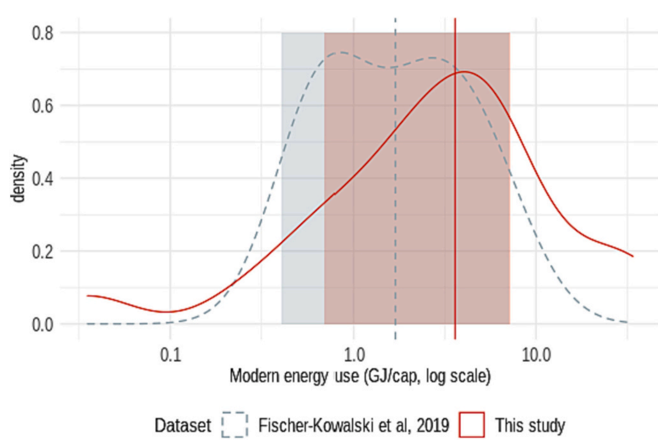

Fig. 2. Recalculated critical energy phase (CEP): Comparison between CEP in [1], and in this study. Figure depicts estimated kernel density distributions of modern energy use (GJ/cap/year, log scale) at time of revolution.

the rarity of revolutions, we grouped years into decades and coded the dependent variable (REV) as 1 if a revolution occurred in this decade and 0 otherwise. We classified the independent variable for the CEP as a categorical variable with three values indicating whether the decade is before, during, or after the CEP. The historical period was then categorized in half-century increments. We incorporate the historical era as a control to determine whether the CEP is truly the relevant characteristic or whether many CEPs just correspond with certain historical eras ("revolutionary decades"); the results are shown in Table S3 in the supplementary information. In the first model, we only consider CEP as an independent variable, and by definition, its coefficient of 0.081 (during CEP) is highly significant ($p < 0.001$). The historical period is then added to two other models (one with time fixed effects, one with time and country fixed effects). If historical epoch played a greater role in explaining the prevalence of revolutions, we would anticipate the CEP coefficient to become smaller. Despite the fact that the period between 1900 and 1950 is also significantly correlated ($p < 0.05$ and $p < 0.01$ in models 2 and 3) with REV occurrences, the coefficient for CEP changes very little (0.073 at $p < 0.001$). This suggests that the occurrence of revolutions in the past was more closely tied to a country's CEP than to a specific historical period.

3.2. *Critical energy phase duration over time and the legacy of colonialism*

Not just the starting year, but also the duration of CEPs differs significantly between countries (Fig. 4). If duration primarily depended on the availability of energy technologies, we would anticipate the adoption of modern energy sources to accelerate with time. Indeed, this is the distinction between the two pioneers of fossil fuel use and all other countries: In Great Britain and the Netherlands, the CEP took longer than anywhere else — more than four centuries (Fig. 4). Nevertheless, the surplus energy they had amassed enabled the two pioneers to establish global trading companies and urban-industrial manufacturing, thereby initiating a new economic order (50). In contrast, other European nations (along with Russia, Japan, Turkey, Brazil, and China), whose CEP began between the late 18th century and the beginning of World War I (1914), completed their CEP in around half a century (median: 55 years, see Table 4). In the group of countries that began their CEP after the beginning of World War I, the median time to complete it was 48 years. Despite having started their CEP a median of 61 years ago, half of the countries in this group have not yet completed it (Table 4).

In view of the fact that several of the countries in our sample were during our observation period colonies of the countries that pioneered the energy transition (see Table S1 in the supplementary information), we investigated the effect of attaining independence on the energy transition. We assume that colonial overlords were not particularly interested in assisting an industrial transformation of their colonies, but rather desired to maintain their agrarian status in order for them to provide agricultural and mining products, as well as slaves [74,75]. Therefore, we hypothesize that "master countries" delayed the use of fossil fuels in their colonies in order to preserve existing systems of exploitation.

