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Views & Comments

Getting to Net-Zero Emissions

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Towards a deeper understanding of viable energy transitions

As we embark on a new decade, the challenges of establishing and maintaining economic wellbeing while confronting a range of sustainability challenges remain ever-present. Four socioeconomic megatrends are at play: population growth, rising gross domestic product (GDP), urbanization, and connectedness. Collectively, these trends will fuel a tremendous increase in the consumption of almost every conceivable commodity, such as energy, food, and materials. It will also increase the pressures on our planet through climate change, biodiversity loss, and increasingly vulnerable supplies of food and fresh water.

In this article, we focus primarily on energy. Transitioning the global energy economy to net-zero-emissions is among the greatest infrastructure challenges of our generation. Scientific and engineering research has significantly improved the technological and economic performance of low-carbon energy technologies and systems, especially for the electricity sector. This research has helped direct several top-down, integrated assessments and other energy system models to derive various least-cost pathways for achieving ambitious climate goals. Despite these efforts, global greenhouse gas emissions have continued to increase.

Scenarios consistent with goals to limit the global average temperature rise to well below 2 °C require an immediate halt in emissions growth and a steep decline to net-zero emissions by around the middle of this century. Five system-level foundations underpin these deep-decarbonization scenarios and should be fundamental in the agendas of research portfolios and national planning functions:

(1) Increasing energy productivity: producing more with less;
(2) Decarbonizing electricity supplies;
(3) Expanding end-use electrification;
(4) Decarbonizing fuels and other carriers;
(5) Applying CO_2 capture and geological storage (CCS) to mitigate residual point source emissions, and potentially to remove CO_2 from the atmosphere.

Projecting the evolution of technology solutions for each of these five foundations and their interactions over the course of a national energy transition can help to direct cumulative project and infrastructure requirements. However, disaggregating these projections to a high level of spatial and temporal granularity is necessary to evaluate the transition viability. Rich insights regarding the required scale and pace of plant and infrastructure construction can highlight a variety of potential bottlenecks and clashes that may restrict planned transitions. These include capacity constraints, impacts on natural environments and communities, expectations for societal change, disparities in employment opportunities, limitations of contemporary market mechanisms, capital investment flows, and erosion of existing asset values. Such insights are critical to guide policies that will support sustained capital investment and public support for low-carbon energy transitions. Thus, there is deep uncertainty regarding the respective contributions that will be possible for each foundation.

Let us consider some examples of the system transitions necessary for each foundation of deep decarbonization.

Foundation 1: Increase energy productivity

Energy productivity (the ratio of final energy consumed per unit of GDP) improves yearly. Historically, the rate of improvement has ranged between 1.0% and 2.5% per annum. However, most deep-decarbonization scenarios require energy productivity to improve by 2.5%–4.0% per annum continuously for the next 40 years. This will require the widespread adoption of the most energy-efficient processes and devices as well as substantial shifts in human behavior and consumption, urban planning, building standards, and industrial practices.

Foundation 2: Decarbonize electricity supplies

The most significant resource options for decarbonizing the electricity sector include wind, solar, biomass, hydro, and nuclear, along with fossil fuel combustion coupled with CCS. While all these technologies will likely be necessary for eliminating electricity sector emissions, they each come with their own social, economic, and environmental challenges. Technological, manufacturing, and supply chain innovations have driven down the capital costs of wind turbines (onshore and offshore) and solar photovoltaic (PV) modules, allowing them to compete in the energy market. Furthermore, innovations in system integration and energy storage have helped alleviate long held concerns regarding the variability of wind and solar. However, both technologies currently account for only 10% of the global generation. Both technologies have relatively low (approximately 20%–40%) capacity factors and high land-use intensities. The best resources with available land are often far

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from the main load centers, and hence, require substantial new transmission infrastructure, which may be resisted by communities. Nuclear power requires the least amount of land but must also overcome significant community concerns regarding safety and waste.

