Energy Research & Social Science 22 (2016) 194–197

Contents lists available at ScienceDirect

Energy Research & Social Science

journal homepage: www.elsevier.com/locate/erss

Short communication

Examining energy transitions: A dozen insights based on performance

Vaclav Smil

University of Manitoba, Winnipeg, Manitoba, R3T 2N2, Canada

ARTICLE INFO

Article history:
Received 31 May 2016
Received in revised form 6 August 2016
Accepted 22 August 2016
Available online 4 October 2016

Keywords:
Energy transitions
Fossil fuels
Biofuels
Intermittent electricity generation
CO_2 emissions
Decarbonization

ABSTRACT

Replacing the current global energy system relying overwhelmingly on fossil fuels by biofuels and by electricity generated intermittently from renewable sources will be necessarily a prolonged, multidecadal process.

Concerns about the consequences of excessive anthropogenic global warming (generally taken as any increase of average tropospheric temperature higher than 2 °C) have made energy transitions a matter of increasing interest. Carbon emissions from changing land cover (above all from tropical deforestation) and emissions of CH_4 and N_2O (largely from agriculture and animal husbandry) and chlorofluorocarbons are significant contributors to the overall anthropogenic radiative forcing but emissions of CO_2 from the combustion of fossil fuels remain the largest source [4]. Consequently, further temperature increase could not be limited without progressive decarbonization of the global energy supply, a topic that has featured prominently in this journal, most notably a recent special issue [11].

This unfolding process is just the latest shift in the continuous retreat from long-established energy uses and the gradual adoption of new sources, and a realistic appraisal of its progress must be based on the understanding of past energy transitions and on an accurate assessment of recent advances. Unfortunately, conflating the progress of modern electronics and advances in changing the composition of the world's primary energy supply—part of a broader phenomenon that I have called the Moore's curse [15]—has led to some unrealistic expectations concerning the pace of future energy transitions. Writing in this journal, for example, Sovacool [19] articulates his belief that future energy transitions can be rapid or accelerated to the point where they can take only a few years or decades. Such wishful thinking is contradicted both by indisputable statistics and by the imperatives of energy conversions. The following 12 points offer concise summaries of basic realities that must be kept in mind as we look ahead.

1. Progress of specific energy transitions on national level has ranged from very slow (more than a century) to very rapid (just a few years)

In some European countries (UK, France, Germany), as well as in the US and in China, it took more than 100 years before coal's use rose from a marginal contribution to the primary energy supply (dominated everywhere by traditional biofuels) to the leading energy source [13,8]. In England coal began to supply more than half of all energy around 1620 [23], in France by 1870 in the USA by the early 1880s [12] and in China only during the late 1960s [13].

But after WW II hydrocarbons displaced wood (often consumed as charcoal) and coal fairly rapidly not only in the Middle Eastern countries and the USSR but also in Japan and The Netherlands. Japan's share of crude oil in primary energy use went from just over 6% in 1950–72% by 1970, and the 1959 discovery of supergiant Groningen field made it possible to accomplish the Dutch transition from coal to natural gas in a single decade. In 1965, when the decision was made to close down all of the country's coal mines, natural gas supplied 5% of the country's primary energy, by 1971 its share rose to 30% and by 1975 it reached nearly 46% as coal fell to just 2.5% [16]. And recently Denmark's wind-powered electricity generation went from 12% in the year 2000–41% in 2014 [3].

E-mail address: vsmil@cc.umanitoba.ca

http://dx.doi.org/10.1016/j.erss.2016.08.017
2214-6296/

2. In contrast, all global energy transitions have been always gradual, prolonged affairs

Coal began to supply more than half of the world's primary energy (including traditional biofuels) around 1900, its contribution peaked at about 55% during the second decade of the 20th century and in 2015 it still provided about 30% of the total [16]. After it reached 5% of the global primary energy supply (around 1840) it took coal 35 years to rise to 25% and 60 years to reach 50% [13]. Given the increasing overall demand and the necessities of developing requisite infrastructures (drilling, pipelines, refineries, liquefaction plants, tankers) it is not surprising that the analogical shifts to crude oil and natural gas took even longer: it took it took 40 years for crude oil to go from 5% to 25% of the global primary supply (1915–1955) and it has been nearly 60 years for natural gas. Moreover, as the supply has become more diversified no primary source will again provide most of the total supply as did traditional biofuels or coal: crude oil peaked at close to 40% during the 1970s and it has since fallen to about 30%, natural gas may never reach even a third of the total supply.

