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Out of Steam
Energy, Materiality, and Political Ecology

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Abstract
Energy is increasingly used as a lens to study wider social processes. For political ecologists, 'energy' has usually been seen as a resource or socio-technical system that gives rise to contentious social relations. This paper instead thinks of energy as a materiality with thermodynamic properties. At once, energy becomes an analytical concept with physical and political-economic dimensions. Developing this perspective, the paper examines the notion of ecologically unequal exchange and unpacks discussions on how energy systems are co-productive of politicised environments. The outcome is an expanded definition of political ecology set out in relation to three modes of social power.

Keywords
energy; thermodynamics; materiality; ecologically unequal exchange; energopower; political ecology

I Introduction

In recent years, a stream of publications has presented the state of the art of political ecology in the field's Anglo-American tradition (Bryant, 2015; Perreault et al., 2015; Turner 2016; 2017; Loftus, 2017; 2018). On the one hand, research is increasingly moving to questions of materiality and relational ontologies (Escobar, 2010); on the other, energy is fast emerging as a key theme. Readers of this journal know that both trends are paralleled by rich discussions in human geography, anthropology, and cognate disciplines more widely (e.g. Bakker and Bridge 2006; Calvert, 2016; Haarstad and Wanvik, 2017). However, while energy is now approached as an integral element of social theory (Bouzarovski et al., 2017a; Solomon and Calvert, 2017), it is less often emphasised how human energy use constitutes a moment where human practice and forms of energy coalesce—that energy use is a mode of human-nature interaction. It has long been a mainstay of political ecology to study such interactions, but despite this, it is only recently that 'energy' has been surveyed in the many overview works of the field (Cederlöf, 2015; Hornborg, 2015; Huber, 2015), testifying to a recent surge of interest in this area.

Two preliminary observations call for attention. First, when energy has been a concern for political ecologists, it has almost exclusively been conceptualised as a natural resource (Huber, 2015). As such, energy is an object for human appropriation, subject to controversial geographies of extraction, processing, and distribution (Bridge, 2009; Bebbington, 2012; McNeish et al., 2015). Michael Watts' (2001; 2004) seminal work on oil in the Niger delta has been particularly influential in establishing this trend. Symptomatically, Peluso and Watts (2001: 24–25, emphasis added) suggest that '[p]olitical ecology provides the tools for thinking about the conflicts and struggles engendered by the forms of access to and control over *resources*.' In the form of a resource, however, 'energy' takes a distinct conceptual shape, and as Power et al. (2016: 12) remark, it is then simply seen as 'an empirical object of inquiry as opposed to an underlying analytical concept.'

Second, political ecologists have tended to focus on the distributional effects of environmental change; notably, how the costs and benefits of resource extraction are distributed unequally among actors (Bryant and Bailey, 1997; Martinez-Alier, 2002; Robbins, 2012). Beyond reference to colonial or neoliberal relations of production, it has less frequently been asked *why* and *how* energy is distributed in the first place. Yet the spatial organisation of energy flows generates uneven geographies of access and control that are central to social and economic life. Jason Moore (2011) and Matthew Huber (2013) argue that rather than focusing on how social life makes use of and degrades an external resource-based nature, political ecologists should ask what the ecology of social life looks like. Indeed, '[i]t is only by looking at the ecological conditions of human economies', as Alf Hornborg (2001: 36) writes, 'that we can adequately conceptualize the mechanisms that generate inequalities in distribution.'

In this paper, I build on these observations to arrive at an expanded definition of political ecology. While 'energy' often takes the form of a resource in the field, I conceptualise it as a materiality with thermodynamic properties that moves through economies and societies in physically and socially uneven ways. The distribution of various energy forms is not a politically neutral process, but one where political and economic actors attempt to organise energy flows through infrastructures to achieve social visions; to maintain or contest social relations; and to engage in contingent everyday practices of energy use. Political ecology, then, is a field that studies how political, economic, and social relations shape and are shaped by energy systems, which co-constitute the ecological conditions of human life.

The paper begins with the question of energy's materiality: I argue that 'energy' ought to be conceptualised not only through its discrete material properties but also through its continuous thermodynamic qualities. This complementary focus was prominent in debates in cultural ecology but have been downplayed by resource-focused political ecologists. The second section establishes the contours of these historical debates that contribute to an understanding of thermodynamics and society. The final two parts then explore how energy systems integrally shape the ecological conditions of social life. The third section engages with the notion of ecologically unequal exchange, which requires us to re-think the ontology of technology to reflect an inherent social relation defined by asymmetries in distribution. In critical tension with the world-systems frame that underpins this perspective, I develop a concept of supply regimes to further this end. The fourth section finally unpacks approaches that have started to conceptualise how the materialities of energy systems co-produce politicised environments for human action. I identify two complementary modes of power that operate through energy use to arrive back at an expanded definition of political ecology.[1]

