



The Energy Pillars of Society: Perverse Interactions of Human Resource Use, the Economy, and Environmental Degradation

John W. Day¹ · Christopher F. D'Elia¹ · Adrian R. H. Wiegman^{1,4} · Jeffrey S. Rutherford^{1,5} · Charles A. S. Hall² · Robert R. Lane¹ · David E. Dismukes³

Received: 22 June 2017 / Accepted: 13 January 2018
© Springer International Publishing AG, part of Springer Nature 2018

Abstract

To meet the COP21 2 °C climate target, humanity would need to complete a transition to renewable energy within the next several decades. But for decades, fossil fuels will continue to underpin many fundamental activities that allow modern society to function. Unfortunately, net energy yield from fossil fuels is now falling, and despite substantial growth in renewable energy, total global energy demand and fossil fuel consumption are still increasing. Recent studies document promising trends in net energy yield from new renewable energy, particularly wind and solar. However, most studies do not fully consider the complexities of multiple factors including production intermittency, storage, the need to replace a massive infrastructure network, and lack of fungibility of different energy sources. Also, oft-overlooked, is that human impacts have caused widespread degradation of natural ecosystems and the provisioning of ecosystem goods and services, especially affecting vulnerable areas like coastal zones and arid regions. An accelerated renewable energy transition to meet climate targets and replace declining stocks of high net yielding fossil fuels will compete with resources needed for crucial investments to mitigate already locked in climate change and environmental degradation impacts. Integrative approaches that include all costs can help balance interdependent factors such as net energy dynamics, resource allocation, and ecosystem degradation. Energy-climate investment pathways produce economic output and quality of life tradeoffs that must be considered. Accordingly, developing future energy policy requires a systems approach with global boundaries and new levels of appreciation of the complex mix of interrelated factors involved.

Keywords Climate change · Fossil fuels · Renewable energy investment · Biophysical economics · Ecosystem degradation and management · Net energy · Energy transition

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s41247-018-0035-6>) contains supplementary material, which is available to authorized users.

✉ Adrian R. H. Wiegman
adrian.wiegman@uvm.edu

John W. Day
johnday@lsu.edu

Christopher F. D'Elia
cdelia@lsu.edu

Jeffrey S. Rutherford
jruthe@stanford.edu

Charles A. S. Hall
chall@esf.edu

Robert R. Lane
rlane@lsu.edu

David E. Dismukes
dismukes@lsu.edu

¹ Department of Oceanography and Coastal Sciences, College of the Coast and Environment, Louisiana State University, Baton Rouge, LA 70803, USA

² College of Environmental Science and Forestry, State University of New York, Syracuse, NY 13210, USA

³ Center for Energy Studies and Department of Environmental Sciences, College of the Coast and Environment, Louisiana State University, Baton Rouge, LA 70803, USA

⁴ Rubenstein School of Environment and Natural Resources, University of Vermont, Burlington, VT 05401, USA

⁵ Present Address: Department of Energy Resources Engineering, Stanford University, 367 Panama St., Stanford, CA 94305, USA

Introduction: Society's Energy-Environment Quandary

Broad scientific consensus exists that human activity is causing climate change, primarily through fossil fuel combustion and degradation of the biosphere (e.g., Steffen et al. 2015; Vitousek et al. 1997). The COP21 global climate accord in Paris brought renewed and warranted attention to how societal energy use must change during this century (UNFCCC 2015; Sgouridis et al. 2016; Hansen et al. 2017). A rapid transition from fossil fuels to renewables has been widely advocated to avoid exceeding climate tipping points by limiting temperature increase to below 2 °C (Kintisch 2015), but few studies have looked quantitatively from an integrated systems perspective at the full complications and complexities of this transition (e.g., Jones and Warner 2016; Anderson 2015). Global carbon emissions cannot exceed 1000 Gt (CO₂-equivalent) for 2011–2100 to have a 66% chance of achieving this goal (IPCC 2014). That would mean that about two-thirds of current fossil fuel reserves, and 90% of low-grade, ultimately recoverable resources (URR), would need to remain unburned by 2100 to meet the 2 °C target (McGlade and Ekins 2015). Sgouridis et al. (2016) modeled the energy investment required to power a transition to renewable energy to meet the COP21 requirements and found that, while the window is narrowing, such a transition is technically feasible by ramping up renewable energy installations by a factor of ~40 to ~110 in two decades (based on a range of energy requirements for renewables and societal energy demand). Here, we review projections for a transition to a renewable energy economy and discuss a number of issues that will complicate this transition.

The staggeringly large renewable energy growth rates required to meet climate objectives (Sgouridis et al. 2016) greatly exceed historical precedents (Maggio and Cacciola 2012; Smil 2016). The extensive fossil fuel infrastructure

that would need to be abandoned, dismantled, and replaced by a renewable infrastructure would require very expensive investments and likely a fundamental reorganization of society (e.g., Jacobson et al. 2015a, b; Trainer 2013). Without successful implementation of carbon capture and sequestration technologies, the margin for fossil fuel emissions gets even slimmer. Just 650 Gt CO₂ can be emitted from 2015 onward for the 2 °C goal to be achieved, or the equivalent of only 12–18 years of projected fossil fuel use (Anderson 2015; Mohr et al. 2015; see SI-1—Section 1 in Supplementary Information). At the same time, ecosystem degradation and climate impacts (such as sea level rise and more extreme weather events) will continue, along with population growth, increasing the costs of maintaining production systems and reducing the provisioning of ecosystem goods and services that are fundamental for supporting the economy. In Table 1, we introduce some of the critical uncertainties in areas affecting the biophysical sustainability of society. This paper is designed to stimulate a broader discussion on these issues and we come back to Table 1 in the final section of the paper.

Web of Science surveys show that most renewable energy and sustainability research, which ultimately influences policy, does not focus on fundamental systems concepts that will affect future energy systems (Brown et al. 2011). We agree and conducted a search containing the phrase “renewable energy” in the literature published through June 7, 2017 (see SI-2). Within the title, keywords and abstracts of 27,687 publications, roughly 25% also contained “solar” or “wind,” less than 5% but greater than 1% contained “intermittent,” “life cycle assessment,” “substitute,” “ecosystem,” or “thermodynamic,” and less than 1% contained “energy density,” “net energy,” “growth rate,” “feedback,” “scarcity,” “environmental degradation,” or “biophysical.” These results suggest that a disconnect exists between discussion of renewable energy development and the biophysical limits constraining that development.

Table 1 Critical uncertainties in areas affecting biophysical sustainability of society

Focus area	Knowledge gaps
Liquid fuels/transportation	Future EROI and production scale of liquid fuels; tradeoffs between low EROI fuels and electricity; future adoption rates of electric vehicles; potential for alternative energy use in long distance transport
Materials/mining/recycling	Electrification potential of remote mining; mineral depletion rates and changes in energy intensity associated with energy transitions; recycling costs and contributions during energy transition; maintenance of infrastructure associated with climate change
Farming/fishing/forestry	Climate and environmental degradation impacts on yield/costs; energy tradeoffs of implementing sustainability measures, such as phosphorus recycling and recovery
Electricity/grid/storage	Grid stability and governance; alternative uses for excess renewable electricity production; ability of data science and automation to manage complexity risks; environmental impacts of scaling renewables
Environment	Degradation and climate impacts on all sectors; ability to reverse trends; permanence of state changes; non-linearity and spatial variability of environmental degradation impacts and loss of ecosystem goods and services

Our central thesis here is the renewable energy strategies mandated in COP21 will be affected and often severely restricted by biophysical realities, including net energy, climate change, environmental degradation, and population growth. Most existing analyses (SI-2) do not adequately consider these realities. Biophysical constraints will likely impede economic growth and activity during any transition to a low carbon system and have the potential to destabilize a growing human population that is extremely dependent on energy intensive food production and distribution. Many areas of the world cannot feed themselves from their local foodsheds and population growth will make ever larger demands on the biophysical base of the earth while continuing to degrade the provisioning of ecosystem goods and services, which, in effect, is a large energy sink for society (Costanza et al. 2014; Schramski et al. 2015). Most existing assessments do not adequately consider the tremendous costs of replacing fossil fuel infrastructure with renewables (Clack et al. 2017), as well as the very large need for overbuilding or storage to deal with issues of intermittency of renewables at a large penetration (e.g., Palmer 2014, 2017). While we do not wish to be Cassandras, we do caution against what we feel is an excessively optimistic approach to considering the challenges inherent in COP21.

In this paper, we review the compelling evidence in support of this premise. This review paper is designed to generate a broader discussion of biophysical realities of implementing a 100% renewable energy system in the twenty-first century. We understand that there are innumerable uncertainties that will affect the success of the energy

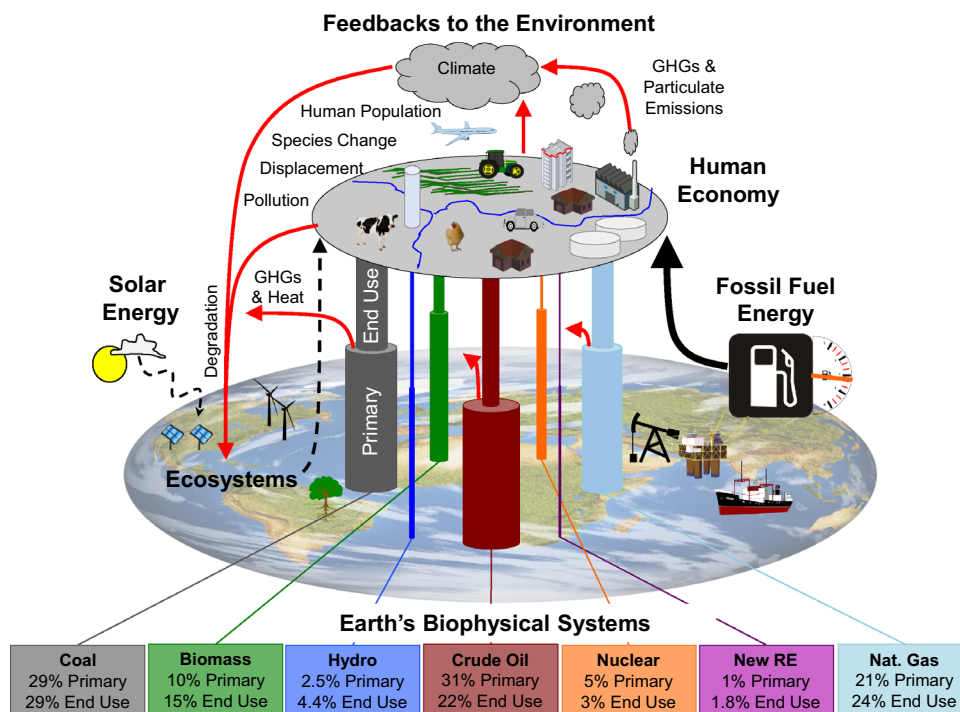
transition, so another objective of this review is to identify major knowledge gaps (Table 1). We hope that the synthesis provided herein will be useful for educators, researchers, and policy makers who are shaping the future.

