Decarbonizing the Atmosphere: Opportunities and Cautions

BY TRUDY E. BELL

The United States has committed itself to cutting net emissions of greenhouse gases at least 50 percent below 2005 levels by 2030—just eight years away. What engineering will that entail?

INTRODUCTION

This past November (2021), the White House issued a 61-page document titled *The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050.* After noting how "[w]ildfires, storms, floods, extreme heat, and other climate-fueled impacts are causing deaths, injuries, degraded health, economic hardship, and damage to the earth's ecosystems," the executive summary stated:

> The most recent report from the Intergovernmental Panel on Climate Change (IPCC) vividly illustrates, with robust scientific confidence, the need to limit warming to 1.5°C, or as close as possible to that crucial benchmark, to avoid [more] severe climate impacts. Achieving this target will require cutting global greenhouse gas (GHG) emissions by at least 40% below 1990 levels by 2030, reaching global net-zero GHG emissions by 2050 or soon thereafter, and moving to net negative emissions thereafter.

"Net negative emissions" will require nothing less than removing carbon dioxide from the atmosphere—a task that will require "scaling up land carbon sinks as well as engineered strategies."[14]

Just what innovations, implementations, and timetable would that require?

SCALE OF THE CHALLENGE

Despite the illusion that the Earth's atmosphere is vast, here are a few perspectives on its actual finitude. Although the nominal edge of space is arbitrarily set to be 50 miles up, over three-quarters of the mass of the atmosphere is concentrated in its lowest layer—the troposphere. The troposphere is only 5 to 10 miles thick, thinner at the poles than at the equator. Now, 5 to 10 miles (horizontally) is a distance that can be jogged or bicycled in less than an hour or driven in under nine minutes. Above the troposphere is the stratosphere, where jets fly.

Compared to the diameter of the Earth, the troposphere is roughly as thin as is the skin on a large apple—yet that all-important layer is where weather happens, people and animals breathe, and industrial processes discharge waste gases.

By mass, the most significant of those waste gases is carbon dioxide (CO_2), the same gas humans and other mammals exhale. Currently, about half the global CO_2 emitted each year by natural and industrial activities is taken up by soil, photosynthesizing plants, and the oceans as part of the natural carbon cycle; the excess beyond the planet's carbon budget remains suspended in the atmosphere[7] (**Figure 1**). But even in minute concentration—parts per million— CO_2 acts like an insulating blanket, trapping heat (long-wavelength infrared radiation) from the sun and warming the planet, in what has long been called the greenhouse effect.

Although the greenhouse effect originally enabled life to arise on Earth, the volume of CO_2, emitted since pre-industrial times—roughly since the founding of the United States—has increasingly thrown off the balance of the planet's natural carbon cycle.[11] Today, anthropogenic processes worldwide release CO_2 into the atmosphere at a prodigious rate: 35 to 40 gigatons (billions of metric tons, denoted $GtCO_2$) ***each year***, largely from combustion of fossil fuels (coal, oil, and natural gas).

For perspective on the physical scale of those emissions, data in $GtCO_2$ can be converted to their solid carbon equivalent (GtC) by multiplying by the fraction 12/44 (the ratio of their molecular weights). So, emissions of 40 $GtCO_2$ would come to just under 11 Gt (10.9, to be more exact) of solid carbon emitted into the atmosphere ***per year***; that much solid carbon would occupy a volume of about 11 cubic kilometers. (For detailed grounding on carbon dioxide and its atmospheric effects, see "Engineering Beyond Carbon: Pulling Answers Out of the Air," *The Bent*, Spring 2007.)

Such voluminous emissions are a big problem, because the excess CO_2 has a centuries-long residence time in the atmosphere. Thus, over the past 250+ years, analyses from tree rings and other sources reveal that CO_2 has been accumulating in the atmosphere at an ever-accelerating rate. It has risen from a concentration of about 280 parts per million (ppm) in 1750 to 410 ppm today—more than half of that rise since the 1970s. Currently, it is continuing to accumulate at a rate of about 2.3 ppm per year.[4,7,13]