II The matter of energy

To speak of materiality, Bakker and Bridge (2006: 18) argue, is to foreground how the bodies and material properties of humans and nonhumans 'make a difference in the way social relations unfold'. In the realm of energy, scholars re-materialising human geography over the past decade have also taken the physical properties of natural resources (oil, gas, electricity) and manufactured infrastructures (pipelines, grids, chokepoints) as their starting point. Luque-Ayala and Silver (2016: 1), for example, see the materiality of electricity as equivalent to 'its flows, cables, meters and pylons'. The objective has been to explore how the 'unruly' (Bakker and Bridge, 2006), 'lively' (Amin, 2014), 'disruptive'

(Barry, 2013), or 'vital' (Bennett, 2010) nature of matter affects social practice. These adjectives speak to the intrinsic capacity of 'nature' to evade human control. Such a perspective on materiality plays into the hands of mainstream political ecology where energy almost entirely has been conceptualised as an object—a resource or socio-technical system.

Gavin Bridge (2011) argues that the material form of oil—liquid, flammable, and extractable through wellheads point-like in space—is productive of specific forms of social relations. The 'geography of holes', for example, gives oil production an enclave character. Oil enclaves become a form of exclusionary zones where transnational capital cuts a slice of territory out of a nation-state for heavy investment. The enclaves are expected to establish a boundary between a zone governed by global standards (Barry, 2006) and an outside that is disentangled from the movement of petro-capital. The irony, which surfaces in studies of oil enclaves in Equatorial Guinea (Appel, 2012), Angola (Ferguson, 2005), Nigeria (Watts, 2004) and the Gulf of Mexico (Zalik, 2009), is that they are deeply entangled in the historical, ecological, and political contexts that petro-capital tries to free itself from. Other studies are also showing how the material properties of oil, gas, and biofuels shape the organisational setup of production networks (Kaup, 2008; Birch and Calvert, 2015; Bridge and Bradshaw, 2017).

Here, the concept of materiality implies that materials condition or constrain human action, although never in a uniform, deterministic manner (Bakker and Bridge, 2006). An analytical distinction is also maintained between the material and the social domains as materials are seen to have *consequences* for social practice (Bridge, 2009; Hornborg, 2017). At the same time, there is currently a tendency in the field to collapse this distinction. Post-human perspectives hold that nonhumans not so much have consequences as *agency* (e.g. Anderson and Wylie, 2009; Kipnis, 2015). 'Energy' is sometimes invoked as a concept in this context to animate matter; 'to convey a vitalist understanding of "matter-energy" or what Deleuze and Guattari termed "energetic materiality"' (Barry, 2015: 110).

Jane Bennett's (2010) work is particularly instructive. Drawing on a Deleuzian rather than Marxian materialism, she establishes the 2003 US-Canada intercontinental blackout as an 'assemblage'. Assemblages are *ad hoc* 'living, throbbing confederations' of humans and nonhumans that cooperate as events unfold (Bennett, 2010: 23). The electrical grid is thus best understood as an active coalition of electromagnetic fields and legislation, coal and lifestyles, wire and economic theory. Yet, at the time of the 2003 blackout, Bennett (2010: 24) argues that the always-present friction among the parts of the assemblage was so great that 'cooperation became impossible'. This leads her to suggest that no single human or nonhuman can be blamed for the infrastructural failure. Instead, agency was distributed across an open-ended collective of animated participants constituting 'the grid'.

Forcefully, Bennett rethinks the political implications of electricity systems. Whether a case of agency or consequence (see Hornborg, 2017 for a critique), she shows how the materialities of energy infrastructures can act not only to condition human action but also to catalyse it, prompting a human response or socio-ecological change. Like Bennett, Andrew Barry (2013) insists on the liveliness of energy infrastructures; however, his point is not to animate them, but to show how unruly materials attain political significance through the production of information. In his words, materials become 'the catalyst[s] for controversies' (Barry, 2013: 153). When a coating material fails in the trans-Caspian oil pipeline he studies, he demonstrates how this material becomes subject to contradictory knowledge claims with ramifications across the globe. Materially, the pipeline is a 'political technology' (Braun and Whatmore, 2010) where measurements and classifications, co-producing it, become objects of government that shape political and economic life.

The materialities of energy resources and infrastructures thus both condition and catalyse human action. It is striking, however, that energy throughout these discussions largely is a question of matter. Confronted with the literature, Barry (2015) notes that the concept of 'energy' has tended to concern either a solid, liquid, or gaseous natural resource distributed through infrastructures, or an ethereal, vitalising quality of matter. But since the late eighteenth century, physicists, chemists, and engineers have developed a foundational understanding of energy in the branch of physics known as thermodynamics. Barry argues that this mode of materiality has been neglected in the social sciences at large. While political ecologists have come to approach energy chiefly in the context of natural-resource struggles, however, the field in part developed from discussions that converged on thermodynamic interpretations of economy and culture. I next revisit these discussions to develop a thermodynamic understanding of materiality. I will then argue that this understanding invites us to reconsider the implications of political ecology.

