HIGH-ENERGY INNOVATION

— A CLIMATE PRAGMATISM PROJECT —

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Consortium for Science, Policy & Outcomes
at Arizona State University

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BREAKTHROUGH INSTITUTE

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EXECUTIVE SUMMARY

In the coming decades, most of the innovation in clean energy technologies needed to combat climate change will likely occur in rapidly industrializing rather than developed nations. This report identifies and maps promising international efforts by private firms and governments in China, India, the United States, Europe, Latin America, and Africa to advance four low-carbon technologies — shale gas, nuclear, carbon capture and storage (CCS), and solar PV — and makes the case for more collaborations between nations.

Technological innovation often occurs where demand is rising the fastest. Wealthy developed nations have seen their overall energy consumption growth slow down in recent decades, along with the rates of economic growth. By contrast, energy consumption in poor and developing (non-OECD) countries is expected to increase 90 percent by midcentury. The so-called "BRICS" — Brazil, Russia, India, Mexico, China, and South Africa — spend more on energy innovation (ie, research, development, and deployment) than do all 29 OECD member nations of the International Energy Agency (IEA).

Today's global energy innovation bears little resemblance to the 1980s-era model of "technology transfer" from rich to poor nations, as enshrined in the United Nations Framework Convention on Climate Change. Industrializing nations have in recent years pioneered innovation of next-generation energy technologies, and are beginning to market those technologies internationally. South Korea, for example, which has seen the cost of building standardized nuclear plants decline over time, is constructing advanced nuclear power plants in the United Arab Emirates for both electricity and desalination.

Basic research in national laboratories is critical but insufficient. Technological progress will come from demonstrating and deploying next-generation nuclear, solar, CCS, and natural gas technologies. Real-world trial and error is critical to technological progress, as the shale gas revolution, which took several decades, showed.

While emerging economies will do the heavy lifting, advanced industrial economies still play important roles. Germany, the global leader in solar deployment, is developing large solar power plants in South Africa and India. US energy utilities are working with Chinese firms to demonstrate carbon capture and storage technologies in Mississippi. Shale fracking technologies developed in the United States are being deployed with the help of US firms and public research agencies in China, which has a more complicated geology and requires significant innovation to become commercially viable.

Policy makers ought to view energy innovation as a global public good. The benefits of creating cheaper and cleaner energy sources are shared by all — not monopolized by individual nations. For instance, the success of nuclear and shale gas in China depend largely on the successful development of similar technologies in the United States. Similarly, the United States may likely benefit from cheaper and safer nuclear, solar, or CCS developed in China. The broader picture is one of shared economic and environmental interests from creating cheap and clean energy.

Governments, industry associations, and philanthropies all have important roles to play in coordinating and contributing to accelerated low-carbon technology innovation within and among nations. While philanthropies have funded major international efforts to increase agricultural yields and improve public health, no such initiative yet exists on energy innovation. Policy makers, for their part, should seek to expand these promising initiatives for both economic and environmental reasons. Such an approach is more likely to succeed than efforts that require shared sacrifice. Governments have long encouraged and invested in technological change to access to cheaper, cleaner forms of energy for economic growth, national security, and environmental quality.

INTRODUCTION

Energy consumption is essential to human development, and global energy use will thus increase significantly over the next century as poor nations achieve modern living standards. This is an overwhelmingly positive process in terms of life expectancy, health, and quality of life. Higher levels of energy consumption will also have significant environmental impacts. Some of the effects will be positive, as electricity and liquid fuels allow people to move away from wood and dung as primary fuels, which contribute to respiratory disease and deforestation. At the same time, rising fossil energy consumption results in high levels of air pollution in rapidly growing megacities and contributes to global warming, with potentially large economic and environmental costs.[1, 2]

Past energy transitions show a trend toward cheaper, cleaner, more abundant, and more-reliable new fuels, as well as the replacement of old energy-conversion technologies with new ones. For more than 200 years, nation-states and private actors have worked to move nations up the "energy ladder," from wood, dung, and charcoal to diversified modern systems consisting of fossil fuels like coal, oil, and natural gas and low-carbon technologies like hydroelectricity, nuclear, and renewables.[3] This is a long-term trend toward less pollution and fewer carbon emissions. To be sure, every nation's geography, energy reserves, and technical capacities differ, and so each national energy modernization process is unique. But the collective desire for cheaper, cleaner, and more reliable energy is behind this emergent global phenomenon of decarbonization.