The Energy Pillars of Society

Fossil energy increasingly powered practically all societal economic growth during the first two centuries of the industrial revolution and economic activity is strongly correlated with energy consumption (Ayres and Voudouris 2014; Brown et al. 2011, 2014; Warr and Ayres 2010; Hall and Klitgaard 2012; Ahmed 2017). An array of energy sources, termed here the “energy pillars” (Fig. 1), supports the modern industrial society. Fossil fuels currently dominate energy use—providing over 80% of global primary energy supply and roughly 75% of energy end use—and power many critical economic activities related to transportation, chemicals and fertilizers, heavy machinery, heavy industry, and considerable domestic use. While the development of renewable resources is making enormous strides, concomitant increases in energy demand have left society still heavily dependent on fossil energy sources (IEA 2017a). Not only did fossil fuel consumption underwrite the remarkable economic development over past century, but it also enabled destabilization of the climate system and biosphere and will continue to do so for the foreseeable future.

The energy pillars draw from Earth’s natural systems to power the economy (Fig. 1). By capturing solar derived

Fig. 1 The energy pillars diagram. This visualization shows how energy drawn from earth systems (black lines) supports the foundation of the economy, and how human activities (red lines) impact the environment. The size of the energy pillars beneath the economy is proportional to their share in the global primary energy (base of the pillar) and energy end use (top of the pillar) (energy data are from LNLL 2013, see Fig. 2 and SI-5). The fuel gauge represents remaining cheap conventional oil; Campbell and Wöstmann (2013) estimate that by 2013 society had burned ~ 1100 GB of about 2200 GB of recoverable conventional oil resources. (Color figure online)



energy fluxes, ecosystems provide much work for humans including provisioning of food and fuel, waste processing, and general material cycling. We believe that their importance as factors in global human energy production and use has not been sufficiently integrated into plans for a transition to a renewable energy economy. Transformations in the human economy now degrade these ecosystems in an alarming way through direct consumption and waste generation, physical alteration, and climate impact through greenhouse gas emissions. This is a critical problem since natural systems ultimately directly and indirectly provide everything that humanity consumes and are crucial in neutralizing or eliminating societal wastes and sustaining the atmosphere.

The Energy Transition

Renewable energy technologies generally have much lower *direct* impacts to the environment than fossil fuels (Asdrubali et al. 2015). To meet climate goals, fossil energy must be rapidly replaced by “new” renewables, which include primarily wind turbines, solar photovoltaic (PV) panels, and solar thermal systems (including concentrated solar power), but also new forms of hydropower (wave/tidal and hydrothermal), biofuels (Heinberg and Fridley 2016), and non-carbon liquid fuels (Armaroli and Balzani 2015). However, the provisioning of useful energy through renewable sources is fundamentally different from fossil fuels that were accumulated and “refined” by nature over tens of millions of years (Dukes 2003). Despite a public perception that a rapid change in energy sourcing is occurring, current output of “new” renewables is only about 1–2% of global energy use (EIA 2016) and current rates of installment of wind and solar, as a whole (12 and 33% yr⁻¹, respectively according to REN21 2017), have diverged from what some models suggest are required to meet the 2 °C climate goal (> 30% yr⁻¹ for the renewables industry, Sgouridis et al. 2016). A renewable energy system will require extensive implementation of new technologies and infrastructure that have yet to be fully developed on the required large-scale. Moreover, such technologies and infrastructure may rely on increasingly scarce materials (Davidsson et al. 2014) and require the investment of substantial fossil fuel resources.

Net Energy Analysis

Fortunately, awareness is increasing about the need to incorporate net energy and life cycle assessment in future energy planning (e.g., Hall 2017; see SI-3). We find it to be remarkable that such straightforward and obvious concepts have not been fundamental metrics in many studies.

Net energy analysis involves the calculation of energy return ratios (ERR) to determine how much useful energy a given technology provides relative to its energy costs.

A popular ERR is energy return on (energy) investment (EROI), calculated as the energy gained from an energy production process divided by the energy required to obtain the energy in question (Murphy and Hall 2011; Hall 2017). ERR calculations require consideration of energy flows over the entire device/project life cycle. If life cycle energy flows are not available, a power return ratio (PRR, i.e., power return on investment) can be calculated using annual energy flows across an energy sector (King et al. 2015). When comparing the ERR values of energy alternatives, one must be aware that boundaries (e.g., mine-mouth versus end use) and functional units (e.g., a megajoule of heat energy versus a megajoule of grid electricity) are not always consistent between studies (Murphy et al. 2016). Societal EROI (SOC_{EROI}) is the aggregated EROI across an economy’s energy sources.

Societies with high SOC_{EROI} values are generally more prosperous, given that more energy is available for discretionary purposes relative to that which must be reinvested in the energy sector and basic maintenance (Hall et al. 2008). Fizaine and Court (2016) reported that historic GDP growth in the US was positive only if the portion of GDP allocated to obtaining energy is less than 11% and estimated that the minimum SOC_{EROI} that coincided with economic growth was about 11:1. Murphy (2013) and Brandt (2017) calculated that discretionary economic production drops rapidly when SOC_{EROI} falls below 5:1. Therefore, for a society to be prosperous, the SOC_{EROI} of its energy sources should be much greater than 5:1. Lambert et al. (2014) estimated that an EROI of 10–15:1 is the minimum SOC_{EROI} needed for modern industrial consumer societies to support such things as modern healthcare, education, and arts (discretionary spending) in addition to basic needs (e.g., food, shelter, and clothing).

Fossil Fuels

Over much of the twentieth century, the mean EROI of fossil fuels was high relative to other energy options but is generally declining due to the depletion of large, high-quality reservoirs and other easily available “conventional” reserves. Using a price-based approach, Court and Fizaine (2017) find that, while the EROI of coal is still rising, the total EROI for fossil energy (coal, oil, gas) is declining with an overall EROI of about 20:1 in 2012. These trends are corroborated by engineering-based life cycle assessment models for large global oil fields (Masnadi and Brandt 2017; Tripathi and Brandt 2017). EROI of tight oil produced from the U.S. Bakken formation ranges from 12 to 29:1 but is declining as sweet spots are exhausted (Brandt et al. 2015; Waggoner 2013). Tight oil production is projected to peak between 2020 and 2025 but production already declined by about 12% from 2015 to 2016 as producers responded to low prices (EIA 2015, 2016). Heavy oil, oil sands, deep water,

and Arctic oil production all have an EROI of 10:1 or less (Brandt et al. 2013; Hall et al. 2014; Moerschbaecher and Day 2011). Thus, to provide the equivalent of current useable energy in the future, more gross fossil fuel energy must be developed, especially on a per capita basis (Hall et al. 2008). In our view, the challenge of increasing net energy available to society in the face of declining efficiencies in production of fossil fuels is a daunting one.

Fossil fuel production will likely peak in coming decades due to a combination of climate policy and declining resource quality (Maggio and Cacciola 2012; Mohr et al. 2015; Sgouridis et al. 2016). With current methods, coal production could theoretically be sustained at high levels out to end of the twenty-first century, but recent trends in climate policy that place disincentives on coal production indicate that a production peak is imminent (Mohr et al. 2015) or has already occurred (Laherrere personal communication). This places more pressure on liquid fossil fuels to provide energy. Failing increases in efficiencies and reservoir recovery rates, the cleaner burning fossil fuels, conventional oil and gas, will likely peak between 2020 and 2040 (Maggio and Cacciola 2012; McGlade 2014; Mohr et al. 2015). Direct substitutes for conventional oil, such as liquid hydrocarbons from bitumen, kerogen, coal, and biomass, often fall below an EROI of 3:1 (Brandt et al. 2013; Hall et al. 2014). EROI of liquid hydrocarbons has been projected to fall most rapidly, perhaps decreasing below 1:1 by 2060 (Garcia-Olivares and Ballabrera-Poy 2015). This is of particular concern, due to the importance of liquid fuels for much of current agriculture, general transportation, heavy industry, petrochemicals, chemical feedstocks, and global trade (Friedemann 2016).

Substitutes and Alternatives

Renewable energy is touted by many as the solution to fossil fuel scarcity and the climate predicament (e.g., Heinberg and Fridley 2016; Jacobson et al. 2015a). This may be so, however renewables have many serious limitations that must be addressed to achieve these goals (e.g., Trainer 2012a, b). Petroleum has many advantages, such as high energy density and transportability, and other sources typically present challenges that are often glossed over with the “And then a miracle happens...” mindset of the well-known Harris cartoon with that caption (Harris 1977). Liquid biofuels have a very low EROI, often barely greater than 1:1 (e.g., Hopkinson and Day 1980; Murphy et al. 2011) and compete with food production and preservation of natural ecosystems (Pimentel et al. 2009).