III Energy as spatiotemporal relation

The science of thermodynamics developed during the industrial revolution, foremost to describe the mechanical effect of heat. In lay terms, the steam engine converted coal (heat) into movement (mechanical energy), and a set of thermodynamic laws was established to describe the process (Caygill, 2007; Lohmann and Hildyard, 2013). The first law of thermodynamics states that energy never can be destroyed or consumed, only be transformed into other forms. The second law then conditions the first: as soon as energy changes form, its quality—or 'orderliness'—diminishes as entropy increases. To return energy to its more orderly form, even more low-entropy energy must be put to work. Ultimately, an energy system requires a continuous supply of low-entropy energy to remain productive, or the system will tend towards thermodynamic equilibrium where there is no free energy available to do work (Kondepudi and Prigogine, 1998).

The laws of thermodynamics explain the concept of metabolism. Metabolism defines a process whereby a living organism (such as a human body) feeds on a continual supply of energy to reproduce itself. Moving from biological to social metabolism, the metabolic process is translated from cellular to societal scale. Marina Fischer-Kowalski (1998: 63) notably argues that humans have tended to sustain food supply collectively and that '[s]ocieties will, in effect, sustain a metabolism that at least equals the total metabolism of their human members.' Society is consequently dependent on a flux of energy and matter that it transforms incessantly while entropy increases (cf. Martinez-Alier, 2007; Newell and Cousins, 2015). The notion of dissipative structures captures the thermodynamic implications of the metabolic process even more clearly. Physical chemist Ilya Prigogine (1993) defined a dissipative structure as a self-organising, highly-ordered organism or system that unavoidably increases entropy yet maintains its internal structure by importing low-entropy energy from its environment. As soon as the system loses its metabolic source, it dissipates through its non-equilibrium structure. Classic examples of dissipative structures are hurricanes, lasers, and so-called Bénard cells (Kondepudi and Prigogine, 1998; cf. Schrödinger, 1944). Through these concepts, a thermodynamic understanding of materiality implies that energy systems are inherently historical-geographical phenomena. They are historical in that entropy provides temporal direction (Prigogine and Stengers, 1984) and geographical in that they require material inputs and generate material outputs. Energy, then, is not an object but a spatiotemporal relation.

Thermodynamics became a concern for social scientists in the 1960s and 1970s. In the 1980s, political ecology in part emerged as a critique of these discussions. Among anthropologists, Leslie White (1943) formulated a theory of cultural evolution based on thermodynamic principles. To White, cultural evolution occurred as a community harnessed greater amounts of energy, stored this energy in increasingly complex technology and hence organised society ever further away from thermodynamic equilibrium. R. N. Adams (1975) later drew on White's work to develop an energy theory of social power. Adams suggested that all things in the natural environment are manifestations of energy. Social actors exercise control over these 'energy forms' to structure the environment in a way that is beneficial to them. When things, controlled by some, enter into reciprocal social relations, they become objects through which social power is exercised. The powerful are then able to constitute and control the environment of others. By consequence, Adams argued, social power can be studied quantitatively by measuring the amount of energy potential that different social actors control. This quantification, however, could only take culturally meaningful energy forms into account and had to entail cultural analysis.[2]

Energy accounting was central to explaining social practice among cultural ecologists more widely. Cultural ecology was guided by two fundamental assumptions: first, that ecosystems were a form of general systems and therefore followed the laws of thermodynamics; and second, that ecosystems left to their own devices would tend towards a harmonious 'steady state'—so-called ecological equilibrium. Equilibrium ecology implied that humans, and particularly groups who did not employ Western scientific management techniques, destabilised ecosystems and upset natural harmony (Dove, 2006). By contrast, cultural ecologists made space for humans within ecosystems, arguing that many cultural practices in fact acted as homeostats, leading the environment back to equilibrium. When social organisation, rituals, and norms were identified as functions of the natural environment, culture and human-nature interactions could also be explained quantitatively by measuring energy flows within a cultural-ecological system (Geertz, 1963; Rappaport, 1967; Nietschmann, 1973). This analysis assumed that the boundaries of social systems corresponded to the boundaries of ecosystems.

In the 1970s, thermodynamics also became a matter for economists. In *The Entropy Law and the Economic Process*, Nicolas Georgescu-Roegen (1971) reasoned that if the second law of thermodynamics was true for general systems, it must also be true for economic systems. Thus, not only the steam engine but all economic activities demanded a constant influx of low-entropy energy and matter to remain productive. In a parallel intervention, Howard Odum (1971) proposed an energy theory of value, arguing that economic value stems from the amount of energy 'embodied' in a commodity; an idea resembling Marx's theory of value as embodied labour-time. Georgescu-Roegen still maintained that value arises from consumer preferences; yet, as consumption necessarily would dissipate energy, a growing economy would spontaneously accelerate the depletion of Earth's finite resources, putting limits to economic growth.

