Halfway Between Kyoto and 2050

Zero Carbon Is a Highly Unlikely Outcome

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Contents

Executive Summary

- This essay evaluates past carbon emission reduction and the feasibility of eliminating fossil fuels to achieve net-zero carbon by 2050.
- Despite international agreements, government spending and regulations, and technological advancements, global fossil fuel consumption surged by 55 percent between 1997 and 2023. And the share of fossil fuels in global energy consumption has only decreased from nearly 86 percent in 1997 to approximately 82 percent in 2022.
- The first global energy transition, from traditional biomass fuels such as wood and charcoal to fossil fuels, started more than two centuries ago and unfolded gradually. That transition remains incomplete, as billions of people still rely on traditional biomass energies for cooking and heating.
- The scale of today's energy transition requires approximately 700 exajoules of new non-carbon energies by 2050, which needs about 38,000 projects the size of BC's Site C or 39,000 equivalents of Muskrat Falls.
- Converting energy-intensive processes (e.g., iron smelting, cement, and plastics) to non-fossil alternatives requires solutions not yet available for large-scale use.
- The energy transition imposes unprecedented demands for minerals including copper and lithium, which require substantial time to locate and develop mines.
- To achieve net-zero carbon, affluent countries will incur costs of at least 20 percent of their annual GDP.
- While global cooperation is essential to achieve decarbonization by 2050, major emitters such as the United States, China, and Russia have conflicting interests.
- To eliminate carbon emissions by 2050, governments face unprecedented technical, economic and political challenges, making rapid and inexpensive transition impossible.

Introduction

Few terms have become as common during the first half of the 2020s as energy transition, decarbonization, and net zero by 2050, all conveying the grand global goal of eliminating fossil fuel combustion—and the attendant emissions of CO_2—by the middle of the 21st century, and hence preventing further undesirable increases of tropospheric temperature.[1] "Net," the zero qualifier, is a hedge that considers the possibility of continued reliance on some fossil inputs whose emissions would be captured from the atmosphere and sequestered, resulting in no additions of anthropogenic CO_2.[2] Unless emission can be decoupled from combustion, severing modern civilization's reliance on fossil fuels is a desirable long-term goal but one that (for many reasons) cannot be accomplished either rapidly or inexpensively.

Globally, coal and oil surpassed wood as the leading energy sources just before the end of the nineteenth century, and hence for the past 125 years we have been a predominantly fossil-fueled civilization (Smil, 2017). In mass terms, we will never run out of fossil fuels: enormous quantities of coal and hydrocarbons will remain in the ground after we end their use because it will be too expensive to extract them. Although the world of the early 2020s is in no imminent danger of running out of fossil fuels, in the long run they would have to be replaced even in the absence of any connections to global warming. Their conversions have made modern civilization possible, but their production, processing, and transportation are often environmentally disruptive, with impacts ranging from land dereliction to water pollution; their combustion generates not only CO_2, but also such pollutants as CO, nitrogen (NO, NO_2) and sulfur (SO_2 and SO_3) oxides and particulate matter; their highly uneven distribution contributes to worldwide economic inequalities; and the quest for secure fossil fuel supplies has led to many detrimental policies and contributed to recurrent conflicts.

Non-carbon alternatives have been making inroads for the past 140 years: the world's first hydroelectric station began to operate in 1882, the same year as Edison's first two

1 Carbon is the dominant constituent of all fossil fuels. Its exothermic oxidation ($C + O_2 \rightarrow CO_2$) releases energy (32.8 MJ/kg) and generates carbon dioxide. Though heavier than the air, the gas mixes rapidly in the atmosphere where it persists for hundreds of years and affects the tropospheric temperature.

2 This implies that effective, affordable, and permanent CO_2 sequestration methods able to operate on scales of hundreds of millions to billions of tons would be available. By 2023 there were about 40 relatively small projects in operation capturing a total of about 45 million tons globally, or a bit more than 0.1 percent of all annual emissions from energy use (IEA, 2023a).

coal-fired power plants started operating. The first commercial nuclear fission reactor was commissioned in 1956, and in 2022 those two modes of electricity generation supplied nearly a quarter of the world's demand.[3] Geothermal generation also goes back more than a century but for many reasons it has never really taken off, while relatively large-scale production of biofuels (above all plant-derived ethanol) has been limited to the USA and Brazil. We remain a fossil-fueled civilization and this brief review demonstrates the high degree of our dependence and low probability, if not impossibility, of energizing the world's economy without any fossil carbon by 2050.

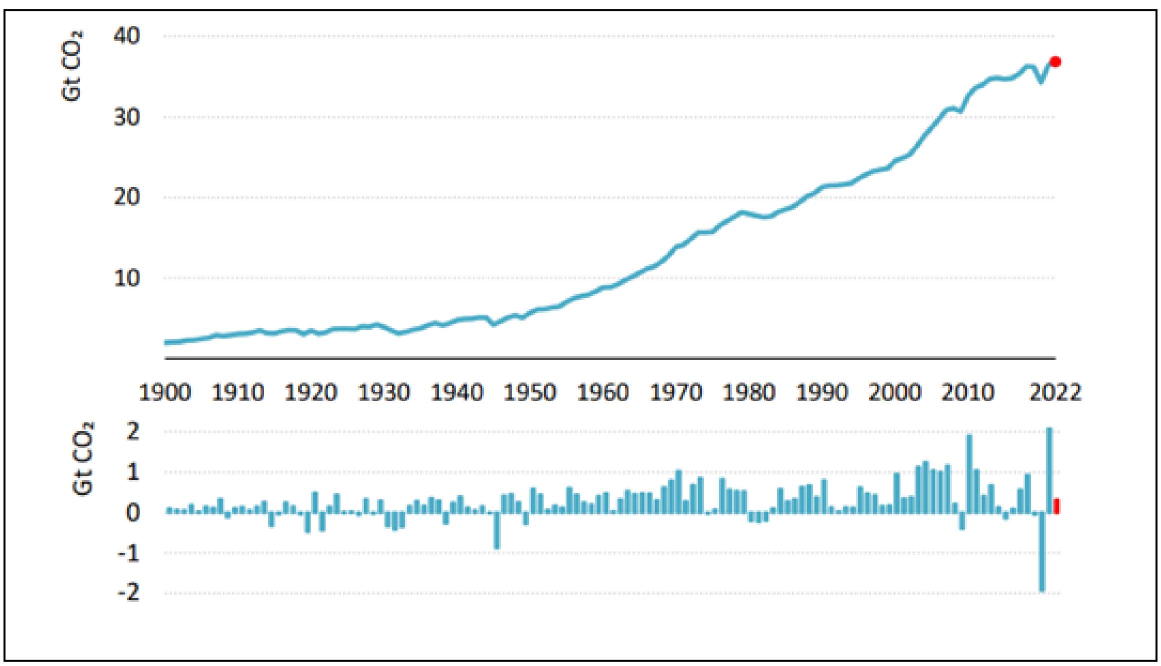
3 All global and national energy statistics can be found in Energy Institute (2023b).

1. Carbon in the Biosphere

The Earth is made hospitable for photosynthesis and habitable for all higher organisms thanks to the regulation of its atmospheric temperature by several naturally occurring trace gases—above all by carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3). Without their presence the planet's surface would be permanently frozen at about -18°C, but by absorbing a small share of the outgoing (infrared) radiation these trace gases keep the mean tropospheric temperature at about 15°C or 33°C higher than in their absence (NASA, 2023).

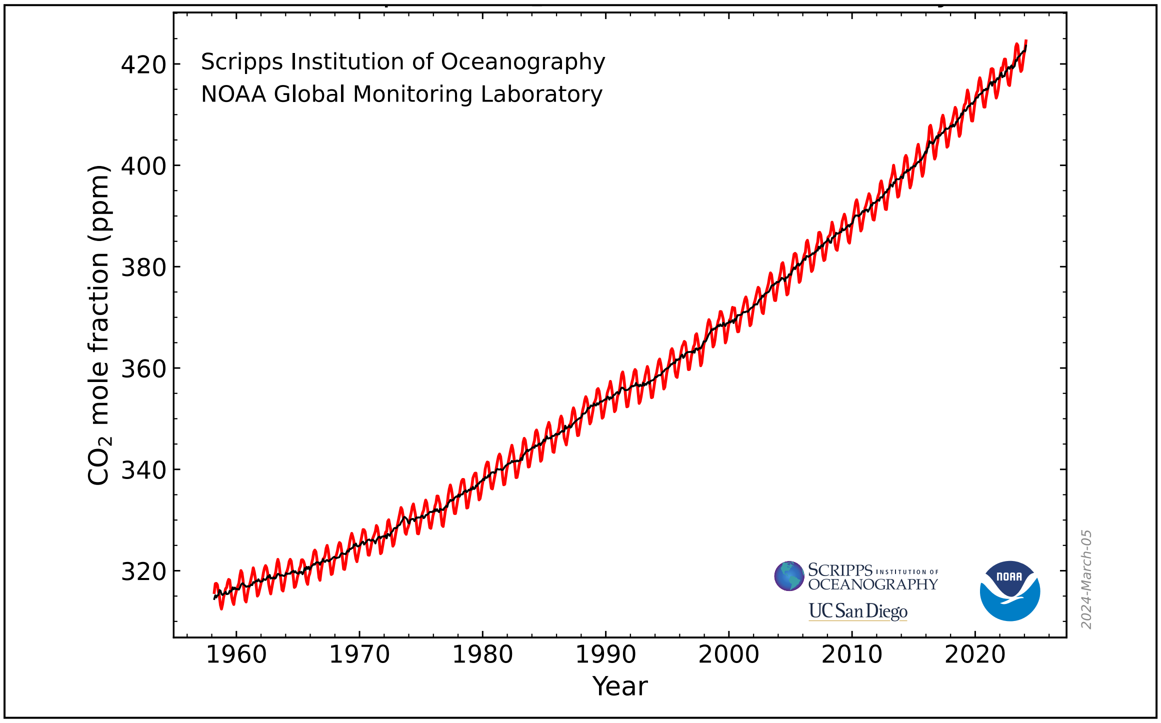
There is nothing new about the realization that these trace gases could affect climate. In 1861 John Tyndall concluded that variation of atmospheric CO_2 "must produce a change in climate" (Tyndall, 1861). In 1896 Svante Arrhenius explained that exponential rise of CO_2 would result in a nearly arithmetic rise of surface temperatures and that the doubling of pre-industrial CO_2 levels might raise the Earth's temperature by 5 to 6°C (Arrhenius, 1896). In 1957 Roger Revelle and Hans Suess concluded that civilization has embarked on a large-scale "geophysical experiment of a kind that could not have happened in the past

Figure 1: Global CO_2 Emissions from Fossil Fuel Combustion Rose 19-fold between 1900 and 2022



Source: IEA, 2023b: 5.