Foundation 3: Electrify end-uses

Electrification of the energy demands that have traditionally relied on oil-/coal-derived liquid fuels and natural gas, including light and medium-duty passenger vehicles, household heating, and process heat, is expected. This will require significant shifts in investment decisions by individuals and firms and often a willingness to write off existing assets. The increasing reliance on electricity as an energy carrier also places additional pressure on the already challenging transformation of the electricity system described above. Furthermore, if the decarbonization of electricity supplies is substantially reliant on solar PV, which is available only during the day, individuals and firms who have long considered electricity to be always available on demand may need to be more conscious of their time-of-day use of electricity.

Foundation 4: Decarbonize fuels and other carriers

Even with increased end-use electrification, all decarbonization pathways still rely on varying quantities of liquid and gaseous fuels, which must be decarbonized if we seek to meet our ambitious climate goals. Hydrogen is expected to play a central role, either as a feedstock for synthetic liquid and gaseous fuels or as a stand-alone carrier, for example, via combustion for power generation and direct reduction of iron ore in steel production. Clean hydrogen can be produced by electrolysis using carbon-free electricity, natural gas reformation coupled with CCS, gasification of coal coupled with CCS, or gasification of bioenergy coupled with CCS. Each of these production methods further complicates the electricity production, biomass production, and CO_2 sequestration needs.

Foundation 5: Apply CO_2 capture, use, and storage (CCUS)

Even with the widespread adoption of foundations 1–4, decarbonization is difficult in sectors such as aviation, agriculture, and industry. CCS, mentioned above as essential for decarbonizing both electricity and fuels, is also an option to substantially decarbonize the industrial production of materials such as cement, iron, steel, and petrochemicals. However, CCS is only likely to reduce emissions from point sources by 80%–95% because of residual emissions. Furthermore, there is a growing expectation that globally, we are unlikely to achieve sufficient emissions reductions rapidly enough to avoid the unacceptable consequences of climate change and that we will need to extract CO_2 from the atmosphere—a practice known as Carbon Dioxide Removal. While increasing natural land sinks through reafforestation, improved agricultural practices or other methods will play a major role; most deep-decarbonization scenarios also rely on bioenergy with CCS (BECCS) as an energy supply technology offering net-negative emissions. Overall, these scenarios require between 5×10^{12} and 3×10^{13} kg of geological CO_2 sequestration per year to be sustainable by mid-century. This scale is on the order of 1000 times the current CCS levels and is comparable to, or in some scenarios, much greater than, the current global extraction rates of oil and natural gas. For BECCS, bioenergy crops are also land-use intensive, and the best sites compete with agricultural crops that are critical for food supplies.

In summary, for the transition to net-zero-emissions, the global economy will require unprecedented rates of deployment of equipment and infrastructure. The government and the private sector must both invest heavily and rapidly despite deep uncertainty around future technology costs and performance. Incumbent assets will need to be retired early and written off. The electricity sector must seamlessly combine with the fuel and industrial sectors. The energy sector will rely on land, oceans, and the deep subsurface in new and expansive ways. Competition for land between wind and solar, bioenergy crops, and food crops will intensify. Population-wide behavior changes regarding energy consumption and the purchase of capital items, such as cars and household appliances, will be necessary. Communities will need to accept large-scale, invasive infrastructure, including transmission lines, pipelines, and renewable energy farms, within their local environments. The markets will require considerable reforms. The extent to which such widespread physical, environmental, economic, and social changes will be possible is uncertain and likely to be regionally variable.

Research has and will continue to be critical, but to be effective, we must ① respect uncertainty by exploring transition scenarios rather than proscribing pathways; ② adopt an integrated systems approach; ③ convene interdisciplinary teams (scientists, engineers, economists, business scholars, social and behavioral scientists, and policy practitioners) concerning key challenges; ④ engage deeply with the private sector and government to ensure a two-way flow of information regarding implementation challenges, research priorities, and findings.