Georgescu-Roegen's and Odum's work have paved the way for the field of ecological economics and the study of the material basis of economic processes (Martinez-Alier, 1987; Hornborg, 2006; Healy et al., 2015). As Newell and Cousins (2015) argue, however, ecological-economic approaches have tended to depoliticise material flows. A key exception is the work of scholars allied with the 'degrowth' movement who add a normative dimension to the material economy. The call for degrowth implies that industrialised economies should be shrunk on a voluntary basis to become socially *and* environmentally sustainable (Martinez-Alier, 2009; D'Alisa et al., 2015; Paulson, 2017). The degrowth argument can fruitfully be juxtaposed with Huber's (2009: 105, original emphases) ecological Marxist perspective, when he asserts that 'fossil fuel energy represents a necessary aspect of capitalist *production* and *circulation*' and indicates that a sustainable economy by consequence also is non-capitalist. This confluence of ecological economics and political ecology is central to a politicised understanding of thermodynamics.

IV Ecologically unequal exchange

When political ecology emerged in the 1980s, it broke with the functionalism that characterised the cultural ecology literature. Instead of explaining social practice as an adaptation to an ecosystem within a bounded space, environmental change had to be explained in relation to international political economy (Watts, 2015). In a seminal text for early political ecology, Stephen Bunker (1985) developed the argument in relation to Georgescu-Roegen's and Odum's thermodynamic economics. Superimposing the world-systems perspective on thermodynamics, Bunker argued that the second law of thermodynamics had a geography: transfers of low-entropy energy, sustaining the metabolism of the 'productive economies' in the industrial core, were imported from 'extractive economies' in the periphery. National development and economic modernisation thus depended on a global political-economic regime that organised energy flows geographically to enhance capital accumulation (see Fig. 1). The flux of energy and raw materials into the productive economies enabled these to develop more complex forms of social organisation but drained the extractive economies of productive potential, perpetuating their underdevelopment. Andre Gunder Frank (2006) later concurred, arguing that the modern world-system is a dissipative structure that transfers disorder (entropy, waste) from core to periphery.

