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The bioeconomics of planetary energy transitions—a theoretical note

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Abstract

Evidence is mounting that unprecedented economic growth experienced by human societies over the past two centuries has induced a state of crisis for the Earth's ecological systems—a crisis that threatens human society's existence and heightens the risk of violent conflict. This article presents a simplified model of bioenergetic evolution on a planetary level. It examines human energy exploitation based on three strategies concerning the natural world: (1) predation, (2) competition, and, more cursorily, (3) mutualism. Predation involves the capture of energy pre-processed by the biotic community (living organisms sharing a common environment). Competition involves appropriating lands to capture solar-generated energy, edging the biotic community out. Mutualism involves engaging the biotic community in a mutualistic effort to harvest energy (and discard energy waste in the form of heat) outside of the planetary system. The model implies that, theoretically, substantial government investment in Earth-based solar generation may be required to effect a planetary energy transition to avert ecological collapse. The model suggests that this transition is not likely to happen automatically as a function of substitution by individual economic actors prior to ecological collapse; rather, it requires top-down coercive and/or incentive measures applied by government.

There is an increasing body of evidence indicating that human societies' unprecedented economic growth in the last 200 years is creating an ecological crisis. Many of the public goods provided by ecological systems—fresh water, clean air, abundant fisheries, nutritious soils, low sea levels, and moderate weather, to name a few—are increasingly at risk. Their failure poses existential threats to the societies humans have collectively built over millennia, and heightens the risk of violent conflict through multiple causal pathways.[1]

The human economy is increasingly recognized as a subsystem of a much more sophisticated energy and resource allocation mega-system—that of Earth's biosphere. Both can be viewed, in the most general terms, as mechanisms for maximizing entropy, though the human+ [2] economy is more highly entropic than the pre-human biosphere. In other words, the addition of a modern human economy to the biosphere requires more energy and generates more heat.[3] This observation harmonizes with recent work in biophysics, suggesting that entropy is a primary selector for self-replicating molecules, and therefore that the evolution of life is "as unsurprising as rocks rolling downhill."[4] Economics increasingly recognizes a mutualism between the human and ecological systems. Economists have been used to analyzing optimal stewardship of "natural resources" and the opportunity costs associated with the privation

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[1] E.g., inter-group fighting over scarce resources, conflicts between environmental migrants and would-be host communities, popular revolts against governments perceived as corrupt or ineffectual in reducing environmental risks, etc.

[2] Human+: Numerous thinkers have been engaged in the process of enlarging their respective, anthropocentric disciplines' fields of view to include non-human biotic life, electronic life (e.g., artificial intelligence), and even collectivities of organisms and their non-organic environments, such as ecosystems and biomes. These thinkers include Eduardo Kohn (2013), Craig Holdrege (2013), Suzanne Simard (2021), Gregory Bateson (2000[1972]), Nick Bostrom (2014), James Lovelock (2020), Donna Harraway (2016), and Kevin Kelly (2010).

[3] Lovelock (2020).

[4] England, quoted in Wolchover (2014). See England (2015).

of "environmental services." But given the scope and scale of ecological collapses around the globe, bioeconomics increasingly presumes the indirect value of ecological systems[5] in a way reminiscent of Kenneth Boulding's ecological economics[6].

Modelling human energy exploitation based on three strategies (predation, competition and mutualism), indicates that substantial government investment in Earth-based solar generation may be required to effect a planetary energy transition to avert ecological collapse and widespread conflict. It also raises doubt that this transition will happen automatically as a function of substitution by individual economic actors prior to ecological collapse; rather, it may require top-down coercive and/or incentive measures applied by government. Managing social and political expectations in this scenario is of the utmost importance.

This new, wider bioeconomic conception tends to call into question the traditional distinction between the human and nonhuman worlds. It may even challenge the utilitarian philosophy undergirding economics, to the extent that the utility of nonhumans, or indeed that of collectivities and other non-individuals (e.g., whole biomes or habitats) is validated. Economists studying peace and conflict dynamics have long relied (often unthinkingly) on the human–nonhuman distinction when analyzing strategies for reducing intra-human forms of violent predation; human predation of the nonhuman world was simply not normally considered violence at all.[7] All the institutional guarantees of property security, contract enforcement, and indeed bodily security and freedom of choice deemed requisite for a well-functioning market economy[8] simply did not pertain to animals, much less to other biota: plants, fungi, bacteria, viruses, or entire symbiotic communities comprising a rich admixture of them all. Rather, the latter could, and can, be owned and allocated as human "resources" and property. Of course, those institutional guarantees not only failed to apply to some humans—people of color and women—until relatively recently in many parts of the world, but even allowed for large segments of the human population to be bought and sold as property themselves. Indeed, the evolution of human rights functioned to include progressively more people as valid economic actors[9], while simultaneously hardening the human–nonhuman dichotomy. That dichotomy endures and structures our economic lives. It is older and more fundamental to modern life than any specifically "Western" conception of the cosmos, perhaps tracing its origins to all six of the so-called neolithic "cradles of civilization,"[10] and certainly manifesting in humanity's oldest recorded tale, *The Epic of Gilgamesh*. But while its origins exceed the scope of this article, its contours very much inform the present project.

This article presents a simplified model of bioenergetic evolution on a planetary level. It examines human energy exploitation based on three strategies concerning the natural world: (1) predation, (2) competition, and, more cursorily , (3) mutualism. These strategies are listed in this sequence to signal monotonically: (a) increasing overhead costs, (b) increasing returns at scale, and (c) decreasing negative environmental impacts per unit of energy harvested. Predation involves the capture of energy that has been pre-processed by the biotic community into a form amenable to human exploitation. Predation may take the form of hunting, timber harvesting, coal mining, petroleum pumping, or other types of energy appropriation. Competition involves appropriating lands (or sea surfaces) to capture solar-generated energy, edging the biotic community out of contention for associated solar energy or resources. Mutualism involves engaging the biotic community in a mutualistic effort to harvest energy (and discard energy waste in the form of heat) outside of the planetary system—a space-based solar energy harvesting model. This article demonstrates the logic of economic evolution from a predatory resource extraction model, to one based on so-called renewable

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[5] Brauer and McDougal (2020).
[6] Boulding (1966).
[7] Important works on "natural resources/ services" and violent conflict are too numerous to do justice by way of summarization, or even citation. Some prominent examples might include Homer-Dixon (1994); Le Billon (2001); Bannon and Collier (2003); Hsiang, Burke, and Miguel (2013); Humphreys (2005). Brauer (2009) is a notable exception.
[8] Williamson (2000).
[9] Choi-Fitzpatrick (2022 forthcoming).
[10] Foster (2021).

resources, and on to a space-based model of energy harvesting and heat disposal. It employs a simple model to argue that the transition away from a predatory model of economic growth requires planning on a planetary scale—something a free market is not equipped to handle. In other words, it requires government intervention.

