Energy Transitions: Fundamentals in Six Points

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Abstract

The public discourse of the unfolding energy transition has been poorly defined, it has been often misinformed and misleading, almost always ahistorical, and overwhelmingly unrealistic. In this paper I focus on six fundamental realities that must be taken into account: There is nothing new about energy transitions; All energy transitions have many specific attributes, but the one currently underway is truly unprecedented; Decarbonization of the global energy supply is taking place not because of resource shortages and excessive prices, or because of the need to do away with inferior efficiencies and to increase supply reliability; Even moderate reductions of annual global carbon combustion are difficult because our dependence on fossil fuels is enormous and because most of the humanity needs more energy and this requirement cannot be met by a rapid expansion of renewables; Global civilization remains highly dependent on fossil fuels and future demand for coal and hydrocarbons will rise in many middle- and low-income countries; And decarbonization includes energy transitions that are relatively easy to accomplish as well as carbon substitutions for which we currently do not have any commercial non-carbon alternatives. As unique and as unprecedented the unfolding global energy transition may be, it shares the key feature with its predecessors: it will be a gradual, multidecadal, inter-generation process with different and diverging national pathways and rates of progress. Still, our commitment to innovation and to better ways of managing our energy use can make a real difference to its rate of progress.

Keywords: Energy transition, decarbonization.

Four decades ago, the Iranian revolution (Ayatollah Khomeini returned to Tehran on February 1, 1979) led to the second round of crude oil price increases. During the first round, in 1973-1974, the OPEC forced the quintupling of the posted price (from $1.9/barrel in 1972 to $10.41/barrel in 1974), the second round had nearly quadrupled that total (to $35.7/barrel by 1980). Crude oil provided the largest share of primary global energy use, and the concerns were about its supply and price. Producers of coal and natural gas saw the higher

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oil prices as an opportunity to increase their share of the market. Discussions of potential global warming were limited to infrequent papers in academic journals, and the broad consensus saw the acid deposition (commonly called acid rain) as the worst environmental problem both in Europe and in North America (Smil, 1987). And in 1979 the USSR invaded Afghanistan and the Chinese had just began (three years after Mao Zedong's death) to talk about the need for economic reforms.

Four decades later we live in a very different world. OPEC is still around but with greatly reduced influence, mainly because of the US re-emergence as the world's largest oil and gas producer (BP, 2019). Globally, crude oil is still the most important fuel but in 2018 it supplied only about 24% more energy than coal, whose production (mainly because of the surge in China) rose by more than two-thirds since the year 2000. Since 1979, oil prices have fluctuated but in real terms they are much lower than they were four decades ago. USSR had collapsed in 1991 while the post-Mao China rose to become the world's largest (in PPP terms) or the second largest (in exchange rated GDP) economy and the largest exporter of manufactured goods. Concerns about acid rain are a distant history and the new consensus sees global warming, caused by the anthropogenic emissions of greenhouse gases, as by far the greatest threat to modern civilization. These emissions come from many sources, but the combustion of fossil fuels dominates, and that is why the energy transition to non-fossil sources, commonly termed decarbonization, has emerged as one of the most prominent global concerns.

Unfortunately, public discourse of the unfolding energy transition has been poorly defined (focusing disproportionately on the decarbonization of electricity generation or on electrification of road transport), it has been often misinformed and misleading (quoting newly installed capacities of renewable conversions rather than their actual generation shares and neglecting difficult industrial transitions), almost always ahistorical (ignoring the lessons of past energy transitions) and overwhelmingly unrealistic (commonly assuming impossibly rapid rates of adoption of non-carbon conversions). I have addressed all of these shortcomings in my recent writings (Smil, 2010, 2014, 2015, 2016, 2017a, 2017b, 2019) and here I will focus briefly on just six fundamental realities, taking into account the recent composition of primary energy supply and its near-term prospects, and stressing the limits of technical innovations.