Thus, we anticipated a lengthy period of little or minimal modern

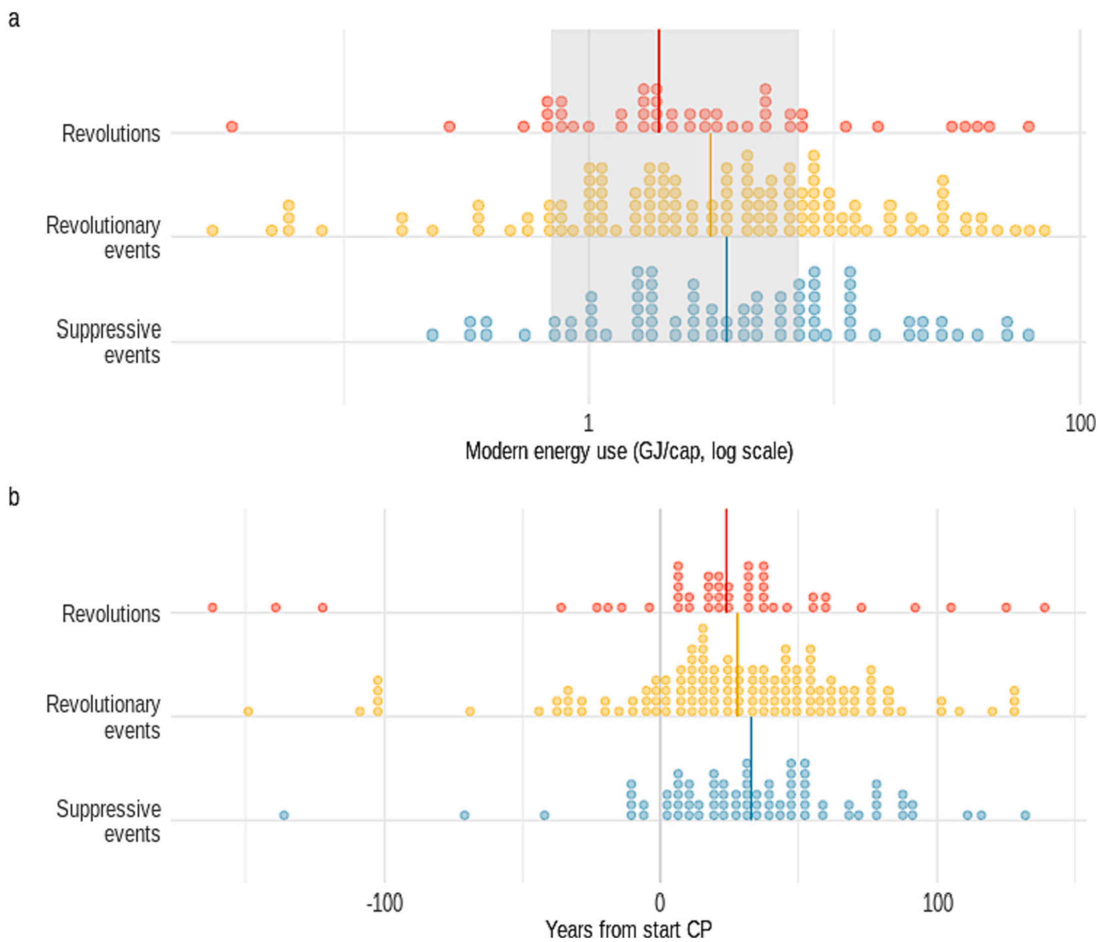

Fig. 3. Turbulent socio-political events (revolutions, revolutionary events, and suppressive events) by (a) level of modern energy use (critical energy phase shaded) and by (b) years relative to the start of critical energy phase.

energy use before the date of independence, followed by a gradual transition to their use after reaching independence. In fact, Fig. 5a demonstrates that the start year of CEP was delayed in former colonies beyond the year of independence, and the longer they had been colonized, the later their CEP began. Fig. 5b demonstrates that the median duration of CEP did not decrease in comparison to their colonial overlords, despite the global dissemination of technological progress. While CEPs appear to be shorter in the group of countries that gained independence most recently (i.e., after World War I), it is important to note that the majority of these countries had not yet finished their CEP by 2013. These findings corroborate the hypothesis that colonial powers, which were themselves much further advanced in industrial development, did little to help the energy transition in their colonies but were more likely to delay it.

We have already demonstrated (Fig. 3b) that REVs occurred with a roughly normal distribution (mean = 21, sigma = 55 years) after the onset of fossil energy use, but SUPs happened slightly later (mean = 34, sigma = 40 years). Now we examine if the occurrence of either of these events affects CEP's duration (Fig. 6). We find that the median duration of CEP was 4 years shorter when a REV occurred during or slightly (one sigma) before the start of the CEP, compared to when no REV occurred (Fig. 6a). In contrast, a SUP event during the same time period increased the median lifespan of CEP by 11 years in comparison to countries without SUP events (Fig. 6b).

