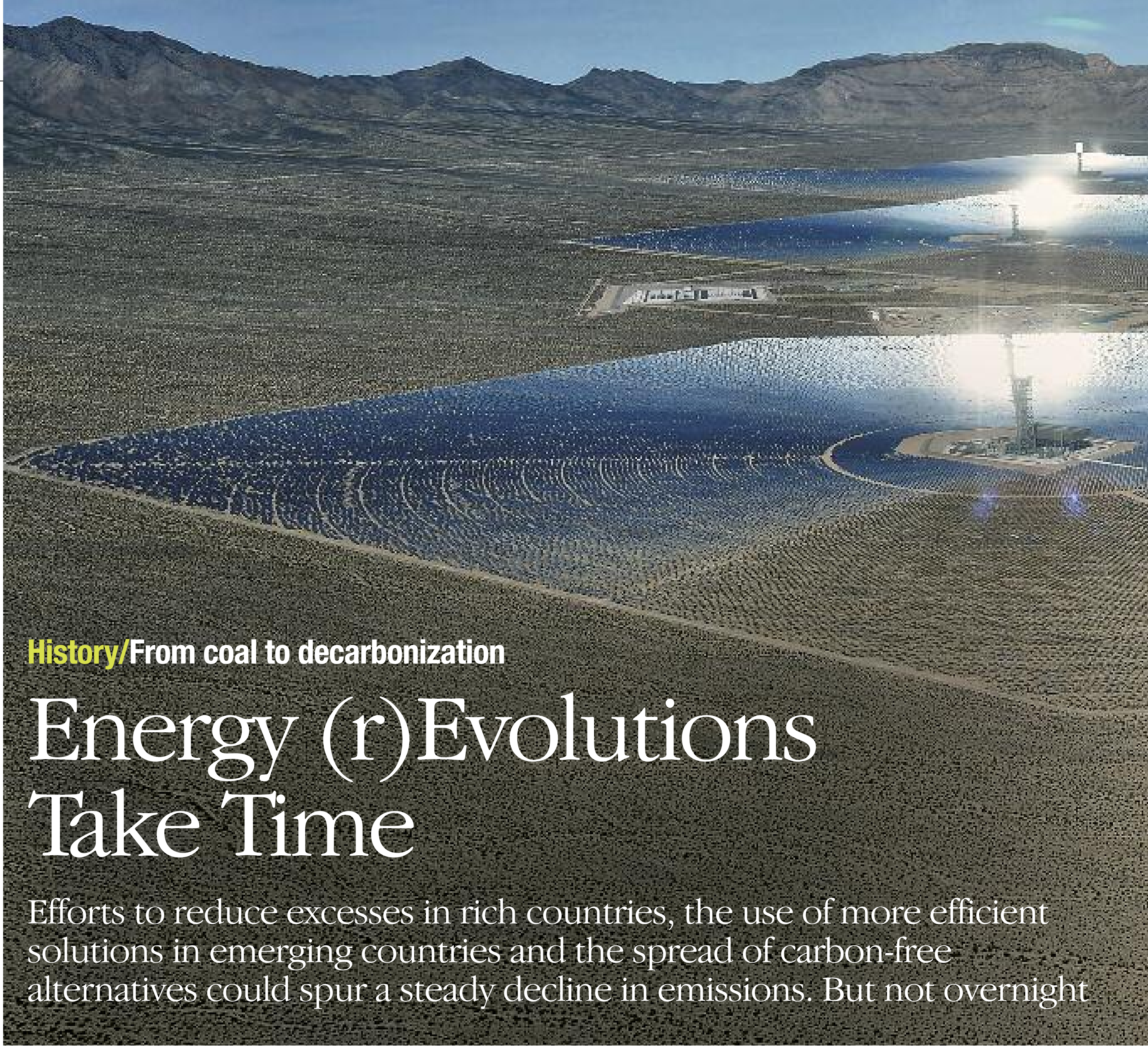

History/From coal to decarbonization

# Energy (r)Evolutions Take Time

Efforts to reduce excesses in rich countries, the use of more efficient solutions in emerging countries and the spread of carbon-free alternatives could spur a steady decline in emissions. But not overnight


VÁCLAV SMIL

He is Distinguished Professor Emeritus in the Faculty of Environment at the University of Manitoba in Winnipeg, Canada. He has published 40 books, taking an interdisciplinary approach to energy, environmental and population change and technology. He is a member of the Royal Society of Canada and the Order of Canada. In 2015 he received the OPEC award for research.