Economy as bioenergetics

Resource distribution is uneven, and energy is no exception to this rule. The amount of solar energy that reaches Earth represents just 5 of every 10 billion Joules of energy output by the Sun (or 0.00000000046% of the Sun's total radiant output). The biosphere captures a very small amount of the solar energy that happens to fall on the Earth. Around 29% of it is reflected back into space.[11] The remainder is absorbed by a combination of the atmosphere and surface of the planet. Of the tiny amount of solar output that falls on photosynthetic biotic life, just 3% is captured by (and used to make more) organic compounds, a tiny fraction of which are eventually transformed into the hydrocarbon chains that fuel the modern carbon economy that characterizes life after the invention of the steam engine.[12]

Of the embodied energy manifest in our ecosystems, humanity appropriates some portion for its own uses and benefits. From a physical point of view, energy is never "generated," but only captured, harvested, exploited. Depending on the quantity appropriated, humanity may thereby imperil the products of natural services that it has come to depend on: fresh water, moderate weather, fertile soil, abundant fisheries, to name a few. As mentioned above, this article draws a distinction between the economy's predatory appropriation of pre-processed embodied energy, and its appropriation of land to process solar energy into usable forms without harnessing the biotic community to do so. We typically deem the latter approach to be "sustainable," but this article argues that it is merely a necessary intermediary step toward greater sustainability. If humanity were collectively to draw its energy needs from the Sun in ways that did not predate the natural world, those energy inputs into the human+ economy might be deemed to be truly exogenous to the planetary system. Such strategies would therefore also require an equally exogenous disposal of energy waste (i.e., heat). But they would require considerable investment, drawing on the previous, appropriative models of development. In this way, every economic advancement up to that point would nevertheless be considered part of a long "bootstrapping" phase of economic development.

We might graphically represent the three energy harvesting strategies in Figure 1A, 1B and 1C. Figure 1A depicts a bioenergetic pyramid in a predatory model of energy acquisition. Above some threshold, humanity is able to make use of the solar energy originally captured and preprocessed by other organisms. We might imagine that technology allows us to lower that threshold, appropriating for human consumption a greater part of the bioenergetic pyramid. Figure 1B depicts a model typically termed "sustainable energy"—harvesting solar (or solar-derived) energy by appropriating some portion of the planet's surface area (i.e., "competition"). It is worth noting that agriculture is itself a basic form of this model, albeit one that captures less solar energy per area in the form of food than a solar panel can store in a battery. It also bears noting that our current economy does a little of both 1A and 1B. Finally, Figure 1C depicts an extra-planetary expansion of solar harvesting capabilities. Such an expansion is deemed to be "cooperative" from the point of view of human–nonhuman relations: the biosphere continues to provide an environment conducive to human flourishing, and humanity in return reduces its ecological footprint.

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[11] Earth Observatory (2009).

[12] Biello (2011).

