Thinking in Energy Systems

Robert A. James *

"When we try to pick out anything by itself, we find it hitched to everything else in the universe."[1]

We find it convenient to refer to energy as an industry or sector, but it is also a system—a web of interconnected components and values that creates and delivers services around the world. When one of those components or values is changed, whether passively or purposefully, the system changes with it. How do we connect one individual element of an energy transition to other elements in the space?

Conceiving all those individual elements and their connections can lead to a characteristic type of random thinking, followed by a characteristic sense of learned helplessness. We say, "well, *this* is connected to *that*, and, oh, *that* is connected to *this other thing,* and—oh, my goodness, it's too complicated, I just can't deal with it." How do you navigate these waters? How can you think enough, but not too much, about energy issues and policies? Allow me to illustrate.

1. Of Podiums and Systems

Figure 1.[2]

This is a very familiar scene across America these days. An executive of some sort—a president, a governor, or a CEO—smooths his or her hair, adjusts the gooseneck microphone, clutches the

---

* Partner, Pillsbury Winthrop Shaw Pittman LLP, San Francisco and Houston; Senior Research Fellow, Institute for Responsible Carbon Removal at American University. This article is based on a speech given to the Contemporary Issues in Energy undergraduate class at Northwestern University on November 6, 2023. The author thanks his Pillsbury colleague Allan C. Van Vliet for research assistance.

[1] JOHN MUIR, MY FIRST SUMMER IN THE SIERRA 211 (1911).

[2] Daniel Kim, Photograph of California Gov. Gavin Newsom announcing ban on new internal combustion cars starting in 2035, *in* Rachel Becker, *Newsom Orders Ban of New Gas-Powered Cars by 2035*, CALMATTERS (Sep. 23, 2020), https://calmatters.org/environment/2020/09/california-ban-gasoline-powered-cars-in-2035/.

podium, and announces an audacious energy transition goal. Here in Figure 1 we see Gavin Newsom declaring that no new cars sold in the state of California by 2035 will be gasoline- or diesel-powered; they will be "zero-emission vehicles" based on batteries or hydrogen fuel cells.[3] This scene has been repeated at gubernatorial podiums in Maryland, in New Jersey, in New York.[4] (It has not occurred to date at podiums in interior states. We will see whether it happens between the coasts.)

The press reports these announcements with active verbs—"banning," "requiring," "phasing out"—as if they have taken effect; you might as well book them. What happens after the podium is deserted? How is such a goal to be achieved? The chief executive strolls off camera, but surely something more has to happen.

> The State Air Resources Board, to the extent consistent with State and federal law, shall develop and propose:
>
> a) Passenger vehicle and truck regulations requiring increasing volumes of new zero-emission vehicles sold in the State towards the target of 100 percent of in-state sales by 2035.
>
> b) Medium- and heavy-duty vehicle regulations requiring increasing volumes of new zero-emission trucks and buses sold and operated in the State toward the target of 100 percent of the fleet transitioning to zero-emission vehicles by 2045 everywhere feasible and for all drayage trucks to be zero-emission by 2035.
>
> c) Strategies, in coordination with other State agencies, U.S. Environmental Protection Agency and local air districts, to achieve 100 percent zero-emission from off-road vehicles and equipment operations in the State by 2035.

Figure 2.

In California, here in Figure 2 is what initially happened: an executive order that was issued that very day.[5] In it, the Governor tells the California Air Resources Board what to do. (The agency in charge is an environmental board, not a unit that regulates vehicles like the Department of Motor Vehicles.)

The executive order has three parts. As an aside, this is a warning for any of you thinking about going into law. The danger is that you will begin proofreading restaurant menus, movie credits, bus advertisements—you will parse anything you read with intense scrutiny. The order states all new passenger vehicles "sold" in the state must be zero emission by 2035. For heavy-duty trucks, it states "sold and operated." For off-road vehicles, it states "operations." Why did they use these

---

[3] *Governor Newsom Announces California Will Phase Out Gasoline-Powered Cars & Drastically Reduce Demand for Fossil Fuel in California's Fight Against Climate Change*, Sept. 23, 2020, OFFICE OF GOV. GAVIN NEWSOM, https://www.gov.ca.gov/2020/09/23/governor-newsom-announces-california-will-phase-out-gasoline-powered-cars-drastically-reduce-demand-for-fossil-fuel-in-californias-fight-against-climate-change/.

[4] Sean Tucker, *Maryland Becomes 7th State Banning New Gas Car Sales After 2035*, KELLEY BLUE BOOK (Mar. 15, 2023), https://www.kbb.com/car-news/maryland-becomes-7th-state-banning-new-gas-car-sales-after-2035/.

[5] Office of the Governor of California, Exec. Order No. N-79-20 (Sept. 23, 2020).

different wordings in the three sections? Few if any people know at the moment. But I guarantee you that some lawyer is already thinking about this.

The air board later emphasized that "the regulation applies to automakers (not dealers) and covers only new vehicle sales. It does not impact existing vehicles on the road today, which will still be legal to own and drive."[6] So when the order bans sales in the state, the target is the worldwide manufacturers that want to sell to dealers or buyers in California. The board is not out to bring cases against dealers or consumers for selling or buying a fossil-fueled vehicle.

Since the order thus applies to sales by automakers of "new vehicles," existing vehicles will exist in an entirely separate regulatory process and market. They may not be banned, but what is going to happen to those cars?

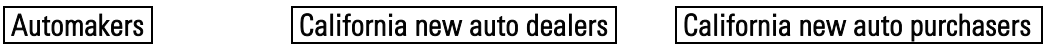

Figure 3.

Already we have the beginnings of an energy system. As Figure 3 illustrates, we have automakers, who are selling to dealers, who are selling to purchasers. In 2024, auto sales are a mixture of internal combustion engine vehicles (what I will refer to as "ICE"); hybrids that are both ICE and electric; and purely electric vehicles (powered by batteries or, mostly for municipal buses or fleets, by hydrogen fuel cells). The goal envisions a future system where, in 2035, all new California sales are of zero–emission vehicles.

A system set up with a number of elements leaves what I will call "boundary issues." (I started off calling them "loopholes," but that may be too pejorative.) What happens to auto dealers in Reno and Las Vegas when a rule comes down that people can no longer buy an ICE vehicle in California? What will happen to recent graduates who drive their gasoline-powered cars from Evanston, Illinois to their new jobs in Los Angeles? A regulation of this type used to enforce a goal always has boundaries.

Three boxes cannot really be the beginning or the end of any energy system. In this case, for the system of electric vehicles, one can imagine just randomly rattling off questions of the type raised in a late-night dormitory hallway bull session. How do we make all these electric vehicles (EVs)? What components are needed to make them? What skills are needed to make EVs that are different from the skills for making ICE? How are they going to be sold, and to whom? Are we going to have the proverbial two cars in every garage, or is the future of EV ownership going to be Zipcar, Uber and Hertz—fleet purchasers rather than individuals?

Right now, people can buy EVs, and by and large they do not. Even in California, where EVs are more popular than in the rest of the nation on average, they were about 22 percent of the market

[6] CALIFORNIA AIR RES. BD., *California Moves To Accelerate To 100% New Zero-Emission Vehicle Sales By 2035*, Release No. 22-30 (August 25, 2022), https://ww2.arb.ca.gov/news/california-moves-accelerate-100-new-zero-emission-vehicle-sales-2035.

through the first nine months of 2023. Adding hybrid and fuel-cell vehicles does not change the result very much–ICE vehicles were still nearly two-thirds of the market.[7] What makes people buy EVs, and what makes people wary of buying them?

In what locations and under what conditions will all these EVs be charged? What is the charging radius needed to avoid consumer "range anxiety"? Where does the electricity come from? If the answer is coal-fired power, what have you gained in an environmental sense by mandating EVs in the energy transition?

What will be the impacts on urban and rural social equity? Is it environmental justice to have lots of charging stations in urban areas, or would such a concentration be further injustice? We have not yet been through an EV product cycle. Is there a market for used Teslas, or let us say "vintage Teslas," that people will always want? (Spoiler alert, most of us tend to prefer the latest gleaming new thing.)

We can rattle off all of these questions in a random manner. And if you randomly rattle, most of us and especially policymakers would eventually throw our hands up and say, "Well, it's too complicated. All these things will have to get worked out by someone. I'm still going to require EV sales and let the world shake out for itself." That is where we can get into problems of what I call underthink and overthink, bookend cases where we do not think systematically.

Here is an example of underthink about a component needed to make EVs. I found a story that points out, quite rightly, that EV production requires an increase in production of special materials.[8] They include lithium, rare earth elements (such as neodymium – more on this later), and other minerals. In the United States, concentrations of those minerals happen to be found in arid regions often associated with lands occupied (both presently and historically) by Native American tribes. The article showcases a proposal from a law school professor to prohibit mining adjacent to sites of particular importance to Native American tribes. But the professor also says that the transition to EVs is important for achieving climate and environmental justice goals.