At the beginning of the 19th century the UK was the only country with significant coal extraction: coal provided 95 percent of Britain's primary energy, and British coal accounted for more than 90 percent of the fuel's global production. Elsewhere the world was, as it had been for millennia, fueled by wood and charcoal, straw and dried dung. Economies of these traditional low-energy societies were stagnant or growing at a fraction of one percent a year. In 1800, wood supplied more than 90 percent of France's energy. Charles Dupin's 1818 inventory of energy (wood, charcoal and a small amount of coal) in Paris added up to only about 20 gigajoules (GJ) per capita, no more than was available in Rome at the time of Marcus Aurelius and no more than today's per capita averages in Tanzania or Togo.

## The first energy revolution

Transition from wood to coal was the modern world's first energy revolution. During the 1830s, high-pressure steam engines began to power the first railroads and oceangoing ships while increasingly efficient stationary steam engines began to provide energy for industrial uses. By the mid-1870s, coal supplied more than half of all primary energy in France. The US had its tipping point between biomass and fossil fuels in 1884, Japan in 1901, and at that time, coal and crude oil also began to provide more than half of the world's final energy consumption. The second modern energy revolution began in 1882 with Edison's pioneering electricity generating plants. During the following 50 years, electricity lit the cities, electric motors transformed industries, transportation, construction (high-rises made possible by electric elevators) and kitchens (refrigerators, electric stoves, small appliances). Concurrently, fossil-fuel-based mechanization of agriculture (steel implements, tractors, combines, fertilizers) released the labor force required by rapid indus-

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**A RECORD SOLAR SYSTEM**
**Aerial view of the Ivanpah solar heating system in California's Mojave Desert. Owned by NRG Energy, Google and BrightSource Energy, it is the largest solar tower system in the world. 347 thousand mirrors are controlled by sophisticated computers that calculate the sun's presence on the reflective surfaces and concentrate that energy in boilers at the top of three towers. There water is heated to produce the steam that provides energy for turbines that supply energy for over 140,000 California homes.**

trialization, and urbanization began to create a new world of rising life expectancies, higher incomes, better housing, and increased education and affluence.

Shortly after 1900, annual per capita energy supply surpassed 150 GJ in the UK, and it reached approximately 100 GJ in the US and 90 GJ in Germany. Many economies, including those of Germany and Japan, grew by 2 percent a year; the US economy grew by 4 percent. The third modern energy revolution was the rise of refined oil products. With the notable exception of the US, where large-scale oil production was driven by pre-WW II discoveries in California and Texas and by early and rapid automobilization, this revolution had to wait until after 1950. Then the exploitation of giant oilfields in the Middle East and the need for higher-quality fuel for post-war reconstruction in Europe and Japan combined with the availability of large oil tankers, rising ownership of automobiles and extensive construction of new pipelines and refineries to make crude oil the world's most important fossil fuel.

## The rise of natural gas

By 1965 its global consumption had surpassed coal and by 1973 crude oil, with 42 percent, provided the highest share of the world's primary energy. OPEC's two rounds of oil price rises cut that share, and eventually the fourth modern energy revolution got underway with the rising reliance on natural gas. Its widespread use became possible with the construction of transcontinental pipelines that spanned North America and connected Siberia with Europe and China, with the exploitation of abundant offshore resources in the Gulf of Mexico, North Sea and Persian Gulf and with the reliance on large liquefied natural gas tankers whose deployment turned gas into a fungible commodity delivered from Qatar to Tokyo and from Texas to Latvia.

The post-WWII decades also saw major expansion of the generation of hydro and nuclear electricity but fossil fuels have remained dominant. In 1950—leaving aside traditional biomass fuels and with 1kWh of non-thermal primary electricity equal to 3.6 MJ—fossil fuels supplied about 98 percent of the world's primary energy, and by the year 2000 that dependence declined only slightly to about 90 percent. This retreat was slowed by China's economic modernization, as the country became the world's largest producer of coal and the world's largest importer of hydrocarbons. Annual per capita averages of primary energy supply rose close to 300 GJ in North America, above 150 GJ in the richest EU countries as well as in Japan, and the Chinese mean is now approaching 90 GJ. This increase of usage was accompanied by a 16-fold increase in the production of global energy during the 20th century.