Given the importance of climbing the energy ladder for human development, continuous technological innovation of energy systems has been a priority for prosperous nations since the Industrial Revolution. Rich nations, in turn, have understood their role in linking energy to human development as one of "transferring" technologies to poor countries.[4] This model has been directly applied in international efforts to address global warming, for example, through the United Nations Framework Convention on Climate Change.[5] In the last decade, the center of gravity on energy innovation has shifted decisively to rapidly industrializing countries. Rapidly industrializing nations dominate the manufacturing of solar, wind, biofuel, and other technologies, and are rapidly deploying and innovating on nuclear, hydroelectricity, and natural gas.[6]

Innovation tends to occur where demand for new technologies is growing fastest, and energy is no exception.[7, 43] As most of the new energy infrastructure over the coming decades will be built in industrializing countries,[8] it is there that we should expect to see — and should work hardest to accelerate — energy innovation. This innovation will create global economic and environmental benefits, as cheaper energy technologies literally fuel productivity gains across all sectors of society. Thus, as this report argues, clean energy innovation is a global public good to be pursued collaboratively by nations seeking to advance ideals of global economic, social, and environmental well-being.

In contrast to this report's view that clean energy innovation requires international collaboration, a number of analysts and policy makers over the past decade have framed energy innovation as a "clean tech race," a zero-sum game played by nations competing to dominate low-carbon energy industries for domestic economic advantage.[9] This view was reinforced by trade disputes over solar panel manufacturing. Efforts by China, the United States, and the European Union to accelerate the deployment of solar power helped drive down costs, but also sparked an international trade war, as manufacturers in rich countries could not compete with cheap Chinese panels.[10] Such competitive framing is ultimately self-defeating. The economic benefits that flow to individual countries by being competitive in manufacturing advanced energy technologies are small compared to the overall public — including economic — benefits of energy that is both cheap and clean.

As such, the crucial yet complex role of energy innovation in global development needs to be reconceived from the bottom up. A new and empowering understanding starts with the recognition that opportunities for energy innovation and decarbonization on our "high-energy planet" are concentrated in rapidly industrializing economies, and that for wealthy countries to contribute decisively they will need to play a different role than either technology provider or economic competitor. This report builds on prior reports, *Climate Pragmatism*[11] and *Our High-Energy Planet,*[1] to argue that rising energy consumption is an opportunity to advance both human development and environmental protection through pragmatic policies — chief among them technological innovation to make energy cheaper, cleaner, more reliable, and more abundant.

RAPID ECONOMIC DEVELOPMENT AND ENERGY INNOVATION

New, transformative technologies are rarely invented in the research laboratory and unveiled to a grateful world. Rather, new materials, processes, and physical phenomena are discovered both in and outside the laboratory. They are applied in new contexts, tinkered and combined with other technologies, sometimes in research laboratories but mostly in the real world — be it a factory floor, battlefield, hospital operating room, or farm. The study of innovation over the past several decades, across multiple contexts, economic sectors, and stages of technology development and use, has consistently concluded that processes of invention and innovation are neither linear nor easily delineated. Invention, innovation, diffusion, and use feed back into and depend upon one another in complex, indirect, and unpredictable ways.[12]

These observations are illustrated by the rise of the Internet and the World Wide Web, two innovations that have revolutionized our world. These drivers of social and economic change were not designed from scratch or even imagined far in advance; they emerged over many decades from advances in information and communications technologies, in network theory and other fundamental sciences. Above all, the Internet and the web as we know them today are the result of the demands, ingenuity, and experience of users, from scientists in academic laboratories, to entrepreneurial individuals and firms looking for new products and markets, to government agencies trying to better deliver services and information.[13]

The implications of these dynamics are significant for global energy innovation efforts. If, as is likely the case, energy technology deployment over the coming decades is overwhelmingly concentrated in developing economies, then that is where most energy technology innovation will likely occur. Innovation activities that are divorced from or not well integrated with the sites of deployment and use are likely to fail. Furthermore, because a nation's capacity to innovate and deliver abundant, cheap energy across its economy are inextricable from broader processes of socioeconomic advancement, energy innovation efforts must be grounded in and contribute to ambitious development agendas.

These dynamics challenge the long-standing framework for global energy innovation. Dating back to the famous UN-commissioned Brundtland Report,[14] which in 1987 articulated a vision for pursuing global sustainability, this framework helped set the agenda for international energy and environmental initiatives. It imagined that poor countries, through the transfer of low-emitting energy technologies from rich nations, could develop their energy systems along trajectories that are radically different from those traversed by early industrializing societies.