All of these statements can be true; all of these statements are true. Mining is needed for EVs, concentrations are found in or near Native American properties that deserve protection, and greater EV use is important to the climate. How do you reconcile all of those truths? If you just say, "don't mine materials essential for EVs here" yet you also say "EVs are essential," your thought is incomplete. You put a period on a thought, but it really should have been a comma. As it stands, you may simply be transferring the burden of mining from an American indigenous location to an indigenous location somewhere else that does not have the same political advocacy behind it. At least as presented in the article, this is underthink. It is not that the concerns voiced are not important or correct. It is that one should say "mine not here *but there, here's why,*" or "make EVs

---

[7] CALIFORNIA NEW CAR DEALERS ASS'N, CALIFORNIA AUTO OUTLOOK, 2 (Oct. 2023), https://www.cncda.org/wp-content/uploads/Cal-Covering-3Q-23_FINAL.pdf.

[8] *Electric Car Revolution Puts Native Communities at Risk,* LEWIS & CLARK LAW SCHOOL NEWSROOM (August 4, 2023).

without mining so much of this material or mining in such a destructive way, *here's how,"* or "make fewer vehicles of any kind necessary overall, *here's how."*

In contrast, overthink is what I have already described as the dorm-hallway conversation, the sense that we cannot do anything until we tackle all of life's problems and figure out answers to all of life's questions. Overthink is saying "since we can't solve everything, we'll take no action until it's all clear."

In any event, that is my topic—what is an entire energy system, and how we can think enough and not too much about it. I am here considering an energy system both as an activity and as a culture.

An energy system is an economic activity. The activity includes producing a primary form of energy, whether fossil or renewable; transforming it into vehicle fuel or electricity; and getting those products to people for their use. End use can be a vehicle, an appliance, a factory, a home, any thing or any place that again transforms that energy.

An energy system is also a cultural phenomenon. We have global and local differences in how we use energy, how we produce it, how we distribute it across our citizenry, and to what applications we put energy to work.

Right up front I must add a complication, namely that systems are made up of systems themselves. To make a vehicle, you need components; to make a component, you need sub-components. Here is where lurks the imminent danger of overthink, or what is sometimes called "analysis paralysis": "There's too much to think about, therefore I won't think about it at all."

2. Systems Thinking of the Woodstock Generation

I will first travel back in time to learn from a couple of prior attempts to think about systems. I will apply that learning to what I will introduce and describe as "an electric vehicle ecosystem." "Ecosystem" is a little grandiose, perhaps, but it helps me think in terms of life cycles and biological relationships. I like that metaphor.

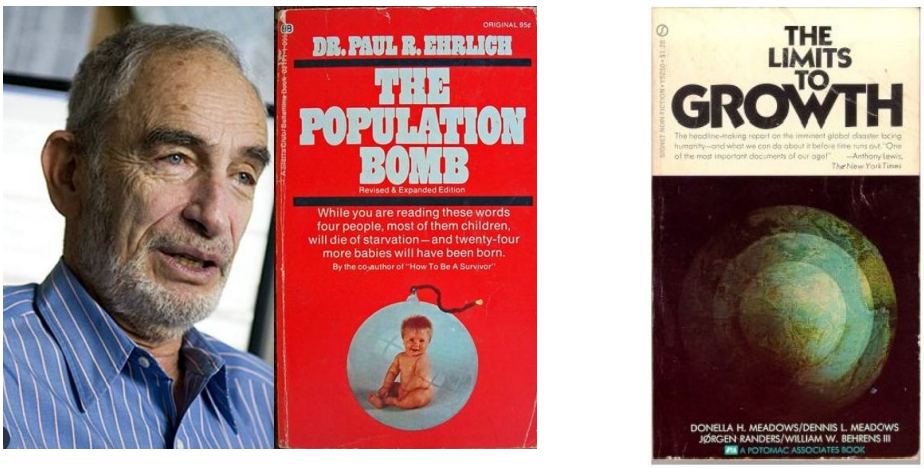

Figure 4.

The two examples I cite hail from the era of present-day college students' grandparents. These are books that you might have found in a milk-crate bookshelf in an off-campus apartment, next to the lava lamp, candles and vinyl records. One is Paul Ehrlich's *The Population Bomb,* and the other is *The Limits to Growth* sponsored by something called the Club of Rome.[9]

The Population Bomb cover had the cartoon bomb you see in Figure 4, a circle with a lit fuse, the explosive you find in the Stratego board game or the "Itchy & Scratchy" cartoon on *The Simpsons*. *The Limits to Growth* cover shows the Earth itself shrinking. These works date to what I refer to as the Woodstock Generation, the era of the original 1969 music festival: *The Population Bomb* was published in 1968, *Limits to Growth* in 1972.

a. The Population Bomb

Paul Ehrlich was a biologist, still is, at Stanford University. He was also a member of the Sierra Club, whose president asked him to write a book on the relevance of population to the environment. He and his wife, Anne, drafted a tome entitled "Population, Resources, Environments." Either the Sierra Club or the publisher said in essence, "We can't market this." Paul became sole author of a book titled *The Population Bomb* (after the name of an earlier

---

[9] PAUL H. EHRLICH, THE POPULATION BOMB (1968) (herein POPULATION BOMB); DONELLA H. MEADOWS, DENNIS L. MEADOWS, JØRGEN RANDERS & WILLIAM W. BEHRENS III, THE LIMITS TO GROWTH (1972) (herein LIMITS TO GROWTH).

Each work has been updated over the years. For *The Population Bomb,* see PAUL EHRLICH & ANNE EHRLICH, THE POPULATION EXPLOSION (1990); for *Limits to Growth,* see DONELLA H. MEADOWS, BEYOND THE LIMITS (1992); DONELLA H. MEADOWS, JØRGEN RANDERS & DENNIS MEADOWS, LIMITS TO GROWTH: THE 30-YEAR UPDATE (2004); DONELLA H. MEADOWS, THINKING IN SYSTEMS: A PRIMER (2008). *Cf.* CHARLES C. MANN, THE WIZARD AND THE PROPHET: TWO REMARKABLE SCIENTISTS AND THEIR DUELING VISIONS TO SHAPE TOMORROW'S WORLD 404 (2019) (each update to *Limits to Growth* "as pessimistic or more so than the original book").

pamphlet) that was put out in paperback.[10] It sold modestly for a couple of years, until the book and author were featured in interviews with Johnny Carson.

Johnny Carson was the host of *The Tonight Show,* the program that is currently hosted by Jimmy Fallon. It is difficult to convey to later generations the significance of environmental science being discussed on the *Tonight Show* of the time. The setting might look like a session with Steven Colbert, Bill Maher, or John Oliver, but this show was universal. Republicans and Democrats, liberals and conservatives (spread across party lines at the time, mind you), Northerners and Southerners, people of all ages, backgrounds, and levels of sophistication tuned in to "Carson," as it was called. Johnny's interest in the subject created a large cultural moment. Ehrlich was on the show several nights, and sales of the book belatedly skyrocketed.[11]

Ehrlich's method was to take well-honed population biology concepts used with lower animals and apply them to the human animal in a popularly accessible manner. So stated, this is nothing new; the concept was recently espoused by William Vogt and Eugene Odum and dates back to Reverend Thomas Robert Malthus and his view of the human prospect, cited by Thomas Carlyle as evidence of the "dismal science" of economics.[12]

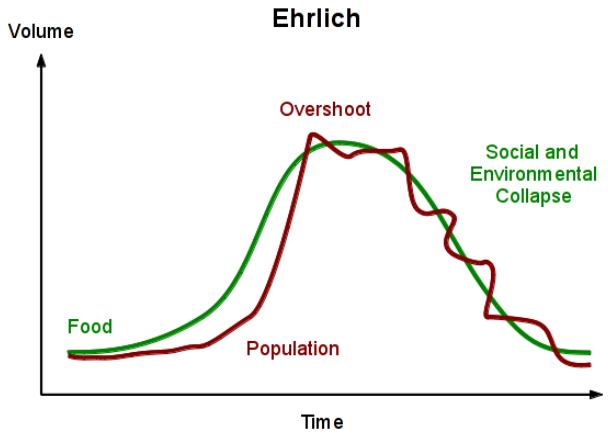

Figure 5.[13]

[10] Charles C. Mann, *The Book That Incited a Worldwide Fear of Overpopulation*, SMITHSONIAN MAGAZINE (January 2018), https://www.smithsonianmag.com/innovation/book-incited-worldwide-fear-overpopulation-180967499/. The formal book was later published as PAUL EHRLICH & ANNE EHRLICH, POPULATION, RESOURCES, ENVIRONMENTS (1970).

[11] Mann, *supra* note 9.

[12] THOMAS ROBERT MALTHUS, AN ESSAY ON THE PRINCIPLE OF POPULATION (1788). *See also* WILLIAM VOGT, ROAD TO SURVIVAL (1948); EUGENE P. ODUM, FUNDAMENTALS OF ECOLOGY (1953); HERMAN E. DALY, STEADY-STATE ECONOMICS: THE ECONOMICS OF BIOLOGICAL EQUILIBRIUM AND MORAL GROWTH (1977).