Because the century saw major gains in energy conversion efficiencies, average global per capita availability of useful energy had gone up more than 40 times between 1900 and 2000, and this surge created the modern world of affluence, longevity and connectivity, but it has also caused significant environmental degradation. Eventually, most societies managed those challenges reasonably well thanks to technical fixes ranging from water treatment, double-hulled tankers and monitored pipelines to electrostatic precipitators for capturing fly ash, desulfurization of flue gases which during the 1980s were seen as the greatest environmental threat in Europe and North America and car exhaust controls by three-way catalytic converters. In many ways the fossil fueled world has become not only richer but also cleaner.

But, due to a rapid oxidation of carbon, burning of fossil fuels generates $CO_2$ and global emissions of this gas have soared from just 29 million →

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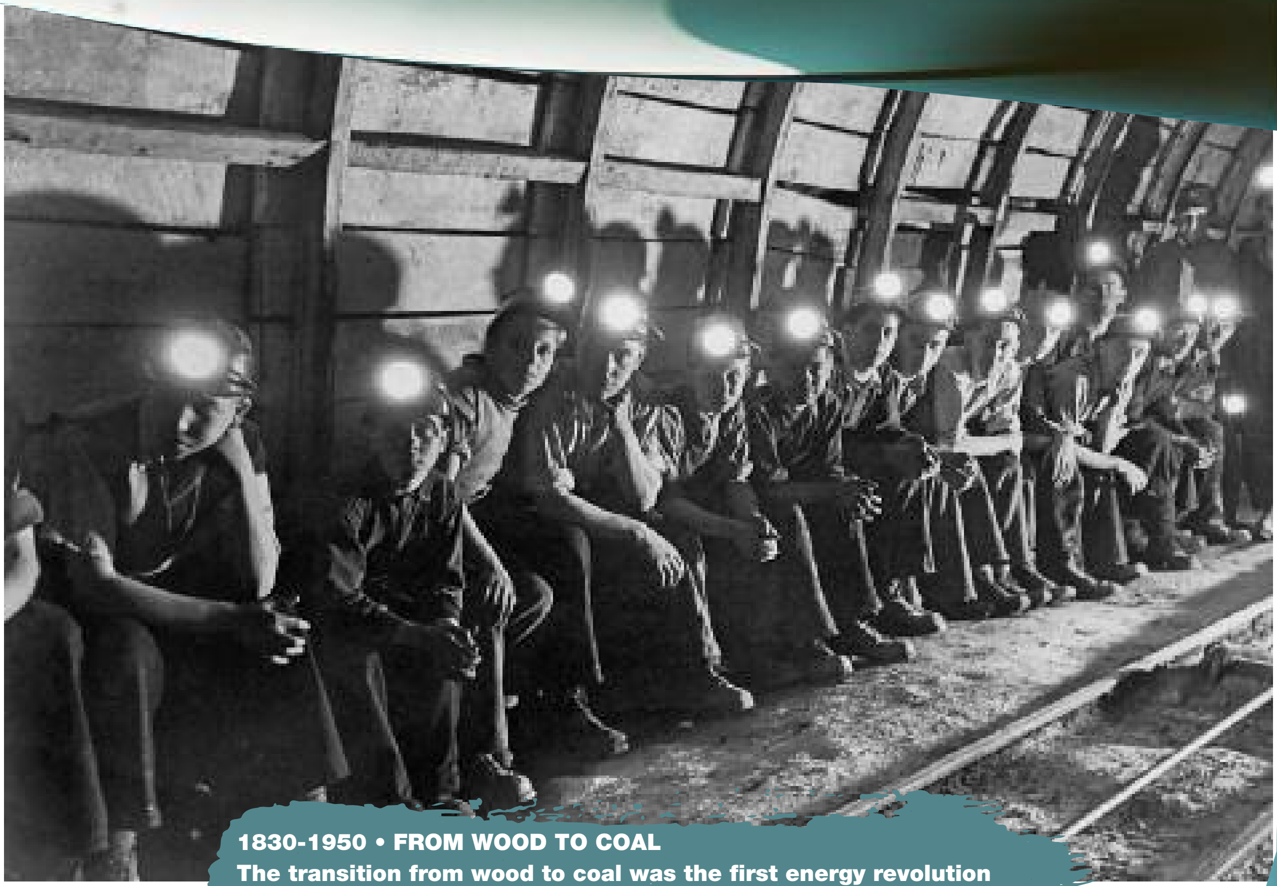