Due to the limited sample sizes, none of these effects were statistically significant, but they may suggest an inverse impact of these two kinds of event on the speed of the energy transition. In general, however, we may conclude that the early phase of the transition to modern energy (CEP), independent of chronological time, attracts socio-political instability, particularly REV and SUP, but that these socio-political events, at least in the short term, have only a small effect on the rate of modern energy adoption.

3.3. Limitations

A critical issue in our study is the identification of revolutions and related events, since there is no common definition for these events. We have attempted to overcome this limitation by providing a clear definition and a transparent set of criteria by which we classify historical events as revolutions, revolutionary, or suppressive. However, there is no guarantee that we have achieved a comprehensive identification of all events that might qualify as revolutions across the wide range of countries. Although we have systematically searched the literature for events that occurred a century before the onset of fossil fuel use, we cannot rule out the possibility that we have missed relevant events, particularly before the period of observation.

It was difficult to determine the actual starting year of modern energy use for some countries because statistical sources start reporting fossil fuel use with some delay. In several cases, we had to extrapolate the start year by linear extrapolation of the historical trend. This may sometimes underestimate the slowness of the start of fossil fuel use and lead to an underestimation of the duration of the CEP.

The energy indicator we used in our analysis (modern energy use per capita of population) ignores that significant amounts of traditional, mainly biotic energy were used in pre-industrial energy regimes (in addition to fuel wood, fodder for draft animals and food for humans, as