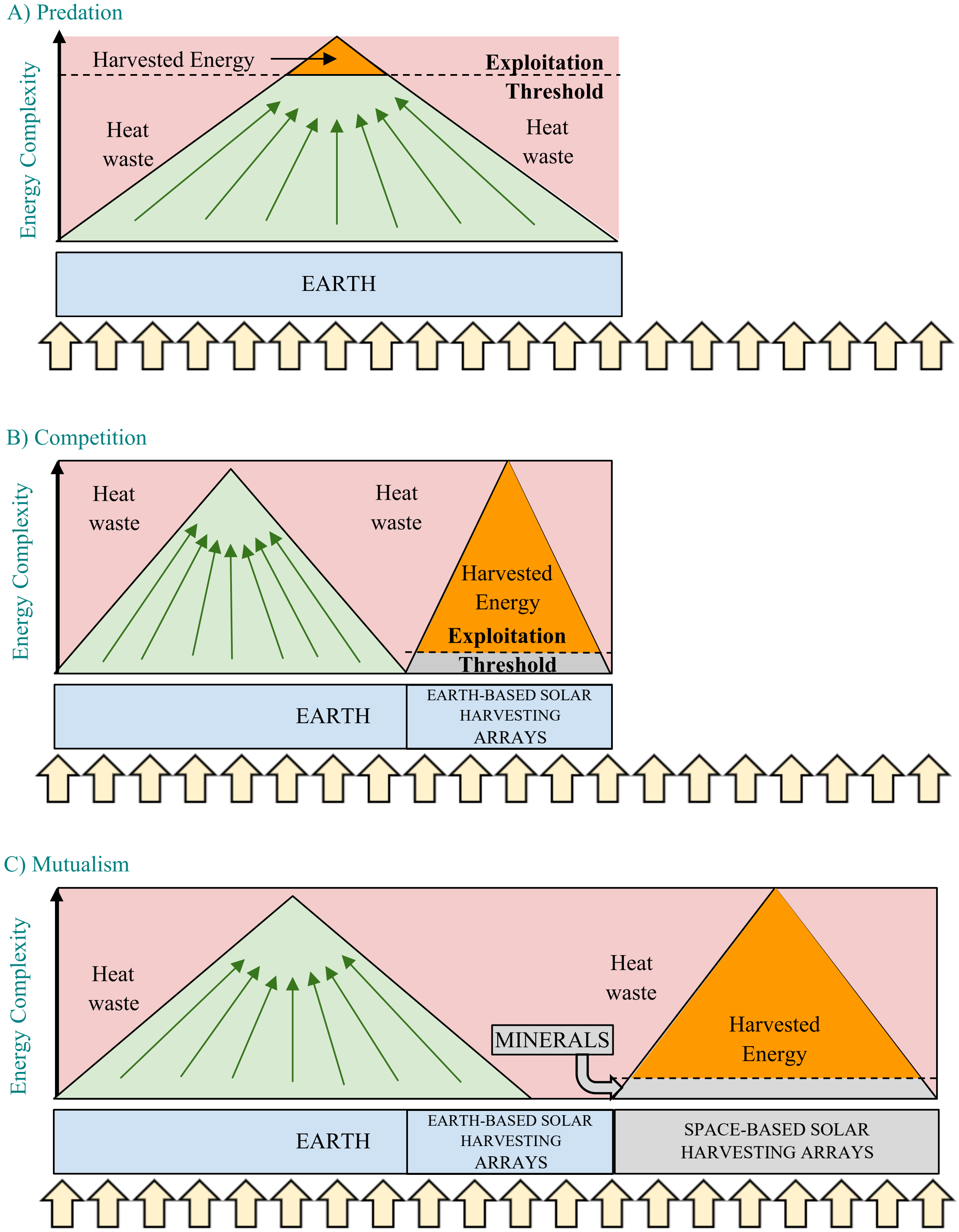

Figure 1: Three energy harvesting strategies: A) predation, B) competition, and C) mutualism

Contextual framing

This study fills a gap in the energy transition literature, which is largely dominated either by quantitative scholars from the technical sub-field of energy economics, or by more qualitative policy scholars hailing from (international) political economy (IPE). Neither the methods, nor the attitude, of these two literatures often match. The empirical bioeconomic and energy economics literature tends, by necessity, to have small units of analysis, focusing on projects, programs, or municipalities (though exceptions exist, especially in computational modeling of the energy industry). The IPE literature tends to use the nation-state as its standard unit of analysis, albeit situated within the broader global context of "problems without borders." The former tends to be more optimistic, opening technically and, sometimes, financially or economically feasible pathways to "sustainability." It often studies outlier or otherwise idiosyncratic cases with an eye toward large-scale reproduction. The latter tends to be more pessimistic, dwelling on political realities that may subvert attempts to make use of those pathways.

The contemporary energy economics literature has emphases on three principal categories: sustainable energy economics, the technical and technological aspects of renewable energy generation and consumption, and estimating or modeling the environmental impacts of various energy production alternatives[13]. In the third category, for instance, energy use and associated emissions have been estimated as a result of a municipal energy transition in China undertaken during the Covid-19 pandemic, finding declines of 34% in energy use and 40% in CO2 emissions[14]. One strand of this literature arose in the context of the lukewarm reception of emissions reductions targets by national governments of the Global North in the first decades of the 21st century. It sought to study the role of the private sector and sub-national governments in advancing climate change mitigation and sustainable energy strategies, especially in the developing world[15]. While largely optimistic, this literature often makes appeals to national or international governments to improve markets for the growth of sustainable technologies by raising awareness and education levels, regulating the markets to exclude bad actors and disempower legacy monopolies that might raise entry costs, and extending credit and finance markets[16]. It should be noted that many of the computational economic models in energy economics rely on equilibrium analyses; some scholars have argued that such models have consistently underestimated the growth in renewable technologies, and that agent-based models are far more responsive to wholesale disruptions of industry, such as that introduced by solar "prosumers" (who both produce and consume energy). They argue that non-linearities and cumulative causation in the renewable sector's growth should make us much more optimistic about an automatic energy transition than equilibrium analyses might suggest.[17]

The political economy literature, as a general rule, identifies areas in which global capitalism has failed to respond to the exigencies posed by the climate and broader environmental crises[18]. These failings may be associated with political stakeholders representing entrenched economic interests from the fossil fuel economy. Such spoilers stand to lose out and therefore impede more efficient transitions[19]. Alternatively, they may find that the capitalism of the "sustainable energy" economy commits many of the same sins of the previous model. The neoliberal approach to energy transitions in Chile, for example, has been described as single-mindedly focused on rapid growth in the lithium mining sector[20]. Such an approach represents an immediate threat to local water sources. More profoundly, it rebuffs participatory development processes that would give value to the voices of those indigenous peoples whose ancestral lands are being mined. It also sits uneasily with the general notion of sustainable development as implying an end to

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[13] Chen, Xiong, Li, Sun, and Yang (2019).
[14] Su and Urban (2021).
[15] Agrawala *et al*. (2011); Pauw and Pegels (2013).
[16] Raberto, Ozel, Ponta, Teglio, and Cincotti (2019); Yadoo and Cruickshank (2012).
[17] Hoekstra, Steinbuch, and Verbong (2017).
[18] Newell (2019, 2021).
[19] As Baker, Newell, and Phillips (2014) describe in the case of South Africa
[20] Furnaro (2019).

economic growth[21]. Given these critiques of undirected capitalism in the energy sector, as well as the importance that political economy tends to lend to the intercalation of industry and institutions of the state, it is perhaps not surprising that much of this literature highlights the role of national governments in pioneering and promulgating experimental policy avenues to effect clean energy transitions[22]. The preeminent role of national policies and governments is further reinforced by other inherent characteristics of the energy sector, including: High overhead costs associated with R&D, scaling, and human resources upgrading; massive complexity and uncertainty in the energy markets internationally; concurrently dynamic technological change; and myriad transition pathways[23].

In summary, then, we have one broad family of literature drawing from economics that is confident in an automatic energy transition driven by market forces (with some government market regulation in the neoclassical model). We have another, drawing from the IPE tradition, that believes in the necessity of government intervention to effect meaningful change (even as they remain skeptical about government's capacity to do so). However, neither literature grapples overmuch with the connection between technology and environmental degradation overall. To the extent that dynamics and non-linearities are considered, they are done so in modeling the human economy. The connection between bioenergetic environmental systems and the overlaying human economy is not usually made explicit as it was, for instance, in the famous 1972 (subsequently updated in 1992 and 2002) biologically informed *Limits to Growth* model[24]. This article provides a simple model to demonstrate that ecological collapse and the energy transition are intimately woven together. Moreover, it shows that there is an argument to be made from the economics side that top-down intervention may be required to effect it, due to nonlinearities not in economic growth patterns, but in the health of the underlying environment systems.