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**1830-1950 • FROM WOOD TO COAL**
**The transition from wood to coal was the first energy revolution in the modern world. The birth of the first power plants, in the early 1900s, transformed industries, transport and construction. Photo: British miners wait for a train to take them to the Markham coal mine in Derbyshire, c. 1950.**

tons in 1800 to nearly 2 billion tons by 1900, to almost 26 billion tons in 2000 and another record in 2018 with about 37 billion tons. Although a large share of these emissions has been absorbed by the ocean and by the biosphere, atmospheric concentrations of $CO_2$ rose from about 280 parts per million (ppm) in 1800 to 410 ppm by the beginning of 2019. This is a historically unprecedented rise because during the past millennium the concentrations remained remarkably stable, just between 275-280 ppm.
In 1896, Svanté Arrhenius calculated that doubling of atmospheric $CO_2$ might increase average temperatures by 5-6 °C the result being, remarkably, of the same order of magnitude as indicated by today's complex climate models containing more than 200,000 lines of code. And in 1957, Suess and Revelle wrote about humanity "carrying out a large-scale geophysical experiment that could not have happened in the past nor be reproduced in the future." While scientists have been aware of the phenomenon of global anthropogenic warming for more than a century, the problem only began to attract wider attention during the late 1980s and now it has become a leading public and political concern.

## Waiting for the fifth energy revolution

The solution appears to be simple enough: replace fossil fuels by non-carbon energy sources. After all, the planet receives enough solar radiation that capturing a mere 0.1 percent of it could satisfy a global demand ten times higher than that for today's energy use. But like its predecessors, global decarbonization, the fifth energy revolution that will do away with fossil fuels and replace them by an uncertain combination of renewably generated electricity, hydrogen and nuclear power, will take a long time to accomplish.
Even if we had all the requisite non-carbon alternatives available for immediate commercial deployment, the scale of the challenge would dictate a long period of transition. The world now extracts about 15 billion tons of fossil fuels containing about 10 billion tons of carbon. Energy released by their combustion accounts for nearly 90 percent of all modern energy supply, a supply that generates about two-thirds of the world's electricity, heats homes for about one billion people, powers more than 95 percent of land-borne, water-borne and air transportation and provides indispensable heat and raw materials

1970-2019 • THE RISE OF GAS
OPEC's oil price rises in the 1970s kick-started the fourth modern energy revolution in natural gas. Photo: a worker prays toward Mecca. In the background, a butane gas tank in Scotland.

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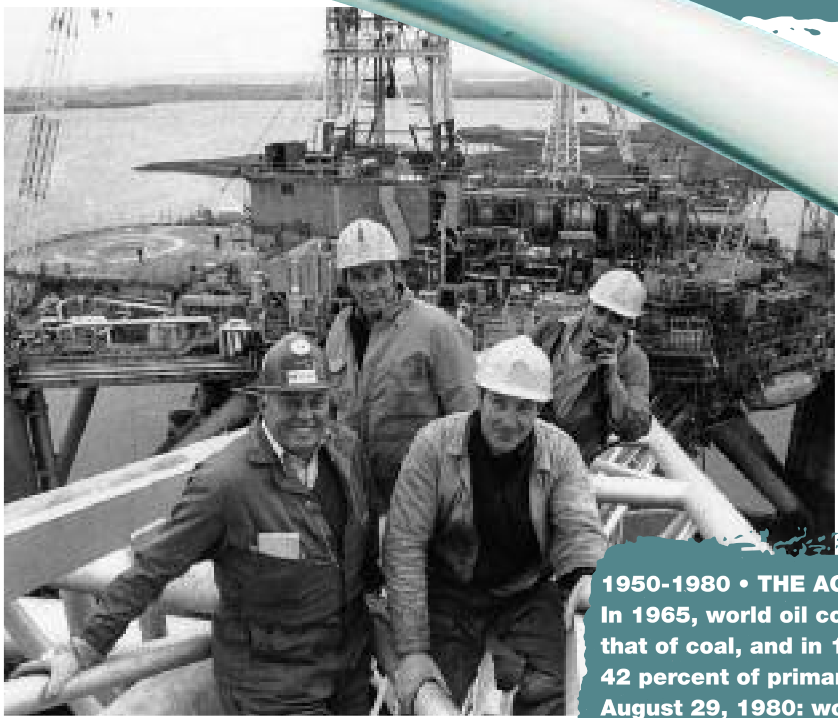

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1950-1980 • THE AGE OF OIL
In 1965, world oil consumption exceeded that of coal, and in 1973 crude oil provided 42 percent of primary global energy. Photo: August 29, 1980: workers at the "Drill Master" oil rig in Stornoway, Outer Hebrides, Scotland.

for the production of the four material pillars of modern civilization, iron, cement, plastics and ammonia. Structures and infrastructures of this immense global fossil fuel system range from more than 1.25 billion road vehicles, hundreds of millions of furnaces, nearly four million km of pipelines and hundreds of thousands of turbines to tens of thousands of large airplanes and steam turbines and thousands of large oilfields, tankers and electricity generating stations. Replacement cost of this global mega system would be, most likely, in excess of USD 30 trillion.