1. *There is nothing new about energy transitions.* Economic accomplishments and quality of life always reflect the levels and modes of energy use and energy transitions thus involve not only the changing supply of primary energies (fuels or primary electricity) but also the introduction of new converters (ranging from boilers to electric motors) and new prime movers used to produce useful thermal, electric and mechanical energies required by food and industrial production, in construction and for services and transportation. Without steam engines and, later, steam turbines, the transition from wood to coal would have been limited just to a more efficient generation of heat. Without gas turbines (jet engines) kerosene refined from crude oil would be used just for lighting.

Even during the pre-industrial era, when traditional biomass fuels dominated the supply of heat and animal and human muscles provided most of the kinetic energy, some societies were gradually turning to higher-quality charcoal, adopted better wood-burning stoves, installed significant capacities of mechanical power in water wheels and wind mills, and improved the performance of draft animals by better harnessing and feeding. And the history of the industrial era could be seen as a continuous sequence of transitions to more convenient and cleaner fuels (from coal to crude oil, natural gas and primary electricity), to better inanimate prime movers (from steam engines to steam turbines and internal combustion engines) and to higher share of final energy use delivered as electricity.

2. *All energy transitions have many specific attributes, but the one currently underway is truly unprecedented.* Studies of past energy transitions show substantial national differences in the composition of primary energy supply and its secular changes as well as in the adoption rates of new energy converters and in the shares of final energy demand. Such major economies as the US, Russia and China have followed the typical sequence from wood to coal to hydrocarbons and to the rising shares of primary (hydro and nuclear) electricity, while many other countries never had a coal industry. There have been major differences in the rates of electrification (and almost one billion people still have no connections to the grid), ownership of cars (its diffusion was relatively rapid in the US, in Europe it was delayed until after WW II, in China it took-off only since 2000) or household converters (for example, clothes dryers and air conditioners are very common in North America, rare in the EU). The current energy transition is unprecedented because of the

reasons for its desired acceleration, because of its requisite scale, and because of its reliance on intermittent sources with low energy and low power densities.

3. *Decarbonization of the global energy supply is taking place not because of resource shortages and excessive prices, or because of the need to do away with inferior efficiencies and to increase supply reliability.* Obviously, there is a finite mass of fossil fuels in the Earth's crust but the best available estimates indicate that their resources could cover the global needs for generations to come (WEC, 2016). Moreover, improvements in extraction, processing and transportation of fossil fuels have made them widely affordable. America's high per capita energy consumption is obviously enabled by the fact that average households spends just 5% of its disposable income on all forms of energy it uses (USEIA, 2014). Moreover, ample availability of fossil fuels has been enhanced and their cost has been reduced by substantial improvements in the efficiency of their uses: as might be expected, energy-intensive industries have seen the most impressive gains but efficiencies of common household and transportation conversions have also improved substantially: for example, today's best gas furnaces are 97% efficient (compared to less than 50% efficient coal-fired stoves of 70 years ago), and the latest jetliners consumed less than a third of kerosene per passenger-kilometers than the first commercial designs of the late 1950s. Finally, fossil fuel-based energy supply is highly reliable.

The quest for abandoning these abundant, affordable and reliable sources of energy is driven overwhelmingly by a single objective, the eventual elimination of fossil carbon from the global energy supply. There has been no shortage of irresponsible speculations about the speed of this transition, with some claims seeing the possibility of a carbon-free world, or at least carbon free national energy supplies, as early as 2030 (J.P. Morgan, 2019). Such completely unrealistic claims ignore both the scale of the required global decarbonization and the need for further increases of energy supply in low-income countries.