The Brundtland Report was a product of energy and development thinking dominant among well-meaning Westerners in the 1960s and 1970s. European and US environmental and development critics, living in the wealthiest and most secure political economies in history, disavowed the modernization pathways their countries had followed. To avoid global environmental, economic, and demographic strife, these critics claimed, poor countries could not follow our example.[15] Influenced strongly by E.F. Schumacher's "appropriate technology" prescriptions,[16] Amory Lovins's warnings against energy consumption and centralized energy systems,[17] and the Club of Rome's dire projections of global resource shortages,[18] a new framework emerged: the soft-energy paradigm. This framework is predicated on two core assumptions: first, that "a low-energy path is the best way toward a sustainable future," as the Brundtland Report insists;[16] second, that existing renewable energy technologies will replace most fossil fuel use, obviating the need for substantial innovation.[19]

The Brundtland framework provided the normative principle for the United Nations and its Framework Convention on Climate Change (UNFCCC), the main instrument by which the international community endeavors to mitigate the climate impact of human activities.[20] It is also the paradigm for low-carbon development initiatives like the Global

Environment Facility (GEF), Climate Investment Funds (CIF), and Clean Development Mechanism (CDM).[21] The UNFCCC reinforced the Brundtland Report's conviction that poor countries could assume novel development pathways through minimized energy consumption and renewable energy deployment, especially through provisions that allow rich countries to meet their emissions reduction commitments most cost effectively by supporting low-carbon projects in developing countries.[22]

Unfortunately, approaching energy system development in poor countries with a single-minded focus on non-emitting renewables — energy technologies with significant limitations for meeting the needs of energy-starved, rapidly urbanizing developing countries — undermines the creation of a robust, diversified energy infrastructure. Off-grid renewables can in some cases provide limited energy access more quickly or cheaply than conventional baseload power and grid expansion.[23] But the priorities of energy system expansion efforts in the developing world, and the donor countries and organizations that work there, must be consistent with broader development objectives that include agricultural modernization, the creation of domestic industrial capacity, and meeting the needs of rapidly growing cities.[1] Powering the development of modern urban, agricultural, and industrial infrastructures requires large quantities of cheap, baseload power and liquid fuels.

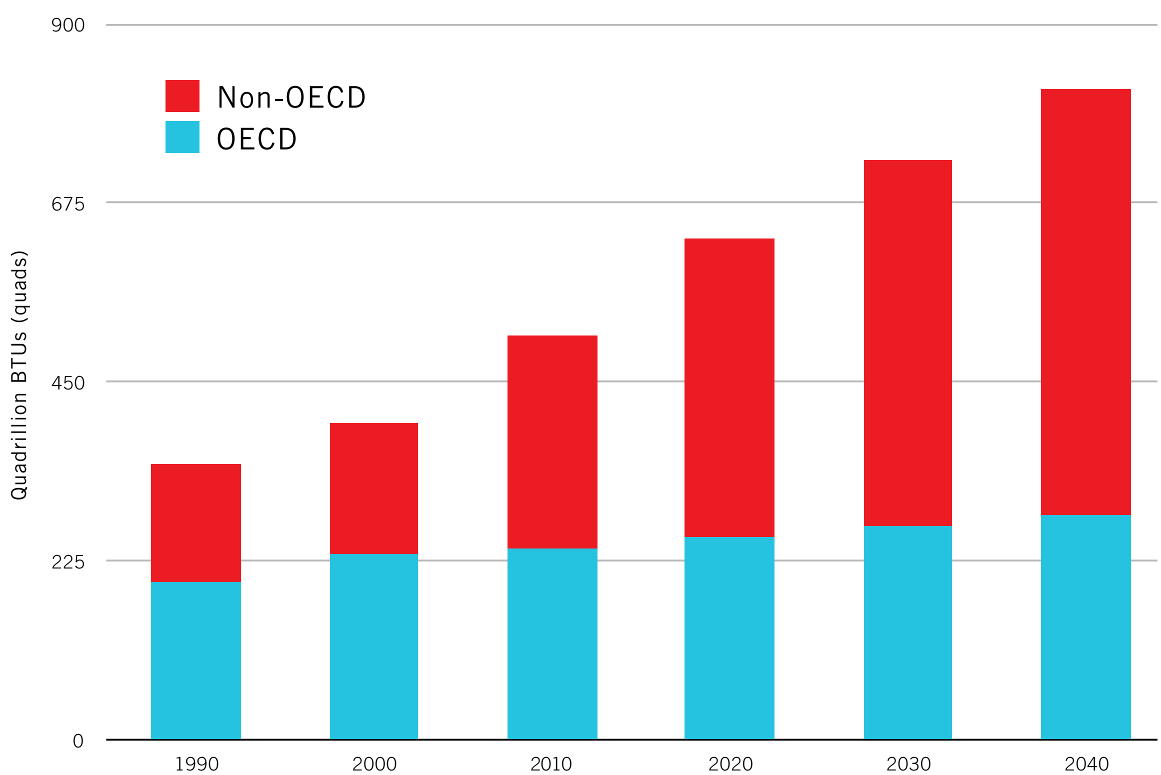
A recent analysis from the Center for Global Development compares access rates in sub-Saharan Africa with a hypothetical $10 billion energy project investment portfolio that comprises only renewables and another with only gas. The gulf in access rates is enormous: "A natural gas-only portfolio could provide electricity access to 90 million people versus 20 to 27 million people with a renewables-only portfolio." A project investment portfolio of two-thirds natural gas projects and one-third renewables would support energy access for 70 million people, or at least 40 million more than renewables alone.[24]