Figure 2: Average Annual CO_2 Concentrations Measured at Mauna Loa Rose by 34 Percent Between 1958 and 2023

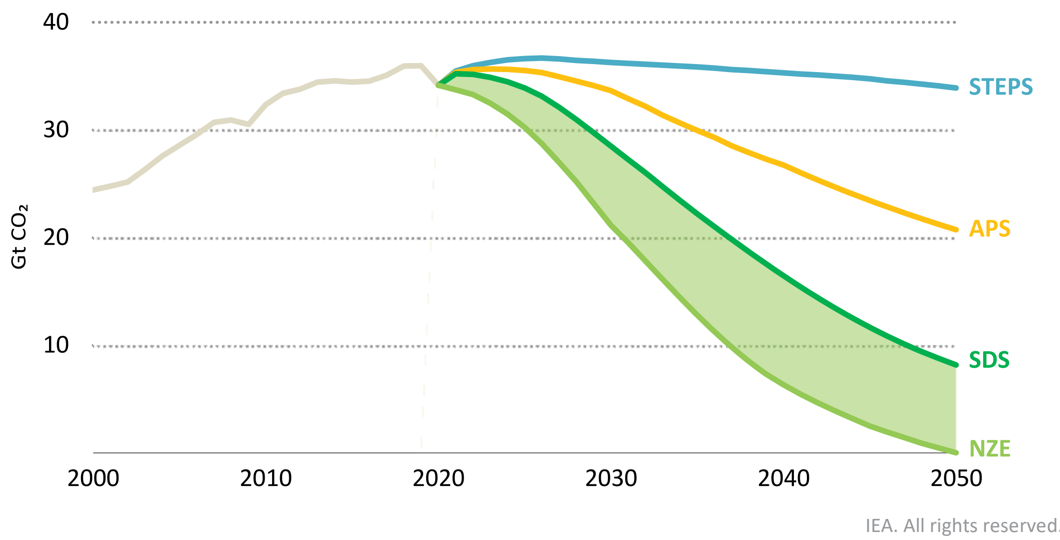


Source: Global Monitoring Laboratory, 2023.

nor be reproduced in the future" (Revelle and Suess, 1957). Just a year later US scientists began to measure CO_2 concentrations at the Mauna Loa Observatory in Hawai'i, which demonstrated their steady annual rise (Global Monitoring Laboratory, 2023). Remarkably, accumulated understanding had no effect on our actions and policies, and it is only since 1988 that global warming began to receive wider public attention when the UN General Assembly endorsed the establishment of the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2021).

Adoption of the UN's Framework Convention on Climate Change (UNFCCC) followed in 1992, and the establishment of its supreme decision-making body, Conference of Parties (COP), in 1995. The Kyoto Protocol, which commits the signatory countries to cut greenhouse gases to "a level that would prevent dangerous anthropogenic interference with the climate system," was adopted in 1997 (UNFCCC, 2023; United Nations, 1998). Since that time the rise in attention paid to the global climate change has been exponential. We have learned a great deal, and although uncertainties remain, basic facts are indisputable.

Figure 3: CO_2 Emissions According to the IEA's Scenarios



The APS pushes emissions down, but not until after 2030; the SDS goes further and faster to be aligned with the Paris Agreement; the NZE delivers net zero emissions by 2050.

Note: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; SDS = Sustainable Development Scenario; NZE = Net Zero Emissions by 2050. After two centuries of rise, fossil fuel combustion is to experience a sudden and steep drop to zero by 2050.
Source: IEA, 2021a: 33.

The best available summaries of global CO_2 emissions show that they increased 19-fold between 1900 and 2022, and that this steady rise was interrupted (for up to three years) fewer than 20 times across the 122-year span (see figure 1) (IEA, 2023b).

Ice core analyses show that CO_2 levels were close to 270 parts per million (ppm) by volume during the preindustrial era; in 1958 (when the Mauna Loa monitoring began) they reached 313 ppm. By the year 2000 they were at 370 ppm, and by the end of 2023 they reached 420 ppm, that is more than 50 percent above the late eighteenth-century level (see figure 2) (Global Monitoring Laboratory, 2023). Notice that the post-1958 rise has been uninterrupted: average annual concentrations show a steady rise that continued even during the years when global CO_2 emissions had temporarily declined: even in 2020, when COVID restrictions cut the emissions by 2 percent, the Mauna Loa level rose by 2.56 ppm.

This rise (together with contributions by CH_4 and N_2O) has translated to about 1.1°C of global warming compared to the late nineteenth-century mean. All continents have been affected. Recent decadal warming gains have been steadily rising and the eight years between 2015 and 2022 were the warmest years on record since 1850 (World Meteorological Organization, 2023). Complex interactions of the atmosphere, hydrosphere, and biosphere and unknown levels of future greenhouse gas emissions make it impossible to pinpoint the degree of global warming that will be experienced by 2050. This brief assessment does not revisit any of these uncertainties and controversies, which have, by now, been widely covered. Instead, it concentrates on the realities, modalities, and probabilities of accomplishing the most important action that many now advocate for keeping the global mean temperature rise to an acceptable maximum: eliminating fossil fuel combustion, specifically, a complete decarbonization of the global energy supply by 2050.

The genesis of this goal goes to the Paris Agreement of 2015 (COP 21) which stated that the world must "achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century" (UNFCCC, 2015). The now common term "net zero" and the year 2050 were used for the first time in the IPCC's *Special Report on a Global Warming of 1.5°C* in 2018: in order to limit the warming to 1.5°C, global net anthropogenic CO_2 emissions must "decline by about 45% from 2010 levels by 2030… reaching net zero around 2050" (IPCC, 2018) (see figure 3).

2. Energy Transitions

The goal of reaching net zero global anthropogenic CO_2 emissions is to be achieved by an energy transition whose speed, scale, and modalities (technical, economic, social, and political) would be historically unprecedented. I will show why the accomplishment of such a transformation, no matter how desirable it might be, is highly unlikely during the prescribed period. What is particularly clear is that (in the absence of an unprecedented and prolonged global economic downturn) the world will remain far from reducing its energy-related CO_2 emissions by 45 percent from the 2010 level by 2030: for that we would have to cut emissions by nearly 16 billion tons between 2023 and 2030—or eliminate nearly as much fossil carbon as the combined emissions of the two largest energy consumers, China and the USA.[4]

The combination of scale and speed is the greatest factor making the unfolding transition so taxing. Miniaturization and relative dematerialization are two qualities admired in a modern society enjoying the benefits of solid-state microelectronics—but in aggregate terms mass will always matter. When the world began to undergo its first energy transition during the nineteenth century, it had to replace about 1.5 billion tons of mostly locally cut and burned wood with coal and, after the 1860s, also with hydrocarbons (Smil, 2016a). In 2022 the world produced nearly 8.2 billion tons of coal, almost 4.5 billion tons of crude oil, and 2.8 billion tons of natural gas, all extracted very efficiently and mostly in a highly concentrated manner from large mines and from enormous hydrocarbon fields on every continent.

In terms of final energy uses and specific energy converters, the unfolding transition would have to replace more than 4 terawatts (TW) of electricity-generating capacity now installed in large coal- and gas-fired stations by converting to non-carbon sources; to substitute nearly 1.5 billion combustion (gasoline and diesel) engines in road and off-road vehicles; to convert all agricultural and crop processing machinery (including about 50 million tractors and more than 100 million irrigation pumps) to electric drive or to non-fossil fuels; to find new sources of heat, hot air, and hot water used in a wide variety of industrial processes (from iron smelting and cement and glass making to chemical syntheses and

4 This, and all of the following calculations of global energy uses and carbon emissions, are based on spreadsheets available at https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fwww.energyinst.org%2F__data%2Fassets%2Fexcel_doc%2F0007%2F1055545%2FEI-stats-review-all-data.xlsx&wdOrigin=BROWSELINK.

food preservation) that now consume close to 30 percent of all final uses of fossil fuels; to replace more than half a billion natural gas furnaces now heating houses and industrial, institutional, and commercial places with heat pumps or other sources of heat; and to find new ways to power nearly 120,000 merchant fleet vessels (bulk carriers of ores, cement, fertilizers, wood and grain, and container ships, the largest one with capacities of some 24,000 units, now running mostly on heavy fuel oil and diesel fuel) and nearly 25,000 active jetliners that form the foundation of global long-distance transportation (fueled by kerosene) (Hedges and Company, 2023; Ener8, 2023; CH-Aviation, 2022).