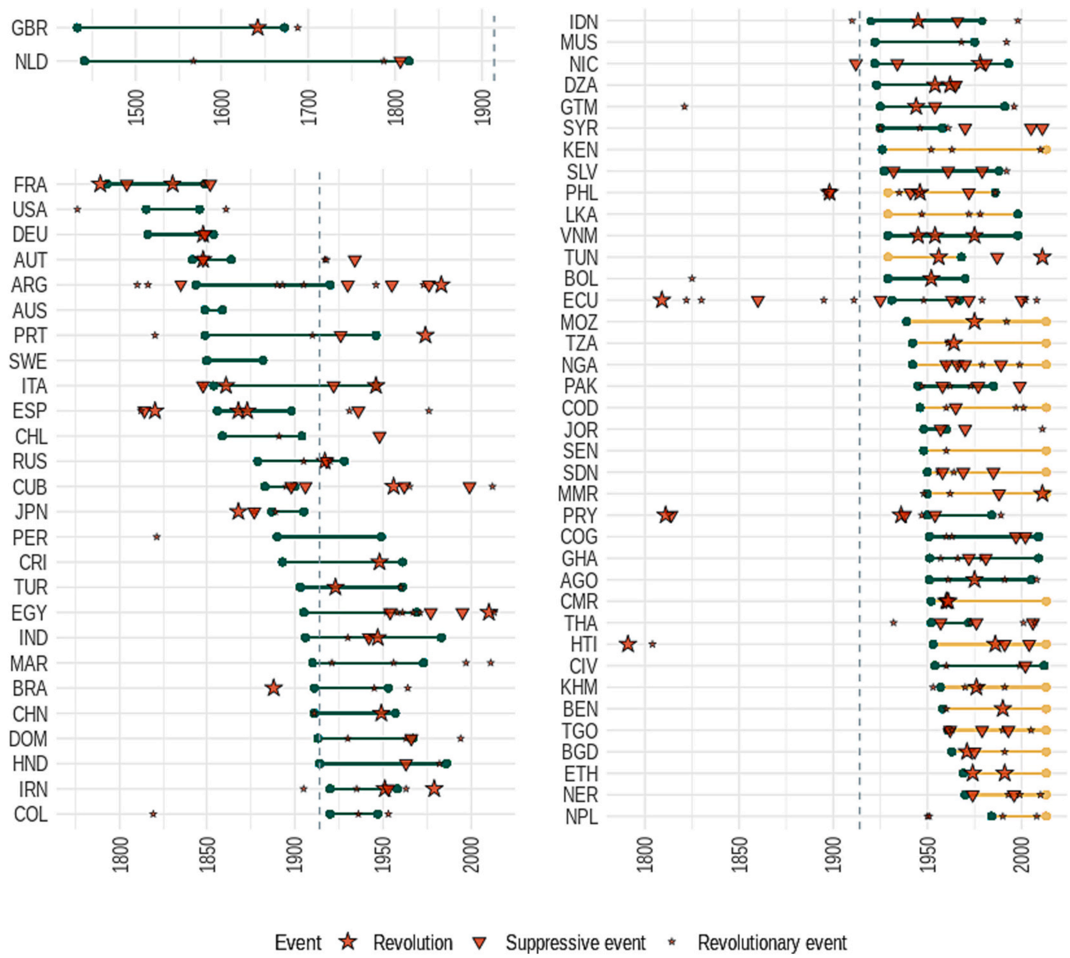

Fig. 4. Country overview with timing of the critical energy phase (CEP), and occurrence of turbulent events. Green coloring indicates that CEP was completed by 2013, yellow coloring indicates that the upper limit of CEP was not yet reached by 2013, or missing data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 4
Critical energy phase (CEP) duration in years (median) for countries who began their CEP prior to World War I (before 1914), between WWI and WWII (1915–1939), within or after WWII (after 1939), and those that have not completed their CEP by 2013.

CEP start	Countries	CEP duration (median years)	REVs in CEP	REVs per country	SUPs in CEP	SUPs per country	SUPs per REVs
CEP before 1914	25	54	13	0.52	11	0.44	0.85
CEP between 1915 and 1939	13	53	10	0.77	11	0.85	1.10
CEP after 1939	8	47	1	0.12	10	1.25	10.00
CEP incomplete	17	61	11	0.65	18	1.06	1.64

well as wind and water power). It would have been interesting to test our hypothesis using an indicator that includes these traditional energy sources. The World Energy Consumption Database [40] provides information on total energy use for 72 countries since 1820, including traditional biotic energy forms, but the latter were estimated only at the level of geographical regions of the world and allocated at the country level using population and per capita values; they are therefore not sufficiently detailed for our analysis. Since total per capita energy use is relatively stable across countries in the early years of fossil fuel use, we expect that we would not be able to identify a relationship between the level of total per capita energy use and revolutions or a critical energy phase.

Finally, it should be noted that we have singled out one explanatory factor – the onset of access to modern energy – for revolutions, but have not been able to show quantitatively its joint contribution with other factors (such as population and urban growth, imperial or colonial policies, technological change, immiseration, education…). Revolutions emerge from contingent historical processes involving a complex interplay of different factors. In particular, the transition to fossil fuels has been identified as a significant backdrop contributing to transformative shifts in societal power dynamics.

4. Discussion and conclusion

We have confirmed evidence that historically the very early phase of the shift in the energy supply of countries from land- and biomass-based energy to fossil fuels and other modern energy can be considered a revolutionary "anteroom" where political and social turbulence and especially "social revolutions" [28,30] occurred more frequently than in any other period before or after. Across centuries, this turbulent period lasted approximately two generations and gradually initiated technological and socio-political change as well as economic growth. The specific actors and causes of each revolution in our dataset were contingent on vastly different historical and societal contexts. But

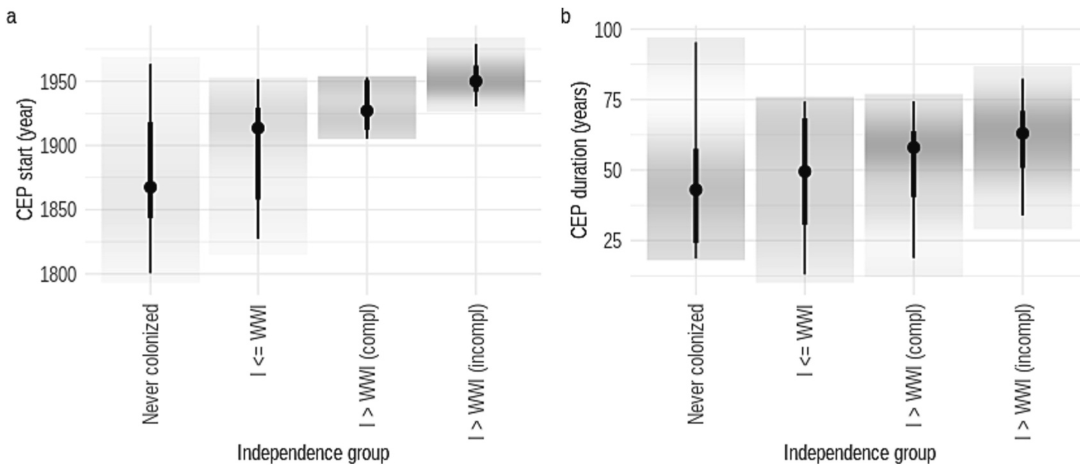

Fig. 5. The beginning year of the critical energy phase (CEP) (a) and the duration of the CEP (b) categorized by time of gaining independence. The graph illustrates the median values (dots), the intervals encompassing 80 % (bold line) and 95 % (line) of the data, and the underlying density distribution (gradient). Both exclude the Netherlands and Great Britain.