Nuclear is another low carbon energy source. EROI for electricity from nuclear is often well above 10:1 (Carbajales-Dale et al. 2012). Nuclear energy can be converted to kinetic energy quite readily, but long lasting nuclear reactions make load management difficult, so nuclear plants tend

to be either on or off, but not dialed up and dialed down. The use of smaller scale, modular nuclear plants may help address that, however, many parts of the world do not seem ready to embrace nuclear expansion, given massive upfront costs, stigma from rare—but dramatic—accidents, long-term waste storage issues, and concerns about terrorist access to fissionable materials.

Wind and solar power (WASP) technologies are improving rapidly (Louwen et al. 2016) and are poised to provide an increasing amount of energy for society, but significant hurdles still exist. These are discussed next.

Wind and Solar Power (WASP)

WASP are often regarded as society’s best options to supply net energy on a large scale in the future. To their benefit, WASP and other new renewables directly generate electricity, which is of a higher quality than heat generated by combustion of fossil fuels (Murphy et al. 2016; Arvesen and Hertwich 2015; Raugei et al. 2012). Because the primary energy contained in fossil fuels must first be converted from heat to mechanical work through a turbine (with an efficiency limited by the second law) before generating electricity, electrification and a transition to renewables would effectively lower total primary energy demand. But care must be taken to avoid the Jevons Paradox where the increase in the efficiency of resource usage is likely to promote growth in resource throughput due to lower resource price (Hall 2004; Hall and Klitgaard 2012; Daly 2017). The trends in net energy improvement of wind and solar have also been impressive. Kubiszewski et al. (2010) estimated an average EROI of operational wind turbines at 20:1, and Koppelaar (2017) estimates the EROI of mono- and poly-silicon solar-PV to be 10:1 and 11:1, respectively. EROI values are variable based on geographic location, system design, changes in technology and boundary assumptions (Raugei et al. 2017; Ferroni et al. 2017). However, any plan to transform the energy system to renewables must account for costs for storage and curtailment losses due to the intermittency of wind and solar power. Storage systems for WASP can reduce EROI up to 40% for solar-PV and 75% for wind (Weißbach et al. 2013), although costs vary by storage mechanism and the requirement can be compensated for by other technologies and demand response (Raugei 2013). The costs of adding large complex infrastructure and management systems to mitigate power volatility are not trivial, and have not been adequately quantified in the literature to date (Clack et al. 2017).

Currently much of the energy and materials (e.g., metals, concrete, petrochemicals) used to build and maintain WASP come from fossil fuels. An important issue that society must address is the extent to which WASP can be self-maintaining

when fossil fuels are phased out and/or exhausted in latter portion of this century (Ferroni et al. 2017). Such concerns must be addressed in a thoughtful way using comprehensive life cycle analyses (Hiloidhari et al. 2017; Masnadi and Brandt 2017) with global boundaries (e.g., Ferroni et al. 2017; building upon Sgouridis et al. 2016).

Growth Rates

To remain below the 650–1000 Gt threshold, installation of renewables must be rapidly accelerated over the next several decades (Sgouridis et al. 2016). In a 100% renewable energy system WASP would need to provide enough net energy to invest in its own growth, maintenance, and storage (Carbajales-Dale et al. 2014; Neumeyer and Goldston 2016), while still supporting the economy's energy needs. Accounting for these uses, the annual installations of renewable energy must increase by a factor of ~40 to ~110 and installed capacity must increase by a factor of ~90 between 2015 and 2035 to meet energy needs and the 2 °C climate target (Sgouridis et al. 2016).

These projected growth rates of WASP are much higher than historical growth (Maggio and Cacciola 2012; Smil 2016) of the fossil fuels they intend to supplant. To increase production of very high EROI fossil fuels by a factor of 10 to 2010 levels took 64, 55, and 110 years for oil, natural gas, and coal, respectively (BP 2016; Maggio and Cacciola 2012). Many suggest based on the rapid growth rates of WASP in recent years that fossil fuels can be replaced quickly (e.g., Jacobson et al. 2015a). Between 2010 and 2015, the annual growth rate for both wind power and solar PV installations has decreased—from 25 to 12% for wind power, and 74–33% for solar PV (REN21 2017; Sgouridis et al. 2016). In the face of increasing global demand, rapid fossil fuel displacement seems unrealistic unless WASP installment can be accelerated and/or energy demand can be mitigated significantly. As installed capacity becomes larger, maintaining high growth rates will be increasingly difficult as the costs of re-investment to new generation, integrating intermittent power into the grid, and resource constraints cannibalize net energy returns (Carbajales-Dale et al. 2014; Neumeyer and Goldston 2016).

Past growth rates of energy sources indicate that growth rates of WASP would need to be much higher than that of fossil fuels—which had far greater EROI at their time of expansion than WASP—to the meet climate targets. This does not mean that such growth rates cannot occur, but does indicate the difficulty of that happening. The additional cost of mitigating environmental stresses and climate change will require even more energy; this is discussed in “[Societal Investments, Environment, and Human Well-being](#)” section. Carefully planned policy interventions will be needed to sustain high growth rates of WASP as resource complications

and environmental pressures provide friction. The history of energy policy suggests that achieving coordinated effort will be a political challenge of the highest magnitude.

Material Demands

Like energy, material costs affect all sectors of the economy (Brandt 2017). Replacing existing fossil fuel infrastructure with WASP will require enormous amounts of material resources (Davidsson et al. 2014). The ability to produce metals, many of which are projected to peak by or before mid-century—notably iron in 2050, copper in 2038, nickel in 2030, zinc in 2025—could limit the rate of renewable energy growth (Sverdrup et al. 2015; Gupta 2018). As in the case of so many mineral resources, metal mining consumes remaining reserves, and ore quality declines. This is problematic because energy requirements for metals production (GJ/T metal) demonstrate a log linear increase with declining ore grade (g metal/T rock) (Fizaine and Court 2015; Harmsen et al. 2013; Sverdrup et al. 2015). Declining ore grade of input metals will likely decrease EROI of renewables.

Scarcity of copper is likely to be particularly problematic. Copper is used ubiquitously in renewable energy technology and electrical systems, as well as being essential for electrical transmission from point of production to point of use. Solar PV technologies require 0.45–5.1 tons of copper per megawatt of name-plate capacity (T Cu MW^{-1}), with monocrystalline silicon PV requiring roughly $0.825 \text{ T Cu MW}^{-1}$. Concentrated solar power requires $1.4\text{--}3.2 \text{ T Cu MW}^{-1}$. Wind power requires $1.0\text{--}1.5 \text{ T Cu MW}^{-1}$ (see Appendix A of Fizaine and Court 2015). Gupta (2018) suggests severe Cu limitations within several decades of exponential PV growth. While certain trace metals (rare earth elements) used for motor and batteries may be substituted or used more efficiently in the future, copper is difficult to substitute for without increasing cost or decreasing electrical performance (Harmsen et al. 2013).

Energy costs for copper production and rare earth metals have a relatively small impact on the EROI of renewable energy systems because these metals make up a small percentage of the mass requirements for WASP and renewable energy systems (Fizaine and Court 2015). Harmsen et al. (2013) projected that EROI decreases from copper depletion will be on the order of 3% in 2050. EROI impacts are larger when all input metals are considered, but the ore grade of input metals would need to decrease by a factor of 10 for significant decreases in EROI of WASP (Fizaine and Court 2015). Rare earth elements, which had recycling rates of roughly 1% in 2013, are more likely to limit renewable energy growth due to bottlenecks in production and recycling capacity than from energy costs (Binnemans et al. 2013; Harmsen et al. 2013). Recycling will be a key sector to track moving forward.

Iron/steel and aluminum represent the higher share (by an order of magnitude) of the mass requirements of WASP between metals (Harmsen et al. 2013). While these elements are abundant, particularly aluminum (Sverdrup et al. 2015) and have high recycling rates (Gutowski et al. 2013), small changes to their energy intensity could lead to significant changes in EROI of WASP (Harmsen et al. 2013); Fizaine and Court (2015) and Harmsen et al. (2013) omitted the consideration of steel and aluminum depletion impacts on EROI. To our knowledge, a modeling study projecting the production and recycling of global materials and associated changes in energy intensity of material supply has not been published. Future studies of this kind are needed to quantify the degree and timescale of impacts of material reserve depletion on net energy of all energy sources.

Substitutability

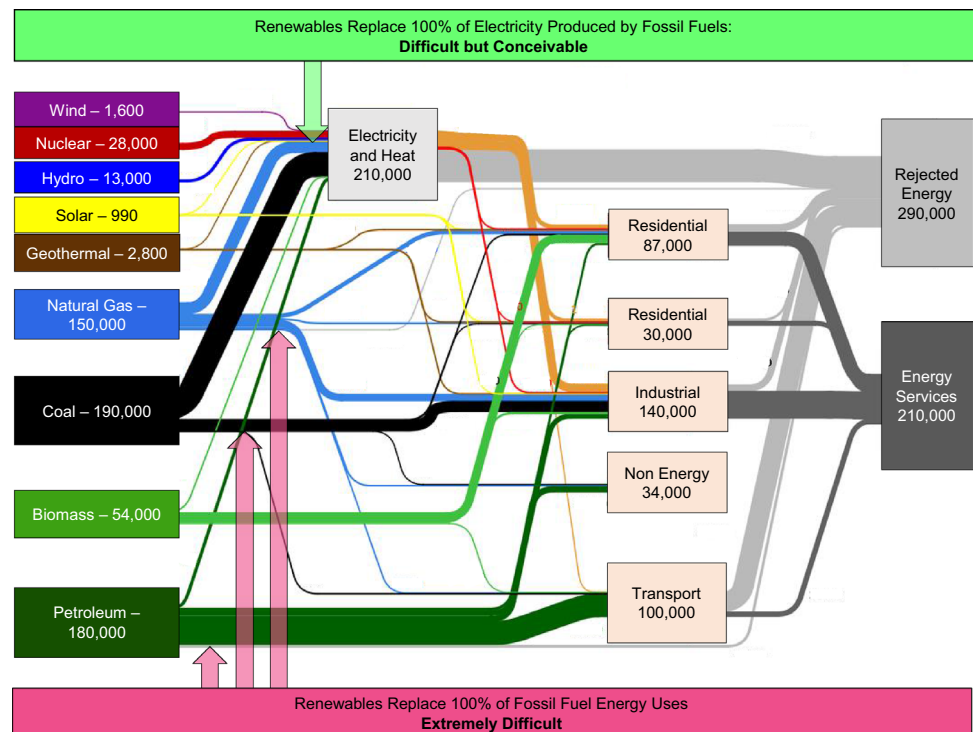
Two tacit assumptions made by many about the renewable energy transition are that (1) all massive transformations of our energy infrastructure can be achieved over a very short period of time, and (2) energy sources are fungible and interchangeable. Trainer (2012a, b; 2013) demonstrates that the latter cannot be true. Electricity accounted for about 18% of world energy end use in 2011 (Fig. 2) and 22% in 2015 (IEA 2017b). Though a challenging task, renewables could theoretically provide this energy. But if the renewable future is to be much like the current one, then all work currently done by fossil fuels must be replaced with electricity.