On the face of it, and even without performing any informed technical and economic analyses, this seems to be an impossible task given that:

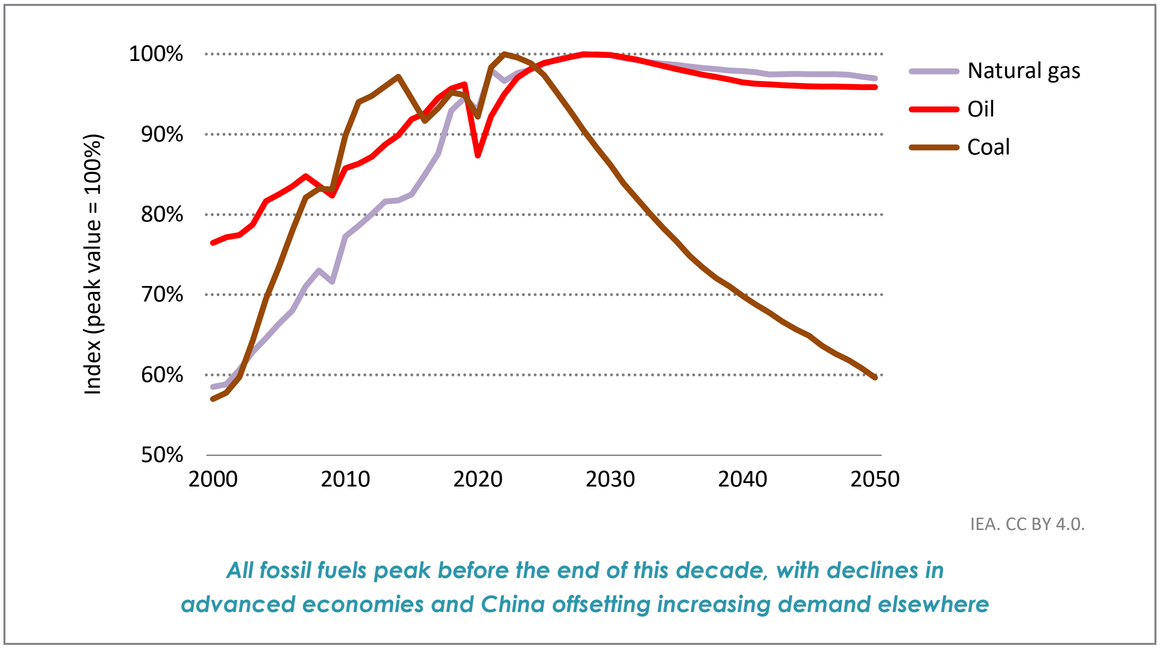
- we have only a single generation (about 25 years) to do it;
- we have not even reached the peak of global consumption of fossil carbon;
- the peak will not be followed by precipitous declines;
- we still have not deployed any zero-carbon large-scale commercial processes to produce essential materials; and
- the electrification has, at the end of 2022, converted only about 2 percent of passenger vehicles (more than 40 million) to different varieties of battery-powered cars and that decarbonization is yet to affect heavy road transport, shipping, and flying (IEA, 2023c).

None of this will come as a surprise to students of energy history as global energy transitions have always been protracted affairs.

Coal surpassed global wood combustion only in 1900, and its share of energy supply peaked only in the mid-1960s. Oil began to supply more than 25 percent of all fossil fuels only during the late 1950s, nearly a century after its first modern commercial extraction, and natural gas began to contribute more than 25 percent of fossil energy supply just before the end of the 20th century, after some 130 years of the industry's development (Smil, 2016). Moreover, even the first grand energy transition still has not been completed more than two centuries after it began. Nearly 3 billion people (in Africa, monsoonal Asia, and Latin America) still depend, mainly for cooking, some also for heating, on traditional biomass energies: fuel wood (and charcoal made from it), straw, and dried dung still supplied about 5 percent of the world's primary energy in 2020.[5]

5 Approximation based on the worldwide annual consumption of 1.9 billion cubic meters of fuelwood (FAO, 2022) and on the assumption that at least 10 percent of crop residues are used for fuel (US EPA, 2023).

Figure 4: The IEA's Global Turning Points Followed by a Long and Substantial Presence of Fossil Fuels in the Stated Policies Scenario



Source: IEA, 2021a: 33.

The International Energy Agency's *World Energy Outlook 2023* illustrates both the widely misunderstood realities and the likely outcomes of the unfolding transition. The outcome of its scenario based on the stated national policies (that is, on policies already adopted by individual states to reach the intended decarbonization goals) was called something that "has never previously been seen" because each of the three fossil fuels was projected to reach a peak by 2030. The peak in energy-related CO_2 emissions is to take place by 2025, and afterwards the demand for fossil fuels is to decline by average of 3 exajoules a year (EJ/year) until 2050 (IEA, 2023d). Those who read just the media reports listing these changes and emphasizing this historic "turning point" were left with the impression that an imminent astounding shift was going to take place—but that would be a fundamental misunderstanding of the process because consumption peaks on the large-scale level (globally and for populous nations, not necessarily for small countries that can shift faster) are followed by long periods of decline.

Indeed, the accompanying figure (see figure 4) from the IEA's *World Energy Outlook 2023* would have returned the consumers of media headlines back to reality. By 2050 even coal consumption, after an unprecedented projected decline, would still be as high as it was at the beginning of the 21st century; both crude oil and natural gas consumption (yet to peak) would be nearly as high (>95 percent) as in 2030; and a steady decline would still leave fossil fuel consumption at about 85 percent of the current level (see figure 4). That is, of course, very far from any zero carbon scenarios.

The gradual nature of energy transitions is an inevitable consequence of the fact that none of them have been just a simple matter of replacing one energy source with another. Consider a common (but completely misplaced) phone analogy (ie., we have largely switched from landlines to mobile phones in only two to three decades, depending how you define the process, so why not to get rid of fossil fuels on a similarly short time scale?). Relying on such an analogy is to commit a serious category mistake, a logical fallacy that compares (and confuses) an extraordinarily complex system of securing a reliable and affordable global supply of energy for a variety of final energy uses with just one type of user assembly (most recently the 5G network).

The current energy networks are complex, their establishment and operation require constant maintenance and upgrading, and their costs are considerable, yet they are only one of many parts that make up the vastly more complex global energy system. That is why global energy transitions are complicated, multifaceted, protracted, and in their details rather unpredictable. They require system changes that involve mass-scale development, adoption, and massive scaling-up of new techniques (be they large-scale "green" hydrogen electrolysis or extensive multiplication of small modular fission reactors). They also require the construction of new extraction, processing, and distribution networks (to produce large quantities of basic materials, metals, synthetic compounds and automated controls). All of these changes require decades of steady, high-level investments and political commitments in to yield major economic and social changes.

In the past, replacing wood stoves with coal stoves, waterwheels and wind mills with steam engines, teams of horses with diesel engines, and oil and gas lamps with electric lights required new, extensive, and complicated infrastructures. They were needed to extract (coal mines, oil and gas fields, and dams), prepare (coal sorting and cleaning, crude oil refining, and natural gas processing), transport (railways, pipelines, ships, trucks, and high-voltage transmission lines), and convert (steam engines, steam and gas turbines, furnaces, boilers, turbogenerators, transformers, and electric motors) new forms of energy.

The unfolding energy transition requires not just very large numbers of new wind turbines and photovoltaic panels to generate "green" electricity. Renewable generation also needs expanded high-voltage transmission lines (overhead wires and undersea cables from offshore wind sites) to bring the electricity from the windiest and sunniest places to often distant cities and industrial areas. As the new energy transition ramps up it will also need capacious electricity storage, such as batteries (or other mechanical, thermal, or chemical arrangements) large enough to cope with the intermittency of wind and solar radiation; the need will become imperative if these sources become dominant generators of electricity and if they are not complemented, as they are today, by base-load nuclear or fossil fueled generation or by near-instant deployment of gas turbines.

Moreover, there are many final energy conversions (ranging from heavy ocean shipping and long-distance commercial aviation to chemical industry dependent on fossil carbon feedstocks) that cannot be readily electrified. Further, we would need substantial quantities of solid and liquid fossil carbon even in the zero-carbon world for paving (asphalt) and for industrial and commercial lubricants.[6] Producing what I have called the four pillars of modern civilization—cement, primary iron, plastics, and ammonia—now depends on fossil fuels, and replacing them with alternatives will require the development of new mass-scale industries and distribution networks ranging from green hydrogen (made by electrolysis of water by green electricity) and ethanol to new synthetic fuels (Smil, 2022a).

Costs can alleviate or aggravate the challenges of complexity. If more complex innovations are cheaper than the established ways, or if their higher costs are outweighed by higher quality, efficiency, and convenience, then the transitions can proceed rapidly. Examples include black versus color television, reciprocating engines versus jet engines in long-distance commercial aviation, landlines versus mobile phones, and high-efficiency natural gas furnaces versus coal stoves. In contrast, renewable conversions start with the inherent disadvantages of having low power density and greater intermittency, and hence their full costs (with service comparable to the on-demand supply and reliability of fossil fuel converters) are considerably higher than the marginal cost of purchasing and installing new PV panels or wind turbines (Smil, 2015; Sorensen, 2015).

