Substantia
An International Journal of the History of Chemistry

Firenze University Press
www.fupress.com/substantia

Citation: V. Smil (2019) What we need to know about the pace of decarbonization. *Substantia* 3(2) Suppl. 2: 69-73. doi: 10.13128/Substantia-700

Data Availability Statement: All relevant data are within the paper and its Supporting Information files.

Competing Interests: The Author(s) declare(s) no conflict of interest.

What we need to know about the pace of decarbonization

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Abstract. Proper recognition of energetic, engineering and economic realities means that the decarbonization of global energy supply will be much more difficult and it will take much longer than is often assumed by uncritical proponents of "green" solutions.

Energy transitions have been among the key defining processes of human evolution (Smil 2017a). The first (millennia-long) transition was from the reliance on traditional biofuels (wood, charcoal, crop residues) and animate prime movers (human and animal muscles) to increasingly common reliance on inanimate energy converters (water wheels, wind mills) and on better harnessed draft animals for fieldwork and in transportation. Transition to fossil fuels (burned to produce heat, thermal electricity and kinetic energy) began in England already during the 16th century but it took off in Europe and North America only after 1800, and in most of Asia only after 1950. This transition has been accompanied by increasing reliance on primary electricity (dominated by thermal electricity since the 1880s, with nuclear generation contributing since the late 1950s).

Post-1800 transition from traditional biofuels to fossil fuels has resulted in gradual relative decarbonization but in enormous growth in absolute emissions of CO_2. Relative decarbonization is best traced by the rising H:C (hydrogen to carbon) ratios of major fuels: they rise from no more than 0.5 for wood and 1.0 for coal to 1.8 for the lightest refined fuels (gasoline and kerosene) and, obviously, to 4.0 for methane (CH_4), the dominant constituent of natural gas (Smil 2017b). The reverse order applies to CO_2 emissions per unit of energy: combustion of natural gas produces less than 60 kilograms of CO_2 per gigajoule (kg CO_2/GJ) while the rates for liquid hydrocarbons are between 70-75. As the global energy transition progressed, coal consumption overtook the burning of traditional biofuels and it was, in turn, overtaken by the combined mass of hydrocarbons (crude oils and natural gases) and rising share of primary electricity has further reduced the average carbon intensity of the world's primary energy supply. The global mean declined from nearly 28 kilograms of carbon per gigajoule (kg C/GJ) in 1900 to about 25 kg C/GJ in 1950 and then to less than 20 kg C/GJ by 2015. But this relative decline has been accompanied by an almost uninterrupted growth of absolute CO_2 emissions. Combustion of fossil fuels contributed just 8 million tonnes of carbon (Mt C) in 1800 (for CO_2 multiply these totals by 3.667), 534 Mt C in 1900, 6.77 Gt in 2000 and 9.14 billion tonnes (Gt) C in 2018 (Boden et al. 2017; IEA 2019). These emissions have been the principal reason for the rising atmospheric concentration of CO_2, from 285 parts per million (ppm) in 1850 to 369.6 ppm in the year 2000 and to 408.5 ppm in 2018 (NASA 2019a; NOAA 2019). In turn, these rising concentrations have been the principal reason for gradual increase of average tropospheric temperature that has, so far, amounted to about 0.8^0 C (NASA 2019b) but that would, in the absence of any remedial actions, surpass 2^0 C or even 3^0 C in a matter of decades and result in rapid anthropogenic global warming (IPCC 2014).

Past transitions were driven by a variety of factors ranging from the need for higher unit power (even small water wheels were more powerful than an ox or a horse) and better conversion efficiency (windmills can lift irrigation water much more efficiently than people) to more affordable supply (heating coal was far cheaper than charcoal) and reduced environmental impacts (natural gas is a much cleaner fuel than coal). In contrast to previous energy transitions the unfolding quest for decarbonization is not primarily driven by resource shortages or technical imperatives (most of the existing conversions are highly efficient and also very reliable). Today's quest for decarbonization has one dominant goal: limiting the extent of global warming. The goal is to establish a new global energy system devoid of any combustion of carbon-containing fuels or the world with net-zero carbon emissions where a limited amount of fossil fuel combustion would be negated by the removal and sequestration of the gas from the atmosphere resulting in no additional carbon releases.

How have we done so far? Concerns about anthropogenic global warming (a phenomenon whose basic cause has been appreciated since the late 19th century) began to receive wider public attention during the 1980s, and the first United Nations Framework Convention on Climate Change was signed in 1992 (UNFCCC 1992). It was followed by the Kyoto Protocol of 1997 and its latest global endeavor was the 2015 Paris Agreement that included nationally determined contributions designed "to combat climate change and to accelerate and intensify the actions and investments needed for a sustainable low carbon future" (UNCC 2019). Numerous meetings and assorted pledges aside, what has actually taken place since 1992?