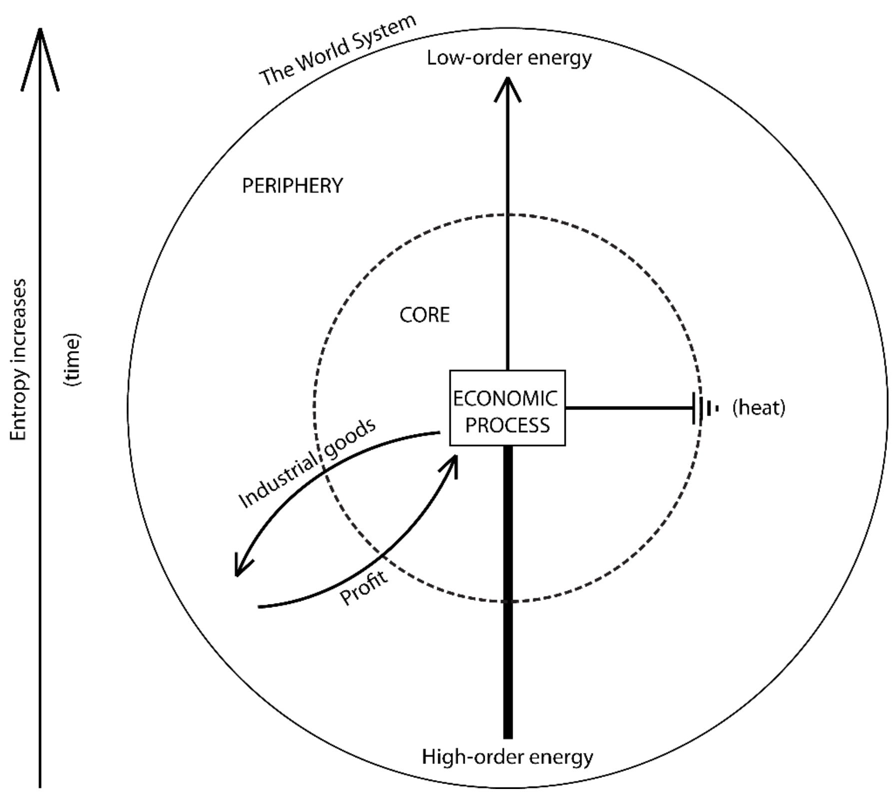

Figure 1 Ecologically unequal exchange

While rooted in the cultural ecology paradigm, Bunker modified a central cultural-ecological assumption in pursuing his analysis. He maintained that social organisation was a function of the natural environment, but this environment was itself a product of global social relations. More recently, Hornborg (2001; 2014; 2017) has rid Bunker's argument of its remaining functionalism. Hornborg notes that industrial machinery and technological complexity often are celebrated as measures of human ingenuity and cultural progress. However, by fetishising technology in this way, we forget that all machines are dissipative structures that only do work as long as they are fed with energy and matter from their environment. Building on Bunker's argument, Hornborg destabilises the 'modern' ontology of technology that sees the technical as a domain separate from 'economy' and 'society' (cf. Latour, 1993). Industrial production depends on a global political-economic regime of low-entropy supply, and in this regime, the sum of commodities exported from the core contains less energy potential than the core imports from the periphery. Capitalists in the core, in turn, charge more money for their exports than for their energy and raw material inputs, which sustains—and conceals—ecologically unequal exchange.

As noted, the thermodynamic perspective also questions the nature of 'value', asking whether it originates from labour, utility, or energy. During the 1970s, neo-Marxist scholars argued that international wage differences allowed core countries to import a surplus of labour-time embodied in commodities from the periphery. This drained the periphery of 'value' and contributed to their underdevelopment (Emmanuel, 1972; Amin, 1976). The underlying unequal-exchange mechanism was a question of exchange-value relations (transfers of labour-time concealed by commodity prices). Here, Bunker added that the core also underpaid 'natural values' as *ecologically* unequal exchange was a matter of asymmetric use-value relations (transfers of energy and raw materials) (cf. Foster and Holleman, 2014: 207). Hornborg argues that mainstream economic theory obscures ecologically unequal exchange when it presents global trade through the lens of monetary exchange. For him, however, the hidden ecological asymmetries do not represent an underpayment of 'value' but instead explain the historically rapid expansion of productive infrastructure in Europe and North America, and the core region's ability to displace the environmental burden of economic growth. Technology is not an index of cultural progress but an index of accumulation, where a population's technological capacity above all discloses its position in the world system. By extension, a mode of social power operates in the world system, defined as 'a social relation built on an asymmetrical distribution of resources and risks' (Hornborg, 2001: 1).

A literature is developing to substantiate ecologically unequal exchange quantitatively (Jorgensen and Clark, 2009; Foster and Holleman, 2014; Hornborg and Martinez-Alier, 2016; see Moran et al., 2013 for a critique). A major concern has been how to study the phenomenon empirically. As Foster and Holleman (2014: 210) point out, most data on trade is measured in prices ('exchange-value') rather than in terms of joules, calories, or tonnes ('real wealth'). Several methodologies to account for energy and raw material transfers have been developed, including material flows analysis (e.g. Schandl et al., 2016), ecological footprints (e.g. Rice, 2007), human appropriation of net primary production (HANPP; e.g. Temper, 2016), embodied energy ('emergy'; e.g. Odum, 1996), embodied labour (e.g. Simas et al., 2015), and embodied land (e.g. Hornborg, 2006). To illustrate the asymmetry of contemporary global energy transfers with one example, Dorninger and Hornborg (2015) find that the United States, the European Union, and Japan together imported a surplus of 34 exajoules of embodied energy from peripheral regions in 2007 (this is equivalent to approximately 5.2 billion barrels of crude oil). With the concept of power density, moreover, Vaclav Smil (2015) has provided an important metric for calculations of the biophysical demands of different energy sources. Power density identifies the energy potential of an energy source in relation to its demands on space (W/m^2). When the awesome power density of fossil fuels is to be replaced by renewable energy sources, great direct and indirect demands on eco-productive space are made (Hornborg et al., 2019). Initiatives for 'green' energy production may therefore be driving a new land rush for environmental ends (Hermele, 2012; Rignall, 2016; Brannstrom et al., 2017). Metrics like the above all hold the promise of nuancing our understanding of ecologically unequal exchange but still require further development.

The world-systems perspective is not *de rigueur* among geographers and anthropologists today. Studies of ecologically unequal exchange nonetheless attest to the existence of global core-periphery relations. The qualitative implications in peripheral areas are evident in a fast-expanding literature, as energy extraction has led to a dispossession of resource wealth and increased marginalisation of subaltern groups. Resource-weak communities have frequently been forcefully resettled to make space for dam reservoirs (McDowell, 1996; Baviskar, 2004; Carse, 2014) but also solar parks (Yenneti et al., 2016). Expert knowledge and industrial socio-ecological practices have taken precedence when 'wastelands' are developed for biofuels, although these lands sustain the energy needs of local communities (Baka, 2017). While resource extraction often improves environmental health in places of consumption, it has produced toxic work environments with gendered, racialised, and caste-based effects on the bodies of workers. This has long been evident in the uranium mines that fuel nuclear reactors (Karlsson, 2011; Hecht, 2012) but also in landscapes of hydraulic fracking and tar-sand mining (Willow and Wylie, 2014; Adkin, 2015). Beside an asymmetrical distribution of resources, industrial-scale energy infrastructures distribute risk unevenly. The Sami of northern Scandinavia were among those worst affected by nuclear fallout from the Chernobyl meltdown, due to the prevailing winds, though they made no use of the electricity the plant generated (Beach, 1990). In the Gulf of Mexico, the risks of offshore oil production were conferred to nonhumans, as the Deepwater Horizon blowout had disastrous effects on marine life (cf. Thibodeaux et al., 2011). Energy-system development thus causes ecological change more widely. Such change shapes the environments for animal life and may violate the integrity of fragile ecosystems; for example, when space is made for power-line corridors (Clarke et al., 2006) or wind turbines (Nadaï and Labussière, 2010).