A model of the biotic system

We begin our model by recognizing that the energy captured by ecological processes is recycled through the system. Phytoplankton are consumed by zooplankton, which are in turn eaten by small crustaceans and fish, etc. Moreover, energy embodied in dead creatures is then recycled through the system via detritivores. The food chain—what Aldo Leopold called the "land pyramid," though of course it also applies to the oceans—is also a system of bioenergy allocation and reuse. This resource allocation system contains and conditions the resource allocation subsystem we call the economy. The proportion that gets reused in the biosphere we call α. We posit therefore that the total welfare of the nonhuman biosphere richness R will be modeled using the function:

$$\text{(1a)} \qquad R = X(1/(1-\alpha))$$

where X represents the quantity of solar radiation input into the biotic system. However, evolution also provides a mechanism through which the system can change and develop over time. Former evolutionary developments serve as the springboards for new developments permitting resource exploitation at scales, and in environments, previously unfeasible. The emergence of the first prokaryotes during the Archean Eon (4.0–2.5 billion years ago) permitted some 2.7 billion years ago the formation of eukaryotic cells, which combined and coordinated various prokaryotes as organelles. Similarly, single-celled eukaryotes were a prerequisite for the evolution of multicellular life about 600 million years ago. Because "higher" organisms often predate "lower" ones, and "lower" ones assist in the decomposition of "higher" ones, the development of a stratified bioenergetic system heightens the degree to which bioenergy is recycled within the biosphere. This kind of endogeneity we represent temporally such that the output of the system at a previous point in time conditions the recycling term for the present:

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[21] Daly (1999); Harraway (2016); Korten (1995); Raworth (2017); Schor (2010).
[22] Arndt, Miller, Tarp, Zinaman, and Arent (2017).
[23] Kern and Markard (2016).
[24] Meadows, Randers, and Meadows (2004).

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(2b) $R_2 = X(1/(1 - R_1\alpha))$

At equilibrium, we can solve for R to obtain:

(2) $R = (1 \pm \sqrt{1 - 4\alpha X})/2\alpha$

This relationship takes the shape of a horizontal parabola. Finally, along with Fujita, Krugman, and Venables (1999), we posit that α is proportional to R_1 up to some maximum point ā, after which no improvements on recycling can be made and when the previous equation is replaced simply by:

(3) $R = X(1/(1 - \bar{a}))$ if $\alpha > \bar{a}$.

Figure 2 encapsulates this model, with overlapping pooling equilibria (solid lines) connected by separating equilibria (dashed lines). This model demonstrates in simple terms what more complex ecological models have shown in less simple terms, namely: past a certain "sustain point," the biosphere is relatively resilient in the face of perturbations (here modeled as reductions in the amount of bioenergy allotted to it). However, past a certain "break point," the system will fall to dramatically lower levels of output. After such a collapse, the cost of repair to the system far exceeds the energy allowance that would have been required to avoid collapse. In other words, the model is not technically a function, as it can take on two potential values of R for given intermediate values of X, depending on whether X is increasing (see the green arrows in Figure 2) or decreasing (see the orange arrows in Figure 2).

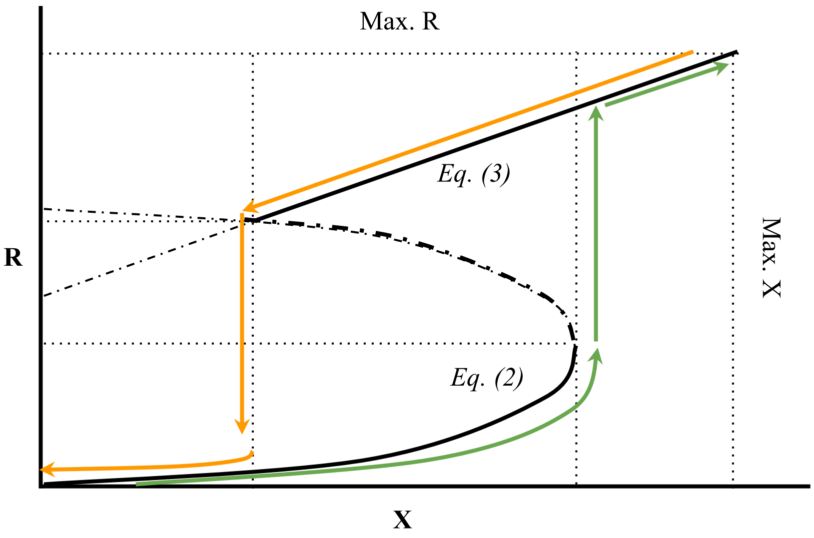

Figure 2: Biosphere richness (R) as a function of solar energy input (X)

All of this we describe as the system at equilibrium and, for our intents and purposes, in the absence of human intervention. Humans in this simplification are able to appropriate energy in two ways: first by direct predation of bioenergetic resources, earning them H_P, and second by appropriating land for solar harvesting, earning them H_L. We then define the marginal human bioenergetic "profits" derived from predation as:

(4) $H_P = (R_{max} - R_P) - s(R_{max} - R_P) = (1 - s)(R_{max} - R_P)$

where R_{max} is the maximum level of natural resources given X, R_P is the level of natural resources given P, and $s < 1$ is the degree to which humans receive natural services from the biosphere. The term $-s(R_{max} - R_P)$ then represents the opportunity costs of ecosystem destruction. Note that marginal returns are declining in predation level, and thus that the optimal solution will not be total predation, but rather some level of predation lower (perhaps just marginally) than that which would cause a collapse. However, given the high elasticity of R when $\alpha > \bar{a}$ $(1/(1 - \bar{a}))$, direct predation may lead toward the break point quite quickly.

Likewise, we define the marginal human bioenergetic "profits" derived from land appropriation as:

$$H_L = tL^{\gamma} - l - s(R_{max} - R_{X-L}) \qquad (5)$$

where L is the amount of land appropriated for energy production, $t \in (0,1)$ is a technological coefficient, $0 < \gamma < 1$ represents decreasing returns to scale, and l is an overhead cost for solar energy capture technology development. t represents the proportion of radiant energy that can be effectively utilized for human benefit; it is bounded between zero and unity in order to prevent the human economy from magically multiplying the amount of energy captured to more than was captured in the first place. Notice that the term denoting opportunity costs stemming from ecosystem destruction—for parsimony's sake, we assume that predation has no overhead costs; this is untrue, but predation overhead costs are generally much lower than the overhead costs of technologically sophisticated solar exploitation.

The results are depicted in Figure 3, where Figure 2 continues to occupy quadrant I, H_P occupies quadrant II (note that R_P is corresponds directly and negatively to R), and H_L occupies quadrant IV (again, with L corresponding directly and negatively to X).