The most important fact is that during those decades of rising concerns about global warming the world has been running into fossil carbon, not moving away from it. Since 1992 absolute emissions of CO_2 from fossil fuel combustion have declined significantly (by nearly 20%) in the EU28 and have grown only marginally (in each case by about 5%) in the US and Japan (Boden et al. 2017) but these accomplishments have not set the world on the road to decarbonization as emissions have nearly tripled in Asia, largely because the Chinese combustion of fossil fuels has almost quadrupled (Boden et al. 2017; PBL 2018). As a result, global emissions of CO_2 increased by more than 60% since 1992, setting yet another record in 2018.

Historians of energy transitions are not surprised by this development, as history shows that neither the dominant sources of primary energy nor the common energy converters can be displaced rapidly and completely in short periods of time. The high degree of the global dependence on fossil carbon and the enormous scale of the fuel-dominated global energy system mean that the unfolding energy transition will inevitably follow the progress of all previous large-scale primary energy shifts and that it will be a gradual, prolonged affair (Smil 2017a). In 1800 traditional biomass fuels (wood, charcoal, crop residues, dung) supplied all but a tiny share of the world's primary energy, a century later their share was about 50%, and at the beginning of the 21st century they still accounted for nearly 10%. This means that even after more than two centuries the world has not completed the shift from traditional biofuels to modern sources of primary energy.

Coal's share of global primary energy supply has been in retreat for generations as the reliance on hydrocarbons has grown – but the fuel still supplies nearly 30% of the total requirement. That is still more than natural gas (whose commercial extraction began about 150 years ago but whose share of total supply has been growing slower than expected) and in absolute terms its output is more than eight times larger than it was in 1900 when the fuel dominated the global energy supply. And while most economies began to reduce their reliance on crude oil in the aftermath of OPEC's two rounds of large price increases during the 1970s, the fuel remains the dominant source of the world's primary energy, supplying nearly 40% of the total.

The unfolding transition toward non-carbon energies has to take place on unprecedented scales. Annual extraction of fossil fuels now includes about 7.7 Gt of coal, 4,4 Gt of crude oil and 3.7 trillion cubic meters of natural gas, altogether an equivalent of nearly 9 Gt of crude oil or about 370 EJ (BP 2018). This grand total is the flux that matters: unlike all other previous shifts in primary energy use, the unfolding decarbonization can achieve its goal – eventual elimination of fossil carbon – only when it succeeds on the global scale. Substantial decline of carbon emissions, even an instant decarbonization of energy supply in a major advanced economy, makes little difference as long as the greenhouse gas emissions from other sources and from other countries keep on rising.

Even after some three decades since the beginning of high-level global warming concerns the unfolding transition is still in its earliest stage and even the relative shift has been, so far, minor. When the shares of primary energy are calculated by excluding traditional biofuels and by converting all non-thermal primary electricity by using its energy equivalent (1 Wh=3,600 J), fossil fuels supplied 91.3% of the world's primary energy in 1990 and by 2017 their share was still 90.4%. As with many phenomena in early stages of expansion, the combined growth of contributions made by new renewables (wind and solar electricity generation and modern biofuels) has been rapid: in the year 2000 they supplied only about 0.2% of the global primary energy supply, their share reached 1.3% by 2010 and 2.2% by 2017 – but that was still well behind the contributions made by either hydro and nuclear generation.

Of course, the shares of new renewables are significantly higher for electricity generation because this sector has been the main focus of the unfolding drive for decarbonization. Photovoltaic cells and wind turbines generated a mere 0.2% of the world's electricity in the year 2000, the share reached 4.5% in 2015 and nearly 7% in 2018 (BP 2018). But even if the decarbonization of global electricity generation were to proceed at an unprecedented pace, only the availability of affordable, massive-scale electricity storage would make it possible to envisage a reliable system that could rely solely on intermittent renewable energies of solar radiation and wind. Even securing just three days-worth of storage for a megacity of more than 10 million people that would be cut off from its intermittent renewable sources (a common occurrence during the monsoonal season in Asia with heavily overcast skies and high winds) would be prohibitively expensive by using today's commercial batteries.

Setting aside exaggerated media claims, a technological breakthrough meeting that requirement appears unlikely in the near future as pumped hydro storage (originally introduced during the 1890s) remains today the only way to store electricity at gigawatt scale. And even major advances toward large-scale electricity storage would not be enough to bring about rapid decarbonization of the global energy supply as electricity generation accounts for no more than 20% of total final energy consumption, and as decarbonizing transportation, heating, agriculture and industrial production is considerably more difficult than installing new intermittent capacities, connecting them with major load centers and securing the required back-up supply.

