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Dear MuseLetter reader,
2022 was the 30th year for this publication, and it's been heartening to see these essays being distributed through an increasing number of online and print publishing outlets. There's more to come!
May your solstice be a time for reflection, rejuvenation, and some time in nature.
Richard

Can Civilization Survive? These Studies Might Tell Us

The world's shift away from its current reliance on fossil fuels will be the biggest, most expensive, and most complex technical project ever attempted by humans. If it fails, that might mean the end of industrial civilization. For it to succeed, enormous amounts of investment and effort, along with some shared sacrifice, will be required. These are the conclusions of key recent studies attempting to model the global energy transition.

Energy is essential; it's what enables us to do literally anything and everything we do. Fossil fuels, with their ability to store and deliver enormous amounts of energy, underpin the modern industrial world. But since fossil fuels are finite and polluting, it's imperative that we plan a shift to renewable energy systems that can be sustained over the long term.

A transition away from fossil fuels is not optional; in some form or other, it is inevitable. However, there are serious questions about how much it will cost in terms of money, energy, and emissions; how fast we can accomplish it; and what kind of society can be supported by the alternative energy sources we adopt—presumably, a suite of sources dominated by solar and wind power.

These questions have political and economic dimensions. But relying on politics or economics to guide the transition would be foolish, without first analyzing the options and their physical-world implications. Otherwise, politicians and economists will just try to maintain our current industrial system as much as possible, even though this system is inherently unsustainable (due to the fact that it depends overwhelmingly on depleting fossil fuels) and is generating cascading crises via climate change.

Trained analysts are using computer-based models to gauge what the energy transition will mean, and how it can best be accomplished. But, so far, transition modeling has received remarkably little attention from policy makers or the general public.

What We Need to Know

The first efforts toward energy transition modeling mostly estimated how many solar panels and wind turbines would be needed to replace the energy we currently derive from fossil fuels, and how much all of that technology would cost. But the energy transition will be a far more complex task than just building new energy generators. Because solar and wind power are intermittent, energy storage will be required, along with more redundancy in generating capacity. Because most of the new energy sources will produce electricity, while most current energy usage infrastructure is designed for storable fuels, we'll have to electrify a great deal of energy-using technology (electric cars are just the start). At the same time, we'll need a whole new industry to make low-carbon fuels for technologies that will be hard to electrify—like cement kilns and airplanes.

The field of system dynamics is ideally suited to energy transition analysis, since its practitioners aim to model changing complex systems. System dynamics studies often produce several possible scenarios, with each scenario based on the adjustment of a key variable.

With regard to the energy transition, we need system dynamics scenario studies that can answer the following questions:

- How much will the transition cost monetarily—not just for panels and turbines, but for the system as a whole, including all the new electrified infrastructure, along with infrastructure needed for energy storage and the production of low-carbon fuels?
- How much energy will it take? Building all this new infrastructure will take energy. In the early phases of the transition, most of that energy will come from fossil fuels, which supply over 80 percent of global energy currently.
- What about carbon emissions? During the energy transition, society will be emitting more greenhouse gases than it would otherwise (due to ramped-up industrial processes needed to build new energy infrastructure). How much more?
- How will the transition affect economic growth, and vice versa? If the global economy continues to grow, that might make the transition harder, as more energy would be required for non-transition purposes. But deliberately contracting the economy in order to direct more energy toward the transition might erode financial (and political) support for the project.
- How will the transition impact society's return on the energy it invests in getting more energy (energy return on investment, or EROI)? It is the high energy profit ratios of fossil fuels that have enabled humanity to construct complex industrial societies in which the great majority of people spend their days using energy rather than producing it. EROI for fossil fuels is generally declining due to the depletion of high-quality stocks of oil, gas, and coal, while EROI for renewables is generally increasing due to technology improvements. But the situation is complicated: during the transition, energy costs will come earlier than the energy paybacks, thereby possibly lowering the EROI for society as a whole, at least temporarily. And EROI for renewables could decline

due to the depletion of mineral and metal ores needed to build these technologies at scale (since it takes more energy to mine and refine lower-grade ores).

- How will the transition be impacted by materials scarcity? The construction of solar panels, wind turbines, batteries, and other renewable energy technologies at scale will require enormous amounts of metals and minerals, some of which are already scarce.
- What are the costs and benefits if the transition goes faster or slower? The speed of the transition could have varying impacts on the economy, on energy availability, on societal EROI, and on greenhouse emissions.