3. Ours is still an overwhelmingly fossil-fueled civilization

In 2015 fossil fuels provided at least 85% of the world's total commercial primary energy supply, excluding the contributions by traditional biofuels (wood, charcoal, straw, dung) whose consumption cannot be accurately measured [1]. If the best estimates of traditional biofuels are included, then the fossil fuels supplied about 80% of the world's primary energy in 2015 [6]. Commercial non-fossil energies continue to be dominated by hydro and nuclear electricity, but the exact share of their combined contribution depends on the conversion factors used: straight thermal equivalent (1 kWh = 3.6 MJ) is commonly used to convert hydroelectricity, while nuclear electricity is converted by the prevailing efficiency of thermal generation, now up to 38% or about 9.5 MJ/kWh. International Energy Agency uses this split option, while the British Petroleum converts all primary electricity by assuming 38% conversion efficiency; accordingly, hydro and nuclear then supplied about 8% of the world's primary commercial energy in 2014.

4. The unfolding energy transition is not just about shifting from one set of primary energy sources to another: its fundamental *raison d'etre* is the prevention of excessive rise of average tropospheric temperature and that can be achieved only by the decarbonization of the global energy supply

CO_2 emitted from the combustion of fossil fuels is quickly distributed throughout the atmosphere and hence the progress of this transition must be measured on the global scale. Individual countries may derive substantial shares of their primary energy from traditional (hydro, biofuels) or new renewable non-carbon sources (wind, photovoltaic and central solar power) but the atmosphere responds to global aggregate emissions of CO_2 that have led to steadily increasing tropospheric concentrations of the gas, from 315.97 ppm in 1959 (the first full year of Mauna Loa measurements) to 400.83 ppm in 2015 [10].

5. There is no evidence that the global primary energy transition has been accelerating during the recent decades, and carbon intensity of commercial energy supply remains high

In 1960 fossil fuels supplied 97% of the world's primary commercial energy, in 1990 their share was 90%, a quarter century later, in 2015, it was about 85% [1]. When traditional biofuels are included, fossil fuels provided 76% of the global total in 1960, and (due to China's post-2000 surge in coal extraction) still about 80% in 2015 [6]. Average carbon intensity of commercial energy supply was about 27 kg C/GJ in 1900, and rising contributions of natural gas and hydro and nuclear electricity lowered the global rate to less than 18 kg C/GJ by the year 2000, an overall decline of about 28% during the 20th century. But due to the post-2000 expansion of Asian coal extraction the rate had actually risen slightly by 2015.

6. Global energy transition has been, so far, overwhelmingly a shift in electricity generation that has had only a small effect on the decarbonization of the overall primary energy supply

As with many phenomena in early stages of their growth, global wind and solar electricity generation have been growing rapidly, averaging, respectively, about 22% and 37% between 2000 and 2015. But after a quarter century of development (1990–2015) they contributed (even when converting all primary electricity at 9.5 MJ/kWh) no more than 1.3% of the world's primary commercial energy supply and after adding modern biofuels all new renewables claimed about 2.5% in 2015. Obviously, converting primary electricity by using straight thermal equivalent (3.6 MJ/kWh) lowers those shares.

7. Global growth of new renewables has not been extraordinarily rapid

Their share has roughly doubled in 25 years, growing at an average annual rate of about 3%, not an unusually rapid expansion during early stages of energy transitions: coal was gaining at a rate of more than 5%/year between 1850 and 1870, oil gains averaged more than 8%/year during 1880–1900, and natural gas gained its global market share at 6%/year between 1920 and 1940 [16]. And in absolute terms primary energy added by new renewables has been only a small fraction of the total added by fossil fuels. In 2015 their extraction was about 175 EJ above the 1990 level, while the combined contribution of wind, solar and modern biofuels was about 7 EJ above their very low 1990 level: during the 25 years since 1990 the world had added 25 times as much energy supply in fossil fuels as it did in the new renewables.