Replacing one source of electricity (e.g., WASP) for others (e.g., fossil and perhaps nuclear) using the existing grid is one thing. Replacing all uses of fossil fuels with electricity is a very different thing, as we discuss below.

Fossil fuels are predominantly used directly or indirectly for transportation, agriculture, heavy industry, climate control, and cooking in homes (Friedemann 2016). The globalized food system is heavily dependent on oil and gas for direct energy uses and for feedstocks for agrochemicals as well as transportation, processing, and preparation. Liquid hydrocarbons are also used to produce many of the devices and material components used by virtually all industries including WASP (e.g., mining, refining, ore processing, manufacturing, and transport, Kerschner et al. 2013). A massive network of infrastructure supports all these, for which there is a huge previous investment of fossil fuels. Replacing all liquid fuel uses with electricity over the span of a few decades would be extremely difficult (and complicated by the fact that the renewable energy system must become completely self-sustaining). While specific fossil fuel uses could be replaced by electricity (e.g., some cars, mining and farming equipment, and climate control) or renewable output of low-grade heat, globally certain energy applications—intercontinental aviation and heavy shipping in particular—cannot readily use electricity and will likely continue to require energy dense liquid fuels.

Conventional liquid petroleum substitutes include biomass fuels, non-carbon fuels, coal to liquids, and liquefied natural gas. All have low EROI and therefore must be

Fig. 2 Sankey diagram for world energy use (petajoules) in 2011 demonstrating the relative difficulty of replacing fossil fuel energy sources with renewables. The vertical arrows indicate the difficulty of end use substitution, with green being challenging but conceivable and pink being very difficult (Reproduced with permission from IEA 2013; LLNL 2016). (Color figure online)



supported by an energy system with an overall higher net energy return. Coal to liquids and liquefied natural gas may serve as useful “bridge fuels” but are still carbon-emitting fuels. Hydrogen is a potential future liquid fuel substitute, but renewable powered hydrogen production currently yields very low to negative net energy ratios (Armaroli and Balzani 2015). EROI for photoelectric cell hydrogen production has been estimated at 1.7 (Sathre et al. 2014). The net energy of hydrogen is similar to biofuels but considering land-use, fertilizer, and food production tradeoffs of biomass fuels, hydrogen appears to be the more sustainable future option if issues with the safety and practicality of storage and distribution can be overcome. Electric and non-carbon liquid fuel transportation alternatives would also require significant infrastructure replacements (Zhao 2017).

Individual components of the transportation system could be converted to electricity. Light duty local transportation could conceivably be replaced with electric vehicles; however, internal combustion vehicles are projected to be the dominant form of ground transport for at least two decades for the 1.1 billion vehicles currently in use. For example, an agent-based model of the United States automotive market projects electric vehicles will make up only 30% percent of vehicles in the United States by 2030 (Noori and Tatari 2016). Given the unlikelihood of renewables being able to meet energy needs for most transportation and heavy industry in the next few decades, arguably the most critical role of fossil fuels will be provisioning of liquid fuels (Friedemann 2016; McGlade and Ekins 2015). But, to what degree can renewable energy, or even the remaining reserves of high EROI natural gas and coal, subsidize production of low EROI oil and liquid fuel substitutes so that long distance transportation (heavy trucking, shipping, and aviation) networks can be operated affordably and at a high level in the future? A main point of our analysis is that these uncertainties must be clarified to assess properly the tradeoffs of major transportation infrastructure investments (e.g., car factories, highway systems, railways, seaports, airports) that will lock in long-term fuel use patterns, affect efficiency of oil refining infrastructure, and impact global carbon emissions.

Financial Investment

Jacobson et al. (2015a, b) estimate that in the U.S. alone the investments to build a 100% renewable energy system (including storage) would be about \$12–17 trillion between 2013 and 2050—although Clack et al. (2017) argue total costs could be much higher. To accomplish this, annual investment in these systems would require a substantial portion of gross economic output. Jacobson et al.’s proposed investment pathway would peak at ~5% of US GDP in 2025 (See SI-4). For renewables to achieve such gains, a massive amount of debt must be taken on. An important question is whether the financial system is

prepared to handle such an investment, and what are the economic implications of implementing such a build out?

Two additional issues must be considered when projecting the cost of future renewable development. First, as the combined effects of energy and resource scarcity, climate change, natural system degradation, and population growth increasingly affect society, they will compete for financing with renewables’ development. Commodity prices can surge as all these factors force economic sectors to compete for scarce resources (Hamilton 2012). Second, one must carefully analyze prescriptive studies such as that of Jacobson et al. (2015a, b) who published WASP scenarios for each state. This often-cited study is used to argue in favor of developing alternatives to replace fossil fuels but Clack et al. (2017) have questioned the modeling assumptions of Jacobson et al. (2015a, b). Our aim is not to scrutinize that paper on a state-by-state basis, but we do emphasize that for Louisiana, a state we know well, we see formidable challenges to implementing Jacobson’s suggestions. Jacobson et al. suggest that offshore wind and photovoltaic solar can provide all energy necessary to supplant fossil fuel use in the state. Louisiana is notorious for its susceptibility to high winds in the form of hurricanes and other tropical storms, but nobody would suggest that this energy can be easily harvested and stored for later use. As was learned in neighboring state Texas, which has extensive wind farms, peak summer demand is out of phase with seasons of higher mean wind velocities. Moreover, as Texas also learned, wind is often available in places remote from where demand for electricity is high. The existing grid simply does not connect the two.

A transition to wind and solar will also be very difficult for Louisiana given the economy of the state and the political forces that depend on existing energy production. Socio-political barriers are not trivial. The major sectors of the Louisiana economy are oil and gas production, oil refining, a petrochemical industry that uses fossil fuels as energy and feedstocks, water borne transportation, agriculture, forestry, fisheries, and tourism. All of these are highly dependent on oil and gas. So, even if the state could produce electricity from WASP that is equivalent to total energy consumption of the state, it would be very difficult to use it for the major economic activities in the state. Finally, Dismukes and Upton (2015) have shown that the economics of offshore wind production are not favorable, with a low internal rate of return rendering capital investment risky.

Societal Investments, Environment, and Human Well-being

If civilization is to be sustainable, society’s energy must be allocated to a host of major sectors, including but not limited to (1) energy, (2) materials, (3) infrastructure maintenance, and (4) staples for human well-being (e.g., food, water,

climate control, public safety, and healthcare), before discretionary spending and investments (Hall et al. 2008). High EROI societies often have a high portion of their energy supply used for discretionary activities, a major indicator of human well-being (Lambert et al. 2014). Discretionary investments such as research and development, new infrastructure, parks, the arts, etc., are particularly important because they lead to economic growth and have long-term impacts on welfare. The costs of providing the foundational services in an economy are impacted greatly by environmental factors such as material resource depletion, ecosystem degradation, population growth, and climate change. A common narrative in biophysical economics is that EROI of energy investments in the energy sector (1) is the dominant driver of discretionary energy use, but spending for other sectors (2)–(4) also impacts discretionary energy (Brandt 2017). For example, in “Material Demands” section, we discussed how energy requirements for materials used in renewable energy affect EROI (Fizaine and Court 2015). In the remainder of this section, we will discuss how changes in these sectors have affected discretionary energy and societal well-being historically and will likely do so in the future.

Historical Perspective on Energy Investment

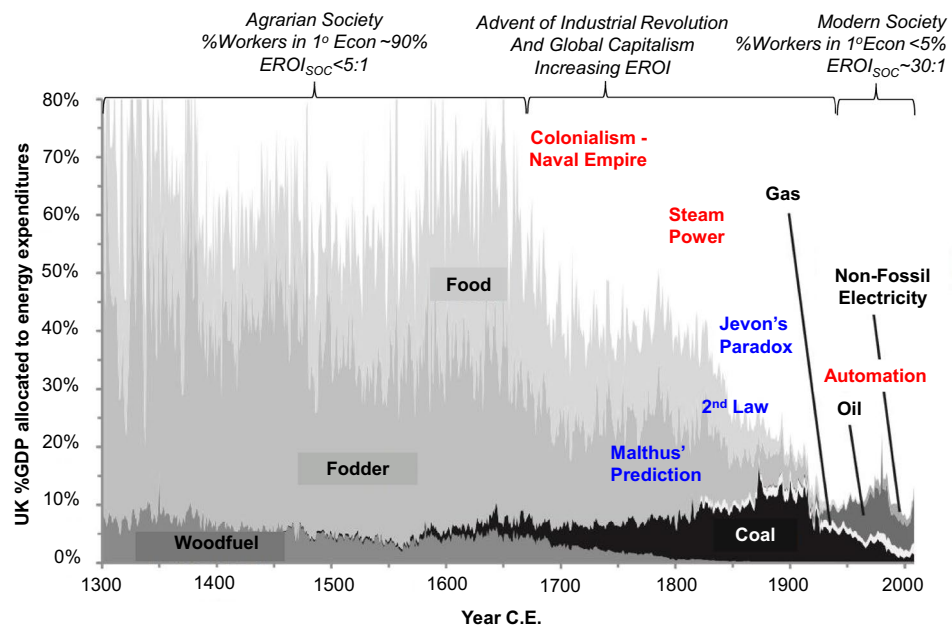
Throughout human history, intermittent solar energy powered the development of society. This enabled, and required, a subsistence lifestyle for most of humanity.