4. *Even moderate reductions of annual global carbon combustion are difficult because our dependence on fossil fuels is enormous and because most of the humanity needs more energy and this requirement cannot be met by a rapid expansion of renewables.* The scale of the required substitution is daunting: in 2018 the world produced

just over 8 billion tonnes (Gt) of coal, nearly 4.5 Gt of crude oil and about 3.9 trillion m^3 of natural gas, or the equivalent of about 9.2 Gt of fossil carbon whose combustion emitted the record amount of nearly 34 Gt of CO_2 (BP, 2019). In 1992, the year of the first global convention on climate change, global CO_2 emissions from fossil fuel combustion were 21.4 Gt. Not only there has been no decarbonization of global energy supply but during the past quarter century of rising concerns about global warming and constant calls for rapid decarbonization the world has been expanding its absolute dependence on fossil carbon, with coal extraction rising by about 70%, crude oil production by nearly 40% and natural gas flows by more than 80%, with the aggregate increase of about 55% for all fossil fuels.

And despite much publicized growth of installed capacities for wind and solar generation, there has been also no recent decline in the world's relative dependence on fossil fuels. After converting all primary energies to a common equivalent (with nuclear electricity equal to 9.5 MJ/kWh and with all other primary electricity at their thermal equivalent of 3.6 MJ/kWh, the UN preference), fossil fuels contributed 90.5% of the world's primary commercial energy in 2018 —compared to 90.1% in 2010 and 89.8% in the year 2000. Using the conversions preferred by the BP Statistical Review (with all primary electricity at 9.5 MJ/kWh) the shares of fossil fuels were 85% in 2018. The third option to aggregate the world's primary energy supply is used by the International Energy Agency, with the global total including the highly uncertain consumption of non-commercial traditional biomass fuels and with the fossil fuels share at about 80% in 2018.

5. *Global civilization remains highly dependent on fossil fuels and future demand for coal and hydrocarbons will rise in many middle- and low-income countries.* High relative dependence (80-90% depending on the conversions used) and its unprecedented absolute scale, now approaching the combustion of 10 Gt of fossil carbon a year, means that there can be no rapid decarbonization on the global level because even major decarbonization achievements on a national level get swiftly swamped by rising emissions in other countries. For example, between 1992 and 2018 the UK reduced its carbon emissions by 33% but that absolute reduction of 190 Mt of CO_2 was made up by India's rising emissions in less than

two years between 2016 and 2018. Given the current state of energy demand, all that any local, regional or national decarbonization gains in affluent countries can do is to reduce the growth rate of annual global CO_2 emissions – but the average atmospheric concentration of CO_2, the only metric that matters in order to moderate any future rate of climate change, keeps rising, from less than 320 ppm in 1958 (when the continuous measurements began at Mauna Loa) to more than 410 ppm by 2019 (NOAA 2019).

And large disparities in per capita energy use – in 2018 the means were 295 GJ in the US, 150 GJ in Japan, 97 GJ in China, 25 GJ in India and only 15 GJ in Africa —guarantee that low— and middle-income Asian and African countries will experience growing demand for more energy in general and for fossil fuels required for their industries and transportation in particular. Not surprisingly, Indian plans envisage quintupling total energy use by 2047 with coal's share at close to 50% (Kumar *et al.,* 2017), and Chinese energy demand, although it had almost quintupled since the late 1980s, is not expected to peak before 2040 after rising by another 30% above the 2017 level (CNPC, 2017). As a result, even a relatively rapid and continuing gradual decarbonization in affluent countries will fall short of the rising fossil fuels consumption in Asia and Africa.

This reality is recognized by all serious long-term energy forecasts. Notably, the latest IEA projection sees carbon emissions rising even under its New Policies scenario (IEA, 2018). And it was also recognized by the Paris agreement: even if all of its signatories were to fulfill their decarbonization pledges, the estimated aggregate greenhouse gas emissions in 2025 and 2030 would "not fall within least-cost 2˚C scenarios but rather lead to a projected level of 55 gigatonnes in 2030" (UNFCC, 2016: 4), that is more than 60% above the 2018 total. Given the scales of the existing emissions and of the likely future energy demand it is certain that fossil carbon will be a major component of the worldwide energy supply even by 2050. And any suggestions that the global decarbonization can be accomplished in just two or three decades are utterly unrealistic and irresponsible.