The cost differences have been narrowing but the latest comparisons of the levelized costs of electricity generation in the US indicate that the overall cost of solar PV (with a capacity factor of 28 percent) entering service in 2027 will be only 9 percent lower than the cost of combined cycle gas turbine (CCGT, capacity factor 85 percent), and that onshore wind will have the same overall cost but offshore wind plus battery storage will be still more than three times as expensive (US EIA, 2022). The promise of low-cost nuclear generation

6 Annual use is now more than 110 million tons of asphalt and more than 40 million tons of lubricants derived from crude refining (Venditti and Fortin, 2023, May 13; Shah, Woydt, and Aragon, 2020).

remains just that: by 2027 advanced nuclear generation is still expected to cost at least twice as much as CCGT, unsubsidized electric cars remain more expensive than comparable gasoline-powered vehicles, and the cost of green hydrogen, now in the earliest stages of development, remains uncertain.[7] The unfolding transition thus relies on techniques that are not (as yet) compellingly and across-the-board cheaper, more reliable, and more than the conversion they are replacing. Moreover, some of them (above all, new reactors and mass-scale electricity storage) will require a great deal of further expensive development.[8]

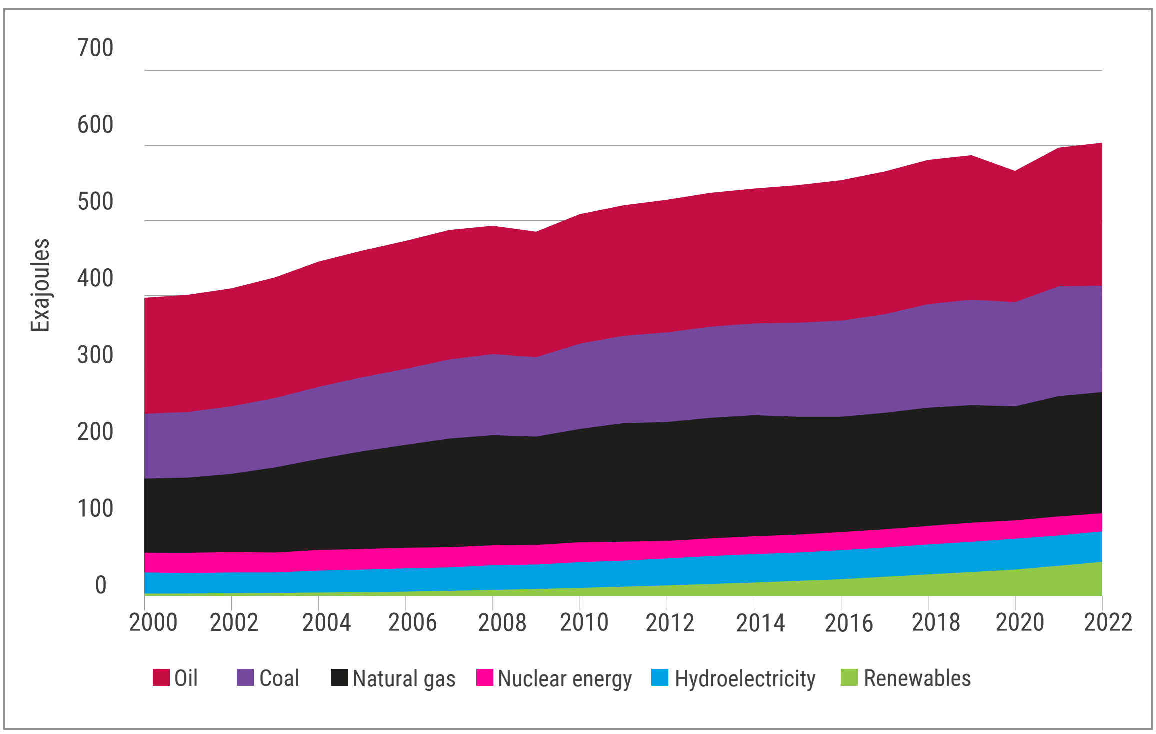
7 Higher EV prices have recently led to slowing sales in the US and to the postponement of new model introductions (see McLain and Rattner, 2023, December 27; Garsten, 2023, December 14).

8 The best available battery has a gravimetric density of 500 watt-hours per kilogram (Wh/kg) (Amprius, 2023). Gasoline rates 12,200 Wh/kg, which is a 24.4 times greater energy density.

3. Our Record So Far

The most obvious way to start assessing the progress of the required energy transition is to look at what has been accomplished during the past generation when the concerns about global decarbonization assumed a new urgency and prominence. Contrary to common impressions, there has been no absolute worldwide decarbonization. In fact, the very opposite is the case. The world has become much more reliant on fossil carbon (even as its relative share has declined a bit). We are now halfway between 1997 (27 years ago) when delegates of nearly 200 nations met in Kyoto to agree on commitments to limit the emissions of greenhouse gases, and 2050; the world has 27 years left to achieve the goal of decarbonizing the global energy system, a momentous divide judging by the progress so far, or the lack of it.

Figure 5: Global Dependence on Fossil Fuels Has Continued to Rise in the Twenty-first Century



Source: Energy Institute, 2023b.

The numbers are clear. All we have managed to do halfway through the intended grand global energy transition is a small relative decline in the share of fossil fuel in the world's primary energy consumption—from nearly 86 percent in 1997 to about 82 percent in 2022. But this marginal relative retreat has been accompanied by a massive absolute increase in fossil fuel combustion: in 2022 the world consumed nearly 55 percent more energy locked in fossil carbon than it did in 1997 (see figure 5) (Energy Institute, 2023b).

The absolute cuts in carbon emissions that took place in large economies such as the EU (-23 percent) and the US (-9 percent) were far surpassed by massive absolute increases in emissions from the world's two largest industrializing nations, China (whose emissions rose 3.3 times), and India (whose emissions rose three-fold). Emissions also rose for Middle Eastern hydrocarbon producers (Saudi Arabia's about 2.3 times) and among other smaller emitters.

The conclusion is unequivocal: by 2023, after a quarter century of targeted energy transition, there has been no absolute global decarbonization of energy supply. Just the opposite. In that quarter century, the world has substantially increased its dependence on fossil carbon. This is a fundamental point: changes in global average atmospheric temperature respond to changes in the total atmospheric burden of radiation-absorbing gases, not to any local or national declines. Between 1997 and 2022 annual emissions of CO_2 from the fossil fuel energy sector (CO_2 from fuel combustion and processing, the CO_2 equivalent of CH_4 from extraction, flaring, and pipeline leakage) rose from about 25.5 billion tons of carbon dioxide equivalent (CO_2e) to about 39.3 billion tons (a 54 percent rise) (Energy Institute, 2023c).

As a result of complex interchanges within the global biogeochemical carbon cycle, only a fraction of these anthropogenic emissions remains in the atmosphere. Most of them are absorbed by the oceans and by vegetation, resulting in increasing concentration of the gas in ocean water (and hence in its acidification) and in the greening of the biosphere (the expansion of plant cover). Consequently, the total atmospheric burden of CO_2 (including the emissions from other sectors) rose from 2.85 trillion tons in 1997 to 3.27 trillion tons in the year 2022, corresponding to the increase of the mean Mauna Loa concentration from 364 ppm to nearly 420 parts per million (up by more than 15 percent).

4. What It Would Take to Reverse the Past Emission Trend

Given these realities, what are the chances of not only decisively reversing the past emission trend and starting global decarbonization, but eliminating the generation of carbon from fossil fuel combustion by 2050? After cutting our *relative* dependence on fossil fuels by just 4 percent during the first half of the prescribed post-Kyoto period, even if there was no further increase in CO_2 emissions we would have to cut it by 82 percent by 2050. In absolute terms eliminating the generation of carbon from fossil fuel combustion would mean cutting energy-related emissions by an average of 1.45 billion tons a year (compared to the average annual rise in emissions of nearly half a billion tons since 1995). That would be like eliminating the equivalent of two years of Saudi emissions, or nearly half of India's 2022 total—every year.

Obviously, any postponement of these annual cuts would then require higher cuts during the later years of the remaining period. Another revealing way of viewing the daunting magnitude of this challenge is to look at the cuts that would have to be made by G20 economies to meet the interim 2030 goals: for nearly all major economies, it would generally mean halving the 2020 emissions, with cuts of 45 percent for Canada and 46 percent for Saudi Arabia, to 55 percent for the EU, 56 percent for the US, and 63 percent for China (McKinsey, 2023). Only an unprecedented economic collapse could bring such cuts during the next seven years.

After increasing our dependence on fossil fuels by almost 180 exajoules since 1997, to reach zero carbon in 2050 we would have to eliminate almost 500 EJ (that is equivalent to about 12 billion tons of crude oil)—even if there were no further consumption increases. But non-carbon energies would have to replace not only all of today's carbon fuels, but also cover all the additional increase in global energy use anticipated by 2050. As expected, long-range forecasts differ, but global energy demand (reduced by higher conversion efficiencies) is set to grow by at least 10 to 15 percent by 2050.[9] In the carbon-free world, these needs would have to be met by a combination of renewably generated electricity, green hydrogen, and green fuels.

9 To see the range of forecasting assumptions, look at studies by the International Energy Agency, the US Energy Information Agency, ExxonMobil, and Det Norske Veritas (DNV).