8. Progress has been gradual even in the case of the most determined, deliberate and costly shift achieved through Germany's *Energiewende*

In the year 2000, when *Energiewende* began, Germany derived 83.7% of its primary energy from fossil fuels, in 2015 that share declined to 79.4% [2]. Average decline has been merely 0.3%/year and its continuation would leave fossil fuels dominant even by 2050. And there have been other surprising outcomes. Germany's consumption of poor-quality *Braunkohle* (lignite) burned to generate thermal electricity had actually slightly increased between 2000 and 2015, while the burning of natural gas, the cleanest and the least carbon-intensive fossil fuel, had decreased by about 10% [2]. Because of the falling overall primary energy use, Germany's 2000–2015 decline of fossil fuel consumption was about 12% in energy terms, but France, Germany's neighbor that has no equivalent of *Energiewende*, reduced its reliance on fossil fuel by about 18% during the same period [6,7]. So much for the unequalled success of *Energiewende*.

9. Intermittency of wind and solar generation has required countries to maintain large fossil-fueled reserve capacities and hence essentially doubling the total installed power

Again, Germany is the most prominent example of this carbon persistence. In the year 2000 the country had 84.2 GW of fossil-fueled generating capacity, in 2014 that total actually rose by about 4% to 87.5 GW—while the combined capacity of renewable generation increased from 6.2 GW to 84.8 GW, almost perfectly matching that of fossil-fueled generators [2]. Increased reliance on intermittent sources with low average capacity factors—in Germany not even 11% for solar and about 17% for wind in 2014—thus required to maintain fossil-fueled capacity of the same (actually slightly increased) magnitude!

10. Even the fastest conceivable adoption of non-carbon energies will fall far short from eliminating fossil fuel combustion by the middle of the 21st century

Recent forecasts published by governments, institutions and companies anticipate that fossil fuel will keep on supplying up to 70% of the world's primary energy by 2040 [16]. Even the scenario for 450 ppm (2 °C) world posits at least 60% share for coal and hydrocarbon, with 29% for all renewables, including hydro and all biomass [7]. None of the published forecasts and scenarios puts new renewables (wind, solar and modern biofuels) at more than 15% by 2040. When assuming that the new renewables (wind, solar, modern biofuels) will reach 5% of the global primary supply by 2020 and then 15% by 2040 their growth would be in line with the pace of previous primary energy substitutions.

11. Replacing thermal electricity generation by new renewables is much easier than displacing liquid fossil fuels in transportation

American ethanol is a perfect illustration of this challenge: after diverting 40% of its most important crop (grain corn) to produce automotive fuel, ethanol's annual output is an equivalent of only 10% of the US gasoline consumption [20,21]. Except for Brazil (with its sugar cane) no other country could divert so much of its largest crop from food to energy use without imperiling its food supply or its ability to export foodstuffs. As for the greatly anticipated production of biofuels from cellulosic phytomass, the up-scaling challenge is perhaps best illustrated by the fact that, after years of delays, the world's first two large plants (in Iowa using corn stover and in Brazil using cane bagasse) began to produce the fuel in 2015 but their combined annual capacity (150 million liters) is equal to just 0.005% of current global demand for transportation fuels [16]. Obviously, even if a rapid 1000-fold expansion would happen within a decade it would still reach only 5% of the current transportation fuel demand.

12. An even greater challenge will be to displace fossil carbon used in the production of primary iron, cement, ammonia and plastics

Annual output of these essential materials is now about 1 billion tonnes of iron (in addition, more than half a billion tonnes of steel are produced by recycling the metal), more than 4 billion tonnes of cement, nearly 200 million tonnes of ammonia and more than 300 million tonnes plastics [14,17,22]. We have no mass-scale alternatives that could be deployed in order to displace coke used in blast furnaces (now close to one billion tonnes a year) and none of the several proposals for producing cement with much lower carbon inputs is in commercial operation. Ammonia synthesis could forgo its critical reliance on natural gas only if we had an unprecedented amount of extremely cheap electricity and plant feedstocks (field or tree crops, crop residues or fast-growing grasses) will not be available at rates required to displace hydrocarbons used in plastic production for decades to come. And it is also necessary to remember that the construction of many new renewable capacities is highly dependent on the deployment of such carbon-intensive materials as steel, cement and plastics [18].

13. Even if alternatives were more readily available we must remember that the existing global energy system based on fossil fuels comprises the largest, and the most expensive anthropogenic infrastructure that cannot be either written-off or displaced rapidly

The entire system now extracts annually about 10 billion tonnes of fossil carbon, it generates nearly 16 PWh of electricity (about two-thirds of the global total) and the following order-of-magnitude estimates indicate the extent of its energetic and financial foundations.