CO_2 is not the only anthropogenic planet-warming gas. Another culprit is methane (CH_4), the principal ingredient of natural gas; primary sources include enteric fermentation from livestock, natural gas systems, landfills, coal mining, and petroleum systems.[4] Methane is some 25 times more powerful than CO_2, meaning that the same warming effect as a given volume of CO_2 would be produced by only 1/25th that concentration of CH_4. However, emitted CH_4 has a much shorter lifetime in the atmosphere: a decade or two. Nonetheless, it is crucial on immediate time scales, as it accounts for half the last century's 1°C rise in global surface temperature.[14]

Other powerful greenhouse gases—notably nitrous oxide (N_2O), sulfur dioxide (SO_2), and fluorinated gases used for refrigerants and air conditioning—also contribute. But in the United States, most of the greenhouse gases emitted are CO_2 (80 percent) and CH_4 (10 percent).[12]

Some 6.6 $GtCO_2$ of those global annual emissions originate from the U.S., second only to China; China emits about twice as much, but the U.S. tops the list for emissions per capita. Moreover, at the same time, a vast number of terrestrial ecosystems that naturally would have absorbed some 27 percent of that carbon from the atmosphere have been lost "because of the clearing of forests, draining of wetlands, and the conversion of forests and grasslands to croplands and pastures."[13]

Today, according to the IPCC, "estimated anthropogenic global warming is currently increasing at 0.2°C…per decade due to past and ongoing emissions."[8] At that rate, between 2030 and 2052, global mean surface temperature is likely to reach 1.5°C higher than it was in 1850-1900, depending on whether and what steps the United States and other countries take to reverse the trend. If nations make immediate and deep reductions in emissions and implement other strong mitigation measures before 2030, by 2100 global mean temperature could stabilize at around 1.8°C higher.

However, if by 2030—that's in just eight short years, folks—too little or nothing is done, and greenhouse gases continue to be emitted and to accumulate at the high rates of business as usual, computational climate models project that by 2100, global surface temperature could reach as high as 3.3°C to 5.7°C more, with concomitant catastrophic climate alterations worldwide. For perspective, noted the IPCC, "The last time global surface temperature was sustained at or above 2.5°C higher than in 1850–1900 was over 3 million years ago."[7] Although 2100 sounds like an irrelevant science-fiction–long time in the future, it is not: a child born today—if able to survive, that is—would celebrate a 78th birthday then.

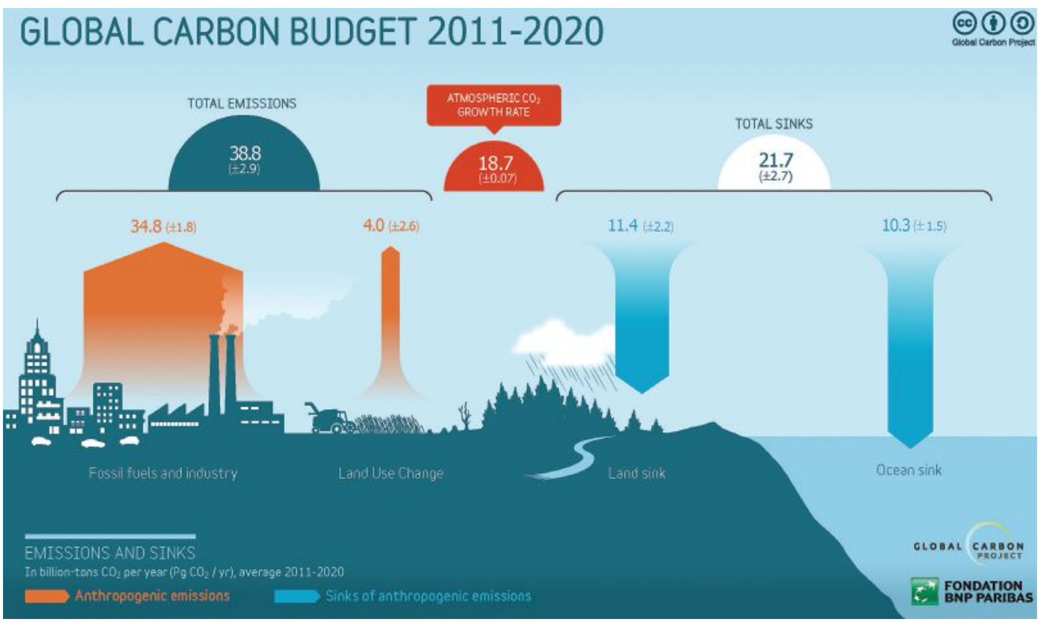

Figure 1: Globally, humans are now releasing close to 40 gigatons (billion metric tons) of carbon dioxide ($GtCO_2$) per year into the atmosphere, of which only about half is being absorbed by natural carbon sinks; the excess remains in the atmosphere. Roughly 7 $GtCO_2$/yr is emitted by the United States. Numbers shown are from 2018; they are larger today. Credit: Global Carbon Project