But we do not have any immediately deployable alternatives for long-distance, mass-scale flying dependent on kerosene to power gas turbines, for long-distance trucking and containerized and bulk ocean shipping dependent on large diesel engines or for the production of basic materials. Steel production from primary iron now requires about a billion tons of coke made from coal annually; cement is produced in large kilns heated by low-quality fossil fuels; hydrocarbons serve as feedstocks and fuel for syntheses of plastics and ammonia, and without ammonia applications we could not maintain the crop yields necessary to feed nearly 8 billion people. Alternatives, including smelting iron with hydrogen, using $CO_2$ in cement or deriving hydrogen for ammonia synthesis from electrolysis of water, are under early development, but the scale of the global demand—1 billion tons of primary iron, more than 4 billion tons of cement, nearly 200 million tons of ammonia and more than 300 million tons of plastics—means that any new non-carbon techniques will take considerable time to displace large shares of today's highly optimized processes.

Moreover, we do not just need to decarbonize the existing supply, we need a large expansion of energy use in most Asian countries and, above all, in Africa. The world of energy affluence, North America, EU, Russia, Japan and Australia, is oversupplied, and despite its long history of improving efficiency, remains inexcusably wasteful. We may have doubled the efficiency of internal combustion engines so that gasoline-fueled machines are now almost as good as diesels but even in Europe the average car mass has more than doubled. A Citroen 2 CV or Fiat Toppolino weighed less than 600 kg; now the bestselling VW Golf weighs about 1,400 kg. We had more than doubled the efficiency of household heating and natural gas furnaces are now more than 95 percent efficient, but the average size of American houses has grown 2.5 times since 1950, and in summer air conditioning keeps the indoor temperature at levels that would trigger heating in winter. Our best jetliners now consume 70 percent less kerosene per passenger-kilometer than did the pioneering designs of the late 1950s, but during the same time total passenger kilometers flown have increased about ten-fold. Simply, in many instances we are using and wasting more because of rising masses, sizes and frequencies of use than we have gained thanks to better designs.

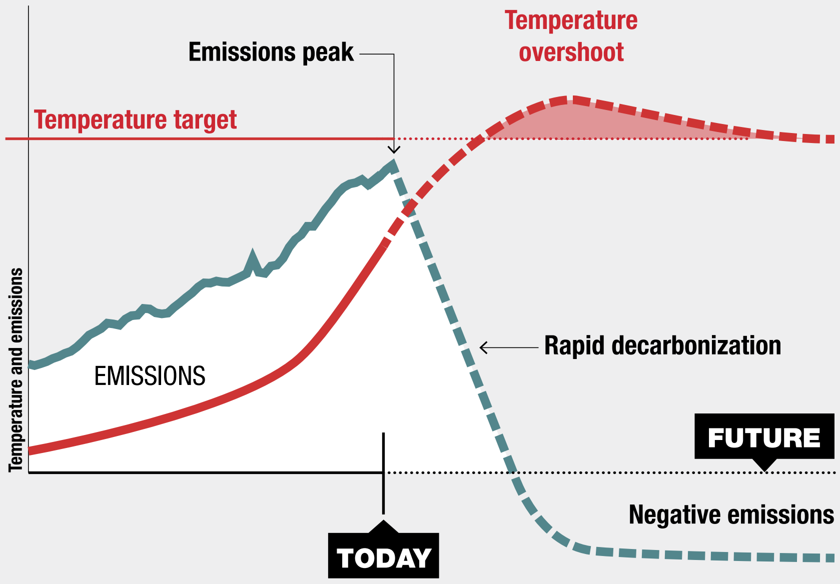
In this affluent world it should be easier to cut the excessive consumption: good quality of life does not hinge on flying for a weekend for €40 from Amsterdam to Cyprus or eating fresh green beans airlifted from Kenya to London in January. But the second world, the countries striving to reach the affluence level shown by China still wants more: Chinese per capita energy supply rose from about 40 GJ in 1980 to nearly 90 GJ in 2018 but the country does not want to stop at this level, one similar to Spain in the late 1980s. And the third world, the countries still stuck in underdeveloped misery, has to multiply its energy use: India's mean is only about a quarter of the Chinese level, and the African ladder descends from Nigeria's inadequate 30 GJ/capita to a dismal 15 GJ in Ethiopia and to barely registering 2 GJ in South Sudan. Yet it will be in sub-Saharan Africa where more than half of the world's population increase will be added during the next 30 years. Obviously, that fast-growing population will tap every available energy source in order to improve their lives and Africa will be opening new oilfields and new coal-fired power plants.

