21st century energy

Some sobering thoughts

Vaclav Smil
Faculty of Environment, University of Manitoba, Winnipeg, Canada*

Transition to new energy sources is unavoidable, but here are five sobering first principles to remember along the way.

Are we about to switch to new energy sources? Grandiose plans are being drawn up for installing veritable forests of giant wind turbines, turning crops and straw into fuel ethanol and biodiesel, and for tapping solar radiation by fields of photovoltaic cells. As with most innovations, there is excitement and high expectation. Will these developments and other renewable energy conversions one day replace fossil fuels? Eventually they will have to, but a reality check is in order.

An impartial examination of some basic principles reveals five factors that will make the transition to a non-fossil world far more difficult than is commonly realised. These are: the scale of the shift; the lower energy density of the replacement fuels; the substantially lower power density of renewable energy extraction; intermittency of renewable flows; and uneven distribution of renewable energy resources.

Consider the **scale of the shift** first. We are now at a point in time comparable to 1850, which marked the outset of the last great energy transition. Then, about 85% of the world's total primary energy supply (TPES) came from biomass fuels. In 2005 about 85% of the total supply originated from fossil fuels. By the late 1890s, when fossil fuel consumption rose to equal the biomass contributions, each of them supplied about 0.7 TW (Terawatts or 10^{12} watts); today, even if we were to replace only 50% of all fossil fuels by renewable energies during the coming decades, we would have to displace coal and hydrocarbons flows of about 6 TW. That is an enormous shift.

Today there is no readily available non-fossil energy source that is large enough to be exploited on the requisite scale. True, energy carried by solar radiation is several orders of magnitude larger than any conceivable global energy demand (see graph 1), but so far, practical conversions into electricity (using photovoltaics) or large-scale industrial heat are quite negligible. Also, other renewable energy flows could not cover today's worldwide total primary energy supply, even if, economics aside, they were fully exploited by current techniques. And even nuclear power's contribution is constrained by limited fissionable material.

The amount of energy contained in a unit of fuel, or **energy density**, is our second key consideration. In the last two energy transitions, from biomass to coal and then from coal to hydrocarbons, lower energy-density fuels were supplanted by more concentrated sources of energy. Air-dry crop residues (mostly straw) contain only 12-15 megajoules per kilogram (MJ/kg), for instance, whereas the energy density of good quality coals is twice as high, at 25-30 MJ/kg; that of crude oil is around 42 MJ/kg. To achieve an equivalent output, a return to solid biofuels would require an average of nearly 3 kg of phytomass in order to replace a unit of fossil fuels; the ratio would be about 1.5 when substituting petrol by plant-derived ethanol. These realities would be reflected in the extent, cost and operation of the needed infrastructures.

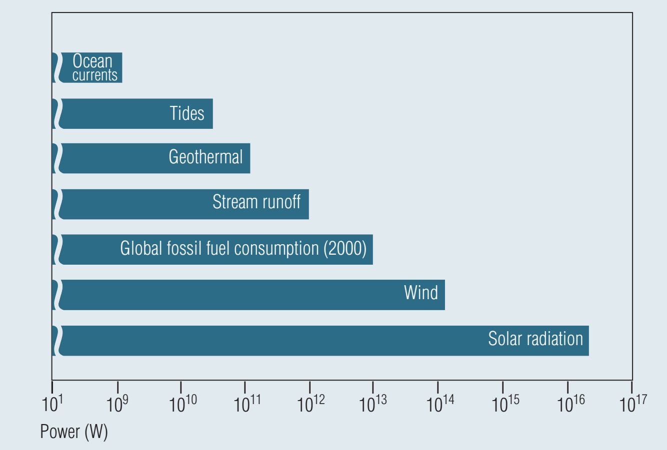
Power density of energy production is a third consideration. Power density refers to the rate of energy production per unit of the earth's area and is usually expressed in watts per square meter (W/m^2).Thanks to the lengthy periods of their formation, fossil fuel deposits are an extraordinarily concentrated source of high-quality energy and are commonly produced with power densities of 10^2 or 10^3 W/m^2 of coal or hydrocarbon fields and hence only small land areas are needed to supply enormous energy flows. In contrast, biomass energy production has densities well below 1 W/m^2, while densities of electricity produced by water and wind are commonly below 10 W/m^2. Only photovoltaic generation, a technique not yet ready for mass utilisation, can deliver more than 20 W/m^2 of peak power.