Agrarian societies have a very low societal EROI, 5:1 or less, compared to the EROI of the modern era, which has been as high as 30:1 (Lambert et al. 2014). This meant that

there was much less discretionary income in agrarian societies. In pre-industrial societies, a high proportion of GDP was used to obtain basic energy to supply food, fodder, and fuelwood (Fig. 3). Climate patterns that influenced the size of harvests led to sharp swings in net energy and quality of life (King et al. 2015). Other non-energy-related pressures including war, plagues, floods, and fires also diverted energy from the discretionary pool—used to build churches, boats, roads, and castles—and led to long periods of stagnation (e.g., the dark ages in Europe, Tainter 1988). Prior to the mid-seventeenth century, British society spent between 50 and 80% or more of GDP to obtain basic energy to survive. MacKay (2009) estimates that an affluent Briton currently consumes approximately 195 kWh per day per person while the *average* American consumes 250 kWh per day per person. He reckons that 400 years ago, in Europe, the average person sustainably consumed about 20 kWh per day per person, primarily from food and wood, which required approximately one hectare of forest per person. Obviously, not nearly enough forest exists now to support present population densities (Field et al. 2008).

The industrial revolution increased efficiency greatly through the widespread exploitation of fossil fuels, automation, and use of electricity. This resulted in energy expenditure in the UK reaching a minimum of about 7% of GDP in the late twentieth century (King et al. 2015), and annual net energy ratios for energy expenditures peaking globally in the late 1990s (King et al. 2015). Food and fodder, which historically had a net energy yield to society and underwrote almost all economic activity, today have mostly become net energy sinks in modern industrial society (Heller and

Fig. 3 Percent of GDP allocated to energy expenditure in the United Kingdom from 1300 to 2008. Energy sources are labeled in black; keystone innovations are labeled in red, and intellectual paradigms are in blue (Reproduced with permission from Fizaine and Court 2016). (Color figure online)



Key: Energy Source, Intellectual Paradigm, Net Energy Keystones

Keoleian 2000). The remarkable achievements of societies running on solar-driven natural resource productivity reflects the high net energy return of food production in traditional agrarian societies with EROI values of 10:1 to as high as 50:1 (Lee 1969; Glaub and Hall 2017). Absent the technology supported by abundant fossil fuels, societal EROI was about 5:1 (Lambert et al. 2014). Until advanced technology developed, abetted by high EROI fossil fuels, all work in society was done with human and draft animals using fuel wood, peat and dung supplemented by modest wind and water power.

Rapidly transforming the energy system to lower EROI renewables to meet climate targets will mean that society must allocate substantially more GDP to investing in renewable energy plants, electric grids, energy storage, and liquid fuel substitutes. These compete with other economic drivers. The proposed transition to 100% renewable energy (Jacobson et al. 2015a, b) would require up to 5% of U.S. 2016 GDP to be allocated to renewable energy investment between 2025 and 2040 (SI-4), in addition to investments in decommissioning infrastructure and fossil fuel production to provide society's remaining net energy requirements (SI-3). This might severely limit discretionary investments by society, which facilitate economic growth (e.g., education, advanced health care, museums) (Hall 2017).

Societal Growth Paradigms

The average societal EROI for energy of a future society powered by renewables is likely to be considerably lower than the average for twentieth century society (Figure. 4 and SI-3) (Garcia-Olivares and Ballabrera-Poy 2015; Sgouridis et al. 2016). A society faced with declining net energy return of energy resources can adjust by two possible trajectories: (1) society offsets energy return losses by expanding the energy system (producing more gross energy) and maintains or increases discretionary output while accelerating depletion of resources, (e.g., complexify and expand), or (2) society is unable to offset energy return losses and discretionary output decreases (Brandt 2017). History is replete with examples of each (Tainter 1988; Tainter and Patzek 2012). These two trajectories represent opposite paradigms in policy and economics, growth versus “degrowth” (van den Bergh 2017).

If the goal of the energy transition is to stabilize humanity on a sustainable trajectory, then further societal growth would seem to challenge this goal unless new efficiencies could occur or new resources are found. Ahmed (2017) reported that declining societal net energy, changing climate, and population growth are associated with increased violence, reactionary political systems, and failing states. Building out human systems to support a higher population with declining net energy and a degraded and more

volatile environment could result in great turmoil if these systems begin to fail. The stability and sustainability of societal dimensions must therefore be a consideration (Bagliani et al. 2010; Stirling 2014).

Population is projected to reach or exceed 9 billion by 2050, with most growth occurring in developing nations (UNESA 2015). Massive increases in global energy production will thus be required just to sustain current levels of access to food, water, shelter, and healthcare, let alone increase current standards of living for the poor (Wagner et al. 2016). Under these circumstances, if society is faced with declining net energy then an equitable choice is to expand the energy system until population stabilizes. Once society transitions to a fully renewable energy system, Sgouridis et al. (2016) demonstrate that society could conceivably maintain net energy per capita for a fixed population (see Fig. 4 and SI-3). However, anthropogenic activities are rapidly changing the environment and creating considerable uncertainty over future environmental stability and the associated costs of structural maintenance and provisioning of human staples. Sgouridis et al. (2016) do not consider the potential changes in energy use in non-energy sectors related to environmental degradation.

Global Environmental Degradation as a Societal Energy Sink

A successful transition to renewable energy in concept will reduce the environmental impact of the energy industry and severe impacts due to climate change (Asdrubali et al. 2015; Sgouridis et al. 2016). However, due to non-linearity, tipping points, and momentum of the biosphere's current trajectory, future environmental degradation associated with historic human expansion will still likely impose major

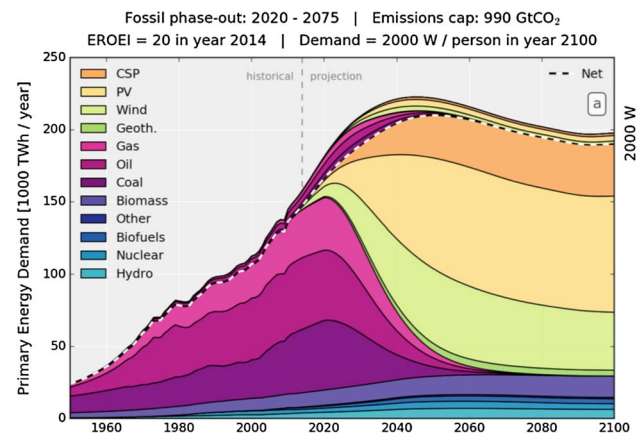


Fig. 4 Simulation showing the extraordinary growth in renewable energy required to offset fossil fuel production, sustain net energy at 2000 W per capita, and remain below 990 GtCO₂ (Reproduced with permission from Sgouridis et al. 2016)

limits (Rockström et al. 2009; Sverdrup et al. 2013). These pressures act as destabilizing energy sinks to the economy that have the potential to disrupt and reduce the functioning of all manner of production systems, especially if humans expand them and make them more complex.

We define environmental degradation as the alteration or disruption of self-regulating natural systems that decreases resilience of the environment to severe perturbation, thus rendering the environment more likely to change state. Examples of environmental state change exist at regional scales (e.g., phosphorus loading in lake sediments leading to long-term eutrophication of lakes; deforestation and farming leading to desertification in the sub-tropics; coastal overfishing and acidification) and at the global scale in the geological record (e.g., dynamic sea level and ice cover during the Pleistocene, transition to the Holocene—a period of stable sea level and temperature). Environmental stability is a crucial factor influencing society. The onset of the stable Holocene epoch corresponds with the period that the first complex human civilizations emerged (Day et al. 2012). The current scale of environmental degradation has many scientists concerned about the risk of transitioning into the Anthropocene—a new geological epoch that will likely be less stable than the Holocene (Rockström et al. 2009, Steffen et al. 2015).

Anthropogenic domination of the environment is global and has resulted in rapid changes in biomass/abundance of species, depletion of soils and low entropy energy stocks, imbalances in material cycles, and physical and chemical changes in the environment, most notably global climate change (Rockström et al. 2009; Schramski et al. 2015; Vitousek et al. 1997). Massive human-caused environmental degradation has been occurring at a global scale since the mid twentieth century and greatly accelerated with the growth of energy consumption (Steffen et al. 2015). Evidence of the environment becoming less stable is mounting; changes are occurring in the form of stochastic events (extreme weather) and constant pressures (increasing pollution, rising sea level, increasing temperature, declining ecosystem services, etc.) (IPCC 2014). These environmental forces affect all aspects of human society (Fig. 5, Sverdrup et al. 2013). Bear in mind that when Paul Ehrlich wrote his classic book, “The Population Bomb,” in 1968, the human population of the planet was scarcely half of what it is now (Ehrlich 1968). The per capita impact factor of that population has also grown during that period of time, so the human “footprint” on earth is much larger that it was a half a century ago (Rees and Wackernagel 2013).

Though variable in time and space, the manifestations of environmental degradation are likely to increase on average with greater human population levels and resource use. For example, with expanding population, supplies of clean freshwater are becoming scarce. In arid and semi-arid

regions of the world, climate change will worsen droughts, increasing reliance upon already depleting freshwater aquifers (Famiglietti 2014). These societies will be forced to use expensive energy intensive methods of freshwater procurement such as long-distance pipelines, pumping from deep aquifers, desalinization plants, and reverse osmosis.