## Vanishing promises

What all of this means for the likely pace of global decarbonization? The recent record is indisputable. Between 1992, the year of the first UN climate convention, and 2017 all major indicators associated with the demand for fossil carbon increased substantially. As a result, during those 25 years the global consumption of fossil fuels rose by 54 percent, $CO_2$ emis- →

# Emissions and temperature overshoot

**Limiting global warming to 1.5 °C requires emissions to start falling immediately at a rapid rate in order to be reduced to zero (or become negative with sequestration) by 2050. The graph is based on IPCC special report on global warming of 1.5 °C published in October 2018.**




Source: IPCC

**LONDON, UNITED KINGDOM**
**Beddington Zero Energy Development (BedZED) is a small eco-friendly neighborhood in the south London suburb of Wallington, built between 2000 and 2002. This is the first carbon-neutral residential area. Almost every apartment in BedZED has a small garden.**

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**AMSTERDAM, NETHERLANDS**
**The Edge Amsterdam, the 40,000-square foot skyscraper home of consulting firm Deloitte, has been named the smartest and most environmentally friendly office in the world. The building is extremely efficient in terms of use of resources, but also in terms of the organization of employee spaces.**

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sions from fossil fuel combustion rose by 57 percent, and, using the UN's conversions, the share of fossil fuels in the global primary energy consumption remained unchanged at about 90 percent. Further, the share of all forms of non-carbon energy (hydro, nuclear, wind, solar, biofuels) in the global primary supply rose by just three percent over the last 25 years, from 12.3 percent in 1992 to 15.3 percent in 2018 (even when using higher conversions for all primary electricity).

The promise of assorted "solutions" is now wearing thin. Work on controlled fusion began three generations ago, small, inexpensive and inherently safe nuclear reactors have been promoted since the early 1980s, and the miracle of cold fusion (LENR) has been around for nearly as long, yet none of these promises have resulted in actual commercial conversions. Mass production of biofuels is inherently limited by the low power density of photosynthesis and by the necessity of material inputs such as water and fertilizer for high-yielding production. New renewables like solar and wind have been making important dents in some national energy balances but without practical non-pumped hydro electricity storage or without unprecedented high voltage direct current (HVDC) interconnections they are not available on demand to supply rising megacities, nor can they energize long-distance transportation. The hydrogen economy is another constantly retreating mirage. And carbon sequestration will not get us to zero anytime soon, as today's large-scale facilities capture less than 50 million tons of $CO_2$, slightly more than 0.1 percent of current emissions.

What would then justify the belief that in the next 25 years we could have non-carbon energies supplying 100 percent or, assuming massive carbon capture, at least 80 percent of the growing global energy demand? The Paris agreement actually confirms a further substantial increase of emissions as it "notes with concern that the estimated aggregate greenhouse gas emission levels in 2025 and 2030 resulting from the intended nationally determined contributions do not fall within least-cost 2 °C scenarios but rather lead to a projected level of 55 gigatons in 2030." This comes as no surprise as recent long-range forecasts indicate strong growth of activities dependent on fossil fuels. The International Civil Aviation Organization expects total air traffic to more than triple by 2040. McKinsey forecasts a 2.5-fold growth in container shipments by 2066. The Food and Agriculture Organization foresees global meat consumption doubling by 2050, and the Organization for Economic Co-operation and Development has steel demand growing by a third by 2025.

Determined efforts to reduce excesses in affluent countries, to adopt the most efficient energy solutions in nations rising from energy poverty, and to accelerate the diffusion of non-carbon alternatives could end the further rise of emissions and enable their steady subsequent decline. But it is highly unlikely that we could engineer an immediate plunge in $CO_2$ emissions and eliminate them by 2050 in order to replicate the trend shown in the IPCC's 1.5 °C report. Global energy (r)evolutions take time and to break that historic pattern would require either a collapse of modern civilization or a supremely coordinated and resolutely executed transformation on the global scale, beginning instantly and proceeding rapidly and at a cost, a major share of the global economic product, that has no precedent in history.