AVOIDING EMITTING CARBON DIOXIDE

At this stage, all strategies for reaching net-zero emissions by 2050—that is, a state where new greenhouse gas emissions from all sectors of the global economy are counterbalanced by natural and technological carbon dioxide removal (CDR)—will require two major steps, taken simultaneously. The first step—and the only long-term solution—is to stop putting carbon into the atmosphere in the first place.

That means rapidly moving away from fossil fuels to zero-carbon sources of energy: renewable resources (e.g., solar photovoltaic, concentrated solar thermal, wind, geothermal, hydroelectric). Zero-carbon sources of energy would also include nuclear power.[20] All are proven technologies operating in commercial utilities, some for decades.

The other major step is itself twofold: **a)** actively capturing interim carbon emissions (from both CO_2 and CH_4) from existing fossil-fuel plants during the transition to zero-carbon sources, and **b)** actively removing built-up legacy carbon dioxide from the atmosphere.[12,14] Indeed, stated the U.S. National Academies of Sciences, Engineering, and Medicine, "NETs [negative emissions technologies] provide the only means to achieve deep (i.e., >100 ppm) emissions reductions, beyond the capacity of the natural sinks."[13] Specifically, by mid-century, it will be necessary to subtract a good 10 $GtCO_2$ /year from the atmosphere worldwide —more than the U.S. emits—and 20 $GtCO_2$ /year by 2100.[11]

For curbing methane emissions, known and existing options can be implemented quickly at comparatively low cost: what The World Bank characterizes as "low-hanging fruit."[5] One unbelievably huge one is: eliminating profligate waste to increase energy efficiency and incidentally maximize profits.

In all too many oil fields, methane gas is treated as a waste product that is routinely and continuously vented or flared into the atmosphere (**Figure 2**). For nine years running, the United States has been one of the top gas flaring countries in the world—most recently, fourth after Russia, Iraq, and Iran.[5] Yet, low-cost (or even profitable) options already exist to detect and repair methane leaks to curb fugitive emissions from refineries and other oil and gas systems.[14]

If all the gas currently flared—i.e., wasted—worldwide were recovered for generating electricity, the annual potential has been estimated at 688 TWh,[21] or somewhere between the annual national power consumptions of Brazil and Japan. Thus, The World Bank has called upon the U.S. and other governments "to put gas flaring reduction front and center" and for oil-producing countries to "position it at the heart of their 'net-zero' and energy transition plans."[5]

There are also vast opportunities for retrofits and new technologies to attain efficiencies. In the U.S., the biggest source of greenhouse gas emissions is the tailpipes of millions of cars and trucks driven by internal combustion or diesel engines, followed by the smokestacks of industry and electric power generating utilities (**Figure 3**). But another major source is the energy consumption by buildings, both commercial and residential, for always-on lights and electronic devices, hot water, heating, and air conditioning. Inadequate insulation in older buildings is also significant (see "Aggressive Engineering for Passive Houses," *The Bent*, Summer 2011).

CARBON DIOXIDE REMOVAL (CDR)

Both natural and engineered strategies exist for removing carbon dioxide from the atmosphere. Some natural strategies are both proven and low-cost, and could be fielded immediately, well before 2030 (local, state, and federal politics willing). Essentially, they are land use and management practices to undo the decades-long human destruction of natural carbon sinks that absorb atmospheric CO_2 through photosynthesis and sequester it in living plants or soils. A detailed discussion of natural strategies is beyond the scope of this article, but it has been estimated that depending on the total acreage of wetlands and shorelines restored, such practices have the technical potential to sequester 1 to 10 $GtCO_2$/year in the U.S. alone.[13]