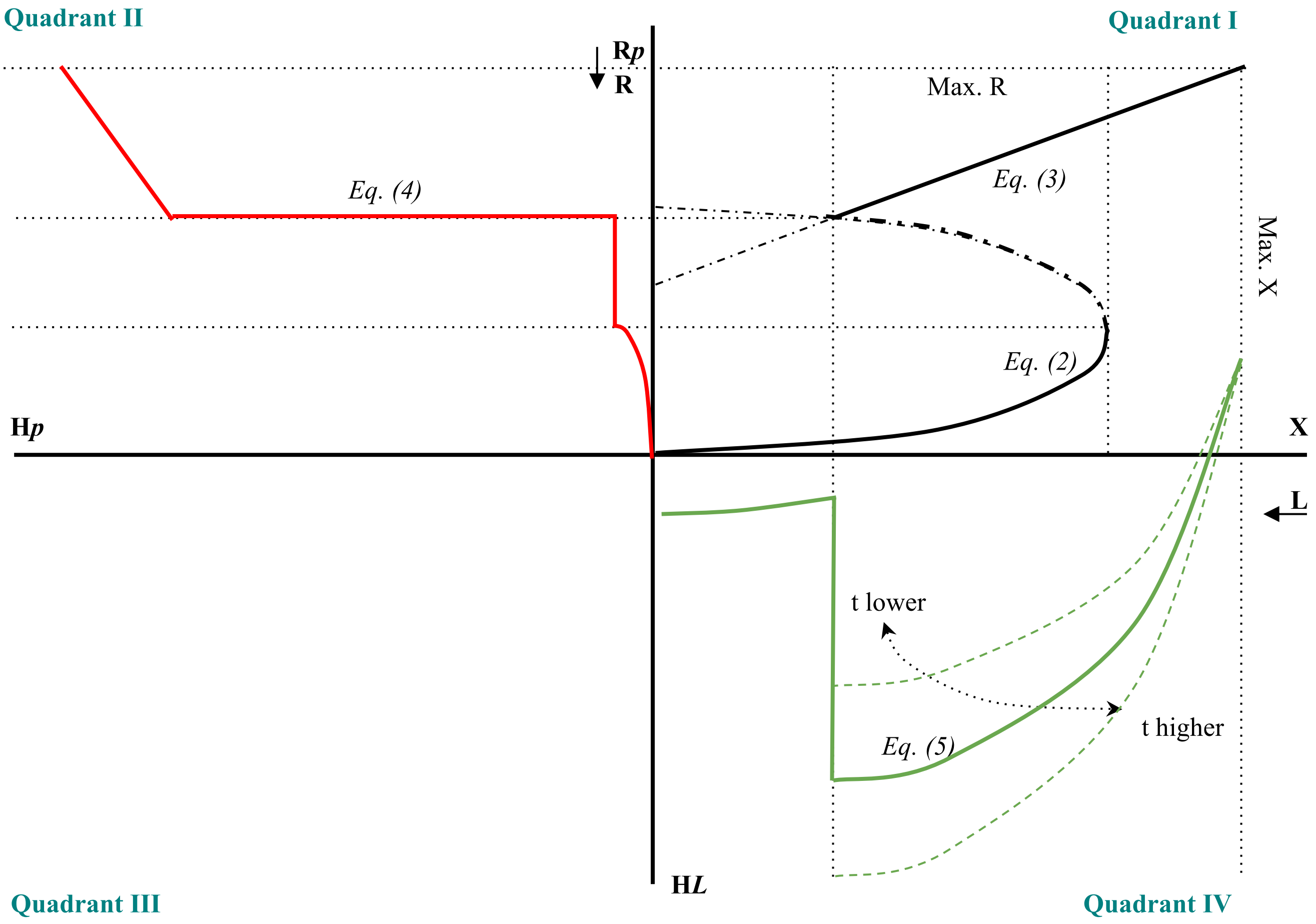

Figure 3: Biosphere richness as a function of solar energy input (black; NE quadrant), net human returns to direct predation (red; NW quadrant), and net human returns to land acquisition for solar generation (green; SE quadrant)

If we want to model at what point the modality of energy harvesting will naturally shift from predation to solar generation, we simply set these two equal to each other such that:

$$H_P = H_L$$

We depict this equation graphically in Figure 4 by permitting investments in predation and solar land use to be fungible (plotted on the x-axis). The results show, as we anticipated, that the ecological breakpoint will be reached more quickly under a predatory model of energy harvesting than it will under a land appropriation model. However, if the technological coefficient is too low or the overhead costs of deploying solar technology too high relative to the ecological breakpoint, the net marginal benefits of a solar economy may not exceed those of a predatory economy before the ecological breakpoint. But even that eventuality is unfeasible, as a post-collapse land-appropriation model of the economy is also greatly impoverished. In effect, there may be a discontinuity between models—a transition from a predatory to a competitive (land-based solar) economy may require coordinated substitution, and at substantial initial cost. Such a transition may not be effected automatically in the classic conception of a free market economy due to the fact that the solar economy may still yield marginal returns below those of the predatory economy until *after* the predatory economy collapses.

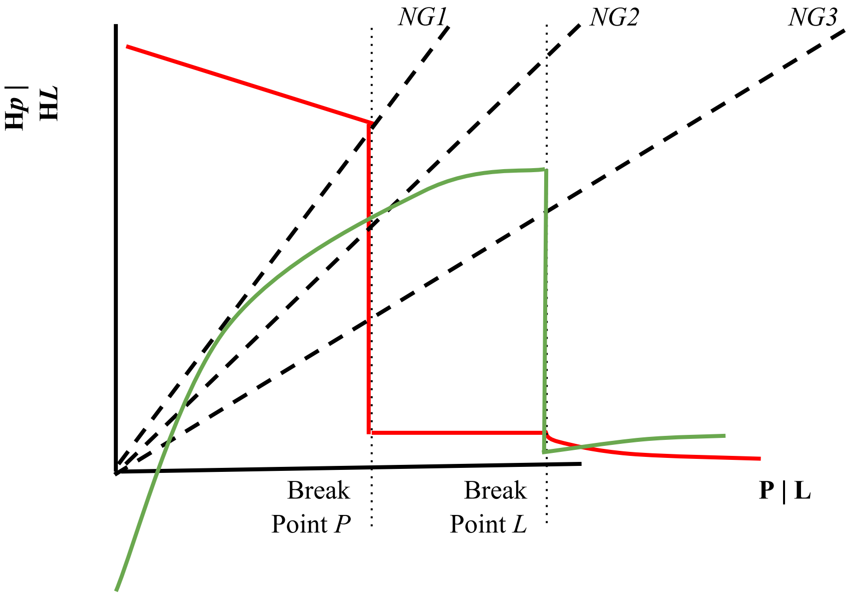

Figure 4: Net human returns to direct predation (red) and land acquisition for solar generation (green), with three possible "no growth" equilibrium lines