Clearly, there's a lot that we need to know. And, adding further to the complexity, we can't just address each of these questions independently, because all of the parts of the energy system, and the industrial system it powers, will be constantly interacting. That's why we need scenarios based on dynamic systems modeling.

Interest in energy transition modeling is fairly recent, but the academic literature is growing quickly. Dozens of relevant research papers have been published in the past decade, though most attempt to answer just one or two of the questions listed above (for example, a report by McKinsey consultants estimated that the global transition will cost $275 trillion over 30 years; that report was criticized here). A full discussion of all these publications would be unwieldy, especially since many do not employ system dynamics methodology. Instead, let's survey just two recent system dynamics studies that address many of the questions I've posed. One study's conclusions are more gloomy, the other's less so.

"Dynamic Energy Return"

The first study is "Dynamic Energy Return on Energy Investment (EROI) and Material Requirements in Scenarios of Global Transition to Renewable Energies" by Iñigo Capellán-Pérez, Carlos de Castro, and Luis Javier Miguel González, published in *Energy Strategy Reviews* in November, 2019. Below, I'll refer to this study simply as "Dynamic Energy Return."

The "Dynamic Energy Return" team of scientists focused on EROI, because they believe it will be the key to the outcome of the energy transition. If societal EROI is high during and after the transition, that means energy will be easier to obtain. And with more plentiful and cheaper energy, other problems will be easier to solve. For example, cheap energy could enable the processing of lower-grade mineral and metal ores in larger quantities, thereby making it cheaper to manufacture renewable energy components and install infrastructure. However, if societal EROI declines, most industrial and economic problems become harder to solve—whether they involve manufacturing or resource acquisition.

This study's findings are worrisome. Currently, according to the authors, the world gains 12 units of energy for every unit of energy invested in producing energy (via drilling oil wells, mining coal, building nuclear power plants, manufacturing and installing solar panels, and so on). A nearly full transition of the global energy system by 2060 would reduce that payback to between 3 and 5 units. The authors note that previous research suggests that an energy profit ratio in the range of 3:1 to 5:1 could not sustain the operation of modern industrial societies.

Societal EROI would decline partly because of the increased need for energy to build new energy infrastructure. Even though the new energy generators would be producing more energy over their lifetimes than would be expended in building them, energy investment would come first while energy payback would be achieved over years or decades. Therefore, a fast transition means that the EROI of the energy system as a whole would decline, at least until after the transition is mostly finished. Moreover, “the production of energy would need to increase by 35% in order to supply the same level of net energy to society during the transition.”

The “Dynamic Energy Return” study also found that greater requirement for raw materials could drive “a substantial re-materialization of the economy.” The authors estimate that cumulative demand would surpass current mineral reserves for tellurium, indium, tin, silver, and gallium.

The implications of the study are startling. If society pursues a fast transition away from fossil fuels and toward renewable energy alternatives while attempting to maintain current levels of energy usage for other purposes (agriculture, manufacturing, building heating and cooling, road and building construction, and transportation), energy systems will be strained, possibly to the breaking point. Indeed, under conditions of declining EROI and resource scarcity, the transition might fail and industrial societies might find it difficult to stave off collapse.

“Energy Requirements”

The second study, “Energy Requirements and Carbon Emissions for a Low-Carbon Energy Transition,” by Aljoša Slameršak, Giorgos Kallis, and Daniel W. O’ Neill, was published in *Nature Communications* in November, 2022. I’ll refer to this study as “Energy Requirements.”

Partly confirming the “Dynamic Energy Return” results, the authors of “Energy Requirements” found that “the initial push for a transition is likely to cause a 10–34% decline in net energy available to society.”

Again, these authors found societal EROI to be a key metric in modeling the transition. Indeed, this study was structured around three scenarios—high, medium, and low EROI. The energy transition’s cost and difficulty increased significantly as the assumed EROI declined.

“Energy Requirements” also investigated the cumulative carbon emissions associated with the transition to a low-carbon energy system, and found that they will likely be substantial, ranging from 70 to almost 400 billion tons of CO_2, depending on the scenario. For comparison, today’s global carbon emissions clock in at about 50 billion tons per year.

By 2050, if society pursues a rapid transition, activities associated with building, operating, and replacing energy generators will produce over two-and-a-half times the percentage share of society’s overall carbon emissions as compared with today’s fossil-dominated energy system. That seems counterintuitive; however, for the current energy system the authors are counting mainly emissions from drilling and mining—not the burning of the fuels that are produced, as those emissions are associated with other economic sectors (agriculture, transportation, manufacturing, etc.). This finding means that, if society's overall emissions are to stay within the budget permissible to limit global warming to 1.5 degrees, the rest of society (i.e., sectors other than the energy industry) will have to reduce emissions, perhaps effectively to zero. How this could be accomplished for sectors such as aviation and the steel and cement industries is barely imaginable. Unless we figure out how to reinvent many key industrial processes, they'll simply have to be significantly downsized.