Of the 4 TWh of electricity the U.S. generated in 2020, a bit over 60 percent came from fossil fuels—natural gas accounting for two-thirds of that energy and coal for the rest.[22] A good share of those power plants, especially the natural gas plants, likely have many years of useful life ahead of them and are thus unlikely to be retired soon. So, the U.S. Department of Energy is focusing

Figure 2: Unwanted methane, a powerful greenhouse gas, is routinely flared into the atmosphere in unconventional oil fields and other facilities across the U.S. and worldwide. The irony of such wholesale waste is that methane is the very product sought and monetized by drillers elsewhere, including in Ohio and Pennsylvania. Credit: Trudy E. Bell

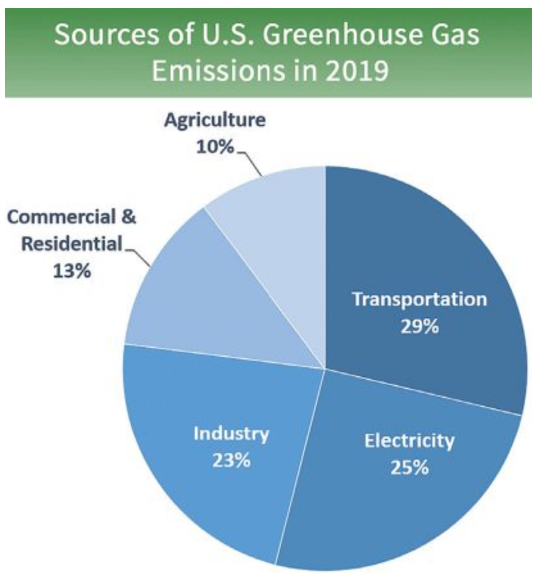

Figure 3: Many engineering opportunities exist across the U.S. economy to deeply curtail the waste of energy and emission of greenhouse gases. Source: U.S. Environmental Protection Agency.

Figure 4: The U.S. Department of Energy's National Carbon Capture Center in Wilsonville, AL, has, for more than a decade, tested 60+ methods of capturing carbon dioxide from flue gases of fossil-fuel power plants as well as testing technologies for direct air capture. It is available to developers in the U.S. and other countries aiming to field pilot technologies with a goal of attaining commercial scale with net-zero greenhouse gas emissions.
Credit: Southern Company

research on methods of removing CO_2 from post-combustion flue gases—potentially useful also for the flue gases from steel manufacturers and other heavy industries reliant on fossil fuels. The goal is to find practical ways to retrofit existing facilities. The DOE is also researching technologies for pre-combustion CDR for fossil-fuel power plants still on the drawing board (**Figure 4**).

Among other things, the DOE is investigating solvents, sorbents, and membranes, plus some advanced novel approaches. Solvent-based techniques involve physical or chemical absorption of CO_2 into a liquid carrier; the absorption liquid is regenerated for reuse by increasing the temperature or reducing the pressure to break the CO_2-carrier bond and release the CO_2. Today's amine-based systems have high capacity to absorb CO_2, and a high tolerance for impurities in the flue gases, but also require high energy to regenerate the absorbent carrier. The search is on for solvents that require lower regeneration energy.

Sorbent-based CDR involves physical or chemical adsorption (with a d) of CO_2 onto or into a solid, which can be similarly regenerated by raising temperature or reducing pressure to desorb (release) the CO_2. Sorbent techniques are less well developed and have technical challenges under active research. Membranes use permeable or semi-permeable materials to separate CO_2 from flue gases, so the search is on for low-cost, durable membranes. Novel approaches include hybrid post-combustion systems as well as investigating cryogenic separation, electrochemical membranes, and other technologies.[15]

In contrast, pre-combustion CDR must be designed into prospective integrated gasification combined cycle (IGCC) power plants before they are built. In an IGCC plant, a carbon-based fuel (usually coal) is reacted with steam and oxygen under pressure to create a synthetic gaseous fuel ("syngas"), which consists mainly of molecular hydrogen (H_2), carbon monoxide (CO), and CO_2. The syngas is used to fuel a gas turbine generator to produce electricity.

In pre-combustion CDR, the CO_2 is captured before the syngas goes to the gas turbine for combustion. Moreover, through what is called a water-gas-shift reaction, CO is converted into CO_2 and hydrogen is produced. Pre-combustion methods are more efficient than post-combustion methods because of the higher pressure of the syngas and the higher concentration of CO_2.[16] The DOE's R&D efforts focus on developing advanced solvents, solid sorbents, and membrane systems for separating the H_2 and CO_2, plus some advanced hybrid or novel approaches that do not themselves require intensive power.