Simply transferring existing renewable technologies to developing countries cannot provide the energy necessary for modernization. Nor can this mechanism catalyze the economic activities necessary to spur indigenous capacities for technological innovation. Perhaps, then, rich countries will develop the low-carbon hardware necessary both to leapfrog fossil energy use and to power high-energy modern economies, and transfer this next generation of innovative energy technology to the developing world?

The reality is wealthy economies are unlikely to offer either the motivation or context in which rapid clean energy innovation might occur. In developed countries, energy demand projections are flat or decreasing. With energy infrastructure and transitions lasting several decades at least, it makes little economic sense for developed nations to make large investments in clean energy innovation. Power plants in the United States have a replacement cost of $1.5 trillion.[25] Sunk costs are a tremendous incentive against disruptive innovation.[26] Of the wealthy nations, only Germany and Denmark are making a comprehensive effort to transform their energy systems to low-carbon ones, and the outcomes of those experiment are both highly uncertain and far in the future.[27]

National interest has often played a key role in driving innovation. The United States' development of light-water nuclear reactors was borne out of defense concerns, with the design originally created for military submarines.[13] The original funding for shale gas exploration — funding that kick-started a decades-long process that ultimately led to fracking — was justified by US concern with its dependency on foreign oil.[28] Energy independence was also a reason for France and Sweden's rapid transitions to nuclear.[29]

FIGURE 1.
WORLD PRIMARY ENERGY CONSUMPTION, 1990-2040



Source: US Energy Information Administration. *International Energy Outlook 2013.*

At times, energy innovation can be a means to gain a comparative advantage in international trade, as has been suggested of China's recent push into solar photovoltaic (PV) manufacturing.[6] But at its core, countries are driven to innovate in the energy domain because cheap, reliable (which often means domestically produced), and abundant energy is essential to economic growth and national prosperity. For most developed countries, cheap and abundant energy already exists.