We may also posit the existence of a line describing a "no growth" scenario, passing through the origin at a 45° angle (if both X and Y axes are using equivalent units). The addition of this line (with three of its possible locations illustrated in Figure 4 by the three bold dashed lines, *NG1*, *NG2*, and *NG3*) implies a single pooling equilibrium for the appropriative model, and implies that there is a good chance (for any *NG* lower than *NG1*) that the equilibrium will actually occur during or after ecological collapse, and too late to recover. By contrast, there may or may not exist a pooling equilibrium in the case of the "competition" scenario of Earth-based solar harvesting. *NG1* implies no possible equilibrium at all; *NG2* implies a pooling equilibrium occurring before ecological collapse; and *NG3* implies a pooling equilibrium after the economy's overshoot of collapse break point *L*. Therefore, the terrestrial solar harvesting model is theoretically indeterminate.

Extensions and conclusions

This model's implications for energy policy are clear enough: theoretically, substantial government investment in Earth-based solar generation is required to effect a planetary energy transition to avert ecological collapse. That is, the model demonstrates a reason for skepticism that this transition will happen automatically as a function of substitution by individual economic actors prior to ecological collapse; rather, it may require top-down coercive and/or incentive measures applied by government. For instance, incentives might include direct subsidies covering the overhead costs of electrification—some energy economists have posited that energy transition will be feasible only if consumer electricity fees are reduced to their marginal costs[25]. They might also include the removal of current direct subsidies for fossil fuels, as well as the removal of indirect environmental subsidies for the sector—the combined total of which summed to around USD 650bn per year in 2021 in the United States alone[26]. The removal of indirect subsidies would likely take the form of Pigouvian taxes levied transnationally on CO2 and other greenhouse gas emissions associated with fossil energy. In short, an energy transition may require planning on a planetary scale. Moreover, such a wholesale transition, involving massive, coordinated investments at a global scale, will be costly for the economy as a whole in the short-term, but beneficial in the long-term. Managing social and political expectations in this scenario is of the utmost importance.

If the model's simplicity is its strength, it is also a weakness. A simple dynamism was introduced in the evolution of environmental systems as a function of solar radiation, allowing discontinuities to develop and diverge from each other. But there is no such dynamism modeling the human economy. Elements such as the overhead costs of renewable technologies remain exogenous and static. However, to the extent that humans are able to analyze environmental changes and anticipate collapse, we might well expect that the opportunity costs of remaining in a predatory energy model would rise. This might have the effect of rounding the sharp downward of the red line in Figure 4, potentially even allowing it to cross the green line before Break Point P. Likewise, the technological constant, t, as well as the returns to scale, γ , from Equation 5 are also both static in the model, but might well not be in life: more investments might drive either one higher, again making it more likely that the green line overtakes the red before Break Point P. Either way, such an intersection would represent a successful "automatic" energy transition. However, since the Earth is currently the sum total of all viable future investment strategies, it would seem prudent not to assume that such happy changes will occur in the nick of time, but rather build in a healthy insurance buffer.

The model is overly simplistic in another way. Ecological scientists have determined that we have already entered the sixth mass extinction event in the roughly 3.8 billion year history of life on this planet.[27] It might therefore be argued that we no longer may aspire to avert an ecological collapse—it is happening. It bears keeping in mind, however, that the parsimony of the model presented above may yield certain insights into nonlinearities of energy transitions, but vastly over-simplifies the ecological dynamics of resilience and collapse, which operate in complexly layered and overlapping ways across varied biomes and habitats. Climatological authorities such as Climate Action Tracker stress the non-binary nature of ecological collapse due to climate change. They observe that the Glasgow COP26 policy goals of getting to worldwide net zero carbon emissions by 2050 are very hypothetical, and that current policies are likely to allow the planet to warm past the benchmark of 1.5C over pre-industrial average temperatures (landing somewhere closer to 2.4C). Climate Action Tracker breaks the effects of climate change on the natural environment into four categories of increasingly catastrophic impact based on global average temperature increases: 0–1.5C, 1.5C–2.0C, 2.0–3.0C, and 3.0–4.0C.[28]

This article's model, as indicated in the introduction, may also be extended to include space-based solar power (SBSP) harvesting—a strategy rather blithely termed "mutualism," but for a reason. Apart from land for human habitation, natural resource extraction, and large energy transmission receivers, SBSP would not require further terrestrial extensification for solar harvesting, and might therefore be expected to yield land back to natural systems. We might envision this model as permitting Figure 3's x-axis to extend to allow the H_L function more "runway" for takeoff, and adjusting the slope ($\triangle H_L / \triangle L$) more steeply for technical reasons, including constant solar exposure

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[25] Heal (2022).
[26] Bertrand (2021).
[27] Barnosky *et al*. (2011); (Kolbert, 2015).
[28] Climate Action Tracker (2021).

(there is no nighttime in space), and the absence of atmospheric interference with solar radiation. However, the present state of orbital launching technology would also make the overhead costs extremely high, further lowering the y-intercept for H_L and likely entirely negating the upside, at least for now. But in the long term, SBSP might more closely resemble "mutualism" between the human and natural environment to the extent that the resources for energy harvesting technology may be mined or captured in space and harvested energy is invested in environmental restoration and re-wilding.