[13] Michael Minn, "visualization of relationship between population and food resources, as conceived by Paul Ehrlich" *in The Catastrophist-Cornucopian Debate*, MICHAELMINN.NET, https://michaelminn.net/tutorials/catastrophist-cornucopian/index.html.

Figure 5 is familiar to anyone who has had courses touching on Malthus. Food supply is increasing at some rate, but population expands at a greater rate. It is sometimes called an "exponential rate," but that is an often-misused term; see the Appendix to this article for more on that nomenclature.

Eventually population overshoots food supply and declines. As Ehrlich's source William and Paul Paddock colorfully expressed the concept, "sometime around 1958, the stork passed the plow." That downward population curve should not be interpreted lightly. Make no mistake, that decline is associated with pyramids of corpses; that line represents famine, pestilence, wars over resources, ultimately death—the four horsemen of the Apocalypse.[14]

You can experience the apocalyptic dread felt by readers of *The Population Bomb* when you turn to the Prologue and read that it is already too late:

> **The battle to feed all of humanity is over. In the 1970's the world will undergo famines—hundreds of millions of people are going to starve to death in spite of any crash programs embarked upon now.**

You can imagine the cultural impact of this paragraph. Only the Marx-and-Engels opener may top it for mass-market dramatic effect.[15]

The Population Bomb system that was exhibited, at least for public purposes, was a very simple one. Birth and death rates were expressed as so many events per 1,000 population. Ehrlich posited current birth and death rates and expected rates of growth and a more limited increase in food resources. He was extrapolating at a modern peak on world population annual growth rate, 2.09 percent in 1968. In 1966 Costa Rica, for example, there were five children for every woman. Even in the United States there were two and a half children per woman.[16] Ehrlich was projecting population in several countries to double soon after publication; in Costa Rica, by 1983.[17] Hence his prophetic vision of famines sweeping the globe in "the 1970's," the decade spanning two to eleven years after the 1968 publication.

What were the outcomes? By 2018, the annual rate of world population growth had halved, to 1.09%.[18] In the United States, the fertility rate is now less than two; we would be declining in population were it not for immigration of all types. Costa Rica's fertility rate growth decreased a great deal, and though the population did double, it did not do so until 1995—many years after the 1983 projection cited by Ehrlich.[19] As Figure 6 shows, China's fertility rate collapsed from a mid-

---

[14] POPULATION BOMB 37; BIBLE, *Revelation* chapter 6.

[15] POPULATION BOMB vi; *cf.* K. MARX & F. ENGELS, MANIFESTO OF THE COMMUNIST PARTY 1 (1848) ("A spectre is haunting Europe – the spectre of communism").

[16] Timelines, GOOGLE DATA COMMONS, https://datacommons.org/tools/timeline (utilizing data published by The World Bank).

[17] POPULATION BOMB 27.

[18] Worldometers, World Population by Year (accessed January 2024).

[19] *See* Google Data Commons, *supra* note 14.

1960s peak to just over one child per woman in 2022, less than half of the "replacement rate" of just over 2 children per woman needed to sustain a population at equilibrium.[20]

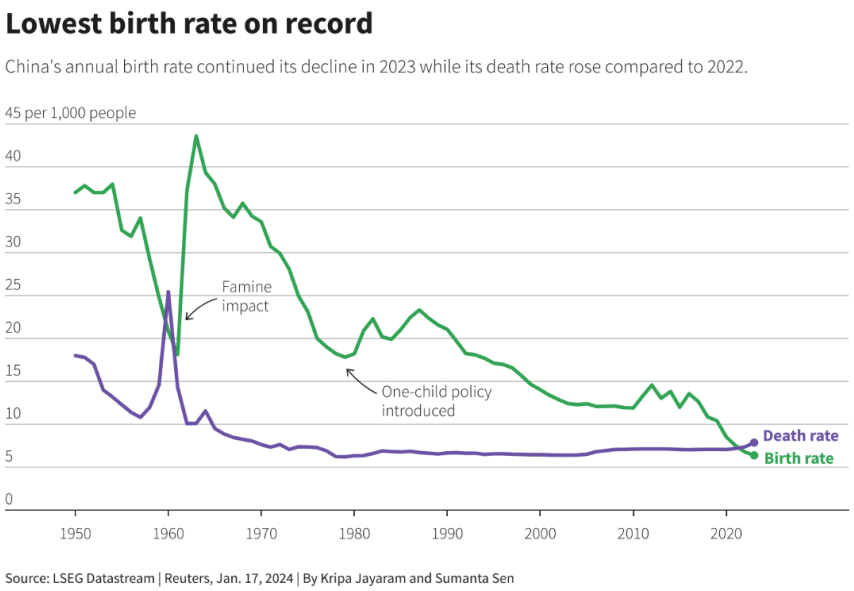

Figure 6.[21]

Nor was the world wracked by massive and widespread famines due to worldwide lack of food. In the seventies, there were in fact zero famines in Central America. There have been horrible famines in Asia and Africa, in Bangladesh and Darfur among other places. But largely we can say with Nobel laureate Amartya Sen that the paramount problem has been not insufficient global calories, but military action and political inaction.[22]

So what happened? Of course, many things happened in the world between 1968 and today. Most notably, there have been greater educational and economic opportunities for women, particularly in agriculturally based countries. Greater female opportunity outside the home or farm is correlated with smaller families. Urban migration and changes in family living patterns also made a difference in family sizes.[23]

Ehrlich quoted with approval Raymond Ewell of SUNY Buffalo, who said, "I don't see how [India] can possibly feed 200 million more people by 1980." Yet it did so. On the food supply side, the great transformation was the so-called Green Revolution led by Nobel laureate Norman Borlaug's

---

[20] *See* Liyan Qi, *How China Miscalculated Its Way to a Baby Bust*, Wall St. J., Feb. 12, 2024; Liyan Qi, *China's Fertility Rate Dropped Sharply, Study Shows*, Wall St. J., Aug. 19, 2023.

[21] Kripa Jayaram and Sumanta Sen, graph of birth and death rates over time in China *in* Farah Master, China's Population Drops for Second Year, With Record Low Birth Rate, REUTERS (Jan. 17, 2024), https://www.reuters.com/world/china/chinas-population-drops-2nd-year-raises-long-term-growth-concerns-2024-01-17/.

[22] *See* AMARTYA SEN, POVERTY AND FAMINES: AN ESSAY ON ENTITLEMENT AND DEPRIVATION (1983); Jeffrey Sachs, *The Real Cause of Famine*, TIME (October 26, 1998).

[23] *See generally* RODOLFO BULATAO, REDUCING FERTILITY IN DEVELOPING COUNTRIES (1984).

work with wheat, coupled with efforts of others on maize and rice. Spectacular increases in cereal yields led to far greater production in places where famines were confidently predicted. Mexico (experiencing a tripling in wheat yield) went from being a food importer to a food exporter. India produced so much wheat that schools had to be used as temporary siloes.[24]

I am not here to say either that the Green Revolution is done increasing food supplies, or that it has been an unqualified success and boon to humankind. There are certainly negative aspects of the Green Revolution in its fostering of crop monocultures, increasing our dependence on fossil-fuel based fertilizers, and shifting economic power to wealthy landowners from poor tenants and laborers.[25] The long term may reveal further shortcomings. But the fact that we are in 2024 without having suffered the great famines predicted over half a century ago, and that we have up to one billion people who are alive today because of the additional food, should give any critic pause.[26] (To be fair, Ehrlich did mention the promising results in Mexico of the high-yield wheat harvest, but he expressed pessimism that the results could be replicated in Asia without the emergence of new pathogens.)

More concerning than Ehrlich's *predictions* of population and famine being off or premature were the potential and actual *prescriptions* for action. In the book he mentioned (before dismissing) the possibility of involuntary sterilization, perhaps by introducing sterilants into "drinking water or staple food," or by mandating vasectomies after the second healthy childbirth. He did not wind up calling for those measures, but the fact that he even talks about them is a bit chilling. He affirmatively championed economic penalties on larger families and "luxury taxes" on childcare goods.[27]

Ehrlich discussed the benefits of "early human sex determination."[28] That is also chilling because, in the absence of breakthrough basic science, that could be heard as a call for the targeted abortion of female fetuses—in cultures where couples tend to continue to produce children until they get a son. Ehrlich partially endorsed the work of William and Paul Paddock, who said that because India will inevitably suffer massive famines, we should cut off food aid to the country right now.[29]

---

[24] *See* MANN, *supra* note 8, at 140-150.

[25] *See* MANN, *supra* note 8, at 154-160 ("By 1968, the Green Revolution was being criticized as environmentally, culturally and socially destructive").

[26] Borlaug said critics never wanted to answer the counterfactual question—where would the world be today if we had the same growth in population and affluence, but none of the yield increases of the Green Revolution. He also acknowledged the Green Revolution was only a temporary if critical reprieve, while world population and especially the uneven distribution of population and resources are brought under control. Norman Borlaug, *The Green Revolution, Peace, and Humanity,* NOBEL PEACE PRIZE LECTURE (December 11, 1970).