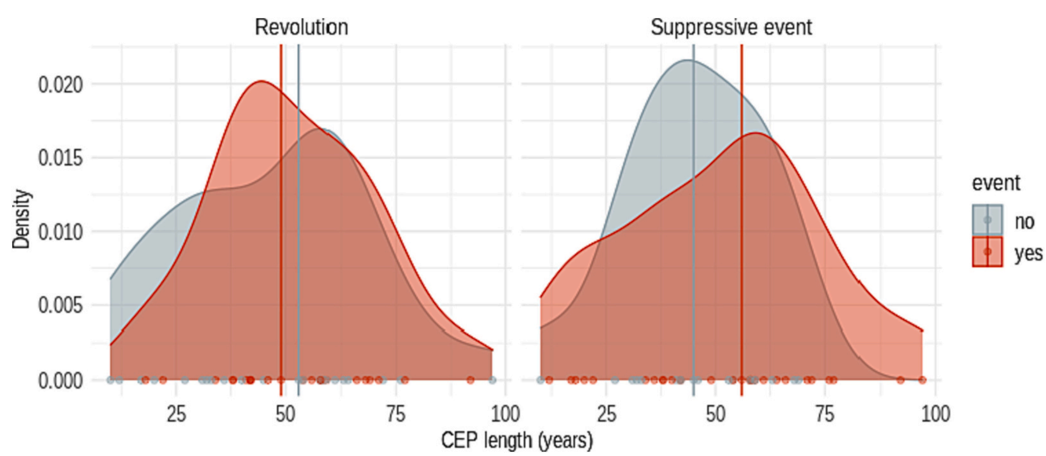

Fig. 6. The impact of revolutions and suppressive events on the duration of the critical energy phase (CEP). Estimated kernel density distribution of CEP length for all countries where a revolution (left) or suppressive event (right) occurred between one standard deviation (sd = 40) of the mean CEP length preceding the start year of the CEP and the end year of the CEP (Figure excludes Great Britain and the Netherlands).

apparently, modern energy generated a new opportunity structure, new promises for new groups of actors, and new threats to established dominant actors. Until the emergence of fossil fuels, both political and economic power were rooted in the land, with biomass as the key and limited resource with a low energy return on investment [51,52]. With access to fossil fuels, not only the overall societal energy level begins to rise, but the control over and the benefits from this larger room to maneuver shifts between groups of social actors within countries. These shifts, apparently, may take place gradually without major political disruptions (as in about half of the countries in our sample), or it may threaten their established socio-political order and its incumbents.[9]

How does this relate to the current global efforts at reducing CO_2 emissions in order to prevent catastrophic climate change, which requires a shift to new, renewable energy sources and a reduction of energy use in the high-income countries, while in the Global South the transition to fossil energy is still an ongoing process?

[9] The period under investigation is also marked by major turbulences in the international political order that may relate to the rising availability and shifts in political control over the new sources of energy. This is beyond the scope of our article. An overview of disruptions in relation to energy across the world, currently and to be expected in the future, is provided in [53].

The prevalent position rejects the analogy to the historical process and presumes that the world is not undergoing a comparable major shift in society-nature interactions. Ecological Modernization theories [54–56] defend the position that technological progress, gains in energy efficiency, and a gradual shift to renewable (or nuclear) energy, combined with the implementation of geoengineering technologies such as carbon dioxide removal from the atmosphere and carbon capture and storage, can enable a smooth transition to an energy system that allows to further increase energy availability while avoiding climate change. It is assumed that such an energy transition can be directed technocratically within the current global political and economic context and does not necessitate profound political and economic change, and thus also avoids social turmoil. There is, however, no empirical evidence that the required rapid absolute decoupling of GHG emissions and climate impact from economic activity can actually be achieved [57,58]. Also the most recent IPCC assessment states that achieving a climate-resilient and sustainable world requires fundamental societal changes, such as changes of core values, worldviews, ideologies, social structures, political and economic systems, and power structures [59].