6. *Decarbonization includes energy transitions that are relatively easy to accomplish as well as carbon substitutions for which we currently do not have any commercial non-carbon alternatives.* Generating increasing shares of electricity by relying on

wind turbines and PV cells is a proven and effective choice – as long as the share of this intermittent generation remains below the level that can be easily handled by existing grids and as long as the back-up capacities are available. In some countries the share of this easy decarbonization of electricity generation is just 15% of the total output, exceptional shares might be up to 40-50%: Denmark's wind now supplies about 45% of all electricity, a high share made possible by the country's relatively small demand (the country is smaller than a medium-sized Chinese city) and high-capacity high-voltage lines sufficient to supply any shortfall by imports from Norway, Sweden and Germany. Going beyond those nation-specific limits requires either significant new storage capacities or new high-voltage transmission, or both. But available batteries limit today's storage to a few hundreds of MW (discharged over 1-2 hours) while a large city consumes electricity at the average rate of about 1 GW; and while Germany needs 7,700 km of new high-voltage transmission lines in order to allow a higher share of intermittent renewables, it has built only 950 km (Dohmen *et al.* 2019).

Decarbonization of seasonal heating in cold climates is much more difficult, but the greatest challenges are the decarbonization of long-range, mass-scale air and water transport and the elimination of carbon as a feedstock and fuel in four industrial processes that provide material pillars of modern civilization (Smil 2014 and 2017b). Electrified railroads (both passenger and cargo) have been the best choice for generations, but the low energy density of existing batteries (maxima at around 300 Wh/kg compared to refined liquid fuels at around 12,000 Wh/kg, or roughly a 40-fold difference) means that intercontinental shipping (tankers, bulk carriers, container vessels) and jet-powered flight will remain dominant for decades to come.

As for the key materials, in 2018 the world required about 4.5 Gt of cement, 1.6 Gt of steel, 300 Mt of plastics and 150 Mt of ammonia. Production of cement now accounts for about 4% of CO_2 emissions from fossil fuels. Production of two-thirds of steel starts with primary iron smelted in blast furnaces whose operation requires about one billion tonnes of coal to make the requisite coke (supplemented by natural gas). Gaseous and liquid hydrocarbons are the feedstocks and fuels for synthesizing numerous plastics, and natural gas is the dominant fuel and feedstock needed to produce ammonia without whose applications at least 40% of humanity would not be alive. Altogether these four industrial processes consume at least 15% of the world's primary energy, and although we have a variety of proposals and experimental techniques to produce these materials without fossil carbon, in none of the above cases they have been commercialized at acceptable price and even if they were already available it would obviously take decades to displace the existing capacities operating at annual rates of 108-109 tonnes.

Many other considerations – including inherently low power densities of intermittent electricity generation by wind and solar radiation and even lower power densities of biofuel production (Smil, 2015) and the unprecedented problems of reliable supply for an increasing number of Asian megacities, some with more than 20 million people (Smil, 2019) – make any rapid decarbonization of global energy supply impossible. Even on the national level the progress has been relatively slow despite some major commitments. Germany's Energiewende (began in the year 2000) is the best example of this deliberate commitment to accelerated decarbonization, but, so far, its results are hardly enviable.

During the past five years the transition to renewables cost the country at least €160 billion (Bundesrechnungshof, 2018) -- but in 2018 coal remained the single largest source of German electricity (generating 37% of the total in 2018), the country now has the second highest electricity price in the EU (behind Denmark), and since the year 2010 it lowered its CO_2 emissions by 7%, the same cut as in the US where the reduction was achieved largely not by mass-scale installation of wind turbines and PV cells but by cost-saving switch from coal- to natural gas-fired electricity generation: in 2018 coal generated only 27% of the US electricity, natural gas 35% (USEIA, 2019).

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