[27] POPULATION BOMB 135-140. *See also* EHRLICH & EHRLICH, *supra* note 8, at 201.

[28] POPULATION BOMB 139.

[29] WILLIAM PADDOCK & PAUL PADDOCK, FAMINE—1975! (1967); POPULATION BOMB 161 ("In my opinion, there is no rational choice except to adopt some form of the Paddocks' strategy as far as food distribution is concerned"). *See* DAN GARDNER, FUTURE BABBLE: WHY EXPERT PREDICTIONS FAIL—AND WHY WE BELIEVE THEM ANYWAY (2010) (when Ehrlich endorsed the Paddocks, "[e]ven in 1968 it should have been clear this was glib nonsense").

Good intentions on environmental subjects sometimes go astray or become co-opted by others for their own purposes. Some of the population concerns espoused by Ehrlich and others were seized on by governments. Charles Mann observes, "[t]he results of the campaign were ghastly. Millions of women were sterilized, often coercively, sometimes illegally, frequently in unsafe conditions, in Mexico, Bolivia, Peru, Indonesia, Bangladesh, and, especially, India."[30]

The defenses of Ehrlich and his fellow advocates (and there are many similar authors; I am citing him as a prominent example) are the ones you would expect. Eventually, they say, they are going to be right; and I agree that they well might be. It is a truism that population cannot grow forever, and it remains a concern that population is still growing in the places that are least able to handle that growth, particularly sub-Saharan Africa these days.

These advocates have joined others in casting doubt on the overall merits of the Green Revolution.[31] More recently, they have cited the population, food and energy production impacts of climate change. That is a factor far more in the public eye today than in 1968, although global warming was certainly cited in the scientific literature at the time.[32] They vehemently denied that they intended China and India to do what the governments did with their recommendations.[33]

In one interview Ehrlich was so exasperated he said, "we never made predictions, even though idiots think we have."[34] I winced reading that, because I might be the kind of idiot he was dismissing. But then I recalled that Prologue saying that the battle to feed humanity was already over, that hundreds of millions would die in the seventies despite any crash program. If that's not a prediction, I don't know what is.

b. Limits to Growth

The second book is *The Limits to Growth*. It was the inaugural publication of The Club of Rome, which described itself as an "invisible college" with a limited membership never to exceed one hundred "representatives." The book did not clarify who all those members were or whom they represented.

---

[30] MANN, *supra* note 8, at 400; Craig Welch, *8 Billion*, NAT'L GEOGRAPHIC 75 (Apr. 2023).

[31] *See* Paul R. Ehrlich & Anne H. Ehrlich, *The Population Bomb Revisited*, 1 ELEC. J. OF SUSTAINABLE DEV. 3 (2009) (defending the original book by suggesting that the agricultural gains of the Green Revolution came at the cost of "serious ecological risks").

[32] *See, e.g.*, Gilbert N. Plass, *The Carbon Dioxide Theory of Climatic Change*, 8 TELLUS 2 (1956).

[33] See Mann, *supra* note 9 (Ehrlich argued that "he did not advocate for the programs' brutality and discrimination"). However, when China ended the one-child policy in 2015, Ehrlich tweeted "GIBBERING INSANITY – THE GROWTH-FOREVER GANG." He elaborated, in the *Grist* interview cited immediately below, that China "has done miracles with a relatively coercive program, but I think now we could get birthrates where they belong without much coercion."

[34] *Paul Ehrlich, Famed Ecologist, Answers Questions,* GRIST MAGAZINE (Aug. 10, 2004). Deep into the 1968 book, Ehrlich offers three very specific scenarios, with details like a war in Thailand, nuclear attacks, and a preferred case of only 500 million fatalities (requiring cessation of food shipments to India and Egypt as "hopeless cases"). POPULATION BOMB 72-79. It was only in reference to these very specific writeups that he uses the terminology of scenarios.

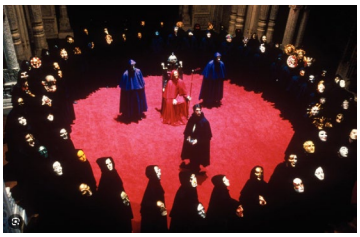

Figure 7.

Growing up before Wikipedia, I had the idea that this was some sort of secret cabal, convening in clandestine locations with wild conclaves and exotic costumes, something like the film *Eyes Wide Shut*. Imagine my disappointment when I found it was a bunch of people in gray suits. I mean, which of the two parties in Figure 7 would *you* rather go to?

The Club of Rome commissioned this study in the heyday of the massive, room-sized mainframe computer. Based on work by Jay Forrester of the Massachusetts Institute of Technology (MIT), a team led by Dennis Meadows of MIT studied a few more elements of a "world system" than at least what Ehrlich presented in his paperback. Not just population, food, and energy, but also industrial measures such as capital stock, nonrenewable resources like oil and gold, pollution, and technology development.[35]

One core assumption was that industrial output drives wealth, and wealth leads to the ability to maintain a population. The economic health of a society was thought to be based on its industrial output. The MIT researchers ran multiple rate scenarios through their programs and reported what the numbers and programs indicated.

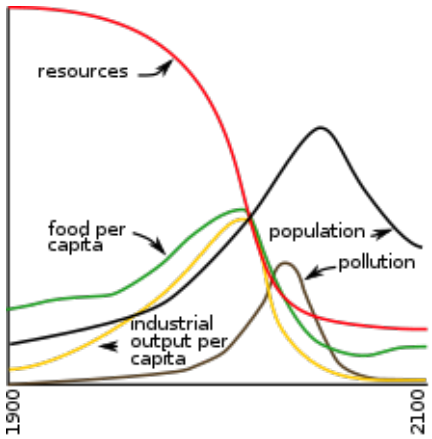

Figure 8.[36]

[35] A helpful summary of the *Limits to Growth* model, and its implications and reception, is Brian Hayes, *Computation and the Human Predicament*–The Limits to Growth *and the Limits to Computer Modeling,* AMERICAN SCIENTIST (May-June 2012). Hayes concludes that *Limits* was useful but was also "a polemical tool."

[36] LIMITS TO GROWTH 124.

Figure 8 is the famous so-called "apocalypse chart" from the *Limits to Growth* book. The accompanying language is more conditional and measured than that of Ehrlich, essentially that "*if* these trends continue, *then* there will be a collapse."

The researchers still maintained that such a decline, if it happens, would be "sudden and uncontrollable." That dark population curve softly decreasing well before the year 2100 is again associated with famine, death, pestilence and war—all the horsemen of Revelation. They stated, "The basic behavior model of the world system is exponential growth of population and capital, followed by collapse," and concluded, "Under the assumption of no major change in the present system, population and industrial growth will certainly stop within the next century, at the latest." But the Club of Rome folks still held out hope that we could avoid this calamity. And to that end, they ran other charts to show how that salvation could occur by living within our means.[37]

The MIT researchers stood by the outputs, averring that the basics are "so fundamental and general that we do not expect our broad conclusions to be substantially altered by further revisions." I grant that these were all explicitly described as scenarios. However, all of the scenarios, including those assuming diversionary and corrective actions, were off. Not a single one corresponded to actual experience in the time frame indicated, though there are some that are now considered consistent with measurements over longer periods.

They predicted commodity price increases that rarely approached actual levels. *Limits* was said to have underestimated the price mechanism: when resources get costly, we substitute for them or find technologies to improve extraction or efficient use.[38]

World GDP continues to increase. We have learned that industrial output is not the only contributor to wealth. We are a far more service-oriented and technology-driven society. *Limits* allowed some factors like pollution to grow for long periods "exponentially"—that overused term, see this article's Appendix!—while others like technology were assumed to grow only "linearly." I would argue the opposite occurred, that after 1972, technology emerged as the factor with greater rates of growth. Moore's law of semiconductor density may finally have lost its head of steam, but it enjoyed a very good run for a very long time.[39]

---

[37] "1. If the present growth trends in world population, industrialization, pollution, food production, and resource depletion continue unchanged, the limits to growth on this planet will be reached sometime within the next one hundred years. The most probable result will be a rather sudden and uncontrollable decline in both population and industrial capacity. 2. It is possible to alter these growth trends and to establish a condition of ecological and economic stability that is sustainable far into the future. The state of global equilibrium could be designed so that the basic material needs of each person on earth are satisfied and each person has an equal opportunity to realize his individual human potential." LIMITS TO GROWTH 23-24, 126, 142.

[38] *See* JULIAN L. SIMON, THE ULTIMATE RESOURCE (1981); JULIAN L. SIMON, THE ULTIMATE RESOURCE 2 (1996); PETER A. VICTOR, MANAGING WITHOUT GROWTH: SLOWER BY DESIGN, NOT DISASTER (2008).