I must stress that the unfolding energy transition will not be replacing today's fossil fuel use and any of its future increases with the equivalent amount of non-fossil energies. That is mainly because the greater electrification of the global energy system based on renewable flows will raise overall efficiency of energy use by reducing conversion losses (Pahud et al., 2023). Specific reductions will vary. Electric vehicles offer especially large efficiency gains: they could go more than four times further on a given amount of energy than gasoline-powered vehicles (Singer et al., 2023). In contrast, there are no early prospects for electrifying intercontinental shipping and flying. Efficiency gains from the electrification of industrial processes would vary widely, and not all of them could be electrified. And there will be negligible gains for space heating, with 100 percent efficiency for electric resistance heating compared to as much as 93 to 99 percent for modern gas furnaces (Lennox, 2024). Of course, heat pumps could provide significant efficiency gains but their coefficient of performance would have to be relatively high in order to be cost-competitive. Eventual overall reductions of energy use due to electrification will also depend on the (yet unknown) shares to be supplied by solar, wind and nuclear generation, by biofuels and by "green" hydrogen. Nuclear electricity generation has been only 33 percent efficient (and no imminent breakthroughs are expected), some biofuels have high energy cost, and one kilogram of the hydrogen is equivalent to about 33 kWh of electricity but its production by electrolysis of water needs about 50 kWh/kg (US EIA, 2023a; Marouani et al., 2023). The new non-fossil global energy system would be less wasteful overall but how much less remains to be seen.

5. The Task Ahead: Zero Carbon Electricity and Hydrogen

Hydroelectricity now supplies about 15 percent of the world's electricity generation, followed by nuclear fission, which generates about 10 percent (Energy Institute, 2023b). New renewables, wind and solar, have grown rapidly during the past three decades and in 2022 they supplied 12 percent of all electricity generation, still less than the total generated by the two older carbon-free alternatives. Moreover, primary electricity (hydro, nuclear, wind, solar, and a small contribution by geothermal plants) accounted for no more than about 18 percent of the world's primary energy consumption, which means that fossil fuels still provided about 82 percent of the world's primary energy supply in 2022. This comes as a surprise to people unfamiliar with global energy statistics. The endless announcements of new wind farms and the sight of large areas covered by PV cells make most people believe that we have gone much further toward renewably electrifying everything.

The ultimate extent of the task of moving to carbon-free electricity generation depends on the as yet unknowable contributions of other generation methods and the eventual extent and modes of electrification. The fate of fission is perhaps the main uncertainty. Despite decades of promises that the arrival of large numbers of small modular reactors (SMRs, up to 300 MW) was imminent, and that they would resurrect stagnating electricity generation by nuclear fission, and despite some 80 different designs, in 2023 not a single SMR was operating anywhere in the West. China has only a single test prototype (IAEA, 2023). Similarly, proponents of geothermal generation stress its enormous potential, but practical advances have been slow there, too.

The eventual need for renewably generated electricity will depend on the extent of direct and indirect uses of electricity. The choice is exemplified in transportation by Tesla versus Toyota: what market shares will eventually be claimed by battery-powered vehicles and fuel cell vehicles (with hydrogen fuel made by electrolysis of water)? Further along the transition road, will airplanes be using much improved (yet currently unavailable high-power density) batteries, burning hydrogen directly, or using fuel cells for electric drive? What is clear is that the total addition of zero carbon electricity will have to go far beyond just replacing today's fossil-fueled generation, which is about 62 percent of the total of more than 29 quadrillion watthours (PWh) in 2022. Electricity demand will continue to grow: the International Energy Agency forecasts annual growth of 3.3 percent until 2050 and that would raise the 2022 total nearly 2.5-fold to just over 72 PWh (IEA, 2022).

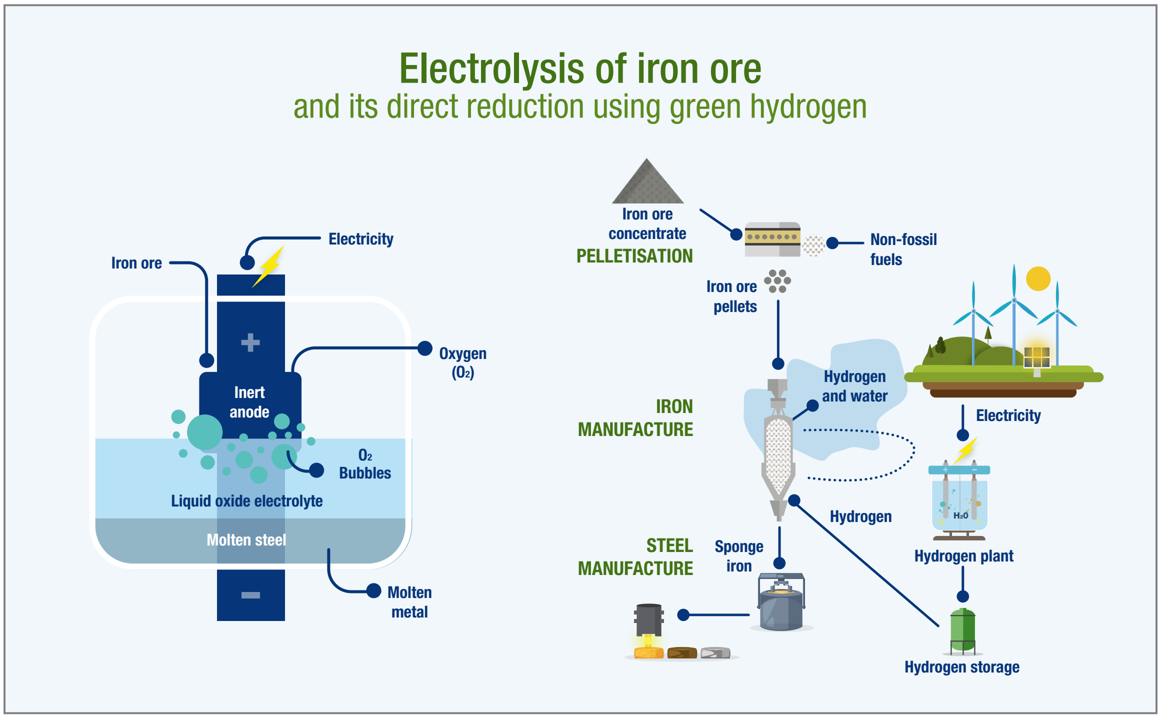
Even if hydro and nuclear were to cover 20 percent of that total, wind and solar would have to reach about 58 PWh in 2050, about 17 times their 2022 output and almost exactly twice the 2022 electricity generation from all sources. (Moreover, their inherent intermittency would require further substantial investments in mass-scale storage and HV transmission to ensure interrupted supply.) That would require sustained annual growth of about 10.5 percent, a rate that looks quite manageable compared to the actual annual growth of about 29 percent for solar and 15 percent for wind between 2012 and 2022—but it will be, as in the case of any long-term growth, harder to sustain as the absolute annual totals become an order of magnitude higher.

Besides the electrification trends already underway (passenger cars, heating, some industrial processes) large shares of non-carbon generation will be needed for electrifying, to the maximum extent possible, all those industries that now rely on coal, oil, and gas. While further expansion of wind and solar generations rests on scaling up well-known, mature conversion techniques, decarbonizing many industrial processes will require the development of new processes, first testing their prototypes and then deploying them commercially around the world. Two key examples show the challenges of such unprecedented efforts.

Steel is, and it will remain, modern civilization's dominant metal, indispensable for all infrastructure, housing, transportation, agriculture, and industrial production (Smil, 2016b). Roughly 30 percent of the world's steel is made by recycling scrap metal: this is done in electric arc furnaces (EAF) and hence this effort can be fully energized by green electricity. But 70 percent of the world's steel comes from basic oxygen furnaces (BOF) using cast (pig) iron smelted in blast furnaces (BF) fueled with coke (made from coking coal), coal dust, and natural gas. In 2022, the output of this primary BF-BOF steel reached 1.4 billion tons. The forecasts are that no less than 2.6 billion tons of the metal will be needed in 2050. Even with raising the EAF steel share to 35 percent, demand would require roughly 1.7 billion tons of green iron (World Steel Association, 2023; ArcelorMittal, 2023). Instead of reducing iron ores with carbon (and emitting CO_2), in the zero-carbon world we would have to reduce them with hydrogen ($Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O$). This means that by 2050 the annual output of 1.7 billion tons of green steel would need about 91 million tons of green hydrogen (see figure 6).

Ammonia is an even more important product: about 85 percent of its annual production is used to make synthetic nitrogenous fertilizers without whose continuing applications

Figure 6: Primary Green Ironmaking



Note: Set-ups such as this one, non-existent in 2023, would need to produce more than 1.5 billion tons of metal by 2050.
Source: Iberdrola, Undated.

about half of today's world population could not survive (Smil, 2022a). Ammonia is now synthesized with nitrogen taken from the air and hydrogen produced through a shift reaction from natural gas, coal, and liquid hydrocarbons ($N_2 + 3H_2 \rightarrow 2NH_3$), with less than 5 percent coming from electrolysis of water (green hydrogen). In 2022 the annual output of ammonia reached about 150 million tons; forecasts are that at least 200 million tons will be needed by 2050. The fossil carbon-free Haber-Bosch ammonia synthesis process would need about 44 million tons of green hydrogen by 2050.