The conclusions of "Energy Requirements" are relatively optimistic: in its "high EROI" scenario, the reduction in societal EROI during the transition is modest, and the jump in emissions is relatively small. Moreover, the authors conclude:

> "A good life could be achieved at lower per capita energy use by improving the efficiency of energy using technologies (e.g. by replacing gasoline-powered cars with electric cars), by shifting from consumption choices with higher energy intensities to choices with lower energy intensities (e.g. from cars to bicycles), and by avoiding the most inefficient alternatives altogether (e.g. flying)."

Comparing Two Studies: What Can We Learn?

Controversy within the community of energy transition modelers largely boils down to differing assumptions about current and future EROI figures for renewable energy sources. In the research literature, some studies suggest that the overall energy return for renewables is far lower than that for fossil fuels, while other studies find the energy return for solar and wind to be somewhat higher than for oil currently. These differences in EROI estimates stem largely from design differences of the studies. Some studies count only the most essential energy inputs to the building and operation of renewable energy generators; these studies tend to find a higher EROI. Other studies draw a wider boundary that includes additional factors, such as energy storage, which yields a lower energy profit ratio.

Renewable-energy EROI pessimists argue that, when modeling a global energy transition, the widest possible boundaries should be used. Indeed, EROI pessimists would likely consider even the "low EROI" scenario of the "Energy Requirements" study to be unrealistic, because it assumes rising EROI figures for renewable energy technologies. Would the EROI figures for renewables really improve, as the depletion of high-grade deposits of minerals and metals forces manufacturers of low-carbon infrastructure to expend more energy in mining and refining?

On the other hand, renewable-energy EROI optimists point to the recent history of falling costs for most of the technologies associated with renewables, and argue that further efficiency improvements are inevitable, especially if resource constraints can be kept in check by substituting common minerals for ones that are growing scarce.

The two studies do agree on some general points:

- The energy transition will require a significant expenditure of energy. This will have implications for the overall economy. In general, energy will tend to be more expensive during the transition (though how much is unclear).
- The energy transition will generate extra carbon emissions (how much is unclear).
- The faster the transition, the more wrenching it is likely to be for society. Therefore, starting sooner is better. That's because, as the EROI of fossil fuels inevitably declines, everything we do that depends on fossil fuels will get harder and more expensive—including the construction of renewable energy infrastructure. Ideally, we should have started the energy transition decades ago, when energy usage was lower, and we had both higher-EROI fossil fuels and a larger carbon budget. Those who seek to delay the transition (as the fossil fuel industry has done) are making matters much worse for society.
- Higher energy usage for non-transition purposes makes the transition more difficult. Because the energy transition will itself require a great deal of energy, both society's total energy demand and its carbon emissions will increase during parts of the transition—unless energy usage for "normal" operations (transportation, manufacturing, etc.) can be curtailed.

In the best-case scenario, the energy transition is certainly possible, if problematic. But well-meaning organizations promoting the notion of "green growth" may be encouraging unrealistic expectations, given the costs and constraints outlined above.

In the worst-case scenario, the pathway to the maintenance of industrial civilization narrows considerably. Indeed, if the conclusions of "Dynamic Energy Return" are correct, a successful transition will probably require fundamental changes not just in industries, but in our economic system as well. And the latter would have significant political implications (the Yellow Vests Movement and the Canada Truckers Protests offer only faint hints of what could be in store).

In all scenarios, some degree of shared effort and sacrifice will be needed throughout society during the transition.

Although reducing energy consumption for "normal" societal operations appears to be a key to the success of the transition, there is still relatively little discussion along those lines among national and global policy makers. That's understandable, given that economic growth requires more energy, and politicians have learned that pro-growth policies are the key to winning elections. This is why climate discussions among political leaders quickly turn away from the subject of limiting consumption and toward carbon offsets and emissions reduction targets that are merely aspirational and that have failed to rein in fossil fuel dependency and global warming. It's also why climate activist Greta Thunberg characterizes most global climate policy discussion as "blah, blah, blah."

Energy transition modeling is complicated and imperfect. But its conclusions so far should be an urgent wake-up call for policy makers everywhere. Hello Washington, Geneva, and Beijing: is anyone listening?