[39] *See* Allen V. Kneese, *Resources for the Future Testimony before U.S. Congress House Committees,* 1973; David Rotman, *We're Not Prepared For The End Of Moore's Law,* MIT TECH. REV. (Feb. 24, 2020), https://www.technologyreview.com/2020/02/24/905789/were-not-prepared-for-the-end-of-moores-law/; Wallace Witkowski, *'Moore's Law's dead,' Nvidia CEO Jensen Huang Says In Justifying Gaming-Card Price Hike,* MARKETWATCH

Limits underestimated the changes in technology. For example, after 50 years of pumping oil, the Kern River field in California was estimated to hold only 47 million barrels in 1949. Enhanced oil recovery techniques including water and steam were introduced. By 2009, 1.3 billion barrels had been produced from that field—and reserves were now estimated at 600 million barrels.[40]

The researchers missed the importance of renewables, saying "pollution-free solar power" "probably would come too late to avert demographic or environmental disaster."[41] (In 2022, renewable sources produced 29% of the world's power.[42]) In 1972, they did not know about the extent of offshore oil, or the availability of hydrocarbons from shale formations, or offshore wind. Other changes have come through plain old human resourcefulness in production, manufacturing, or consumption.

c. Lessons Learned

What lessons can we take from these two analyses of the Woodstock generation?

I give each credit for identifying a manageable number of factors, and expressing quantities and relationships in quantitative terms so that we can calculate predicted results and observe variances from measured results. These expressions are useful and bear a family resemblance to the kind of modeling we employ in studying climate change and other aspects of the energy transition.

I further credit them for launching a wide-ranging discussion of the impact of population and the relation of industrial activity to growth and prosperity. We might disagree with the formulas and conclusions, but they caused the subjects to be publicly debated to a greater degree than in prior decades. There certainly are positive outcomes of both *The Population Bomb* and *Limits to Growth*.

There are also a series of observations that any of us can make about these works that are constructively critical in nature. Acknowledging the unfair benefit of hindsight, and subject to all my personal biases as an American energy lawyer of my generation in private practice, I offer the following thoughts.

First, all of these output quantities depend on a large number of factors, not all of which were captured in the models. You should not represent any output with just a line. A one-dimensional forecast is an exercise in hubris. Such projections should be bands of uncertainty, and the bands should expand as time progresses. The analysts must admit to us (and to themselves) that there is some play in each of them.

Second, scenarios are for brainstorming more than they are for policy advocacy. The *Limits to Growth* researchers explicitly framed their alternatives as scenarios, and Ehrlich said his overall

---

(Sept. 22, 2022), https://www.marketwatch.com/story/moores-laws-dead-nvidia-ceo-jensen-says-in-justifying-gaming-card-price-hike-11663798618 .

[40] MANN, *supra* note 8, at 400.

[41] LIMITS TO GROWTH 145.

[42] INT'L ENERGY ASS'N, *Renewable Energy Progress Tracker* (Jan. 11, 2024), https://www.iea.org/data-and-statistics/data-tools/renewable-energy-progress-tracker .

conclusions were scenarios. Both took comfort and refuge in saying "this was just one scenario; another might lead to a different result, or take place over a different number of years." If you are writing a science fiction novel, or commissioned to brainstorm possible multiple outcomes, that may be acceptable. If you are going to argue for a policy, though, urging powers that be to take or refrain from a specific action, then dealing in scenarios is insufficient. Saying "I want to change the world, I want you to do this and stop doing that, but hey, that is based on a scenario that may or may not happen?" Not for me. At least the range of scenarios you present should include at least one that approximates recent experience, as one possible future experience within the relevant time frame.

Third, predictors of any stripe need to take a bit more ownership of what they were doing. If you make a prediction, do so with a band of uncertainty and a dollop of humility, and reveal your doubts about the measures and relationships. Admit when a prediction turns out to be wrong, and join the rest of us in exploring why it was wrong (or perhaps only premature).

Fourth, systematic thinking requires work across disciplines. These include not just science and technology but also social fields—economics, sociology, psychology, political science, and awareness of cultural attitudes.

Fifth, a call to action should be actionable. Be specific what a decision-maker is to do with your analysis. Some latter-day green analysts say we should have fewer vehicles, not cleaner ones—that even an eco-conscious car in every driveway is a "climate disaster." The question for them was not whether we should have EVs or ICEs, it was whether you should have a car at all.[43] But they have not yet convinced a politician to take such an action, such as proclaiming that people in (say) Wyoming should take the bus or bicycle to their jobs. Their vision of a world with greatly diminished individual motorized transportation needed more of an advocacy plan.

Sixth and finally, a call of action should be honorable. By that, I mean the analyst must consider what might happen to recommendations when they fall into other people's hands. It is insufficient at the least to say, "We didn't intend a government to apply coercive measures to disfavored populations."

To reiterate, I think both of these books are still important. I still have them on my shelf, upgraded from a milk crate. I enjoyed re-reading them and newly reading the updates. The issues they describe have not gone away. Furthermore, I believe they have inspired many good examples of thinking in energy systems.[44]

---

[43] *See* Ailessa Walker, *An EV in Every Garage is a Climate Disaster,* NEW YORK, Jan. 25, 2023, Walker in turn cites a report entitled "Achieving Zero Emission with More Mobility and Less Mining" (advocating mass transit, walking, and biking instead of so many vehicles of any type, whether EV or ICE).

[44] *See* Eric A. Taub, *Building a More Sustainable Car, From Headlamp to Tailpipe,* N.Y. Times, Sept. 9, 2021; Eric A. Taub, *E.V.s Start with a Bigger Carbon Footprint But That Doesn't Last,* N.Y. Times, Oct. 19, 2022; Brad Plumer, *To Cut Emissions to Zero, U.S. Needs to Make Big Changes in Next 10 Years,* N.Y. Times, Dec. 15, 2020.

We live in a world of constraints. That fundamental message of these books still holds. However, extrapolating on rates and curves to the degree that they did should give us some pause. These works provide us with some teachable moments for how to think anew about any energy system.

3. An Electric Vehicle Ecosystem

Now I return to where I started out, which is to talk about EVs.

In the podium example, we saw a simple policy system: the government regulates the automakers and the other two actors fend for themselves accordingly. The policymaker's impulse is to target one element in the energy system. But if you narrow your focus like that, the other elements and their development tend to be discussed randomly, in that dorm-hallway bull-session style, without being systematic.

So, with apologies for the pun, fasten your seatbelts. Here as Figure 9 is my vision of one way to think about an electric vehicle ecosystem.

An Electric Vehicle Ecosystem

1. Components	*2. Manufacturing*	*3. Distribution*
4. Ownership	*5. Demand Factors*	*6. Charging & Power*
7. Maintenance	*8. Life Cycle*	*9. Stranded ICE*
10. Equity & EJ	*11. Policy Boundaries*	*12. Crossovers*

Figure 9.

I proceed on the assumption that nobody can keep more than about a dozen things in his or her mind very effectively. That is about the carrying capacity of a telephone number with an area code and an extension. More than twelve elements is just an externally maintained list and no one can keep all of them in view at a time. So I try to confine my factors to a dozen or fewer—but I also cheat, by making that a dozen at any level of thinking. Any of the dozen elements can harbor a nestled dozen, and so on.

I present this top-level dozen as a quartet of trios. The first three elements should be familiar to you from the podium example: what components are needed to make an EV; how do you make an EV; and how do you distribute those EVs to the end user.

The second trio opens with who are the purchasers of EVs. Next, what makes people eager or reluctant to buy an EV? Then, where are all these EVs going to be charged, and where does the electricity come from?

The third trio starts by observing that these EVs must be maintained in different ways than are ICE. Some ways of maintaining ICE will wither away, but new ways must somehow appear. Next, what happens to old EVs? What is the fate of a (say) 2028 Nissan Leaf in 2035? Will there still be a market for such an asset?

Then there is an element that energy transition advocates do not always like to talk or think about, the "stranded asset." We have all these ICE vehicles already on the road. We have fuel pipelines and storage tanks. We have gasoline and diesel service stations. We have infrastructure not directly related to transportation but that will be impacted by the transition from ICE to EV—assets like backup diesel power generators attached to people's houses. What will happen to those generators when there is no longer enough automotive demand to keep all the service stations open? We have all these people working in an ICE and fossil fuel economy. What are you doing about their employment opportunities? Not only technically and economically, but politically?

My final trio begins as it should with social equity and environmental justice. How does the energy transition create winners and losers, and how can that allocation of outcomes be managed through policy to mitigate impacts on vulnerable populations? How do we protect the interests of people with less voice in the political process?

Next are the policy boundaries. I already gave one example, the Las Vegas and Reno car dealers responding to a California ICE ban, and there are more like that. The twelfth and final element is "crossover," which is another of my cheat codes—a "crossover" is a law student's term for an examination question that straddles several disciplines. I can stick anything I want in that box.

I will not go into total detail on each of these. But I do want to descend one further level—to show you how each of these dozen might be further subdivided.