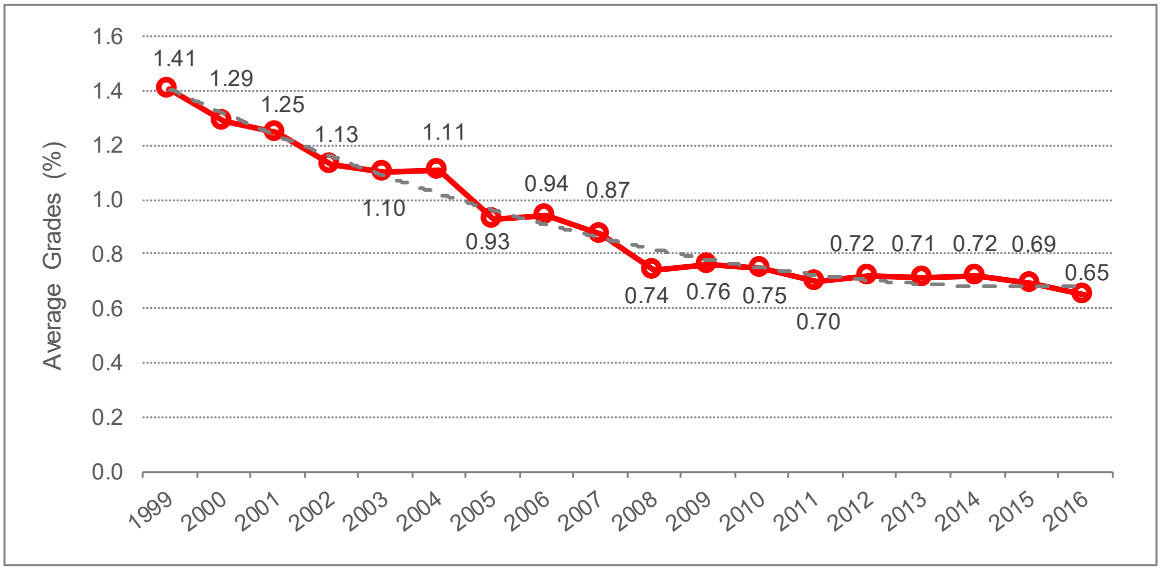
These two key material processes, the making of steel and ammonia, would need an annual production capacity of some 135 million tons of green hydrogen by 2050. However, depending on additional needs for transportation and heating, from industries (from glassmaking to food preservation), and for peak electricity generation, the total demand for green hydrogen could be easily as high as 500 million tons by 2050. Electrolytic production of green hydrogen needs about 50 MWh/ton: making 500 million tons of green hydrogen by 2050 would thus require about 25 PWh of green electricity, the total equal to about 86 percent of the 2022 global electricity use (IRENA, 2023). To repeat, this renewably generated electricity would be dedicated to the production of green hydrogen alone! How fast can we get there? In 2023 an IEA review estimated that in 2030 the global output of green hydrogen could reach 38 Mt, but only if all intended projects for electrolytical processing (or from fossil fuels with carbon capture) were completed (IEA, 2023e).

But half of this potential output comes from projects that are still undergoing feasibility studies or are at the early stages of realization, while the projects under construction or those that have received final investment decisions made up only 4 percent of all announcements. Production targets by HyDeal España are an excellent example of this uncertain state. In 2021 the International Renewable Energy Agency (IRENA) welcomed HyDeal España's announcement of "the world's largest renewable hydrogen giga-project." Then in September 2023, the company more than halved its 2030 target for electrolyzer capacity from 7.4 GW to 3.3 GW, as it announced a new goal of producing 150,000 tons of green hydrogen by 2031 (Fertiberia, 2022; HyDeal, Undated; Biogradlija, 2023, September 15). And the "giga" label should be put into practical perspective. An annual output of 150,000 tons of green hydrogen would be enough to synthesize 700,000 tons of ammonia, which would supply about 0.65 percent of the nitrogen now applied every year to the world's crops. Conversely, that means we would need more than 150 equally sized "giga" projects to cover today's global demand for the most important plant macronutrient.

As for green steel, the first steel plant smelting iron ore with hydrogen produced by renewably generated electricity is now under construction in northern Sweden. The plan is to make 1 Mt of steel in 2026 and then to ramp it up to 5 Mt by 2030 (Jones, 2023, February 22). An annual output of 1 Mt is equivalent to 0.07 percent of the world's 2022 primary steel production. To make all primary steel (1.7 Gt) green by 2050, the world would need to open 340 Boden-like plants (assuming 5 Mt/year each) between 2030 and 2050. That is one every three weeks during that 20-year period, preferably located near green hydrogen electrolytic plants and near plants producing pelleted or briquetted iron without any fossil fuel.

This pace of required hydrogen and steel plant additions illustrates another fundamental factor that is likely to affect the unfolding global energy transition: every one of its components will generate unprecedented demand for materials and the challenge is made more difficult both by higher material intensities of some new techniques and by complicated access to many essential resources (Smil, 2023a). Wind turbines are perhaps the best illustration of the former reality. While gas turbines—today's dominant on-demand

Figure 7: The Declining Quality of Chilean Copper Resources Between 1999 and 2016



Source: Mills, 2022, October 27.

generators of electricity—are highly efficient (>60 percent) and compact machines that need less than 10 tons of materials per installed MW, and no more than 30 t/MW when adding all associated structures, large wind turbines need typically about 500 t/MW of materials (Carrara, Alves Dias, Plazzotta, and Pavel, 2020). Reinforced concrete for foundations dominates, followed by steel for tall towers, epoxy resins, balsa and carbon fibers for blades, plastics, copper, aluminum, ceramics for the nacelle, and two rare metals, neodymium and praseodymium, for permanent magnets.

Materials for electric vehicles fits into both categories of concern. A typical electric vehicle contains more than five times the amount of copper (80 versus 15 kg) of an internal combustion car engine. Replacing today's 1.35 billion light-duty gasoline and diesel vehicles with EVs and supplying the expanded market (estimated at 2.2 billion cars by 2050) would thus require nearly 150 million tons of additional copper during the next 27 years. That is an equivalent of more than seven years of today's annual copper extraction for all of the metal's many industrial and commercial uses (EIA, 2021, October 26). In addition, the IEA estimates that, compared to 2020, the take-over of EVs by 2040 would need more than 40 times as much lithium as is currently mined, and up to 25 times the amount of graphite, cobalt, and nickel (IEA, 2021c). Cumulative demand for materials to achieve total decarbonization by 2050 has been estimated at about 5 billion tons for steel, nearly a billion tons for aluminum, and more than 600 million tons of copper (to list just the three largest items). Such massive mineral needs bring not only technical and financial concerns, but also environmental and political implications (Energy Transitions Commission, 2023; Sonter, Maron, Bull, et al., 2023).

Copper offers a stunning example of these environmental externalities. The metal content of exploited copper ores from Chile, the world's leading source of the metal, has declined from 1.41 percent in 1999 to 0.6 percent in 2023, and further quality deterioration is inevitable (see figure 7) (Lazenby, 2018, November 19; Jamasmie, 2018, April 25; IEA, 2021c).

Using the mean richness of 0.6 percent means that the extraction of additional 600 million tons of metal would require the removal, processing, and deposition of nearly 100 billion tons of waste rock (mining and processing spoils), which is about twice as much as the current annual total of global material extracted including harvested biomass, all fossil fuels, ores and industrial minerals, and all bulk construction materials.10 Extracting and dumping such enormous masses of waste material exacts a very high energy and environmental price as it puts new, supposedly "green" energy uses even further from the goal of maximized material recycling. Moreover, copper's production is dominated by just a few countries (Chile, Peru, China, and Congo), and China alone refines 40 percent of the world's supply. China processes even more of the other minerals required for green energy conversion: nearly 60 percent of lithium, 65 percent of cobalt, and close to 90 percent of rare earths (IEA, 2021d; Castillo and Purdy, 2022). That makes OPEC's grip on crude oil (now 40 percent of global production) a relatively restrained affair!

Further, when countries from Canada to Germany find it impossible to construct enough basic housing for their populations, it is obvious that any accelerated installation of green energy projects and infrastructure will be restricted by shortages of experienced labour. Germany, thanks to its Energiewende (energy transition) is the EU's leader in the pursuit of greenness and it is already affected: in 2023 the country lacked about 216,000 skilled workers to expand solar and wind power, and the now mandatory installation of heat pumps needs another 80,000 technicians (KOFA, 2022; Smarter Europe, 2023). Similarly, the US is finding that labour shortages will slow down any radical plans it has for green energy transitions (Colman, 2023, February 27).

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10 See the best estimates of annual global material flows in Smil (2023a).

6. Costs, Politics, and Demand

We do not know either the eventual magnitudes and shares of specific energies that would enable the carbon-free world to be a reality or the extent of their global infrastructures. These realities cannot be determined decades ahead; they will be formed gradually and, to a significant degree, unpredictably. This makes any overall cost estimates questionable. We also need to interpret properly the trend of decreasing costs of newly installed wind and solar capacities. As is common with most new conversion techniques undergoing large-scale commercialization, these per-unit declines of installed capacity have been substantial, but during the next quarter century they cannot be expected to continue at rates similar to those experienced since the year 2000. More importantly, those two renewable, and hence intermittent (variable), modes of generation need back-up when nights, cloudiness, and calm (or winds too strong to operate wind turbines) intervene (BloombergNEF, 2023, June 7).[11]

As long as solar and wind supply relatively low shares of total electricity generation, such needs are readily covered by existing base-load coal-fired or nuclear generation, by near-instantly available gas turbines, or by imports from neighboring countries.[12] Once the intermittent sources become dominant and all gas-turbines are gone, they will need either extensive high-voltage interconnections to bring electricity from more distant regions or substantial capacities of longer term electricity storage. Construction of much-needed high-voltage lines has been notoriously behind the anticipated completion dates (with causes ranging from vigorous NIMBY opposition to the high cost of new links), be they in the US (from the interior to the coasts) or Germany (north-south). Meanwhile, the IEA has estimated that meeting the global decarbonization goals would require adding or refurbishing more 80 million kilometres of transmission grids by 2040. That is the equivalent of the entire existing global grid in 2023 and one predicated on the further mass-scale mobilization of steel, aluminum, copper, and cement (Appunn, 2021, April 29; IEA, 2023f).