This critique is the starting point of the counter position, which argues that major absolute reductions in global fossil fuel use and natural resource use in general are required to allow humanity to remain within a safe planetary operating space [60–62]. Proponents of “degrowth”, for example, question the possibility of a sufficiently fast decoupling of resource use and economic growth based on technological innovation alone and argue that rapid reductions in resource use are not possible without a radical change of the current economic and social system [63–65]. Achieving wellbeing for all within planetary boundaries necessitates a large redistribution of access to energy services within industrial countries [66] and a massive worldwide realignment of wealth between the Global North and South [67], as well as high and low income citizens [64].

Such issues are, however, not yet successfully given consideration in international (climate) policies that largely adhere to the status quo-affirming ecomodernist narrative favoured by incumbent elites. This understanding of reality cannot accommodate the aforementioned redistributive demands, as these would likely be sufficient to destabilize the global economy in its current form. In contrast, political movements that recognize these demands, which might be summed up broadly as climate justice movements, tend to emphasize the necessity for profound economic and social transformation, for example, in the form of expropriation of excess wealth, and economic democratisation through social provisioning of sustainable basic services [68,69]. Bottom-up movements from a feminist (e.g., [70]) or developing countries perspective like "leave oil in the soil" in Nigeria or Ecuador [71] intersect with the global environmental justice movement.

What relevance might our findings about the greater incidence of social turmoil during the early stages of a shift in the energy and resource base of societies have in this context? We speculate briefly on some features of the currently required resource transition that may increase or decrease the potential for the emergence of social mass movements analogous to those addressed in our historical analysis.

First, the revolutionary movements that we analysed were preceded by new ideas and visions (such as the Enlightenment and Socialism), which moulded the mindsets of many people. But, according to our findings, these visions required a coincidence with new material conditions (such as a new source of energy) to trigger revolutionary mass action. Currently, science is a major actor in supplying arguments against a continuation of the current course of resource use and global inequality. It offers new ideas and visions — and natural conditions evolve as negatively as projected by science. In stark contrast to the historical transition, however, the now required transition is likely to reduce energy availability and thus does not offer the promise of a continuation of increasing material wealth for all. Rather, it will require a new perspective on what defines well-being and quality of life.

Second, the current relationship between economic and political power is less direct than it was for landed elites in the past. Even while it has been demonstrated that fossil elites exert disproportionate influence over political decision-making [72,73], they usually do not hold political office. Colgan et al. [25] present an interesting argument from a political economy perspective. They argue that progressing climate change and international and national climate policies of decarbonization trigger severe tensions between economic actors who hold assets linked to carbon-based sources of energy (such as oil and gas companies) and those whose assets suffer from impacts of climate change (such as insurance companies or real-estate holders who expect or experience a devaluation of their assets following climate events). The same tension arises also between countries deriving their core income from the extraction and sale of fossil fuels (such as Saudi Arabia and Russia), and countries that are particularly vulnerable to impacts of climate change. These tensions, so the authors argue, are bound to become "existential", both with policy efforts at substituting fossil with renewable energy sources, and with increasing climate impacts. Thus, political and economic conflicts, both within and between countries, are to be expected.

Third, historical social mass movements played mostly on a national stage. Due to the economic globalization of the previous centuries and the rule-based global order established to sustain and enforce it, national-level political leverage is severely constrained. At the same time, global democratic institutions as established after the catastrophe of the Second World War, are themselves relatively weak. Thus, struggles for economic/climate justice do not have strong policy institutions to address. Nevertheless, bottom-up social movements to bring about a socio-ecological transformation spring up worldwide, targeting the economic system and property relations as well as political inertia while simultaneously defending democratic accomplishments.

Based on these observations we think it can indeed be argued that there evolves a situation analogous to the past structural conflict between a land-based and a fossil fuel-based energy system that gave rise to the revolutions addressed in our article — this time not just on sequential national levels, but internationally. The global movement for climate justice may be a first indication in this direction. But their goals are contested in the population and we increasingly also observe counter movements that aim at preventing global social and political change.

CRediT authorship contribution statement

MFK, FK and PPP wrote the text; FK compiled the energy data; RKS and StS compiled the data on historical events, with MFK corroborating; PPP performed the statistical analysis and designed the figures and the SI; RKS edited the text.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.erss.2023.103280.

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