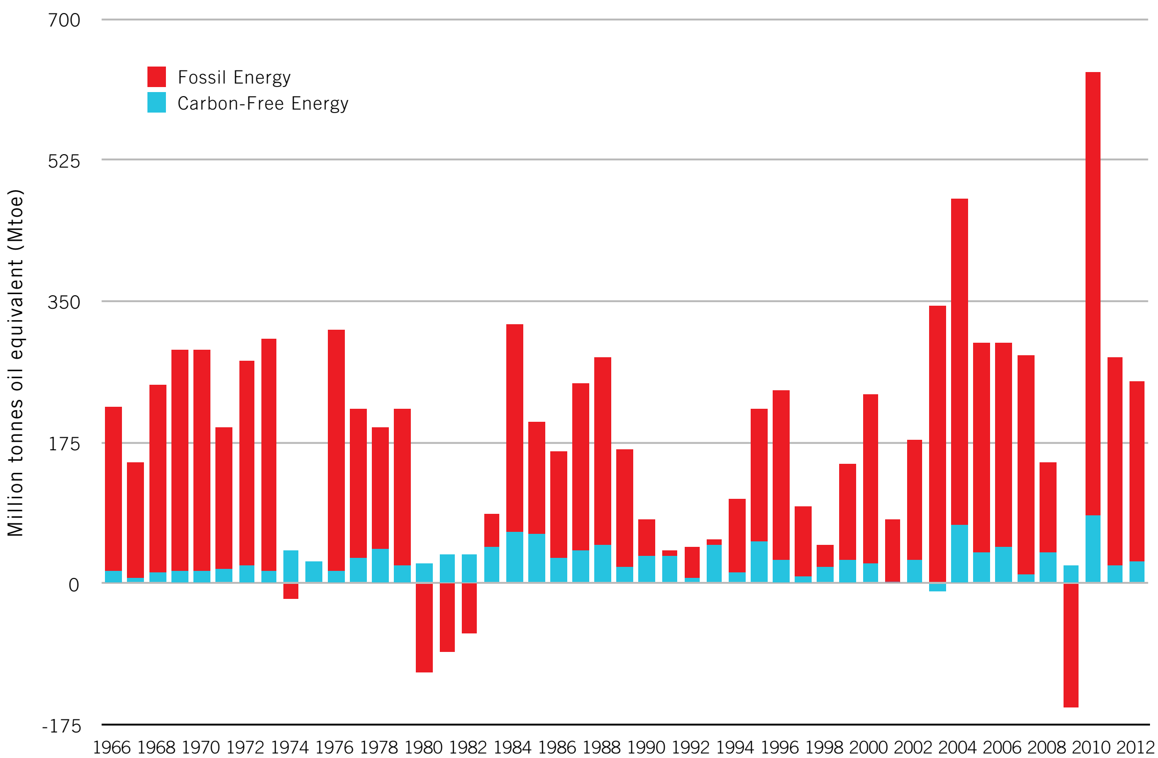
By contrast, rapidly industrializing countries are power hungry. As illustrated in Figure 1, nearly all the growth in energy markets and the majority of new energy technologies deployed in the coming decades is projected to occur in the developing world.[8] This is a direct result of building out energy systems to support development ambitions and provide citizens with access to the energy they need to prosper.

Societies that have successfully accelerated their development have done so by expanding modern diversified energy systems, building the knowledge and experience necessary for improved performance and continual learning in the process.[30] The pattern of gradually strengthening innovation capacity, specific to historical and national contexts, has been central to the modernization of every industrialized and industrializing nation, from England to the United States to South Korea to Brazil.[31]

All the components of a country's energy system — power plants, pipelines, electricity grids, and so on — are tightly interdependent. In other words, energy systems are an example of "technological lock-in," where complementarities between individual technologies and infrastructure are very strong.[32] This locked-in aspect of a nation's energy system means that technological innovations that fit relatively seamlessly into the existing regime are adopted far more quickly than those that do not. This is why, as we discuss in more detail below, the fracking revolution occurred in the United States and accounted for the speedy reductions in carbon emissions, in contrast to the much slower diffusion of renewables. Fracking was made possible by incremental improvements of existing hydrocarbon extraction technologies, and the resulting natural gas could be incorporated into existing energy infrastructure.[28] Such "path dependencies" are characteristic of modern, locked-in energy systems.

FIGURE 2.