Assuming that the sector has used just 5% of cumulative material deployment, energy embodied in materials used to construct coal mines, hydrocarbon fields, pipelines, refineries, gas liquefaction, tankers, power plants and transmission grids is equivalent to at least 15 billion tonnes of crude oil. And assuming that the capital investment has amounted to just 2% of the cumulative gross world product [5,9], the creation of the entire fossil fuel-based energy system has consumed at least $25 trillion (in 1990 international dollars) during the 20th century. Scale matters.

14. Conclusion

We now have a truly global energy supply system relying overwhelmingly (~85% in 2015) on fossil fuels. Replacing it by new arrangements based on (mostly liquid) biofuels and intermittent (mostly wind and solar) electricity generation is—even after ignoring all environmental and social problems associated with the requisite up-scaling of biofuel production, and all technical challenges associated with mass-scale reliance of generating electricity with low capacity factors—a task that will necessarily occupy us for generations to come.

References

[1] British Petroleum, BP Statistical Review of World Energy, BP, London, 2015.
[2] Bundesministerium für Wirtschaft und Energie, Zahlen Und Fakten: Energiedaten, BWE, Berlin, 2016 http://bmwi.de/BMWi/Redaktion/Binaer/energie-daten-gesamt,property=blob,bereich=bmwi2012,sprache=de,rwb=true.xls.
[3] Danish Energy Agency, Energy Statistics 2014, Danish Energy Agency, 2015 http://www.ens.dk/sites/ens.dk/files/info/tal-kort/statistik-noegletal/aarlig-energistatistik/energystatistics2014.pdf.
[4] Intergovernmental Panel on Climate Change, Climate Change 2013–The Physical Science Basis, Cambridge University Press, Cambridge, 2013, pp. 2014.
[5] International Energy Agency, World Energy Investment Outlook, IEA, Paris, 2014.
[6] International Energy Agency, Energy Balances of Non-OECD Countries, IEA, Paris, 2015.
[7] International Energy Agency, Energy and Climate Change, IEA, Paris, 2015 https://www.iea.org/publications/freepublications/publication/WEO2015SpecialReportonEnergyandClimateChange.pdf.
[8] A. Kander, P. Malanima, P. Warde, Power to the People: Energy in Europe Over the Last Five Centuries, Princeton University Press, Princeton, NJ, 2013.
[9] A. Maddison, Historical Statistics for the World Economy: 1-2003 AD, 2007.
[10] NOAA, Trends in atmospheric carbon dioxide. ftp://aftp.cmdl.noaa.gov/products/trends/co2/co2_annmean_mlo.txt, 2016.
[11] M. Sarrica, S. Brondi, P. Cottone, B.M. Mazzara, One, no one, one hundred thousand energy transitions in Europe: the quest for a cultural approach, Energy Res. Soc. Sci. 13 (March) (2016) 1–14.
[12] S.H. Schurr, B.C. Netschert, Energy in the American Economy 1850–1975, Johns Hopkins University Press, Baltimore, MD, 1960.

[13] V. Smil, Energy Transitions: National and Global Perspectives., Praeger, Santa Barbara, CA, 2010.

[14] V. Smil, Making the Modern World: Materials and Dematerialization, Wiley, Chichester, 2014.

[15] V. Smil, Moore's curse, IEEE Spectr. 26 (April) (2015) http://spectrum.ieee.org/energy/renewables/moores-curse.

[16] V. Smil, Energy Transitions: National and Global Perspectives, second ed., Praeger, Santa Barbara, CA, 2016, in press.

[17] V. Smil, Still the Iron Age: Iron and Steel in the Modern World, Elsevier, Oxford, 2016.

[18] V. Smil, What I see when I see a wind turbine, Spectrum 27 (March) (2016) http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7420393.

[19] B.K. Sovacool, How long will it take? Conceptualizing the temporal dynamics of energy transitions, Energy Res. Soc. Sci. 13 (March) (2016) 202–215.

[20] US Energy Information Administration, Primary Energy Overview, US Energy Information Administration, 2016 http://www.eia.gov/totalenergy/data/monthly/pdf/sec1_3.pdf.

[21] US Energy Information Administration, How much ethanol is in gasoline, and how does it affect fuel economy? http://www.eia.gov/tools/faqs/faq.cfm?id=27&t=10, 2016, 2016.

[22] United States Geological Survey, National Minerals Information Center. http://minerals.usgs.gov/minerals/, 2016.

[23] P. Warde, Energy Consumption in England and Wales, 1560–2004, Consiglio Nazionale della Ricerche, Napoli, 2007.