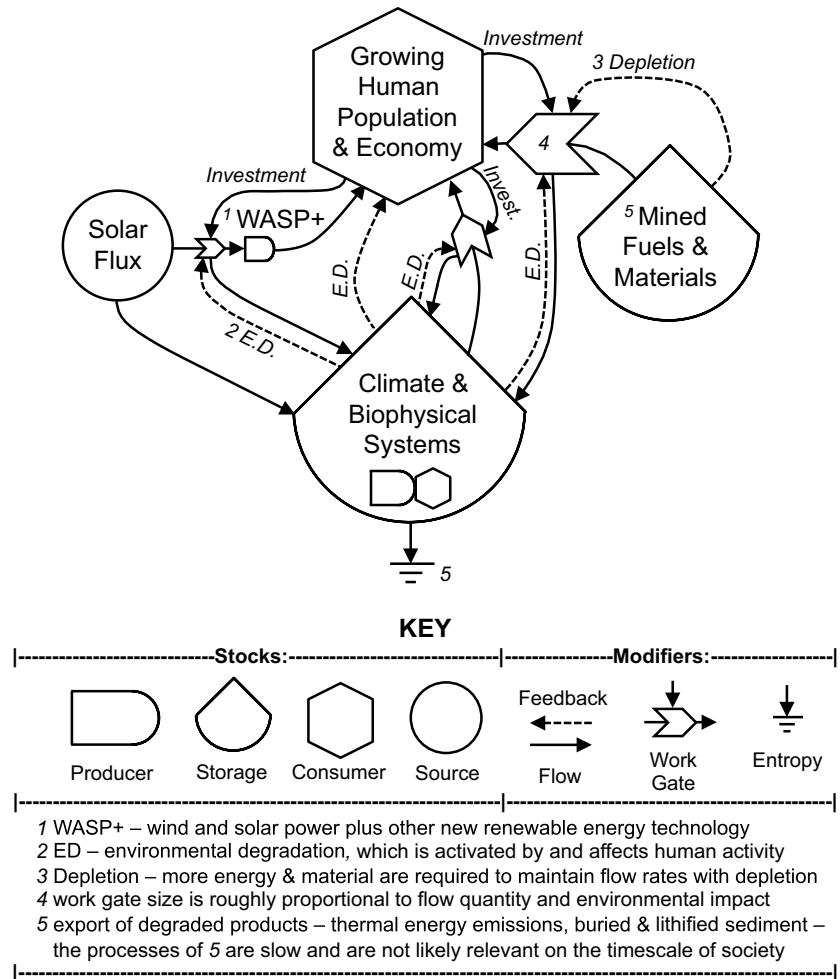
Coastal areas exhibit high levels of urbanization and population growth (Nicholls et al. 2011). Sea-level rise projections range from 0.7 to 2.0 m by 2100 (Horton et al. 2014). There are 72–187 million people in the coastal zone that would be displaced by 0.5–2.0 m of sea-level rise expected by the end of the century (Nicholls et al. 2011). Ten percent of the world’s population and almost two-thirds of urban settlements with populations greater than 5 million are in coastal areas less than 10 m above sea-level that are at high risk of catastrophic damages from stronger storms and other hazards caused by climate change (McGranahan et al. 2007; Day et al. 2016). As the severe Gulf-Atlantic hurricanes of 2017 portend, coastal societies will be forced to build and maintain large coastal protection systems and to direct significant energy resources to emergency evacuations and rebuilding. In places that cannot afford such systems, recurring impacts from sea-level rise and coastal storms will force many people to migrate inland or succumb to natural disasters. In addition to drought and sea-level rise, negative impacts of land-use change and pollution will pose additional stress.

Due to their complex nature, the costs of mitigating environmental stresses fall outside of the boundaries of most studies, as a result their level of impact on society is poorly understood especially as they pertain to the energy transition. Calculating energy and material balances for all sorts of industrial–ecological systems (e.g., “biophysical,” “energy,” and “life cycle” analysis with global boundaries, see Arbault et al. 2013; Flynn and Traver 2013; Moss et al. 2014) is needed to quantify the net energy implications of human development and environmental degradation. In addition, geography, equity, and cultural impacts of energy and climate adaptations must receive more attention (Bagliani et al. 2010; Stirling 2014).

Conclusions

The renewable energy transition is a topic that is justifiably receiving increasing attention in both public discourse and the scientific literature. We believe that the inherent difficulties in effecting this transition are not sufficiently considered in the existing literature, and a central goal of this review is to call attention to the need to do more comprehensive and system level thinking about the significant challenges of replacing fossil fuels and mitigating environmental stressors that lay ahead.

Fig. 5 Conceptual flow diagram of earth and the energy and material factors that influence the human economy



According to our survey of the Web of Science, relatively few studies discuss the thermodynamic and biophysical implications of switching from fossil fuels to a renewable energy system (see SI-2). We reviewed the factors that will impact the success of this transition, including net energy ratio, intermittency/storage, growth rate, material scarcity, substitutability, and financing. Feedbacks among human resource use, ecosystem health, climate change, population growth, and societal stability are also important (Figs. 1, 5; Table 1) (Ahmed 2017; Schramski et al. 2015), but these are rarely discussed in energy transition literature, which indicates a general lack of consideration for the influence of earth system dynamics on human activity (Rockström et al. 2009). We argue that critical thinking about these issues requires such consideration, as well as honest and open debate about such issues.

How the interactions of environmental degradation—including but not limited to climate change, energy scarcity, population growth, and material consumption—will impact society in the coming decades is not well understood. Much additional research is needed to begin estimating the bounds of these impacts (Table 1). We suspect that the pressures of

environmental degradation will generally coincide with the energy transition and will likely increase if society chooses to become more complex and expand. While global environmental degradation patterns have been well documented and correlate with human expansion (e.g., Dearing et al. 2015; Steffen et al. 2015; Schramski et al. 2015), these impacts vary in time and space making historical accounting, let alone prediction, very difficult (Crépin and Folke 2015; Dearing et al. 2015). Accordingly, the associated societal costs remain largely unquantified (Crépin and Folke 2015). Incremental increases in the cost of business resulting from forced adaptation to environmental pressures and lack of infrastructure maintenance will, in our view, very likely reduce society's resources available for the energy transition.

Biophysical economics is an emerging discipline that aims to develop understanding needed to model policies proposed to address the problems above, identify system interactions, and discern the thermodynamic implications for society. However, many topics that we have discussed (listed in Table 1) are still poorly understood and have not been fully integrated into workable models of the global biophysical economy. For example, our understanding of

how environmental degradation affects the economy, and how it will change over time in an energy-scarce world is especially limited. Thus, we cannot say how long society can grow before biophysical constraints including environmental degradation and declining net energy impose limits. Because human welfare and economic well-being are positively related to the availability of useful discretionary per capita energy (Brown et al. 2014; Lambert et al. 2014), we can infer that the combination of environmental degradation and declining net energy might result in a multiplier effect on the general cost of economic production and potentially reduce human welfare (see Wiegman et al. 2017). Technological innovation and redesign of socioecological systems will be needed to relieve such pressures. This could require switching to growth neutral or ‘agrowth’/‘degrowth’ economic policies (van den Bergh 2017) either voluntarily or through necessity—policies that are neither popular politically nor advocated by most economists. Without passing judgment here on this wisdom or value of such a switch, we do believe that such a change would be extremely difficult to effect.

New ways are needed to think about an old and important topic—energy. We have shown here that looking at energy solely through the lens of traditional economics or reductionist disciplinary science and without considering global boundaries has deficiencies that biophysical economics aims to address. Of course, the problem will take additional changes of approach and perspective as well. Given the link between the burning of fossil fuels and climate change, a controversial and polarizing topic, the public dialogue about energy has demonstrated little eclecticism. The realization that the fueling of society requires massive amounts of energy that will be very difficult to generate using renewable technologies must be part of our energy conversation. We particularly emphasize that abandoning existing energy infrastructure for renewable energy infrastructure is a risk; it will be difficult and require a massive energy investment itself especially in the near term. We also consider climate change to be a substantial enough risk that we must think seriously and rapidly about its mitigation, so what we say here must not be misinterpreted as a defense of maintaining the status quo. This will all happen during a period of a significant increase in global population where achieving sustainable development goals will put greater demands on natural resources at the same time the world is moving towards more violence and instability. Instead of name-calling and invectives, society needs to accept the challenge ahead of producing enormous amounts of fungible energy with the lowest possible environmental impact. This is the grand challenge of the present century, and we believe that this challenge will decide the fate of our planet and humanity for generations to come.

Acknowledgements This work was supported by the Gulf Research Program of the National Academies of Sciences, Engineering, and Medicine [Award Number 2000005991]; the Coastal Sustainability Studio [Award Number 1512], and the Department of Oceanography and Coastal Sciences, both at Louisiana State University. Additional support was received by a National Science Foundation funded workshop: Implications of Net Energy for the Food-Energy-Water Nexus, hosted at Linfield College (Co-PI’s Thomas Love and David Murphy) [Award Number 1541988]. We also acknowledge the comments of two reviewers that greatly improved the paper.

Author Contributions All authors contributed to the conception, writing, and development of this work.

Compliance with Ethical Standards

Conflict of interest The authors declare no competing financial interests.

