Energy transitions

To a physicist, energy is perhaps the most fundamental quantity. It runs through the universe as the source of all that is dynamic and changing, and yet also all that is durable and structured. Never created or destroyed, energy only changes form — from mass into light, or from bound-up chemical or nuclear structures into kinetic motion. Energy is also more crucial to our human activities than any other resource. We can build with many materials, travel, compute or communicate by many means, but any activity at all requires energy.

Throughout history, our evolving energy technology has determined our human capacities. The conquest of fire offered heat, a means to manufacture tools and cook food, vastly boosting our ability to draw calories from the environment. As hunter-gatherers, early humans found energy through foraging, using around 5,000 kcal per person per day. Later, as farmers, we were able to harness as much as 30,000 kcal per day through animal use and organized production. The use of coal and the exploitation of steam power in the seventeenth century marked another discrete leap — in the era of fossil fuels, by 1970, humans were able to draw on some 230,000 kcal per person per day.

But this latest stage of our history is moving toward its definitive end, as high-quality fossil fuels grow more scarce. Given the constraints of climate change, renewable energy looks to be our obvious future. But that future will not come about easily, and will require much more than just developing the right technology. History teaches that every major energy transition has also required a wrenching and tumultuous shift in fundamental human values. We're starting to fight over those values right now.

In his book *Foragers, Farmers, and Fossil Fuels*, historian Ian Morris relates how any particular energy source — a "mode of energy capture", as he puts it — sets limits on the kind of social organization able to harness and use that energy effectively. For example, hunter-gatherers favoured strict egalitarianism and sharing of resources, which let them cooperate on difficult tasks, and readily punished transgressions with violence. In contrast, farming societies were much less violent and embraced strong social hierarchies needed to mobilize mass human and animal labour. Finally, our fossil fuel era has recently favoured more equal, democratic societies, but has also been tolerant of great wealth disparities.

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The coming challenge is not only to access ever more energy, but also to do so in a way that keeps our biosphere within liveable bounds. In this, the values many people cherish today may not be so useful. The struggle to invent new values is already evident in the polarized issue of how to respond to human-induced climate change, as several recent papers in *Nature Energy* illustrate. While many people and nations are eagerly investing in a coordinated push to realize a renewable energy future, a well-funded resistance shows few signs of capitulating, and has newfound optimism from political events in the United States, now the sole nation on Earth not participating in the Paris climate agreement.

One clear factor likely to speed the broad replacement of fossil fuels is investment in basic research on renewable technology, as well as support for efforts to bring uncertain technologies into the marketplace. The US government has a long history of supporting such efforts. In particular, the Advanced Research Projects Agency — Energy (ARPA-E) research programme has been devoted to supporting risky research on innovative energy-technology improvements. As Laura Diaz Anadon and colleagues note, however, the current Republican administration under Donald Trump has recently proposed a 57% reduction across the board in US government funding for energy research, development and demonstration, and plans to eliminate the ARPA-E programme entirely (*Nat. Energy* **2,** 760–763; 2017). It also foresees terminating a Department of Energy loan guarantee programme encouraging exploration of new vehicle-manufacturing techniques and weatherproofing of low-income housing. The administration has close ties to the fossil fuel industry and aims to block or delay any shift toward renewable energy.

Another way to discourage this shift is to support further fossil fuel exploration, production and use. For a decade or more, governments have proclaimed publically their desire to end direct and indirect subsidies to fossil fuels, but it hasn't happened, as Peter Erickson and colleagues document (*Nat. Energy* **2,** 891–898; 2017). Recent data in the US — currently the world's largest oil producer — show that subsidies continue to have a massive effect on shaping the energy industry, unknown to most people. For a set of undeveloped US oil fields, for example, Erickson and colleagues looked at how available subsidies influenced their profitability, finding that, at a crude oil price of US$50 per barrel, more than half of new oil field development would not be profitable without subsidies. Opponents of solar and other renewable energy often argue that they can't compete economically against fossil fuels without government help, but this argument typically ignores persisting fossil fuel subsidies.

As a final sign of determined resistance to a deep energy transition, consider how solar energy has been included in future scenarios outlined by the most influential international climate body, the Intergovernmental Panel on Climate Change (IPCC). It surprised me to learn that the most recent 'fifth assessment' report by the IPCC, relased in 2014, does not even identify solar energy as an important option, but instead emphasizes other technologies including bioenergy and carbon capture and storage (F. Creutzig *et al.*, *Nat. Energy* **2,** 17140; 2017). In part, this reflects energy analysts' broad failure to foresee the recent fast advance of solar technology. As Creutzig and colleagues note, it also highlights an apparent IPCC preference for technologies aiming for the removal of atmospheric carbon, thereby making future negative permissions possible. This idea plays a key role in IPCC scenarios that keep ultimate warming below 2 °C without also requiring strong emissions reductions now. Again, the analysis seems to work hard to find a way to keep fossil fuels in use.

The fossil fuel industry may hope that technology will come to the rescue of their profits, saving the climate yet also allowing CO_2 emissions to continue unimpeded. It's an effort to cling to the present, and to delay what looks to be an inevitable transition into a fundamentally new energy era for humanity. ❐

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