SEQUESTERING THE CO_2 — SAFELY

All these systems, however, face a huge challenge: once you capture the CO_2, what do you do with it? In theory, the gas can be compressed into a liquid for transportation either to an installation that has need of CO_2 as part of an industrial process (e.g., in making a product)—an option often called carbon capture, utilization, and storage (CCUS). Alternatively, it could be injected deep underground, perhaps into a saltwater aquifer, for (hopefully permanent) sequestration.

However, compressing the gas is an energy-intensive process. And transportation could involve pipelines. Ordinary oil and gas pipelines are unsuitable because of the cryogenic requirements to keep the CO_2 liquefied. So, engineers may be faced with the possible necessity of designing or building a wholly new pipeline infrastructure around the country.

There are serious technical challenges. Colorless and odorless, CO_2 is an asphyxiation hazard both to humans and livestock, plus gasoline and diesel-powered vehicles require air to run. CO_2 is also heavier than air, so a leak could allow it to collect in hollows and valleys. Ultimately, it would end up back in the atmosphere at large, defeating the whole purpose of capturing it. Thus, there are significant concerns should a CO_2 pipeline (or disposal site) leak, as happened for the first time on February 22, 2020: a Denbury Resources CO_2 pipeline ruptured half a mile from the village of Satartia, in Mississippi's rural Yazoo County, sending 45 people to hospitals and necessitating the evacuation of 300 more.[2]

VACUUMING THE AIR

One category of negative emissions technologies that has captured the imaginations of policymakers and the general public, as well as engineers, is direct air capture (DAC): removing CO_2 from the ambient air. Air is constantly mixing everywhere around the planet, so anywhere worldwide has about the same 410 ppm concentration of CO_2. Thus, a DAC facility could be located anywhere on the globe.

However, the concentration of CO_2 in ambient air is thousands of times more dilute than it is in flue gases, so monumental energy is required to draw in large enough volumes of air to treat. The process of heating a solvent or sorbent to release to CO_2 is also power hungry, as are other phases of the process.

In 2020, two authors at RWTH Aachen University, Germany, published a life-cycle analysis of a hypothetical low-temperature solid sorbent DAC plant, from resources through construction, operation, and end of life. They concluded that placing such a plant on non-arable land in Iceland would be optimum, as the electricity there is from renewable geothermal and the CO_2 can be stored nearby underground (virtually eliminating the need for pipelines) in the safest possible way: as a solid.[3]

To that end, last September (2021) the firm Climeworks from Zurich, Switzerland, inaugurated what they hailed as the largest commercial DAC facility in the world in Hellisheiði, Iceland. Called Orca, the Icelandic word for "energy," it is capable of annually removing 4,000 tons of CO_2 from ambient air. That is, of course, minuscule compared to the magnitude of the need: 250,000 DAC facilities the size of Orca would be needed to remove just 1 $GtCO_2$ per year. But the facility is of a modular design that is intended to be readily scaled up to any desired size (**Figures 5**).

Figures 5: Beginning operation in September 2021, the Orca direct air capture (DAC) facility (above) in Iceland is powered by a nearby geothermal generating plant. Orca is constructed with eight modular units, each about the size of a shipping container, stacked two high. Each unit has a dozen giant fans (facing away from the viewer) that draw in ambient air, which passes over a sorbent filter that traps CO_2. Once the filter is saturated, the unit heats the sorbent to the boiling point of water to release the separated CO_2, which is piped to a connecting building. There it is mixed with water (27 tons of water per ton of CO_2); the resulting carbonated water then is piped about a quarter mile where it is injected deep into the Earth. Underground, it chemically reacts with Iceland's abundant basalts to produce carbonate minerals (left), permanently trapping the CO_2 over about two years. Credit: Climeworks

IS IT ENOUGH? GLOBAL WARNINGS

In 2016, many of the world's nations adopted Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC) Paris agreement to limit total warming below 2°C, with an aspirational target of 1.5°C. At this late date, however, National Academies observed that even holding warming to 2°C is "exceedingly challenging."[13]