11 For backup needs, see Delarue and Morris (2015) and Solomon, Child, and Caldera (2017).

12 In 2022 the US capacity factors ranged from more than 90 percent for nuclear generation, 62 percent for natural gas, 36 percent for wind, and 25 percent for PV solar (EIA, 2023b). Denmark is an excellent example of a country that balances a high share of intermittent generation (wind accounted for almost exactly 50 percent of total generation in 2021) with imports. In 2021 its net electricity imports were equal to about 15 percent of domestic generation (net imports of 22.3 petajoules (PJ) from Norway and 17.5 PJ from Sweden; net exports to Germany of 14.3 PJ and 8 PJ to the Netherlands (Danish Energy Agency, 2023).

And, so far, only pumped hydro storage (requiring specific terrain configuration and impossible in lowlands) can provide as much as a gigawatt of power for many consecutive hours. But renewably electrified megacities of the 2040s in monsoonal Asia might need (during a typhoon day) storage of many gigawatts (5 to 20 GW) for 10 to 20 hours (rating up to 400 GWh), while today's largest lithium-ion (Li-ion) battery energy storage (Moss Landing in California) is rated at 750 MW/3 GWh, two orders of magnitude lower.[13] Obviously, costs of these necessary transmission or storage arrangements (back-ups) will have to be added to the cost of wind turbines and PV panels in all systems dominated by intermittent generation.

Another category mistake involving costs is to hope that the global energy transition to zero fossil carbon can be achieved by embarking on an equivalent effort and cost of the dedicated targeted development so famously exemplified by the construction of the first nuclear bombs (the Manhattan Project) or putting men on the Moon (Project Apollo). We have comprehensive data about the cost of those two endeavours and after converting them to 2022 monies they look, when seen from the spending perspective of the 2020s, like extraordinary bargains: the Manhattan Project (1943-1945) cost just $33 billion (in 2022 dollars) or 0.3 percent of GDP for those years, while the Project Apollo (1961-1972) came in at $207 billion (in 2022 dollars) or 0.2 percent of GDP for those 12 years (Smil, 2022b).

Nobody can offer a reliable estimate of the eventual cost of a worldwide energy transition by 2050 though a recent (and almost certainly highly conservative) total suggested by McKinsey's Global Institute makes it clear that comparing this effort to any former dedicated government-funded projects is another serious category mistake. Their estimate of $275 trillion between 2021 and 2050 prorates to $9.2 trillion a year. Compared to the 2022 global GDP of $101 trillion, this implies an annual expenditure on the order of 10 percent of the total worldwide economic product for three decades, rather than 0.2 or 0.3 percent for a few years (McKinsey and Company, 2022; World Bank, 2023).

In reality, the real burden would be far higher for two reasons. First, it cannot be expected that low-income countries could sustain such a diversion of their limited resources and hence this global endeavour could not succeed unless the world's high-income nations annually spend sums equal to 15 to 20 percent of their GDP. More importantly, this ultimate global transformation project would face enormous cost overruns. As the world's most comprehensive study of cost overruns (more than 16,000 projects in 16 countries

13 Recent electricity demand for the Tokyo region has been averaging around 30 GW (TEPCO, 2023; Lewis, 2023, August 3).

and in 20 categories, from airports to nuclear stations) shows, 91.5 percent of projects worth more than $1 billion have run over the initial estimate, with the mean overrun being 62 percent (Flyvbjerg and Gardner, 2023). Applying a 60 percent correction would raise McKinsey's estimate of the cost of global decarbonization to $440 trillion, or nearly $15 trillion a year for three decades, requiring affluent economies to spend 20 to 25 percent of their annual GDP on the transition. Only once in history did the US (and Russia) spent higher shares of their annual economic product, and they did so for less than five years when they needed to win World War II.[14] Is any country seriously contemplating similar, but now decades-long, commitments?

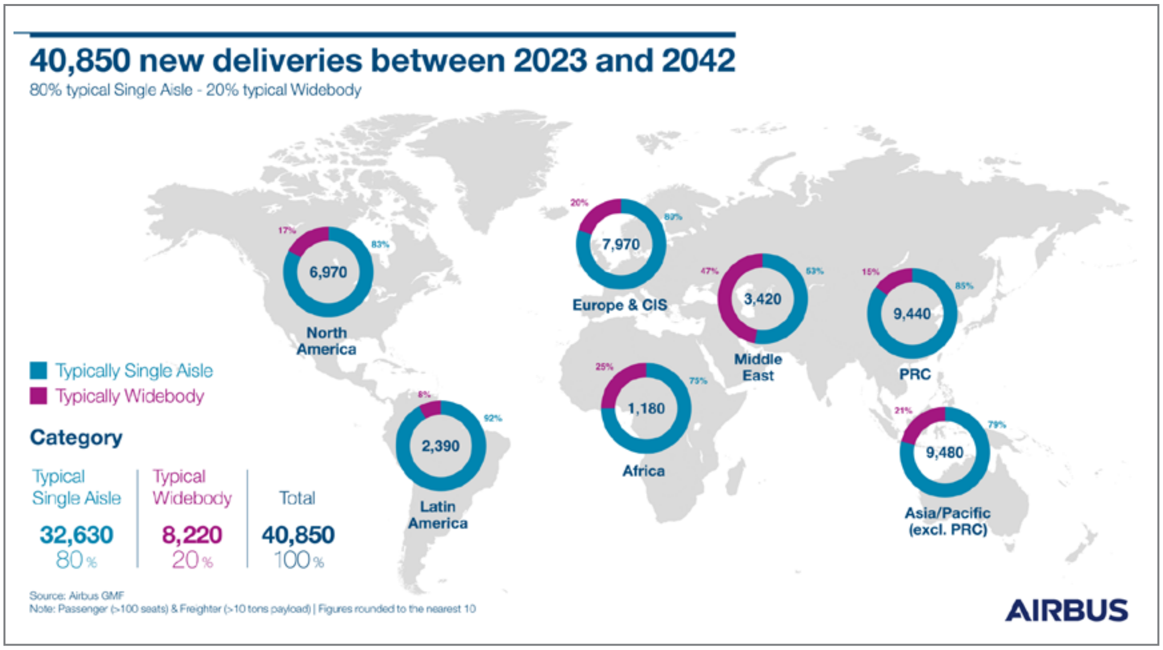
In 2024, the political implications and complications of eliminating carbon emissions by 2050 are self-evident. Global warming is a global problem and decarbonization cannot be achieved without worldwide participation, with most of the burden carried by a small group of the largest emitters. China is now responsible for 31 percent of global emissions from energy use, the US for 14 percent, the EU for 11 percent, India for 8 percent, Russia for 4 percent, and Saudi Arabia and Indonesia each for about 2 percent. What are the chances that this Big Seven will move harmoniously and steadfastly for the next 27 years toward the common goal of zero carbon by 2050?

What incentives does Russia have—being in a *de facto* state of war with EU/US in Ukraine—to join the West in decarbonizing when hydrocarbon exports are the foundation of its otherwise weak economy? How eager will China be to work with India (there is still no peace treaty between the two nations) and with the US, bent as it is on a newly embraced decoupling? Why would India, now trying to replicate (at least to some degree) China's post-1990 economic ascent, forgo the use of its coal when China has quadrupled its extraction during the past 30 years? Not surprisingly, we see headlines such as "India May Boost Coal Power Fleet 25% by 2030 Amid Rising Demand" (Singh and Kitanaka, 2022, September 23). Moreover, as recent numbers indicate, China is far from done with its massive use of fossil fuel: its coal output reached a new record in 2022 and the country approved the construction of 106 gigawatts of new coal-fired power, the highest capacity since 2015 (Reuters, 2023, February 26).

We must also consider the poorest continent, the population of which will grow from 1.2 to 2.5 billion by 2050. Africa has seen how China became relatively rich during the past generation by quadrupling its combustion of fossil carbon and becoming the world's largest producer of cement, steel, plastics, and ammonia. Affluent countries themselves

14 The best reconstruction of wartime US expenditures shows the annual rate rising from about 16 percent of GDP in 1942 to 37 percent in 1945 (Tassava, 2008).

Figure 8: Forecast of New Airplane Deliveries between 2023 and 2042



Source: Airbus, 2023.

have no large-scale non-fossil alternatives that could be transferred to Africa and enable the continent to pursue green development. That is why "African Nations Tell COP27 Fossil Fuels Will Tackle Poverty" (Mcfarlane and Abnett, 2022, November 10).