While ecologically unequal exchange operates on a global scale, several contemporary processes complicate the world-systems narrative. Recent indications of Chinese net biophysical imports question the traditional core-periphery dualism (Yu et al., 2014), even if such a pattern can be interpreted as a sign of shifting hegemony in the world system. A more differentiated account of the global economy complicates the story further. It is not yet clear how the offshoring of industrial production; the uneven energy supply needs of the digital economy; emerging geographies of renewable energy technologies; and asymmetric energy flows on subnational scales can be reconciled within the world-systems framework. Counterhegemonic energy flows within the global totality also present a conceptual challenge. In the late 1980s, for example, Cuba imported crude oil from the Soviet Union in direct exchange for sugar on a set quota of approximately 1 for 6 tonnes (Cederlöf, 2017: 158). A substantial share of this oil went straight into the Cuban sugar industry, but trade still represented a large net flow of energy from the industrialised Soviet Union to agrarian Cuba.

Beyond ecologically unequal exchange, it is reasonable to argue that energy consumption always is dependent on political-economic regimes of low-entropy supply. All open energy systems require a continuous influx of energy potential to remain productive.

Supply regimes make visible how historically and geographically specific institutional arrangements are set up and maintained to sustain the input of energy potential into an energy system. These regimes should not be linked to certain scales *a priori* but must be studied historically and without scalar prejudice. Bridge and Bradshaw (2017) and Mulvaney (2016) have recently shown how 'global production networks' (GPNs) and 'commodity chains' provide tools for critical analysis of the actors, institutions, and activities that commodify energy resources and technologies across whole systems. Such tools can bring greater nuance to our understanding of ecologically unequal exchange. At the same time, a thermodynamic perspective on energy goes beyond the resource focus in studies of GPNs. It asks not only how value is added across production networks, but also how these networks channel energy potential geographically and thereby contribute to establishing the uneven ecological foundations of human life.

V Energy, or social life as a political-ecological process

The thermodynamic perspective presents a further area of research that calls for attention. In the world-systems frame, an individual 'machine' is only fully explained with reference to the totality of global ecological flows. By focusing on international trade relations, energy use is placed far from narratives of social change and the glow of electric light. By contrast, studies of electrification and the construction and maintenance of energy infrastructures have a long tradition in science and technology studies (STS). Here, the concept of socio-technical systems highlights how the design and operation of energy technologies are shaped by socio-cultural dynamics (Hughes, 1983; Nye, 1998; Hecht, 2009). As Bridge (2018: 13) notes, however, the converse of the socio-technical systems perspective—that energy systems are socially productive—has yet to be better understood. Miller et al. (2015: 30) persuasively argue that STS analyses have failed to take the metabolic dimensions of socio-technical systems into sufficient consideration, despite human life being 'thoroughly wrapped up in systems for producing and consuming energy.' Instead of focusing on social power in terms of inequalities in distribution, this draws attention to the interaction of energy use and social power in social reproduction. Through the lens of energy, social life is seen as a political-ecological process.

Recent work in energy geographies shows how the construction and maintenance of electricity infrastructure creates social differentiation on various scales. In contexts as diverse as Bulgaria and the American South, grid-based electrification campaigns have reinforced racialised identities and inequalities (Babourkova, 2016; Harrison, 2016). Frequent blackouts in African cities have also had both class-based and gendered implications as the urban middle-classes can afford photovoltaic backup technologies (Silver, 2016) and the responsibility of acquiring alternative energy resources often falls to women (Kesselring, 2017). Notions of infrastructural violence (Appel, 2012; Rodgers and O'Neill, 2012), energy vulnerability (Bouzarovski and Petrova, 2015; Bouzarovski et al., 2017b), and energy justice (Sovacool and Dworkin, 2015; Jenkins et al., 2017) conceptualise such socially unequal effects of energy infrastructure. From the dominant socio-technical perspective, however, these concepts fail to take the metabolic dimensions of energy systems into consideration, as violence, vulnerability, and justice are seen to be the inadvertent *effects* of socio-technical systems. From a thermodynamic perspective, the distributional effects of human economies are located in their ecological conditions. If energy systems are socio-culturally productive, energy justice is an internal, fundamental characteristic of a metabolic system and its underlying political-economic rationale (Hornborg et al., 2019).