Finally, while many technologies are deemed to be more or less "sustainable," this model suggests that none are necessarily in the absence of government interventions involving some combination of incentives and coercion. The "competition" approach of Earth-based solar harvesting may be truly sustainable, finding an equilibrium position within the ecological limits of the ecosystem. But it might also *not* be, and we lack an empirical test of which it is. Erring on the side of prudence then, guaranteed sustainable economic performance in any model described above requires that governments or other institutions restrain resource exploitation. In some ways, this should come as no surprise. Hardin's famous "Tragedy of the Commons" made a similar claim over half a century ago. [29] Douglas North defines institutions as the formal and informal "humanly devised constraints that structure human interaction",[30] and economic performance is now widely acknowledged to be enabled and conditioned by them in all of their manifestations[31]: the firm;[32] common pool resource (CPR) management institutions and community-driven regulation;[33] the rule of law;[34] state regulation of industry and natural resource exploitation systems;[35] and global trade infrastructure.[36] Such humanly devised constraints usually promote economic growth by eliminating predation among those recognized as valid economic actors (for example, the wide-ranging debate on the relationship between slavery abolition and economic growth[37]).

In effect, then, this model suggests that progress toward sustainability necessitates recognizing some traditionally non-economic (and non-human) actors as exempt from human predation. The art and practice of peacebuilding and conflict transformation has developed a long tradition of breaking down dichotomous frames: "us" and "them," "in" and "out," "native" and "foreign." Transitions toward true sustainability will likely involve a kind of ecological peacebuilding—abandoning the human–nonhuman dichotomy in favor of a greater inclusivity based on a deepening appreciation of inter-species interdependence.[38]

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References

Acemoglu, D., Johnson, S and Robinson, J. A. 2001. The Colonial Origins of Comparative Development: An Empirical Investigation. *American Economic Review, 91*(5), pp.1369–1401. https://doi.org/10.1257/aer.91.5.1369

Acemoglu, D., Johnson, S and Robinson, J. A. 2005. Institutions as the Fundamental Cause of Long-Run Growth. In P. Aghion and S. Durlauf (Eds.), *Handbook of Economic Growth*. North Holland: Elsevier. https://doi.org/10.3386/w10481

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[29] Hardin (1968).
[30] North (2003).
[31] (Acemoglu, Johnson, and Robinson, 2005); Rodrik (2000).
[32] As articulated early on by Veblen (1904).
[33] O'Rourke (2002); Ostrom (1990).
[34] Haggard, MacIntyre, and Tiede (2008); (Kennedy, 2006).
[35] (Acemoglu, Johnson, and Robinson, 2001); Evans (1995); Snyder and Bhavnani (2005).
[36] Roy (2019).
[37] Wright (2020).
[38] Haraway (2016).

Agrawala, S., Carraro, M., Kingsmill, N., Lanzi, E., Mullan, M and Prudent-Richard, G. 2011. Private Sector Engagement in Adaptation to Climate Change: Approaches to Managing Climate Risks. https://doi.org/10.1787/5kg221jkf1g7-en

Arndt, C., Miller, M., Tarp, F., Zinaman, O and Arent, D. (Eds.). 2017. *The Political Economy of Clean Energy Transitions*. New York: Oxford University Press. https://doi.org/10.1093/oso/9780198802242.001.0001

Baker, L., Newell, P and Phillips, J. 2014. The Political Economy of Energy Transitions: The Case of South Africa. *New Political Economy, 19*(6), pp.791–818. https://doi.org/10.1080/13563467.2013.849674

Bannon, I and Collier, P. 2003. *Natural Resources and Violent Conflict: Options and Actions*. Washington, D.C.: World Bank. https://doi.org/10.1596/0-8213-5503-1

Barnosky, A. D., Matzke, N., Tomiya, S., Wogan, G. O. U., Swartz, B., Quental, T. B. and Ferrer, E. A. 2011). Has the Earth's sixth mass extinction already arrived? *Nature, 471*, pp.51–57. https://doi.org/10.1038/nature09678

Bertrand, S. 2021. *Proposals to Reduce Fossil Fuel Subsidies*. Retrieved from Washington, D.C.:

Biello, D. 2011. Plants versus Photovoltaics: Which Are Better to Capture Solar Energy. *Scientific American*.

Boulding, K. E. 1966. The Economics of the Coming Spaceship Earth. In H. Jarrett (Ed.), *Environmental Quality in a Growing Economy* (pp.3–14). Baltimore, MD: Resources for the Future/Johns Hopkins University Press.

Brauer, J. 2009. *War and Nature: The Environmental Consequences of War in a Globalized World*. New York: Alta Mira Press.

Brauer, J and McDougal, T. L. 2020. Bioeconomic Peace Research and Policy. *Peace Economics, Peace Science and Public Policy, 26*(3). https://doi.org/10.1515/peps-2020-0034

Chen, B., Xiong, R., Li, H., Sun, Q and Yang, J. 2019. Pathways for sustainable energy transition. *Journal of Cleaner Production, 228*, pp.1564–1571. https://doi.org/10.1016/j.jclepro.2019.04.372

Choi-Fitzpatrick, A. 2022 (forthcoming). *The Future of Human Rights*. Retrieved from Cambridge, MA:

Climate Action Tracker. 2021. *Glasgow's 2030 credibility gap: net zero's lip service to climate action*. Retrieved from https://climateactiontracker.org/documents/997/CAT_2021-11-09_Briefing_Global-Update_Glasgow2030CredibilityGap.pdf

Daly, H. 1999. *Ecological Economics and Sustainable Development, Selected Essays of Herman Daly*. Northhampton, MA: Edward Elgar.

Earth Observatory. 2009. Earth's Energy Budget. Retrieved from https://earthobservatory.nasa.gov/features/EnergyBalance/page4.php#:~:text=Thus%2C%20about%2071%20percent%20of,surfaces%20and%20the%20atmosphere%20itself

England, J. L. 2015. Dissipative Adaptation in Driven Self-assembly. *Nature Nanotechnology, 10*, pp.919–923. https://doi.org/10.1038/nnano.2015.250

Evans, P. B. 1995. *Embedded Autonomy: States and Industrial Transformation*. Princeton: Princeton University Press. https://doi.org/10.1515/9781400821723

Foster, C. 2021. *Being a Human: Adventures in Forty Thousand Years of Consciousness*. New York: Metropolitan Books.