The energy supply chain of today's fossil-fuelled civilisation works by producing fuels and thermal electricity with power densities that are one to three orders of magnitude higher than the common power densities with which our buildings, factories and cities use commercial energies (see graph 2) . In a future solar-based society inheriting *today's* urban and industrial systems, we would harness various renewable energies with at best the same power densities with which they would be used in our dwellings and factories. Consequently, in order to supply a house with electricity, photovoltaic cells would have to cover the entire roof. A supermarket would require a photovoltaic field roughly ten times larger than its own roof, or 1,000 times larger in the case of a high-rise building. In other words, a transition to renewable energy would greatly increase the fixed land requirements of energy production and would also necessitate more extensive rights-of-way for transmission.

By far the greatest land requirements in such a solar society would arise if we were to

Energy potential

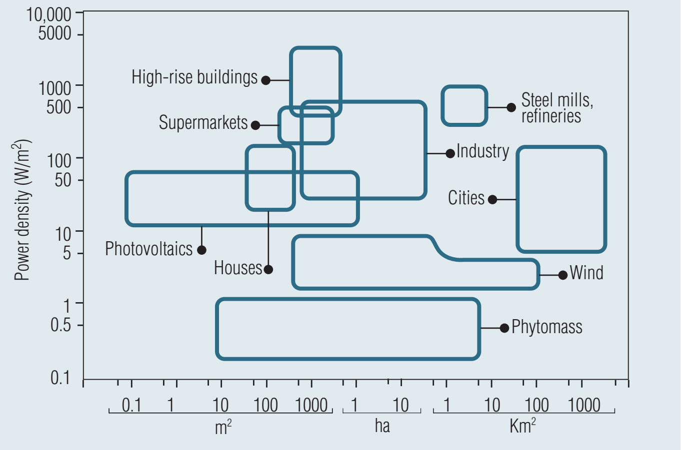
Global flux of renewable energies vs. fossil fuel consumption



Source: V. Smil

A new scale

Comparison of power densities of energy consumption and renewable energy production



Source: V. Smil

replace all crude oil-derived liquid fuels with phytomass-derived biofuels. Production of US corn ethanol has a power density of just 0.22 W/m^2; that means that more than twice the country's entire cultivated area would be needed in order to satisfy the country's demand for liquid transportation fuel!

Intermittency of supply is our fourth reality check. Modern societies are dependent on massive incessant flows of energies; growing demand for fuels and electricity fluctuates daily and seasonally, but the base load–which is the minimum energy needed to meet the needs of the day–has also been increasing. Easily storable high-energy density fossil fuels and thermal electricity generating stations operate with high load factors (>75% of the year for coal-fired stations, > 90% for nuclear plants) and so can meet these needs. In contrast, because wind and direct solar radiation are intermittent and far from predictable, they can never deliver such high load factors. PV generation is still so negligible that it is impossible to offer any meaningful averages, but annual load factors of wind generation in countries with relatively large capacities, such as Denmark, Germany and Spain, are just 20-25%: large wind turbines are thus idle for an equivalent of 270-290 days a year! Also, an unexpected drop-off in generation can cause sudden supply interruptions. Unfortunately, we still lack the means to be able to store wind- or solar-generated electricity on a large scale.

Geographical distribution is the final sobering consideration. Much is made of an uneven distribution of oil and gas, but renewable flows are also spread out unevenly: cloudiness in the equatorial zone reduces direct solar radiation; whole stretches of continent have insufficient wind; there are too few sites with the best potential for geothermal, tidal or ocean energy conversions, etc. In fact, some densely populated regions have no significant locally available sources at all and many reliably windy or sunny sites are far from major load centres, which means their exploitation would require entirely new mega-infrastructures.

> **Today there is no readily available non-fossil energy source that is large enough to be exploited on the requisite scale.**

Three key factors drove the 19th century transition to fossil fuels: declining resource availability (deforestation), higher quality (higher energy density, easier storage, greater flexibility) and lower cost of coals and hydrocarbons. On these three points at least, there is no urgency for an accelerated shift to a non-fossil world: fossil fuel supplies are adequate for generations to come, new energies are not qualitatively superior, and their production will not be substantially cheaper.

Arguments for an accelerated transition to a non-fossil world are predicated almost entirely on concerns about climate change. Even then, because of the enormity of requisite technical and infrastructural requirements, many decades will be needed to capture substantial market shares on continental or global scales. A non-fossil world may be highly desirable, but getting there will demand great determination, cost and patience. ■

*Vaclav Smil is a Distinguished Professor in the Faculty of Environment at the University of Manitoba in Winnipeg, Canada. He is a Fellow of the Royal Society of Canada and the author of many books and papers on energy, environment, population and economic affairs.

References

- V. Smil (2006), *Transforming the 20th Century*, New York: Oxford University Press.
- V. Smil (2006), *Energy: A Beginner's Guide*, Oxford: Oneworld Publishing.
- V. Smil (2003), *Energy at the Crossroads*, MIT Press, Cambridge, MA.