1. Components

1.1 Semiconductors • 2021 average car, 1200 chips • 2024 EV, double that? • Customized design chips	1.2 Advanced Steel Products • Paper-thin metal • Metal-plastic hybrids	1.3 Advanced Plastics • Lighter, more energy efficient • But still a fossil fuel product • PFAS, plastic recycling challenges
1.4 Traction Motors • 1.4.1 Rare earth magnets • Copper wiring	1.5 Other Critical Minerals • Nickel for steel alloys • Rare earth for glass tinting	1.6 Lithium-Ion Batteries • Lithium • Cobalt, manganese • Electrolytes
1.7 Conventional Auto Parts • Tires, axles, interior, rest of vehicle	1.8 Navigation Systems • Super GPS, connected vehicles (CV) • Autonomous vehicles (AV)	1.9 Testing & Certification • Safety concerns • ASTM, ISO, …
1.10 Component Workforce • Equity/EJ opportunity • Skills training & retraining	1.11 Component Logistics	1.12 Supply-Chain Regulation

Figure 10.

1. Components.

Take element 1, the components that are needed to make EVs. It is remarkable how complicated the modern vehicle of any type, whether ICE or EV, has become. Over a thousand computer chips are needed for a 2021 model ICE. For an EV made in the next couple of years, that figure will

likely be doubled. Chips have been subject supply challenges; many come from Taiwan, which is a politically challenging place to be getting your materials from these days.[45]

Electric vehicles are heavy. A lithium-ion battery pack weighs a lot more than a gas tank. An EV may weigh 500 to 1000 pounds more than a comparable ICE. The 2024 Hummer EV SUV produced by General Motors weighs nearly 10,000 pounds. This impacts the design of existing parking structures that were not designed for all that extra weight. They may require some reinforcement or even some demolition and replacement. All that weight is driving the call for advanced products that have much of the strength without some of the mass. For example, advanced steel and advanced plastics. From where do we currently get plastics? Fossil fuels. Those materials, along with the recycling and supply chain issues, will require solutions.[46]

EVs use traction motors, motors of a different type than what we have in the ICE vehicle. They need special minerals for top performance, and those minerals come from some places that are rather challenging to get supplies from at the moment. Lithium-ion batteries require lithium, of course, but also cobalt and other materials mined in locations that raise logistics and equity issues.

We now have fancy navigation systems to connect the vehicle to the built environment. They need all testing and certification. EVs have been challenged by safety concerns with batteries and navigation systems. People need to be newly trained to design, make and install these new parts. There will be component regulations to cope with. (You can keep on going enumerating these sub-elements. I will keep to a dozen maximum at any level.)

2. Manufacturing

2.1 Design	2.2 Robotics/Workforce	2.3 Plant Siting
2.4 Production Management	2.5 Foreign vs Domestic	2.6 Testing & Certification
		2.9 Manufacturing Regulation

Figure 11.

3. Distribution

3.1 EV Sales Regulation	3.2 Distribution	3.3 Sales Channels
3.4 Sale, Finance & Lease	3.5 Tax and Grants	3.9 Sales Regulation

Figure 12.

4. Ownership

4.1 Who will be the buyers?	4.2 Economics of EV ownership	4.3 Future of vehicle ownership
4.4 Rental market impacts		4.9 Ownership Regulation

Figure 13.

[45] *See* Asa Fitch, *EVs Boost Chip Demand, Despite Semiconductor Makers' Woes,* Wall St. J., March 5, 2023; Seema Verna, *How electric vehicles are revolutionary in semiconductors,* Timestech of India, March 7, 2023.

[46] *See* Bob Tita, *The Paper-Thin Steel Needed to Power Electric Cars is in Short Supply*, Wall St. J., March 27, 2023; Laura Putre, *U.S. Steel bets on mini- mills, EV motors for near-term sustainability,* INDUSTRY WEEK, July 24, 2023.

2. Manufacturing.

Briefly on manufacturing, the question is not whether people *or* robots are used but how are each employed. Where are factories being sited—in the Midwest, in the Sun Belt, or overseas? Will the carmakers keep their inventories close at hand, "just in case," or rely on "just in time" deliveries? The Covid pandemic certainly moved people more towards "just in case," because one cannot count on a port necessarily being open for export or import.[47]

3. Distribution.

Will EVs be marketed through independent dealers? While some EV makers prefer direct distribution, local laws may protect the incumbent ICE dealers. What will happen to the GM or Ford dealer in your hometown as a result of this transition?[48]

If EVs have a different useful life than an ICE, technically or in the consumer's eye, how is that going to affect leasing? Leasing versus purchase decisions have turned for generations in terms of expectation of how long a vehicle is held by one owner or lessee.

4. Ownership.

Who are the EV owners going to be? Is it going to be each of your families having the proverbial two cars in the garage, or are the owners going to be Lyft and Avis? Who are going to be the repurchasers—who buys a used EV at this moment, and who will buy used EVs in the future?[49]

5. Demand Factors

5.1 Demand enhancers	5.2 Demand dampeners	5.3 Advertising & Influence
5.4 Political culture wars		5.9 Advertising Regulation

Figure 14.

6. Charging & Power

6.1 Charger manufacture	6.2 Charger siting	6.3 Chargers and the grid
6.4 Charger operation	6.5 Power for the chargers	
	6.8 Alternatives	6.9 Charger & power regulation

Figure 15.

7. Maintenance

7.1 EV Servicing	7.2 EV Servicing Siting	7.3 Battery Changeout
7.4 EV Repairs	7.5 Insurance for EVs	7.9 Maintenance Regulation

Figure 16.

---

[47] *See* IEEE, *The electric vehicle transition explained*, January 23, 2023; C3 Controls, *Understanding the design and manufacturer of electric vehicles – new trends in technology* (accessed January 22, 2024).

[48] *See* Arlene Karcidis, *EV industry pushed for direct-to-consumer sales option,* Waste360, October 3, 2022; CHARGEPOINT, TRENDS AND PREDICTIONS IN FLEET ELECTRIFICATION (2020).

[49] On Hertz, compare Tim Mulaney, *Post-Covid, Post-bankruptcy Hertz is All-In on Electric,* CNBC, May 14, 2023, with Ian Thomas, *Hertz Makes "Agile" Decision to Shift Strategy and Sell EV, Teslas,* January 24, 2024. For a contrary view, see Congressman Bob Latta, *Rush to expand electric vehicle fleet is misguided,* Washington Times, August 15, 2023.

5. *Demand Factors.*

What makes some of us excited about EVs – that incredible acceleration, the thrill of being part of something new, the potentially lower operating and maintenance cost? I would suggest taking a look at which people jumped to hybrids, then consider what they would do if they needed to rely solely on chargers, rather than being able to charge from a flywheel while they drive.

Conversely, what holds someone back from buying EVs? For starters they cost more, at least in the short term. People are worried about the driving radius from the charging infrastructure, the so-called "range anxiety." 90-plus percent of all rides are less than 20 miles, but people feel they need to have a car that can go several hundred miles between charges. People know a gasoline fill-up takes a certain number of minutes and you are off and running. How long is charging going to take, and are you going to be able to charge up to 100% each time?[50]

What kind of advertising is going to be used to emphasize the desired features and to respond to the problematic features? What kind of social media are going to be used to send those messages?

How do you respond to the culture wars raging right at the moment? To buy or drive an EV in 2024 is to make a political statement. Is that going to increase or decrease over time? How are you going to sell EVs in red-county America?

6. *Charging & Power.*

Where will the chargers be located? Will they go in existing gas service stations? Or will they go in different locations—dedicated facilities, or parts of existing buildings, or the home. Are you going to be able to use your electric vehicle as a way of powering your home during a wildfire or other outage, or for selling power into the grid when that is advantageous?

Where is the power for these chargers going to come from? Is it fossil fuel? If it is not, is it a renewable source that is dependent on the time of day for the sun or the wind? Do you have battery storage that offers a sufficiently large, fast and continuous rate of charging? Right at the moment, people charge during the day at their office or parking garage, or at home overnight on a trickle charge in their garages. How are changes in time and place of charging going to affect energy demand?[51]

---

[50] *See* Robert M Charette, *Convincing consumers to buy EVs,* January 23, 2023; IEEE, *The EV transition explained,* January 23, 2023; Mario Herevez, *Counteracting electric vehicle range concern with a scalable behavioural intervention,* NATURE ENERGY 7 (2022) 503; G. Grishna, *Understanding and identifying barriers to electric vehicle adoption,* TRANSPORTATION RESEARCH INTERDISCIPLINARY PERSPECTIVES 10 (2021) 100364.

[51] *See* PriceWaterhouseCoopers, *On-the-go charging is key to EV growth,* 2024; Philipp Kamshall, *Building the electric vehicle charging infrastructure America needs,* McKinsey, April 18, 2022; Mohammed Shalid Mastori, *An in-depth analysis of electric vehicle charging station infrastructure: policy implications and future trends*, ENERGY REPORTS 8 (2022) 11504; Elias Tibeiro da Silva, *Unleashing the circular economy in the electric vehicle battery supply chain*, RESOURCES, CONSERVATION & RECYCLING 193 (223) 106969.

7. *Maintenance.*

Much will change in the world of maintenance. The transmission shop must be re-conceived in the new environment; changes in EV torque are caused by voltage and current, not by gears of a transmission, whether automatic or manual. These batteries are also going to need to be changed out. How and where is that service going to occur?