CARBON-FREE ENERGY AS PORTION OF ADDED ENERGY CONSUMPTION, 1966-2012

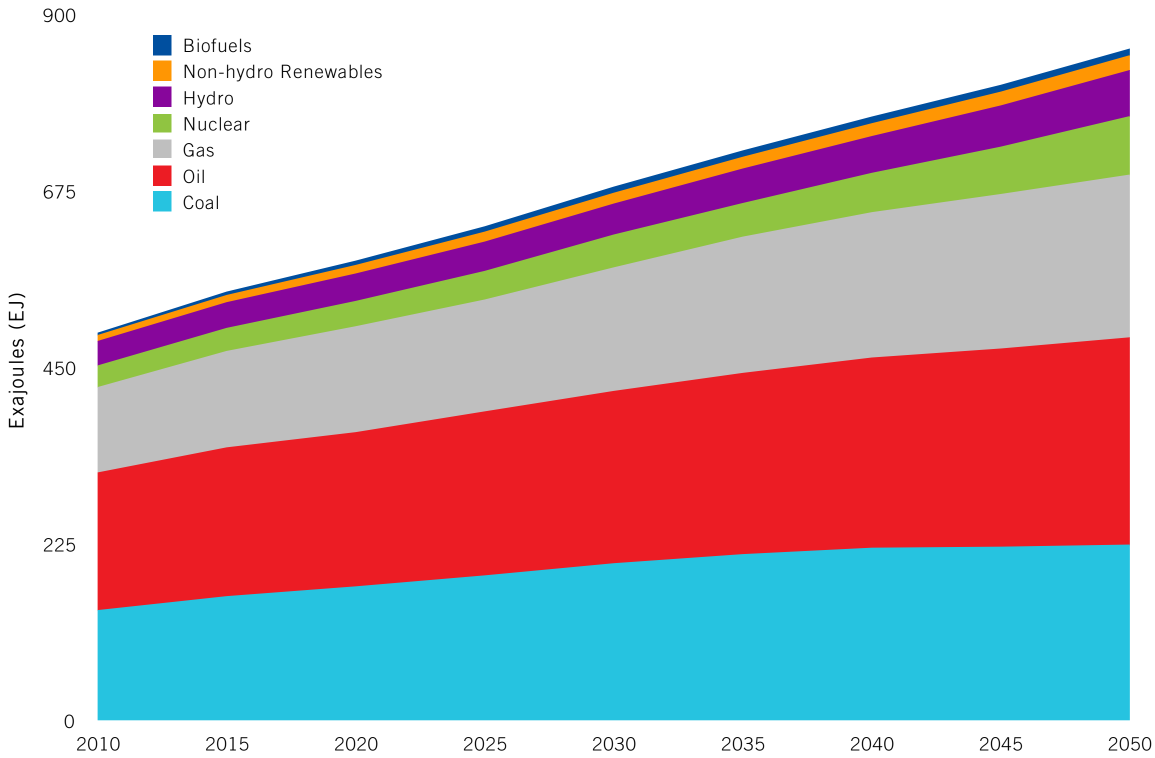


Source: BP. "Statistical Review of World Energy 2012."

If rich countries are constrained by technological lock-in and path dependencies, in developing countries the relative lack of preexisting infrastructure means energy innovation can explore new and diverse technologies and development pathways as they build out their energy systems to meet their economic and social needs. This presents both an opportunity and a challenge: On the one hand, developing countries are less invested in the prevailing fossil fuel regime. On the other, developing countries will continue to exploit fossil fuels as the most efficient path to modernization.[1]

No country has succeeded in achieving significant human development or economic growth without a leading role for fossil fuels, along with other modern technologies like large hydroelectric power.[33] To date, there are no countries even attempting to pursue a development path similar to that encapsulated by the Brundtland's low-energy framework. The world's growth in fossil fuels consumption is still far outpacing that of clean energy (see Figures 2 and 3).[34]

FIGURE 3.
PROJECTED GLOBAL PRIMARY ENERGY CONSUMPTION, 2010-2050



Source: MIT Joint Program on the Science and Policy of Global Change. "MIT Energy and Climate Outlook 2014."

Yet the sheer scale of providing the energy necessary to power economic and social growth has compelled developing countries to invest in a wide range of technologies. Whether it is experiments with renewables and storage in the United Arab Emirates' Masdar City,[35] grid expansion in Brazil,[36] or underground coal gasification in South Africa,[37] industrializing countries are not restricting themselves to conventional fossil fuels. Indeed, developing countries may transition to advanced energy systems faster, with a greater variety of energy sources, and more efficiently than has been the case in the United States.[38]

China, in particular, is heavily investing in clean energy, partly as a means to gain a competitive advantage but mostly to pursue an "all-of-the-above" strategy and deal with mounting pollution problems in its cities. The country is pioneering fourth-generation nuclear reactors, such as sodium-cooled fast reactors, high-temperature gas reactors, and salt-cooled reactors.[39] Combined, the emerging economies of Brazil, Russia, India, Mexico, China, and South Africa provide as much public funding on energy research, development, and deployment as do all 29 wealthy member countries of the International Energy Agency.[40]

Of course large-scale investments in clean energy are not occurring evenly or equally across the developing world. Clean energy innovation requires a robust industrial base, with easy access to both suppliers and consumer markets. In most developing countries, the process of industrialization is still in its infancy and research and manufacturing capacities remain modest — weaknesses that will be ameliorated as these countries work to expand their energy systems. They are doing this in part with help from affluent donor nations, but mostly (and most pragmatically) with the assistance of rapidly developing countries, most notably China.