References

- Ahmed NM (2017) Failing states, collapsing systems: biophysical triggers of political violence. Springer, Cham
- Anderson K (2015) Duality in climate science. *Nat Geosci* 8(12):898–900
- Arbault D, Rugani B, Tiruta-Barna L, Benetto E (2013) Energy evaluation of water treatment processes. *Ecol Eng* 60:172–182
- Armaroli N, Balzani V (2015) Solar electricity and solar fuels: status and perspectives in the context of the energy transition. *Chemistry* 22(1):32–57. <https://doi.org/10.1002/chem.201503580>
- Arvesen A, Hertwich EG (2015) More caution is needed when using life cycle assessment to determine energy return on investment (EROI). *Energy Policy* 76:1–6
- Asdrubali F, Baldinelli G, D’Alessandro F, Scrucca F (2015) Life cycle assessment of electricity production from renewable energies: review and results harmonization. *Renew Sustain Energy Rev* 42:1113–1122
- Ayres R, Voudouris V (2014) The economic growth enigma: capital, labour and useful energy? *Energy Policy* 64:16–28
- Bagliani M, Dansero E, Puttilli M (2010) Territory and energy sustainability: the challenge of renewable energy sources. *J Environ Plan Manag* 53(4):457–472
- Binnemans K, Jones PT, Blanpain B, Van Gerven T, Yang Y, Walton A, Buchert M (2013) Recycling of rare earths: a critical review. *J Clean Prod* 51:1–22
- BP (2016) BP statistical review of world energy 2016. British Petroleum, London
- Brandt AR (2017) How does energy resource depletion affect prosperity? Mathematics of a minimum energy return on investment (EROI). *Biophys Econ Resour Qual*. <https://doi.org/10.1007/s41247-017-0019-y>
- Brandt AR, Englander J, Bharadwaj S (2013) The energy efficiency of oil sands extraction: energy return ratios from 1970 to 2010. *Energy* 55:693–702
- Brandt AR, Yeskoo T, Vafi K (2015) Net energy analysis of Bakken crude oil production using a well-level engineering-based model. *Energy* 93:2191–2198
- Brown JH, Burnside WR, Davidson AD, DeLong JP, Dunn WC, Hamilton MJ, Mercado-Silva N, Nekola JC, Okie JG, Woodruff WH, Zuo W (2011) Energetic limits to economic growth. *BioScience* 61(1):19–26
- Brown JH, Burger JR, Burnside WR, Chang M, Davidson AD, Fristoe TS, Hamilton MJ, Hammond ST, Kodric-Brown A,

- Mercado-Silva N, Nekola JC (2014) Macroecology meets macroeconomics: resource scarcity and global sustainability. *Ecol Eng* 65:24–32
- Campbell CJ, Wöstmann A (2013) *Campbell's atlas of oil and gas depletion*. Springer, New York
- Carbajales-Dale M, Krumdieck S, Bodger P (2012) Global energy modelling—a biophysical approach (GEMBA) part 2: methodology. *Ecol Econ* 73:158–167
- Carbajales-Dale M, Barnhart CJ, Benson SM (2014) Can we afford storage? A dynamic net energy analysis of renewable electricity generation supported by energy storage. *Energy Environ Sci* 7(5):1538–1544
- Clack C et al (2017) Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar. *Proc Natl Acad Sci USA*. <https://doi.org/10.1073/pnas.1610381114>
- Costanza R, de Groot R, Sutton P, van der Ploeg S, Anderson SJ, Kubiszewski I, Farber S, Turner RK (2014) Changes in the global value of ecosystem services. *Glob Environ Change* 26:152–158
- Court V, Fizaine F (2017) Long-term estimates of the energy-return-on-investment (EROI) of coal, oil, and gas global productions. *Ecol Econ* 138:145–159
- Crépin A, Folke C (2015) The economy, the biosphere and planetary boundaries: towards biosphere economics. *Int Rev Environ Resour Econ* 8(1):57–100
- Daly HE (2017) A further critique of growth economics. In *Green Economy Reader*. Springer International Publishing, pp 55–66
- Davidsson S, Grandell L, Wachtmeister H, Höök M (2014) Growth curves and sustained commissioning modelling of renewable energy: investigating resource constraints for wind energy. *Energy Policy* 73:767–776
- Day JW, Gunn JD, Folan WJ, Yáñez-Arancibia A, Horton BP (2012) The influence of enhanced post-glacial coastal margin productivity on the emergence of complex societies. *J Island Coast Archaeol* 7(1):23–52
- Day JW, Agboola J, Chen Z, D'Elia C, Forbes DL, Giosan L et al (2016) Approaches to defining deltaic sustainability in the 21st century. *Estuar Coast Shelf Sci* 183:275–291
- Dearing JA, Acma B, Bub S, Chambers FM, Chen X, Cooper J et al (2015) Social-ecological systems in the Anthropocene: the need for integrating social and biophysical records at regional scales. *Anthr Rev* 2(3):220–246
- Dismukes DE, Upton GB (2015) Economies of scale, learning effects and offshore wind development costs. *Renew Energy* 83:61–66
- Dukes JS (2003) Burning buried sunshine: human consumption of ancient solar energy. *Clim Change* 61(1–2):31–44
- Ehrlich P (1968) *The population bomb*. Ballantine, New York
- EIA (2015) *Annual energy outlook 2015*. U.S. Energy Information Administration, Washington
- EIA (2016) *Annual energy outlook 2016*. U.S. Energy Information Administration, Washington. https://www.eia.gov/forecasts/aeo/tables_ref.cfm
- Famiglietti JS (2014) The global groundwater crisis. *Nat Clim Chang* 4(11):945–948
- Ferroni F, Guekos A, Hopkirk RJ (2017) Further considerations to: energy return on energy invested (ERoEI) for photovoltaic solar systems in regions of moderate insolation. *Energy Policy* 107:498–505
- Field C, Campbell J, Lobell D (2008) Biomass energy: the scale of the potential resource. *Trends Ecol Evol* 23(2):65–72
- Fizaine F, Court V (2015) Renewable electricity producing technologies and metal depletion: a sensitivity analysis using the EROI. *Ecol Econ* 110:106–118
- Fizaine F, Court V (2016) Energy expenditure, economic growth, and the minimum EROI of society. *Energy Policy* 95:172–186
- Flynn KM, Traver RG (2013) Green infrastructure life cycle assessment: a bio-infiltration case study. *Ecol Eng* 55:9–22
- Friedemann AJ (2016) *When trucks stop running: energy and the future of transportation*. Springer, Cham
- García-Olivares A, Ballabrera-Poy J (2015) Energy and mineral peaks, and a future steady state economy. *Technol Forecast Soc Change* 90:587–598
- Glaub M, Hall CAS (2017) Evolutionary implications of persistence hunting: an examination of energy return on investment for !Kung hunting. *Hum Ecol* 45(3):393–401
- Gupta AK (2018) Materials: abundance, purification, and the energy cost associated with the manufacture of Si, Cd, Te, and CIGS PV. In: Letcher T, Fthenakis VM (eds) *A comprehensive guide to solar energy systems: with special focus on photovoltaic systems*. Elsevier, Oxford
- Gutowski TG, Allwood JM, Herrmann C, Sahni S (2013) A global assessment of manufacturing: economic development, energy use, carbon emissions, and the potential for energy efficiency and materials recycling. *Annu Rev Environ Resour* 38:81–106
- Hall CAS (2004) The myth of sustainable development: personal reflections on energy, its relation to neoclassical economics, and Stanley Jevons. *J Energy Res Technol* 126:85–89
- Hall CAS (2017) *Energy return on investment*. Springer, Cham
- Hall CAS, Klitgaard K (2012) *Energy and the wealth of nations: understanding the biophysical economy*. Springer Science & Business Media, New York
- Hall CAS, Powers R, Schoenberg W (2008) Peak oil, EROI, investments and the economy in an uncertain future. In: Pimentel D (ed) *Renewable energy systems: environmental and energetic issues*. Elsevier, London
- Hall CAS, Lambert JG, Balogh SB (2014) EROI of different fuels and the implications for society. *Energy Policy* 64:141–152
- Hamilton JD (2012) *Oil prices, exhaustible resources, and economic growth (No. w17759)*. National Bureau of Economic Research, Cambridge
- Hansen JP, Narbel PA, Aksnes DL (2017) Limits to growth in the renewable energy sector. *Renew Sustain Energy Rev* 70:769–774
- Harmen JHM, Roes AL, Patel MK (2013) The impact of copper scarcity on the efficiency of 2050 global renewable energy scenarios. *Energy* 50:62–73
- Harris S (1977) *What's so funny about science?* Wm. Kaufmann, Inc., Los Altos
- Heinberg R, Fridley D (2016) *Our renewable future*. Island Press, Washington, D.C.
- Heller MC, Keoleian GA (2000) *Life cycle-based sustainability indicators for assessment of the US food system, vol 4*. Center for Sustainable Systems, University of Michigan, Ann Arbor
- Hiloidhari M, Baruah DC, Singh A, Katagi S, Medhi K, Kumari S et al (2017) Emerging role of geographical information system (GIS), life cycle assessment (LCA) and spatial LCA (GIS-LCA) in sustainable bioenergy planning. *Bioresour Technol* 242:218–226. <https://doi.org/10.1016/j.biortech.2017.03.079>
- Höök M, Li J, Johansson K, Snowden S (2012) Growth rates of global energy systems and future outlooks. *Nat Resour Res* 21(1):23–41
- Horton BP, Rahmstorf S, Engelhart SE, Kemp AC (2014) Expert assessment of sea-level rise by AD 2100 and AD 2300. *Quat Sci Rev* 84:1–6
- Hopkinson CS, Day JW (1980) Net energy analysis of alcohol production from sugarcane. *Science* 207(4428):302–304
- IEA (2013) *World energy outlook 2013*. International Energy Agency, Paris
- IEA (2017a) *World energy outlook 2017*. International Energy Agency, Paris
- IEA (2017b) *Key world energy statistics 2017*. International Energy Agency, Paris
- IPCC (2014) *Climate change 2014: synthesis report*. In: Pachauri RK, Allen MR, Barros VR, Broome J, Cramer W, Christ R, Church JA, Clarke L, Dahe Q, Dasgupta P, Dubash NK (eds)

- Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change
- Jacobson MZ, Delucchi MA, Bazouin G, Bauer ZA, Heavey CC, Fisher E, Morris SB, Piekutowski DJ, Vencill TA, Yeskoo TW (2015a) 100% clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for the 50 United States. *Energy Environ Sci* 8(7):2093–2117
- Jacobson MZ, Delucchi MA, Cameron MA, Frew BA (2015b) Low-cost solution to the grid reliability problem with 100% penetration of intermittent wind, water, and solar for all purposes. *Proc Natl Acad Sci USA*, 112(49):15060–15065
- Jones GA, Warner KJ (2016) The 21st century population-energy-climate nexus. *Energy Policy* 93:206–212
- Kerschner C, Prell C, Feng K, Hubacek K (2013) Economic vulnerability to peak oil. *Glob Environ Chang* 23(6):1424–1433
- King CW, Maxwell JP, Donovan A (2015) Comparing world economic and net energy metrics, part 2: total economy expenditure perspective. *Energies* 8(11):12975–12996
- Kintisch E (2015) After Paris: the rocky road ahead. *Science* 350(6264):1018–1019
- Koppelaar RHEM. (2017) Solar-PV energy payback and net energy: meta-assessment of study quality, reproducibility, and results harmonization. *Renew Sustain Energy Rev* 72:1241–1255
- Kubiszewski I, Cleveland CJ, Endres PK (2010) Meta-analysis of net energy return for wind power systems. *Renew Energy* 35(1):218–225
- Laherrere J (2017) Personal communication. Email correspondence with C.A.S. Hall
- Lambert JG, Hall CA, Balogh S, Gupta A, Arnold M (2014) Energy, EROI and quality of life. *Energy Policy* 64, 153–167
- Lawrence Livermore National Laboratory (LLNL) (2016) Energy flow charts. <http://flowcharts.llnl.gov>. Accessed 25 Jan 2016
- Lee R (1969) Kung Bushman subsistence: an input-output analysis. In: Vayda AP (ed) *Environment and cultural behavior*. Natural History Press, New York, pp 47–79
- Louwen A, Van Sark WG, Faaij AP, Schropp RE (2016) Re-assessment of net energy production and greenhouse gas emissions avoidance after 40 years of photovoltaics development. *Nat Commun* 7:13728
- MacKay DJC (2009) *Without the hot air*. UIT Cambridge Ltd, Cambridge
- Maggio G, Cacciola G (2012) When will oil, natural gas, and coal peak? *Fuel* 98:111–123
- Masnadi MS, Brandt AR (2017) Energetic productivity dynamics of global super-giant oilfields. *Energy Environ Sci*. <https://doi.org/10.1039/C7EE01031A>.
- McGlade CE (2014) *Uncertainties in the outlook for oil and gas* (Doctoral dissertation, UCL (University College London))
- McGlade C, Ekins P (2015) The geographical distribution of fossil fuels unused when limiting global warming to 2 °C. *Nature* 517(7533):187–190
- McGranahan G, Balk D, Anderson B (2007) The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. *Environ Urban* 19(1):17–37
- Moerschbaeche M, Day Jr JW (2011) Ultra-deepwater Gulf of Mexico oil and gas: energy return on financial investment and a preliminary assessment of energy return on energy investment. *Sustainability* 3(10):2009–2026
- Mohr SH, Wang J, Ellem G, Ward J, Giurco D (2015) Projection of world fossil fuels by country. *Fuel* 141:120–135
- Moss AR, Lansing SA, Tilley DR, Klavon KH (2014) Assessing the sustainability of small-scale anaerobic digestion systems with the introduction of the energy efficiency index (EEI) and adjusted yield ratio (AYR). *Ecol Eng* 64:391–407
- Murphy DJ (2013) The implications of the declining energy return on investment of oil production. *Philos Trans A Math Phys Eng Sci* 372(2006):20130126
- Murphy DJ, Hall CA (2011) Energy return on investment, peak oil, and the end of economic growth. *Ann N Y Acad Sci* 1219(1):52–72
- Murphy DJ, Hall CAS, Powers B (2011) New perspectives on the energy return on (energy) investment (EROI) of corn ethanol. *Environ Dev Sustain* 13(1):179–202
- Murphy DJ, Carbajales-Dale M, Moeller D (2016) Comparing apples to apples: why the net energy analysis community needs to adopt the life-cycle analysis framework. *Energies* 9(11):917
- Neumeyer C, Goldston R (2016) Dynamic EROI assessment of the IPCC 21st century electricity production scenario. *Sustainability* 8(5):421
- Nicholls RJ, Marinova N, Lowe JA, Brown S, Vellinga P, De Gusmao D, Hinkel J, Tol RS (2011) Sea-level rise and its possible impacts given a ‘beyond 4 C world’ in the twenty-first century. *Philos Trans A Math Phys Eng Sci* 369(1934):161–181
- Noori M, Tatari O (2016) Development of an agent-based model for regional market penetration projections of electric vehicles in the United States. *Energy* 96:215–230
- Palmer G (2014) *Energy in Australia: peak oil, solar power, and Asia’s economic growth*. Springer, New York
- Palmer G (2017) A framework for incorporating EROI into electrical storage. *Biophys Econ Resour Qual* 2(2):6
- Pimentel D, Marklein A, Toth MA, Karpoff MN, Paul GS, McCormack R, Kyriazis J, Krueger T (2009) Food versus biofuels: environmental and economic costs. *Hum Ecol* 37(1):1–12
- Raugei M (2013) Comments on “Energy intensities, EROIs (energy returned on invested), and energy payback times of electricity generating power plants”—making clear of quite some confusion. *Energy* 59(15):781–782
- Raugei M, Fullana-i-Palmer P, Fthenakis V (2012) The energy return on energy investment (EROI) of photovoltaics: methodology and comparisons with fossil fuel life cycles. *Energy Policy* 45:576–582
- Raugei M, Sgouridis S, Murphy D, Fthenakis V, Frischknecht R, Breyer C, Bardi U, Barnhart C, Buckley A, Carbajales-Dale M, Csala D (2017) Energy Return on Energy Invested (EROEI) for photovoltaic solar systems in regions of moderate insolation: a comprehensive response. *Energy Policy* 102:377–384
- Rees WE, Wackernagel M (2013) The shoe fits, but the footprint is larger than earth. *PLoS Biol* 11(11):e1001701
- REN21 (2017) *Renewables 2017 global status report*. REN21 Secretariat, Paris
- Rockström J, Steffen W, Noone K, Persson Å, Chapin FS III, Lambin EF, Lenton TM, Scheffer M, Folke C, Schellnhuber HJ, Nykvist B et al (2009) A safe operating space for humanity. *Nature* 461(7263):472–475
- Sathre R, Scown CD, Morrow WR, Stevens JC, Sharp ID, Ager JW, Walczak K, Houle FA, Greenblatt JB et al (2014) Life-cycle net energy assessment of large-scale hydrogen production via photoelectrochemical water splitting. *Energy Environ Sci* 7(10):3264–3278
- Schramski JR, Gattie DK, Brown JH (2015) Human domination of the biosphere: rapid discharge of the earth-space battery foretells the future of humankind. *Proc Natl Acad Sci* 112(31):9511–9517
- Sgouridis S, Bardi U, Csala D (2016) The sower’s way. Quantifying the narrowing net-energy pathways to a global energy transition. *Environ Res Lett*. <https://doi.org/10.1088/1748-9326/11/9/094009>
- Smil V (2016) Examining energy transitions: a dozen insights based on performance. *Energy Res Social Sci* 22:194–197
- Steffen W, Broadgate W, Deutsch L, Gaffney O, Ludwig C (2015) The trajectory of the Anthropocene: the great acceleration. *Anthropog Rev* 2(1):81–98

- Stirling A (2014) Transforming power: social science and the politics of energy choices. *Energy Res Soc Sci* 1:83–95
- Sverdrup HU, Koca D, Ragnarsdóttir KV (2013) Peak metals, minerals, energy, wealth, food and population: urgent policy considerations for a sustainable society. *J Environ Sci Eng B* 2(4B):189
- Sverdrup HU, Ragnarsdóttir KV, Koca D (2015) An assessment of metal supply sustainability as an input to policy: security of supply extraction rates, stocks-in-use, recycling, and risk of scarcity. *J Clean Prod* 140:359–372
- Tainter JA (1988) *The collapse of complex societies*. Cambridge University Press, Cambridge
- Trainer T (2012a) A critique of Jacobson and Delucchi's proposals for a world renewable energy supply. *Energy Policy* 44:476–481
- Trainer T (2012b) Can Australia run on renewable energy? The negative case. *Energy Policy* 50:306–314
- Trainer T (2013) Can Europe run on renewable energy? A negative case. *Energy Policy* 63:845–850
- Tainter JA and Patzek TW (2012) Our energy and complexity dilemma: prospects for the future. In: *Drilling Down*. Springer, New York
- Tripathi VS, Brandt AR (2017) Estimating decades-long trends in petroleum field energy return on investment (EROI) with an engineering-based model. *PLoS ONE* 12(2):e0171083
- UNESA (2015) *World Population Prospects, 2015 Revisions, Data Booklet*. United Nations Economic & Social Affairs (UNESA)
- United Nations Framework Convention on Climate Change (UNFCCC) (2015) Decision 1/CP.17. Durban Platform for Enhanced Action (decision 1/CP.17) Adoption of a protocol, another legal instrument, or an agreed outcome with legal force under the Convention applicable to all Parties. <https://unfccc.int/resource/docs/2015/cop21/eng/109r01.pdf>. Accessed 20 April 2016
- van den Bergh J (2017) A third option for climate policy within potential limits to growth. *Nat Clim Chang* 7(2):107–112
- Vitousek PM, Mooney HA, Lubchenco J, Melillo JM (1997) Human domination of Earth's ecosystems. *Science* 277(5325):494–499
- Waggoner EG (2013) Sweet spots, EROI, and the limits to Bakken production. Thesis (MS) State University of New York College of Environmental Science and Forestry
- Wagner L, Ross I, Foster J, Hankamer B (2016) Trading off global fuel supply, CO2 emissions and sustainable development. *PLoS ONE* 11(3):e0149406
- Warr BS, Ayres RU (2010) Evidence of causality between the quantity and quality of energy consumption and economic growth. *Energy* 35(4):1688–1693
- Weißbach D, Ruprecht G, Huke A, Czerski K, Gottlieb S, Hussein A (2013) Energy intensities, EROIs (energy returned on invested), and energy payback times of electricity generating power plants. *Energy* 52:210–221
- Wiegman AR, Day JW, D'Elia CF, Rutherford JS, Morris JT, Roy ED, Lane RR, Dismukes DE, Snyder BF (2017) Modeling impacts of sea-level rise, oil price, and management strategy on the costs of sustaining Mississippi delta marshes with hydraulic dredging. *Sci Total Environ*. <https://doi.org/10.1016/j.scitotenv.2017.09.314>
- Zhao B (2017) Why will dominant alternative transportation fuels be liquid fuels, not electricity or hydrogen? *Energy Policy* 108:712–714