Repairs are going to be interesting because EVs are heavier. An EV accident is thus likely to cause and to suffer more damage. How will that affect the risk management market, including individual and fleet insurance? How do you retrain the ICE maintenance workers for some of the new positions?[52]

8. Life Cycle

8.1 EV Aftermarket	8.2 EV Parts	8.3 EV Parts Recycling
8.4 EV Disposal		8.9 Life Cycle Regulation

Figure 17.

9. Stranded ICE

9.1 The vehicles themselves	9.2 Service and repair stations	9.3 Remaining ICEs
9.4 Capital in ICEs	9.5 Government transition assistance	9.6 Workforce Retraining

Figure 18.

10. Equity & Environmental Justice

10.1 Transition Winners/Losers	10.2 Equity in Transition	10.3 Equity in Supply Chain
10.4 Equity in Infra	10.5 Tax and Grants	10.6 Environmental Justice

Figure 19.

8. *Life Cycle.*

What is the useful life of any kind of vehicle? Who buys an older ICE today? I drive a 2011 model; even though it runs great and burns no oil, I am envious of my wife's new hybrid because it has blind spot detection and driver assist. I was getting the state of the art with a new model twelve short years ago. I am not in the market for a new ICE, but I would never think of getting a 2011 car again of *any* type. Some of the traditional motivations for buying used cars may go away.

What is the fate of these old or damaged EVs, and how will they be disposed of at the end of their lives? Can you extract and recycle the valuable parts, and then are the other parts going to stay in America or be shipped them off to another country, with attendant social justice implications?[53]

---

[52] *See* Keith Buglewicz, *How much is electric car maintenance?,* Carmax, June 12, 2023.

[53] *See* Shreg Verna, *Life Cycle Assessment of Electric Vehicles*, MATERIALS TODAY PROCEEDINGS (2024); Cyberswitching, *Electric Car Resale Values: Unveiling the Resilience Of EVs In The Secondhand Market*, Sept. 1, 2023; Ula Chrobek, *What Will It Take To Recycle Millions Of Worn-Out EV Batteries?* KNOWABLE MAGAZINE, November 4, 2022.

9. Stranded ICE.

We must at last face these stranded assets from the gasoline era, the ICE vehicles themselves. There will be fewer and fewer traditional service stations and repair shops. There are many investments set up strategically for the gasoline economy that will not make sense going forward.

Beyond passenger cars, there are still going to be some hard-to-abate sectors that will not convert immediately to EVs. Aircraft and vessels of any scale are not going to be electric for a while; the same may be true of equipment needed for farming, construction, and remote operation. Some industrial materials, like plastics, will still be derived from or produced using fossil fuels.[54]

How is all this activity with the stranded asset base going to be financed? How will capital flow into a sunsetting part of the economy? And how will that sunset affect other parts of the economy – the parts that still rely on these hard-to-convert assets but are themselves retooling for a world without them?

10. Equity and Environmental Justice.

I have been describing along the way some of the social equity and environmental justice elements. Is it just to put chargers in urban America? Or is it socially equitable to keep them dispersed away from urban America? Is justice to be found in proximity of vulnerable populations to the new industrial locations, or in spreading the impacts of cars waiting to charge up farther away?

The equity concerns also apply to the supply chain. Some of the critical EV minerals come from places where American labor and environmental standards are not observed. How will those concerns be dealt with, by moving production to the United States or effecting social change in those other locations?[55]

11. Policy Boundaries.

11.1 California mandates EVs, responses?	11.2 Federal vs. state policies	11.3 State vs. local policies
11.4 Buy American	11.5 Tax and Grants	11.6 Boundary Regulation

Figure 20.

12. Crossovers

12.1 Impact on Transit	12.2 Impact on Political Economy	12.3 Impact on Real Estate
12.4 Autonomous Vehicles	12.5 Impact on Privacy	12.6 Tax and Grants
		12.7 Crossover Regulation

Figure 21.

[54] *See* Cheryl Winokur Munk, *How Gas Station Economics Will Change in The Electric Vehicle Charging Future*, CNBC, August 19, 2023; Clean Mobility Shift, *World's Largest Auto Makers Will Face Stranded Assets and Financial Risks as Transport Decarbonization Takes Centre Stage in Global Climate Action*, November 18, 2022; IEEE, *The Aftershocks of the EV Transition Could Be Ugly*, January 23, 2023.

[55] *See* Neha Palmer, *Access To Electric Vehicles Is An Environmental Issue*, SCIENTIFIC AMERICAN (November 2, 2021); ABT Associates, *Best Practices for Helping Governments Prioritize Equity in the Siting of Electric Vehicle Infrastructure*, 2023; Argonne National Laboratories, *Electric Vehicle Charging Equity Considerations*, January 6, 2022.

11. Policy Boundaries.

Policy boundaries are both interesting and challenging. If California creates an island of EV-only sales in 2035, how will other states respond? Will people in Idaho look at that and consider opportunities to market ICEs to Californians? Many incentive policies in the United States are explicitly conditioned on Buy American procurement. What does "Buy American" mean in the context of EVs? What if, as is likely, other countries or trading blocs retaliate so that it becomes more difficult to sell GM or Ford EVs in Asia? There are going to be all sorts of policy tools, carrots as well as sticks, to try to encourage people to achieve any policy goal. Policies have boundaries, and boundaries lead to strategic behavior.[56]

12. Crossovers.

The crossovers transport us into other topics of all types. Privacy, sub-element 12.5, is a favorite one for me. Your vehicle knows a lot about you. It knows where you have been. It can predict where you are going. What does your EV know, who is it telling, and how can you control or at least be aware of the flow of that information?

Politics in sub-element 12.2 are another interesting topic. ICE are produced in the American Midwest, in Michigan, Illinois, Ohio and Indiana. Many EVs by contrast are made in California, Nevada and now Texas. EV brands are being made overseas for the largest manufacturers, especially those in the People's Republic of China. What are the political impacts of such a shift in industry employment centers? What roles will unions play? What about other political factors, if there is a change in employment concentrations, and therefore of population and legislative apportionment, and therefore of politics?

What happens to public transit in an EV world? Does this transition create a greater or lesser demand for high-speed rail, or other public transit on fixed routes like trains and subways? Are we going to encourage people not to have cars at all, at the same time as we are touting EVs over ICE? All of this is before we even turn attention to autonomous vehicles, which is sub-element 12.4—it was probably a dirty trick to put robot cars into this article, but there they are.[57]

1.4.1 Traction Motors.

And then just to torture you, if I go back up to Figure 10 and the chart for element 1, EV Components, you will see Traction Motors, sub-element 1.4. What goes into a traction motor? Among other things, you need a magnet to make a motor. And to make a specialized magnet, you need some inputs that are referred to as rare earths.

In sub-element 1.4 nested on Figure 10, I ominously labeled a sub-sub-element 1.4.1 on rare earth magnets. And I even created just for scary purposes, Figure 22—a separate 1.4.1 chart just about

---

[56] *See* Collin McKenacher, *EV Policies Twist and Turn as Sunak and Trump Play Politics*, Bloomberg News, October 6, 2023.

[57] *See* EV Adoption, *15 Shifts: How the Transition to Electric Vehicles Will Transform Industries, Jobs, and The Environment*, January 1, 2019.

rare earths for EV motors, with sub-sub-sub-elements further nested inside. Even that level of system detail recapitulates a detailed system of its own.

1.4.1 Rare Earths For EV Motors

1.4.1.1 Light rare earths • Neodymium (Nd) and praseodymium (Pr) • Source of strongest tiny magnet	1.4.1.2 Heavy rare earths • Terbium (Tb) and dysprosium (Dy) • Needed to maintain magnetic force at high temperature	1.4.1.3 Mining • Rare earths very similar chemically • Very different magnetic effects • Water requirements
1.4.1.4 Alloy flakes and metals • NdPr oxides mixed with other materials • Further processing into metals	1.4.1.5 Production of magnets • Metals are "winnowed" and "sintered" • 98% of all magnets made in PRC	1.4.1.6 Tax and grants • Department of Defense grants • Tax credits
1.4.1.7 Magnet finance • Buyer financing through long term supply		1.4.1.8 Magnet Regulation • International trade, customs duties

Figure 22.

Ms. Farnsworth probably did not get to rare earths in your high-school chemistry class. These are the elements with atomic numbers 57 to 71 confusingly and imprecisely stashed way down at the bottom of the conventionally printed periodic table. There are different types of rare earths, some of which are better for different applications. Some, like the element neodymium, are best where you need a very strong and really small magnet.[58] (There are several rare earth magnets in your smartphone, and they are also used in power tools, speakers, wind turbines and defense systems, among many other places.)

Rare earths are mined, separated, and processed into magnets. 98% of the world's finished magnets currently come from China. Currently people are working on restarting magnet production in the United States, but it is slow going. The company that mines raw earth ore in California must currently ship it to China to be made into magnets; it is working with auto companies that want American-made magnets to justify building a factory in Texas to make them here in the United States.

Lo and behold there is sub-sub-sub-element 1.4.1.7, "magnet finance." I mention this level of arcane detail because that is specifically where I currently fit in. I represent that company in negotiating advance purchase agreements so it can build the United States magnet factory. This humble example shows you what path a career may take—from being a student or scholar thinking about energy and environmental policy in broad terms, to also playing a role on one specific but important aspect of the energy transition.