Electrification of passenger cars is in its earliest stage, with 5.4 million electric vehicles on the road by the end of 2018, still less than 0.2% of all vehicles registered worldwide (Insideeves 2019). More than a century after they were first seen as the best road transportation choice, electric cars are finally ascendant, but even under the best circumstances it will take many decades to accomplish the transition from internal combustion engines. The International Energy Agency sees 160-200 million electric vehicles by 2030, BP expects 320 million by 2040 and my best forecast (based on a polynomial regression) is for 360 million in 2040 (IEA 2018; BP 2019). But by that time there might be about 2 billion vehicles on the road globally (compared to about 1.25 billion today), and hence even 400 million electric cars would be just 20% of the total. Forecasting the future adoption of hydrogen-fueled vehicles is even more uncertain, but it is hard to see how even the most likely combined progression of electric and hydrogen cars would completely eliminate internal combustion engines before 2040, or even soon after.

Given the energy density of today's best commercial batteries, the electrification of trucking, shipping and flying is even more challenging. The key to understanding the fundamental difficulty is to compare the energy densities of the best Li-ion batteries with the energy density of diesel fuels used in trucking and shipping. Today's widely deployed Li-on batteries have an energy density of up to 260 Wh/kg, and it is foreseen that they could reach up to 500 Wh/kg in the future (J.P.Morgan 2019). In contrast, diesel fuel used in land and marine transport and aviation kerosene have, respectively, energy densities of 12,600 Wh/kg and 12,800 Wh/kg), which means that today's dominant liquid transportation fuels are nearly 50 times as energy dense as our best commercial batteries - and this gap is not to be closed anytime soon. Shipping and flying present particularly insurmountable challenges as only high energy density fuels can power massive container ships carrying more than 20,000 steel units on their long intercontinental routes (Smil 2019) and high-capacity commercial airliners.

While air conditioning is powered by electricity, seasonal heating in cold parts of Eurasia and North America now relies overwhelmingly on natural gas delivered by large-diameter trunk lines and dense networks of small-diameter distribution lines serving more than half a billion customers. Obviously, replacing this fuel supply and abandoning this extensive infrastructure will not be achieved over a single generation. And even more intractable challenges come with the decarbonization of industries producing what I have called the four pillars of modern civilization: ammonia, cement, steel and plastics (J.P. Morgan 2019).

Mass-scale production of these materials (annual outputs are now close to 200 Mt for ammonia, about 4.5 Gt for cement, 1.6 Gt for steel ad about 300 Mt for all kinds of plastics) now depends on large-scale inputs of fossil fuels, both for process heat and as feedstocks. Without Haber-Bosch synthesis of ammonia (with natural gas as the dominant feedstock and fuel), nearly half of today's humanity would not be alive as even the most assiduous recycling of all available organic matter could not supply enough nitrogen to feed nearly 8 billion people. Cement and steel are the two irreplaceable infrastructural components. Cement is produced in kilns heated by low-quality fossil fuels, two-thirds of all steel are made in basic oxygen furnaces from pig iron that is smelted in blast furnaces with the aid of about one billion tonnes of coke, augmented by natural gas (Smil 2016). And gaseous and liquid hydrocarbons are the dominant feedstocks (and fuel) for synthesizing a wide variety of plastics.

All of these processes have one important characteristic in common: there is no available non-carbon alternatives that could be readily deployed on mass commercial scales. There are some interesting innovations, and entirely new pathways might be possible – ranging from new catalyses for ammonia synthesis (Ashida et al. 2019) to hydrogen-based steelmaking (Green 2018) – but none of these innovations has been deployed even as pilot plant experiments and, once again, it is obvious that scaling up those processes that may eventually prove acceptable in order to reach annual outputs of hundreds of millions, even billions, of tonnes is a task that would take generations to accomplish.

Yet another important factor to consider are the enormous energy, food and material needs of emerging economies. China's post-1990 surge in demand for these inputs indicates the extent of future needs. China's population of 1.39 billion people will be soon surpassed by India – whose per capita energy use is only about a quarter of the Chinese level (BP 2018) – and between 2015 and 2050 1.3 billion people will be added in Africa where per capita use is generally well below the Indian level. Much like China has done by more than quadrupling its fossil energy use since 1990, these populous modernizing countries or regions will use any available source of energy to raise their standard of living and to build their essential infrastructures. Not surprisingly, India's total primary energy consumption is forecasted to increase nearly five-fold between 2012 and 2047 according to a recent study by the National Institution for Transforming India (NITI Aayog), and coal is expected to remain its dominant fuel (Thambi et al. 2018).

In conclusion, the verdict – based on the history of past energy transitions, on the unprecedented scales of the unfolding shift, on the limits of alternative pathways, and on the enormous and immediate energy needs of billions of people in low-income countries – is clear. Designing hypothetical roadmaps outlining complete elimination of fossil carbon from the global energy supply by 2050 (Jacobson et al. 2017) is nothing but an exercise in wishful thinking that ignores fundamental physical realities. And it is no less unrealistic to propose legislation claiming that such a shift can be accomplished in the US by 2030 (Ocasio-Cortez 2019). Such claims are simply too extreme to be defended as aspirational. The complete decarbonization of the global energy supply will be an extremely challenging undertaking of an unprecedented scale and complexity that will not be accomplished – even in the case of sustained, dedicated and extraordinarily costly commitment – in a matter of few decades.

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