Furnaro, A. 2019. Neoliberal energy transitions: The renewable energy boom in the Chilean mining economy. *Environment and Planning E: Nature and Space, 3*(4), pp.951–975. https://doi.org/10.1177/2514848619874685

Haggard, S., MacIntyre, A and Tiede, L. 2008. The Rule of Law and Economic Development. *The Annual Review of Political Science, 11*, pp.205–234. https://doi.org/10.1146/annurev.polisci.10.081205.100244

Haraway, D. J. 2016. *Staying with the Trouble: Making Kin in the Chthulucene*. Durham, NC: Duke University Press. https://doi.org/10.2307/j.ctv11cw25q

Hardin, G. 1968. The Tragedy of the Commons. *Science, 162*(3859), pp.1243–1248. https://doi.org/10.1126/science.162.3859.1243

Heal, G. 2022. Economic Aspects of the Energy Transition. *Environmental and Resource Economics*. https://doi.org/10.1007/s10640-022-00647-4

Hoekstra, A., Steinbuch, M and Verbong, G. 2017. Creating Agent-Based Energy Transition Management Models That Can Uncover Profitable Pathways to Climate Change Mitigation. *Complexity, 2017*, 1967645. https://doi.org/10.1155/2017/1967645

Homer-Dixon, T. 1994. Environmental Scarcities and Violent Conflict: Evidence from Cases. *International Security, 19*(1), pp.4–40. https://doi.org/10.2307/2539147

Hsiang, S. M., Burke, M and Miguel, E. 2013. Quantifying the Influence of Climate on Human Conflict. *Science, 341*(6151). https://doi.org/10.1126/science.1235367

Humphreys, M. 2005. Natural Resources, Conflict and Conflict Resolution: Uncovering the Mechanisms. *Journal of Conflict Resolution, 49*(4), pp.508–537. https://doi.org/10.1177/0022002705277545

Kennedy, D. 2006. The "Rule of Law," Political Choices and Development Common Sense. In D. M. Trubek and A. Santos (Eds.), *The New Law and Economic Development: A Critical Appraisal* (pp.95–173). New York: Cambridge University Press. https://doi.org/10.1017/CBO9780511754425.004

Kern, F and Markard, J. 2016. Analysing Energy Transitions: Combining Insights from Transition Studies and International Political Economy. In T. Van de Graaf, B. K. Sovacool, A. Ghosh, F. Kern and M. T. Klare (Eds.), *The Palgrave Handbook of the International Political Economy of Energy* (pp.291–318). London: Palgrave Macmillan UK. https://doi.org/10.1057/978-1-137-55631-8_12

Kolbert, E. 2015. *The Sixth Extinction: An Unnatural History*. New York: Picador.

Korten, D. 1995. *Sustainable Development: Conventional versus Emergent Alternative Wisdom*. People-Centered Development Forum. Retrieved from https://davidkorten.org/wisdom/

Le Billon, P. 2001. The Political Ecology of War: Natural Resources and Armed Conflicts. *Political Geography, 20*, pp.561–584. https://doi.org/10.1016/S0962-6298(01)00015-4

Lovelock, J. 2020. *Novacene*. Cambridge, MA: MIT Press.

Meadows, D., Randers, J and Meadows, D. 2004. *Limits to Growth: The 30-Year Update*. White River Junction, VT: Chelsea Green.

Newell, P. 2019. Trasformismo or transformation? The global political economy of energy transitions. *Review of International Political Economy, 26*(1), pp.25–48. https://doi.org/10.1016/S0962-6298(01)00015-4

Newell, P. 2021. *Power Shift: The Global Political Economy of Energy Transitions*. New York: Cambridge University Press. https://doi.org/10.1017/9781108966184

North, D. C. 2003. *The Role of Institutions in Economic Development*. Retrieved from Geneva, Switzerland:

O'Rourke, D. 2002. Community-Driven Regulation: Toward an Improved Model of Environmental Regulation in Vietnam. In P. B. Evans (Ed.), *Liveable Cities? Urban Struggles for Livelihood and Sustainability*. Berkeley, CA: University of California Press.

Ostrom, E. 1990. *Governing the Commons: The Evolution of Institutions for Collective Action*. Cambridge, UK: Cambridge University Press. https://doi.org/10.1017/CBO9780511807763

Pauw, P and Pegels, A. 2013. Private sector engagement in climate change adaptation in least developed countries: an exploration. *Climate and Development, 5*(4), pp.257–267.
https://doi.org/10.1080/17565529.2013.826130

Raberto, M., Ozel, B., Ponta, L., Teglio, A and Cincotti, S. 2019. From financial instability to green finance: the role of banking and credit market regulation in the Eurace model. *Journal of Evolutionary Economics, 29*(1), pp.429–465.
https://doi.org/10.1007/s00191-018-0568-2

Raworth, K. 2017. *Doughnut Economics: Seven Ways to Think Like a 21st Century Economist*: Chelsea Green.

Rodrik, D. 2000. Institutions for High-Quality Growth: What They Are and How to Acquire Them. *Studies in Comparative International Development, 35*, pp.3–31.
https://doi.org/10.1007/BF02699764

Roy, M. 2019. Elevating Services: Services Trade Policy, WTO Commitments and Their Role in Economic Development and Trade Integration. *Journal of World Trade, 53*(6), pp.923–950.
https://doi.org/10.54648/TRAD2019037

Schor, J. 2010. *Plenitude: The New Economics of True Wealth*. New York: Penguin Press.

Snyder, R and Bhavnani, R. 2005. Diamonds, Blood and Taxes: A Revenue-Centered Framework for Explaining Political Order. *The Journal of Conflict Resolution, 49*(4), pp.563–597.
https://doi.org/10.1177/0022002705277796

Su, C and Urban, F. 2021. Circular economy for clean energy transitions: A new opportunity under the COVID-19 pandemic. *Applied Energy, 289*, 116666.
https://doi.org/10.1016/j.apenergy.2021.116666

Veblen, T. 1904. *The Theory of Business Enterprise*. New York: Charles Scribner's Sons.

Williamson, O. E. 2000. The New Institutional Economics: Taking Stock, Looking Ahead. *Journal of Economic Literature, 38*, pp.595–613.
https://doi.org/10.1257/jel.38.3.595

Wolchover, N. 2014. A New Physics Theory of Life. *Quanta Magazine*.

Wright, G. 2020. Slavery and Anglo-American capitalism revisited. *Economic History Review, 73*(2), 3 pp.53–383.
https://doi.org/10.1111/ehr.12962

Yadoo, A and Cruickshank, H. 2012. The role for low carbon electrification technologies in poverty reduction and climate change strategies: A focus on renewable energy mini-grids with case studies in Nepal, Peru and Kenya. *Energy Policy, 42*, pp.591–602.
https://doi.org/10.1016/j.enpol.2011.12.029

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