[58] *See* Robert A. James et al., *Critical Materials for the Energy Transition: Of "Rare Earths" and Even Rarer Minerals,* JD Supra, August 11, 2022.

I have touched some but far from all of such elements. I just wanted to show that one, 1.4.1.7, as an example of the detail that one can get into. You might well be saying at this point, "Rob, now we're in analysis paralysis." I would probably have to admit that you would be right.

I still think that humans are capable of analyzing connections between things down to this degree. I cannot do it in a single article like this, but I can certainly imagine a two- or three-day conference where experts in each of these twelve elements, and many of the sub-elements, talk about them in a way that would inform overall policy. That conference would give us a pretty good picture of what it really takes to achieve 100% new zero-emission vehicles in the year 2035.

4. "Nuanced, Bold & Courageous LLP"

There is an adage in science: "all models are wrong, but some models are useful." Creators and users of models should approach them with a great deal of humility and skepticism. They should be simple, so you can tell a compelling story, but they should not be too simple. Neither extrapolating on a curve nor assuming constant conditions is appropriate. You need to say why you think that curve or condition will continue. And if you are tempted to think that nothing will change, remember another adage, this one from economics: "if something can't continue forever, it will stop." Sometimes people forget those twin adages when they start running programs, generating charts, and drawing conclusions.

You should expect politicians, policymakers, and advocates to keep doing what they are doing, which is to hit one convenient target and to hit it hard. They do not typically consider it their job to describe the entire system. They tend to want to seize on a transaction or actor that is, shall we say, politically exposed. In this case, it is popularly more palatable to regulate auto makers than it is to pursue local dealerships or potential car buyers.

But that expectation should not apply to everybody in the energy and environmental discussion. Policy analysts, citizens, students—and by students I include all of us—need to look at the impact on the entire ecosystem. If you are asked to evaluate the prohibition of mining of lithium near Native American property, you should analyze what would be the impact on EV production. Are you just diverting mining of critical materials to some other site, with some unknown impact on some other vulnerable population? Be forthright enough to talk about the entire impact on the system—especially when you are an analyst, or a citizen, or a student.

Know the details. I may be in the minority on this, but I deny that it is analysis paralysis to go to a second or even a third layer of sub-elements beneath the primary elements. (Maybe fourth tier, like "1.4.1.7," went a bit too far; I will concede that one.) It is not overthinking to consider a reasonable number of network connections related to the policy that is under discussion. We can have a conversation in which we keep a number of these concepts in mind, even if at the end of the day this or that particular adjacent subject must be left in the hands of experts.

Even when we cede ground to experts, we should know who those experts are. We can be observant of biases, without being experts ourselves. At some point, all of us run out of expertise. It is good to be knowledgeable about something, but to the left and right of your own expertise, it is ever more important to understand who is undertaking these investigations and how they feel

about the policy issues. If in fact they should be looking at your area of expertise, then it is *you* who needs to speak up in a louder and more persuasive voice.

Two final thoughts. First, you should be nuanced. You should be thinking with care and sensitivity about the detailed changes and variables, and about the interdisciplinary nature of energy, the environment, and the broader culture.

Second, you should be bold and courageous. Do not use all this complexity as an excuse for withdrawal. Do not say that any energy system is so complicated that we should throw our hands up and not try to analyze the necessary elements and their implicit connections.

Be nuanced, but be bold and courageous.

Appendix. What is "exponential growth"?

If you ever hear that something is growing exponentially, or are tempted to say such a thing yourself, please pause and think.

Exponential growth occurs where the variable in a rate equation is an exponent—more precisely, where the variable is a part of a positive exponent greater than one and the entire rate is positive as well. The result is that the rate of growth (the derivative) is proportional to the variable itself. In population biology, the derivative of an exponential growth function might be

$$dN/dt = (b - d)N,$$

where N=population, t=time, b=birth rate, and d=death rate.

Exponential growth shows up where the amount of a quantity at time t+1 depends on the amount of that quantity at time t. Bacteria growth, spread of viruses, compound interest, even Moore's law are exponential in nature for some portion of their relevant life.

A typical exponential growth formula is

$$x(t) = x_0(1 + r)^t,$$

where t is time, x is the quantity at time t, x_0 is the initial quantity, and r is the growth rate.

So if the simple interest rate is 8 percent per year (2 percent per quarter) and you let $10 compound for 20 years (compounded as divided into 80 quarters), you will nearly quintuple your money—you will have $x(80) = \$10(1.02)^{80} = \$48.75$.

The danger of using "exponential growth" in policy studies is that outside of compound interest, real-world trends rarely keep up at such a pace. Little in the real world grows at exponential rates for long. Here are two memorable quotes to live by:

> "Anyone who believes exponential growth can go on forever in a finite world is either a madman or an economist."
>
> "Population growth can obey the exponential equation only under special circumstances and for short periods of time. Any population miraculously permitted to grow at its full exponential rate for just a few years will come to weigh as much as the visible universe and to expand outward at close to the speed of light."[59]

[59] Kenneth Boulding, quoted in EHRLICH & EHRLICH, *supra* note 8, at 159; EDWARD O. WILSON & WILLIAM H. BOSSERT, A PRIMER OF POPULATION BIOLOGY 102 (1971).

Eventually, growth in the real world will run up against limits of inputs or other constraints from the environment. At that point, growth will likely better be described as "logistic," with a plateau, or an oscillation between or among various states.

A logistic curve has derivative

$$dN/dt = r((K - N)/K)N,$$

where K is the carrying capacity of the environment. You can see that as N gets larger it approaches K, and thus the factor (K – N) approaches zero. The resulting derivative, the rate of growth, tapers flat. K, and (K – N) in particular, are where pure mathematics meets messy reality.

Moreover, some non-exponential curves grow more rapidly than some exponential curves for a while. The below chart shows that, given certain coefficients or powers, it is possible that both a linear growth curve (50x) and an algebraic (cubic) growth curve (x^3) will grow *faster* than an exponential growth curve (2^x), at least for a while.

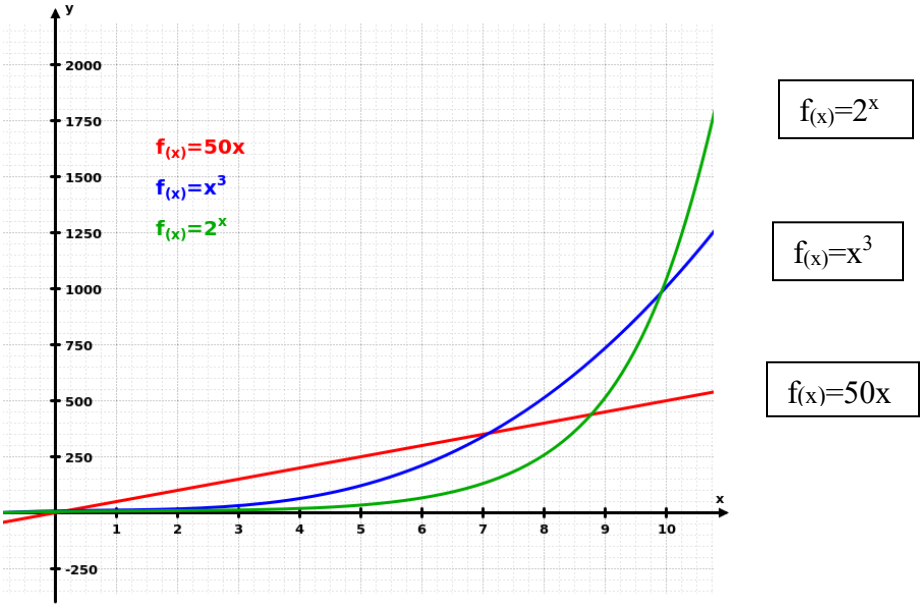

Figure 23.

The distinction matters. Many viruses spread exponentially. The HIV virus turned out to spread at a non-exponential rate. That distinction was critical in public health decision-making.[60]

[60] For an excellent exposition, see Manil Siri, *"Stop Saying 'Exponential.' Sincerely, A Math Nerd,"* N.Y. Times, March 6, 2019.

It can be misleading to say "exponential growth" when all you really mean is "rapid growth" over some limited time interval. Recently, a sports article breathlessly reported that a couple of losses by rivals made another team's path to a number-one seed "exponentially easier."[61] Well, maybe.

Limits to Growth has an excellent discussion of exponential rates and the implicit ceilings on such growth over time. Nonetheless, the researchers allowed exponential rates to take place far longer than what has been experienced in reality.

"Exponential" should not be used as a debater's hyperbole for "a lot." When someone talks about exponential growth, or should you ever get the urge to do so, please dig a bit deeper.

[61] Jose Luis Sanchez III, *49ers Officially Clinch The Number One NFC Playoff Seed After Eagles Loss: The Path To The Super Bowl Grew Exponentially Easier For The San Francisco 49ers*, SPORTS ILLUSTRATED, Dec. 31, 2023.