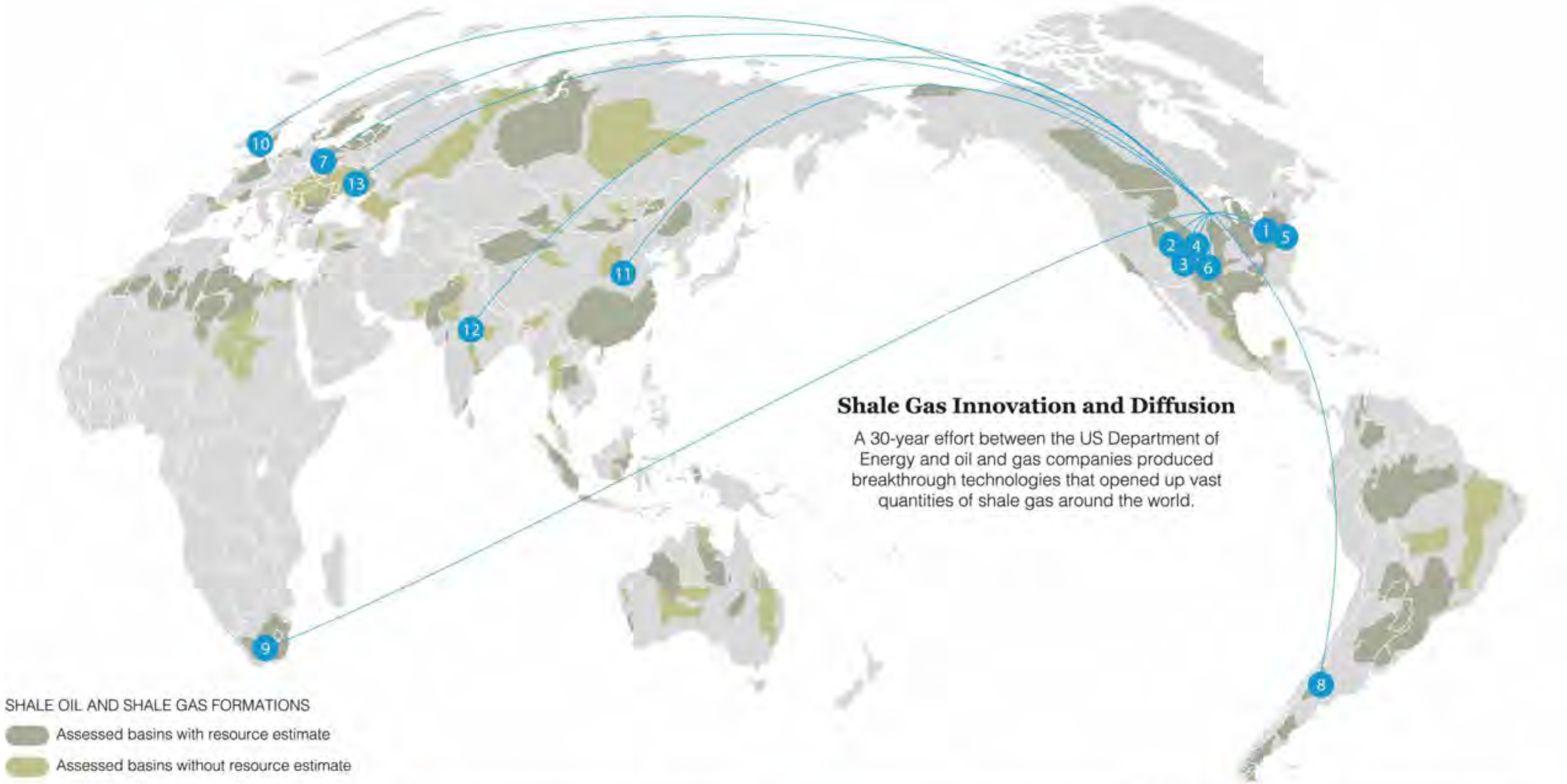
Our focus is thus squarely on rapidly industrializing countries. Substantial research, commercial, trade, and investment potentials already exist in these countries. Coupled with growing demand for essentially everything, and especially energy, it is in industrializing countries that policy makers should target interventions aimed at advancing and accelerating clean energy innovation.

Below we evaluate energy innovation progress on four technologies with the potential to provide cheap, clean, and reliable baseload power through rapid deployment in industrializing economies. We focus on these four not to suggest that they should be the only energy technologies pursued by international efforts, but rather to illustrate the distinct challenges facing different technologies, including their innovation and diffusion in different national contexts.

SHALE GAS

The recent boom in natural gas production in the United States, brought about through technical innovations in the recovery of natural gas from previously inaccessible shale rock formations and land-use policies that favor private development, has helped lower electricity costs and benefitted the petrochemical and manufacturing industries.[41] Even more significantly, it has contributed to a drop in US carbon dioxide emissions to their lowest levels in two decades,[42] as inexpensive natural gas accelerates the closure of aging coal plants around the country.