To examine the politicisation of environments for human life, through energy use, anthropologist Dominic Boyer has sketched the contours of a Foucauldian approach. Boyer (2011; 2014) argues that the management of life and population in modern society—what Foucault calls biopolitics—should be read alongside a notion of 'energopolitics'. Energopolitics conceptualises how biopower is conditioned by the ability to control the flow of particular energy forms through society. In *Carbon Democracy*, Timothy Mitchell (2011) shows how the Western socio-economic development model after the Second World War—combining state-mediated economic growth with liberal democracy—relied on imperial control over oil infrastructure in the Middle East to sustain its socio-ecological reproduction. In *Lifeblood*, Huber (2013) argues that the reproduction of the neoliberal US economy is contingent on the materiality of refined petroleum. Petrol, in particular, makes it possible to traverse the United States' suburban landscapes of private property, which embody notions of self-realisation, freedom, and 'the American way of life'. In the Caribbean, by contrast, Cederlöf and Kingsbury (2019) demonstrate how regional oil trade in recent years has been an attempt to upset the legacy of neoliberal reform. To sustain the 'island energy metabolism' (Harrison and Popke, 2018), the Caribbean island-states have imported Venezuelan oil through the regional alliance PetroCaribe in return for services and goods or through deferred payments into a regional development fund. PetroCaribe builds on a political-economic rationale seen to undermine structural inequalities on the world market. While re-orchestrating energy flows, the treaty members have formed a collective regional identity reflecting this rationale, opening up for post-neoliberal development. In all the above cases, the notion of energopower captures how particular configurations of energy and political power shape the conditions of social, political, and economic possibility.

Energopower can also be seen to work through so-called smart grids. Bulkeley et al. (2016) show how smart technologies increase surveillance of individual behaviour through extensive metering and monitoring, and transform everyday social practices in households based on differentiated pricing mechanisms. Smart grids thus enact a political-economic logic that postulates a neoliberal subject—a rational 'resource man' (Strengers, 2013)—who is given responsibility for clean, efficient energy use. Andres Luque-Ayala (2016) and Francesca Pilo' (2017) put a similar perspective to work in order to understand the 'regularisation' of electricity supply in São Paulo and Rio de Janeiro. Infrastructural access is a means for *favela* dwellers to gain formal recognition by the state; yet, the process is shaped by the public-private partnerships that organise Brazil's electricity sector. Through the installation of smart meters in securitised locations, utilities turn informal energy consumers into customers. By formalising energy use as market-based exchange, utilities create new subjects operating under a particular political-economic rationale. These are low-income customers who operate 'as the engine of an emerging neoliberal economic model centred around the poor' (Luque-Ayala, 2016: 187).

While energopower operates to reproduce subjectivities, a third kind of social power also characterises the interface of social life and energy infrastructure. Mitchell (2011) demonstrates how coal satiated the need for low-entropy supplies during western Europe's industrialisation. Yet the need to cut, lift, and transport coal also produced spaces at critical chokepoints in the energy system where workers had the ability to disrupt the flow of low-entropy energy into the economy. Workers could enact a supply squeeze that threatened the metabolic reproduction of socio-economic relations. Through sabotage along the commodity chain, coal workers forced political elites, intent on growing the economy, to democratise society. With the more general transition from coal to oil, however, the labour movement's influence waned as expert managers and engineers controlled closed oil pipelines and tankers. While overly simplifying political history here, Mitchell shows how seemingly apolitical technical choices in relation to low-entropy energy sources enable and foreclose contingent forms of resistance. In these terms, resistance is based on a tactical kind of power whose mode is disruption and whose means is energy infrastructure.

Andreas Malm (2016) takes Mitchell's argument further back in time to study the transition from water to steam power in nineteenth-century Britain. This socio-ecological shift is often fetishised in narratives of the industrial revolution, locating its roots in the ingenuity of engineers and the invention of the steam engine. But Malm argues that the transition was politically motivated. The water-wheel economy was stuck in the fixity of space and time; bound to rivers far from urban labour markets and dependent on the vicissitudes of rainfall and temperature. As a result, the water economy relied on a work force that was available at times of high water flow. This provided both motivation and opportunity for labour protest based on the ability to disrupt production. Steam, by contrast, was abstract in space and time. It could be deployed at will in urban factories, allowing capital to circulate and accumulate with increasing flexibility, and momentarily foreclosed opportunities for labour protest. As Mitchell demonstrates, however, the transition to steam power unintentionally produced new spaces enabling workers to sabotage the metabolism of coal-fired capital. In its most crude sense, tactical power can be seen at work in the context of war. The destruction of oil refineries, gas pipelines, and electrical substations is a key offensive stratagem, cutting of low-entropy energy supplies to the enemy.[3]