And the need for energy and associated infrastructure is immense. Except for South Africa, Sub-Saharan Africa's per capita energy use is less than 10 GJ/year, compared to India's 26 GJ and China's 112 GJ (Canada uses nearly 370 GJ a year per capita). No wonder that African politicians demand the development of fossil fuel resources to lift the continent's living standards perhaps to the Indian level! Development of some large natural gas reservoirs in Africa looks particularly appealing as the liquefied fuel can be readily exported worldwide; new gas fields are now under development in Senegal, Ghana, Nigeria, Cameroon, Angola, Mozambique, and Tanzania. They will not start producing before 2030 only to be shut down in the effort to decarbonize a decade or two later (Casey, 2023, September 13).

And let us not forget that it was not any accelerated production of wind or solar electricity, nor any green hydrogen, but the diversion of liquefied natural gas from the US, Qatar, and Nigeria that prevented crippling supply shortages in the EU following Russia's invasion of Ukraine in 2022 and 2023, and that large-scale natural gas exports, not any construction of PV cells, are the foundation of the Russia-China alliance (Miller, 2023, May 17). The demand for fossil-fueled machines remains high everywhere. Post-COVID, airlines are placing record orders for large new jetliners: in 2022 United Airlines ordered 200 jets; in 2023 Indigo (India's largest airline) ordered 500 and Air India 470 jets. The latest forecast by Airbus is that more than 40,000 new jetliners will be needed between 2023 and 2042—and these kerosene-fueled machines typically operate for up to 30 years (see figure 8) (Reuters, 2023, June 20; Airbus, 2023).

Orders for massive diesel-powered cruise ships reached 56 new vessels by August 2023 and, again, they will not be launched before 2030 with the intent of sailing for just a few years (Cruise Industry News, 2023, August 24). Too many realities point to the same conclusion: there will not be cuts in fossil carbon of anywhere near 50 percent by 2030—and no zero carbon by 2050.

7. Realities versus Wishful Thinking

Since the world began to focus on the need to end the combustion of fossil fuels, we have not made the slightest progress in the goal of absolute global decarbonization: emission declines in many affluent countries were far smaller than the increased consumption of coal and hydrocarbons in the rest of the world, a trend that has also reflected the continuing deindustrialization in Europe and North America and the rising shares of carbon-intensive industrial production originating in Asia. As a result, by 2023 the absolute reliance on fossil carbon rose by 54 percent worldwide since the Kyoto commitment. Moreover, a significant part of emission declines in many affluent countries has been due to their deindustrialization, to transferring some of their carbon-intensive industries abroad, above all to China.

Denmark, with half of its electricity now coming from wind, is often pointed out as a particular decarbonization success: since 1995 it cut its energy-related emissions by 56 percent (compared to the EU average of about 22 percent)—but, unlike its neighbours, the country does not produce any major metals (aluminum, copper, iron, or steel), it does not make any float glass or paper, does not synthesize any ammonia, and it does not even assemble any cars. All these products are energy-intensive, and transferring the emissions associated with their production to other countries creates an undeservedly green reputation for the country doing the transferring.

Given the fact that we have yet to reach the global carbon emission peak (or a plateau) and considering the necessarily gradual progress of several key technical solutions for decarbonization (from large-scale electricity storage to mass-scale hydrogen use), we cannot expect the world economy to become carbon-free by 2050. The goal may be desirable, but it remains unrealistic. The latest International Energy Agency *World Energy Outlook* report confirms that conclusion. While it projects that energy-related CO_2 emissions will peak in 2025, and that the demand for all fossil fuels will peak by 2030, it also anticipates that only coal consumption will decline significantly by 2050 (though it will still be about half of the 2023 level), and that the demand for crude oil and natural gas will see only marginal changes by 2050 with oil consumption still around 4 billion tons and natural gas use still above 4 trillion cubic meters a year (IEA, 2023d).

Wishful thinking or claiming otherwise should not be used or defended by saying that doing so represents "aspirational" goals. Responsible analyses must acknowledge existing energy, material, engineering, managerial, economic, and political realities. An impartial assessment of those resources indicates that it is extremely unlikely that the global energy system will be rid of all fossil carbon by 2050. Sensible policies and their vigorous pursuit will determine the actual degree of that dissociation, which might be as high as 60 or 65 percent. More and more people are recognizing these realities, and fewer are swayed by the incessant stream of miraculously downward-bending decarbonization scenarios so dear to demand modelers.

Long-term global energy forecasts offering numbers for overall demand or supply and for shares contributed by specific sources or conversions are beyond our capability: the system is too complex and too open to unforeseen but profound perturbations for such specificity. However, skepticism in constructing long-term estimates will lessen the extent of inevitable errors. Here is an example of a realistic 2023 forecast done by Norwegian risk management company DNV that has been echoed recently by other realistic assessments. After noting that global energy-related emissions are still climbing (but might peak in 2024 when the transition would effectively begin) it concludes that by 2050 we will move from the present roughly 80 percent fossil/20 percent non-fossil split to a 48 percent/52 percent ratio by 2050, with primary energy from fossil fuels declining by nearly two-thirds but still remaining at about 314 EJ by 2050—in other words, about as high as it was in 1995 (DNV, 2023).

Again, that is what any serious student of global energy transitions would expect. Individual components change at different speeds and notably rapid transformations are possible, but the overall historical pattern quantified in terms of primary energies is one of gradual changes. Unfortunately, modern forecasting in general and the anticipation of energy advances in particular have an unmistakable tendency toward excessive optimism, exaggeration, and outright hype (Smil, 2023b). During the 1970s many people believed that by the year 2000 all electricity would come not just from fission, but from fast breeder reactors, and soon afterwards came the promises of “soft energy” taking over (Smil, 2000).

Belief in near-miraculous tomorrows never goes away. Even now we can read declarations claiming that the world can rely solely on wind and PV by 2030 (Global100RE-StrategyGroup, 2023). And then there are repeated claims that all energy needs (from airplanes to steel smelting) can be supplied by cheap green hydrogen or by affordable nuclear fusion. What does this all accomplish besides filling print and screens with unrealizable claims? Instead, we should devote our efforts to charting realistic futures that consider our technical capabilities, our material supplies, our economic possibilities, and our social necessities—and then devise practical ways to achieve them. We can always strive to surpass them—a far better goal than setting ourselves up for repeated failures by clinging to unrealistic targets and impractical visions.

Failing to reach an unrealistic goal of complete global decarbonization by 2050 means failing to limit average global warming to 1.5°C. How much higher the temperature might rise will not depend only on our continued efforts to decarbonize the global energy supply but also on our success in limiting CO_2 and other greenhouse gases generated by agriculture, animal husbandry, deforestation, land use changes, and waste disposal. After all, those contributions account for at least a quarter of global anthropogenic emissions but, so far, we have been almost exclusively focused on CO_2 from fossil fuel combustion. But that is a topic for another inquiry.

8. Closing Thoughts

I will close with some simple historical and order-of-magnitude perspectives. My reconstruction of global energy supply (including the traditional biomass energies) shows that fossil fuels, and later also hydro and nuclear electricity, rose from just 2 percent in 1800 to 95 percent in 2020 (Smil, 2016a). After more than two centuries the first energy transition is still not complete.

And the second one? Even if we were to assume that, because of higher conversion efficiencies of an extensively electrified economy, we will need to replace only 300 EJ, rather than 500 EJ of today's fossil fuel supply by 2050, then 85 percent of the task is still ahead of us. As of 2022 renewable energies supplied only about 45 EJ and that has prorated to annual gain of 1.7 EJ during the past 27 years. But to eliminate fossil carbon by 2050 new energy additions would have to average about 9.4 EJ a year during the next 27 years, implying an annual transition pace nearly six times faster than during the past 27 years. Can we, instantly, sextuple (or "just" quintuple or quadruple) our annual achievements and maintain those news levels until 2050?

The unfolding transition is only the second such fundamentally transformative event in history, and these two events share a similar goal: a complete change of the energy foundations of the entire civilization. In comparison to today's technical achievements and options, the first grand transition began to unfold with rudimentary technical capabilities, but, eventually, it certainly surpassed the initial expectations for it; it created new, affluent, high-energy societies.

Even though we are technically far better equipped than we were 150 to 200 years ago, the task presented by the second energy transition appears to be no less challenging. Just before the end of 2023 the International Energy Agency published its estimate of global investment in "clean energy"—in other words, essentially the recent annual cost of the energy transition. In 2023 it was close to $2.2 trillion (IEA, 2023g). Even if we were to replace just 60 percent of today's fossil fuel consumption, we should be investing about six times more, or about $13 trillion a year, to reach zero carbon by 2050. Making it $15-17 trillion a year (to account for expected cost over-runs) seems hardly excessive, and it takes us, once again, to a grand total of $400-460 trillion by the year 2050, good confirmation of a previously derived value. This is not a forecast, just a plausible estimate intended to indicate the commonly underestimated cost of this global endeavour.

No natural laws bar us from making the enormous investments needed to sustain such massive annual shifts: we could resort to an unprecedented, decades-long, and civilization-wide existential mobilization of constructive and transformative efforts or, conversely, we could deliberately reduce our energy use by lowering our standard of living and keeping it low to make it easier to displace all fossil carbon.

In the absence of these two radical choices, we should not ignore the experience of the past grand energy transition (from traditional biomass energies to fossil fuels) and we should not underestimate the concatenation of challenges presented by practical engineering, material, organizational, social, political, and environmental requirements of the unfolding transition to a fossil carbon-free world that have been partially reviewed in this essay. When we do assess these challenges realistically, we must conclude that the world free of fossil carbon by 2050 is highly unlikely.

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