In fact, as early as 2018, the IPCC noted that nations' pledged reductions in the Paris agreement were not enough to achieve what is needed. Indeed, "[p]athways reflecting current nationally stated mitigation ambition until 2030 are broadly consistent with cost-effective pathways that result in a global warming of about 3°C by 2100, with warming continuing afterwards. ...*The lower the emissions in 2030, the lower the challenge in limiting global warming* to 1.5°C after 2030 with no or limited overshoot"(italics added).[8]

In April 2020, the European open-access journal *Frontiers in Climate* published a special multi-author issue on the role of negative emission technologies in addressing climate goals. The overall conclusion was that "the era of unabated CO_2 emission to the atmosphere must end, and we are now called upon to implement a rapid transition to net-zero greenhouse gas emissions."[23] It is crucial, however, that NETs not be viewed as a replacement for reductions in emissions, but as an additional means for accelerating reductions, including reductions of legacy emissions. Yet, already there is evidence of "efforts and suggestions [by fossil fuel interests] to use NETs to sustain fossil fuel use."[23]

It will also be imperative to minimize energy-intensive applications, or at least not power them with fossil fuels. One example is massively multiplayer online computer gaming, although nationwide and global numbers are elusive.[9] A more quantified example is the rapidly growing energy consumption of blockchain applications such as cryptocurrency mining (especially when using Proof-of-Work),[10,18] and non-fungible tokens (NFTs) embraced by the digital art world as a means of certifying authenticity.[1]

As of mid-December 2021, an online tool from the Cambridge (University)

Centre for Alternative Finance calculated that the energy consumed annually worldwide by just the single biggest cryptocurrency Bitcoin was just under 128 TWh, surpassing the entire annual energy consumption of whole countries, including Norway and Argentina (**Figure 6**).[21] Moreover, that power consumption and concomitant carbon footprint are increasing apace.

'HARSH ARITHMETIC'

The magnitude of the challenge and urgency to head off the worst of climate change has become so great that the National Academies has recommended research into large-scale moderate- to high-risk approaches to increase how much CO_2 the oceans can absorb. The oceans cover 70 percent of the planet and already absorb about a quarter of annual CO_2 emissions, at the expense of becoming both more acidic and warmer —consequences that, among other things, have impaired the ability of shellfish to form shells, bleached coral reefs, and contributed to the worldwide rise of sea levels. Warmer water is also less able to absorb CO_2 than colder water.

In addition to various biological approaches to altering seawater chemistry, the National Academies identified possible engineering methods to make the oceans colder and more alkaline, as well as to sequester the CO_2. Possible technologies include means for mining, pulverizing, dispersing, and dissolving natural silicate and carbonate materials across the oceans, vertically transporting CO_2-rich waters to great depths as well as augmenting the upwelling of cold water from the depths, and electrochemical means of increasing alkalinity and/or stripping the gas from seawater for undersea sequestration.[11]

However, *Frontiers in Climate* cautioned that "an unsettling gap" exists between model scenarios of the potential of carbon dioxide removal technologies and their practical use at a global scale, requiring intensive research.[23] Also lacking is full understanding of possible unintended consequences of such planet-wide alterations. And common to all forms of CDR "is the requirement to track the CO_2 along the value chain in both space and time."[23] That would entail rigorous accounting and verification of both emissions and removals, all the way from the mining of raw materials and manufacture of parts through consumer use and end-of-life disposal.

For example, hydrogen-powered vehicles have been hailed as zero-carbon—and that may be true for "green" hydrogen derived from the electrolysis of water powered from a zero-carbon fuel. But today, most hydrogen is produced from fossil fuels, notably through steam methane reforming (SMR) from natural gas. A relatively new concept is "blue" hydrogen produced by SMR with carbon capture and storage; however, recent computational modeling reveals that the production of "blue hydrogen has emissions as large as or larger than natural gas used for heat."[6]

Similarly, the current widespread move to all-electric vehicles will reduce overall CO_2 emissions ***only if*** the recharging stations are connected to power plants using zero-carbon sources—otherwise, they just create greater demand for fossil fuels. It will also be important to account for CO_2 emissions (not to mention other unintended environmental consequences) generated by the large-scale mining and processing of the