The implications of energopolitics and the exercise of tactical power for a renewable energy transition have yet to be more closely examined. The energy potency and spatially abstract qualities of fossil fuels mean that they provide 'baseload' in electricity systems—that is, the minimum amount of energy required across a period of time—while compensating for energy 'losses' in transmission (Cederlöf, 2015). Renewable energy sources are instead often intermittent, their large-scale use requiring demand management and energy storage to maintain stable voltages throughout the day. Energy storage in batteries or pumped hydroelectric stations can be a means to counteract rapidly increasing entropy in electricity grids. These storage media nonetheless contribute to increasing entropy themselves. Here, Malm (2016) argues that the integration of dispersed renewable energy technologies into centralised grids, allowing flexible energy distribution, will demand great intercontinental planning efforts that run contrary to geopolitical contingencies. It will also likely entail a rescaling of energy supply systems. Oil can be shipped across oceans and continents with ease, but renewable energies have geographical limitations due to entropy increases in transmission. Ultimately, the incorporation of renewables into electricity grids will produce new political geographies of energy infrastructure (Bridge et al., 2013), becoming arenas for energopolitics and the exercise of tactical power.

VI Conclusion

When energy has been a concern for political ecologists, it has usually been conceptualised as a natural resource or socio-technical system, giving rise to contentious extractive geographies and unequal distributive outcomes. From a thermodynamic perspective, energy instead becomes an analytical concept with far-reaching perspectival implications: more than an object, an energy system is a political, socio-metabolic strategy for attaining energy potential. When social actors organise energy flows spatially to enable social action, the resulting energy systems internalise political-economic logics. Beyond a focus on natural-resource based struggles, this prompts a definition of political ecology as a field that studies how political, economic, and social relations shape and are shaped by energy systems, which co-constitute the ecological conditions of human life. Thermodynamically speaking, energy use is contingent on supply regimes that sustain socio-metabolic processes. These regimes keep energy systems from 'dissipating' as non-equilibrium ecological structures, even as they generate potentially violent, politicised environments. Supply regimes rest on a form of social power defined by asymmetries in distribution, where the demand for low-entropy energy gives rise to processes of dispossession and marginalisation. While ecologically unequal exchange identifies a global pattern, supply regimes should not be assumed to exist on specific scales *a priori*. To the contrary, they should be studied in diverse contexts.

Historically situated infrastructures redistribute energy potential across space in order to enable or foreclose human action. When social actors build and maintain infrastructure, they also form social subjectivities and relational geographies (Huber, 2013; Boyer, 2014). Political ecologists should therefore ask how specific entropy-increasing practices are made possible by infrastructural arrangements, situated in larger social projects, and how energy systems are constitutive of often multi-scalar social relations. Drawing on methodologies developed to study the material economy, these questions can be approached not only qualitatively but also quantitatively (cf. Smil, 2015; Huber and McCarthy, 2017; Hornborg et al., 2019). While energy systems reflect asymmetries in distribution, they also give rise to tactical and structural modes of power. As Mitchell and Malm demonstrate, energy systems allow actors to make political claims by disrupting low-entropy supplies within a given energy system. Tactical power works through sabotage, blockade, foot-dragging, re-engineering, and infrastructural destruction. Energopower, by contrast, can be seen to operate within settings, but also organises the settings themselves based on the control over energy. The construction and maintenance of energy infrastructures is key to the exercise of energopower, as it renders some kinds of social behaviour possible while foreclosing others (Cederlöf, 2019). Given the acute need for a low-carbon transition in the global economy at present, we ought to examine energy use from a thermodynamic perspective. We will then appreciate it as a highly political form of human-nature interaction.

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[1] In focusing on these literatures, the paper does not pay immediate attention to other productive discussions with resonances in political ecology, including but not limited to the political economy of energy transitions (see instead Newell and Mulvaney, 2013; Power et al., 2016), the governance of urban energy infrastructure (Rutherford and Jaglin, 2015; Castán Broto, 2017), or scholarship theorising pragmatist approaches to energy use (Marres 2012; Shove and Walker, 2014).

[2] White's and Adams' cultural ecology must be read as products of their time. White's deterministic work was a polemic with the Boasians on the definition of 'culture' as a general or particular phenomenon. Adams' notion of things existing as ontologically stable objects that actors can control or not is clearly problematic in light of more recent poststructuralist and actor-network theories.

[3] Tactical power can also be seen in studies on the role of electricity and water meters in market deregulation and the privatisation of public utilities. Meters serve as regulatory devices that grant people access or disconnection from an infrastructural network based on their ability to pay. However, urban residents tamper with and seek to bypass the meters through creative re-engineering and other methods, resisting the political-economic rationale conferred through them (Cupples, 2011; von Schnitzler, 2013; Baptista, 2015).

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