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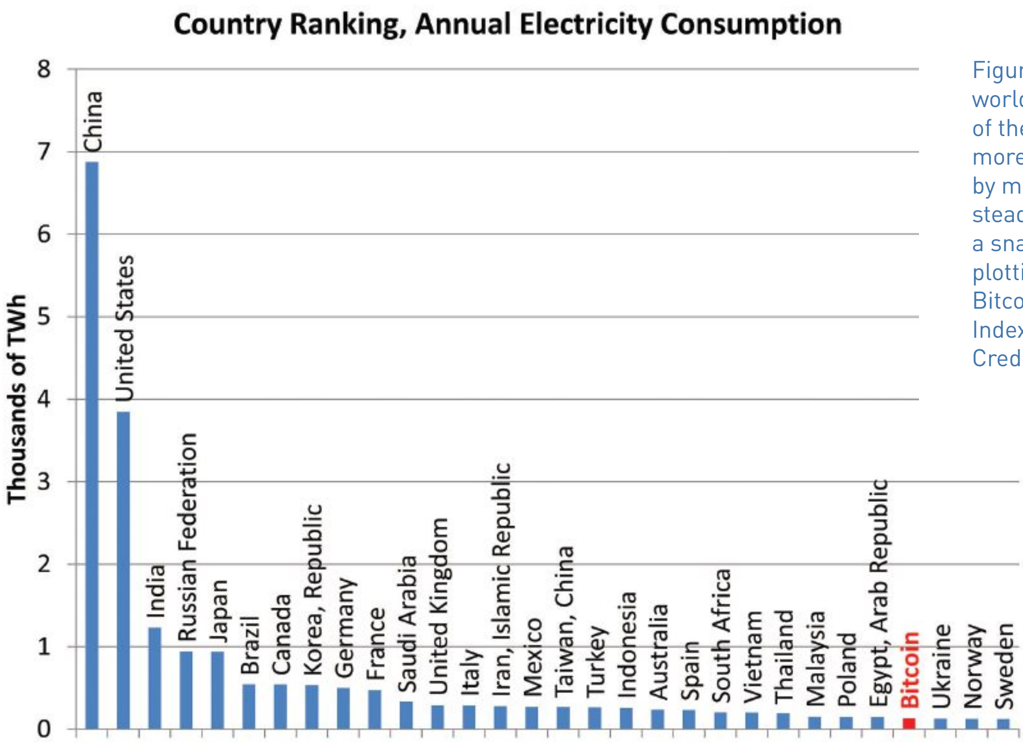

Figure 6: "Mining" operations worldwide for Bitcoin, the largest of the cryptocurrencies, consumes more power annually than is used by many entire nations, and is steadily increasing. Chart represents a snapshot as of December 11, 2021, plotting data from the Cambridge Bitcoin Electricity Consumption Index, University of Cambridge. Credit: Trudy E. Bell

DECARBONIZING —
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AT THIS LATE DATE, HOWEVER, NATIONAL ACADEMIES OBSERVED THAT EVEN HOLDING WARMING TO 2°C IS "EXCEEDINGLY CHALLENGING."

materials necessary for electric vehicle batteries, such as lithium, antimony, and nickel.[19]

Upshot: to achieve the climate goals outlined by the White House in November of reducing net emissions of greenhouse gases at least 50 percent below 2005 levels by 2030, the New York-based research and consulting firm Rhodium Group estimated that the U.S. would need to cut emissions by about 5 percent per year over the next eight years. That is much faster than was being achieved pre-pandemic.

Preliminary figures for 2021, however, indicate that the nation's greenhouse gas emissions ***rose*** 6.2 percent after having plummeted by 10 percent in 2020 following the global economic shutdowns during the initial coronavirus outbreak. That sharp rebound to business as usual has put "the U.S. even further off track from achieving its 2025 and 2030 climate targets," the Rhodium Group warned. "...[A]ll must act quickly in order to put the U.S. on track."[17]

"The harsh arithmetic of climate change demands ambition and extraordinary response," stated one author in *Frontiers in Climate*, "demanding innovation, research, and investment in whole new fields of knowledge...," as well as designing and financing major projects at the multitrillion dollar scale, and ensuring societal acceptance. "These additional dimensions should prompt humility and (ideally) additional ambition, given the scope of the work."[23]

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