Though hydraulic fracturing's diffusion across the United States since 2005 has been rapid,[43] the actual innovation process occurred over decades. The technique of fracturing



Shale Gas Innovation and Diffusion

A 30-year effort between the US Department of Energy and oil and gas companies produced breakthrough technologies that opened up vast quantities of shale gas around the world.

SHALE OIL AND SHALE GAS FORMATIONS

- Assessed basins with resource estimate
- Assessed basins without resource estimate

1970s-2000

1. The Eastern Gas Shales Project was a federally funded shale fracking research and development and demonstration project that constructed test wells in major shale plays in the eastern **US**.
2. The Western Gas Shales Project was a federally funded unconventional oil and gas research, development, and demonstration project in southwestern states including **Colorado** and **New Mexico**.
3. Sandia and Los Alamos created the Natural Gas & Oil Technology Partnership, which eventually included work from several other **US** Department of Energy labs. Sandia was instrumental in developing and sharing critical microseismic imaging technology with Mitchell Energy.
4. Los Alamos National Labs in **New Mexico** performed significant research, development, and testing of early microseismic imaging technologies for application in both oil and gas exploration and initially for the Lab's Geothermal Program.
5. The **US** Department of Energy funded and executed much of the major groundbreaking unconventional gas innovation from the 1970s through the 2000s. Congress also created the Section 29 tax credit for unconventional gas that lasted from 1980 to 2002.
6. The Barnett Shale in northeast **Texas** was the site of Mitchell Energy's major technological breakthroughs in shale gas fracking in the 1980s and 1990s.

2000-today

7. Chevon, Cuadrilla (UK), and other multinational O&G firms have invested with Polish companies in exploration of Polish shale energy resources. State-controlled energy companies PGNiG and PKN Orlen are leading shale gas exploration in **Poland**.
8. Total, Shell, and Exxon Mobil have all invested in **Argentina's** Vaca Muerta shale formation. Chevron and YPF, Argentina's state oil company, have a joint venture to develop shale resources.
9. In 2012 **South Africa** lifted a national fracking moratorium, opening investment and exploration opportunity for international oil companies, including Royal Dutch Shell.
10. France-based Total became the first major multinational to enter into shale gas exploration in the **UK**. Cuadrilla is drilling dozens of exploratory wells there.
11. **China's** Sinopec bought $2.5 billion stake in Devon Energy in 2012. Other Chinese O&G firms have bought stakes in US oil production projects developed by Chesapeake.
12. Shale gas was the top priority at the **US-India** Energy Partnership Summit, attended by new Indian PM Narendra Modi, in September 2014.
13. **Ukraine** has signed agreements with Royal Dutch Shell and Chevron for shale gas exploration.

rock to recover fuels was invented in the late 1940s, but it required many additional innovations — the result of public-private partnerships and federal investments at many points in the process — to develop a method of fracking that was economically viable.[28] The version of fracking that came to dominate was the one that took advantage of resources available to US companies, particularly the abundant water supplies that made it feasible to inject millions of gallons of water into underground rock formations.[43] Fracking's economic success also depended on external factors such as the continuous improvements to the country's energy infrastructure, especially its natural gas pipelines.

The possibility of cheaper and cleaner energy from shale gas has prompted interest from governments around the world. If it can achieve the necessary innovations for tapping perhaps the largest shale gas reserves on the planet, China may be able to reduce its dependence on coal and shift to a lower-carbon economy.[44] European countries such as the United Kingdom are also exploring the possibility of exploiting shale gas.[45]

However, caution is warranted. The large deployment of fracking technology faces significant hurdles outside of the US context. China's nascent industry is plagued by technical bottlenecks, lack of adequate water supply, and poor infrastructure.[46] Drilling an exploratory shale gas well in China still costs much more than it does in the United States.[47] In Europe, the challenges are more likely to be political and legal.[22] Unlike in the United States, European landowners do not automatically own the rights to extract the resources from the ground beneath their property, making the building of new extraction plants fraught with political difficulties.[48]

From this example, three lessons are clear. First, incremental innovation within an existing and powerful segment of the energy sector has lowered American carbon emissions and reaped substantial benefits to the economy.[48] The shale gas revolution has reduced US power sector emissions on the order of 150 to 200 megatons annually over the past decade, and cheaper energy costs have provided a $100 billion-per-year boost to the US economy.[49] Second, the diffusion of energy technologies beyond the techno-economic system from which they emerge is rife with challenges. Third, and precisely because this process is so hard, the transfer of expertise and technical knowledge (rather than merely dropping in hardware) is critical to accelerating diffusion.

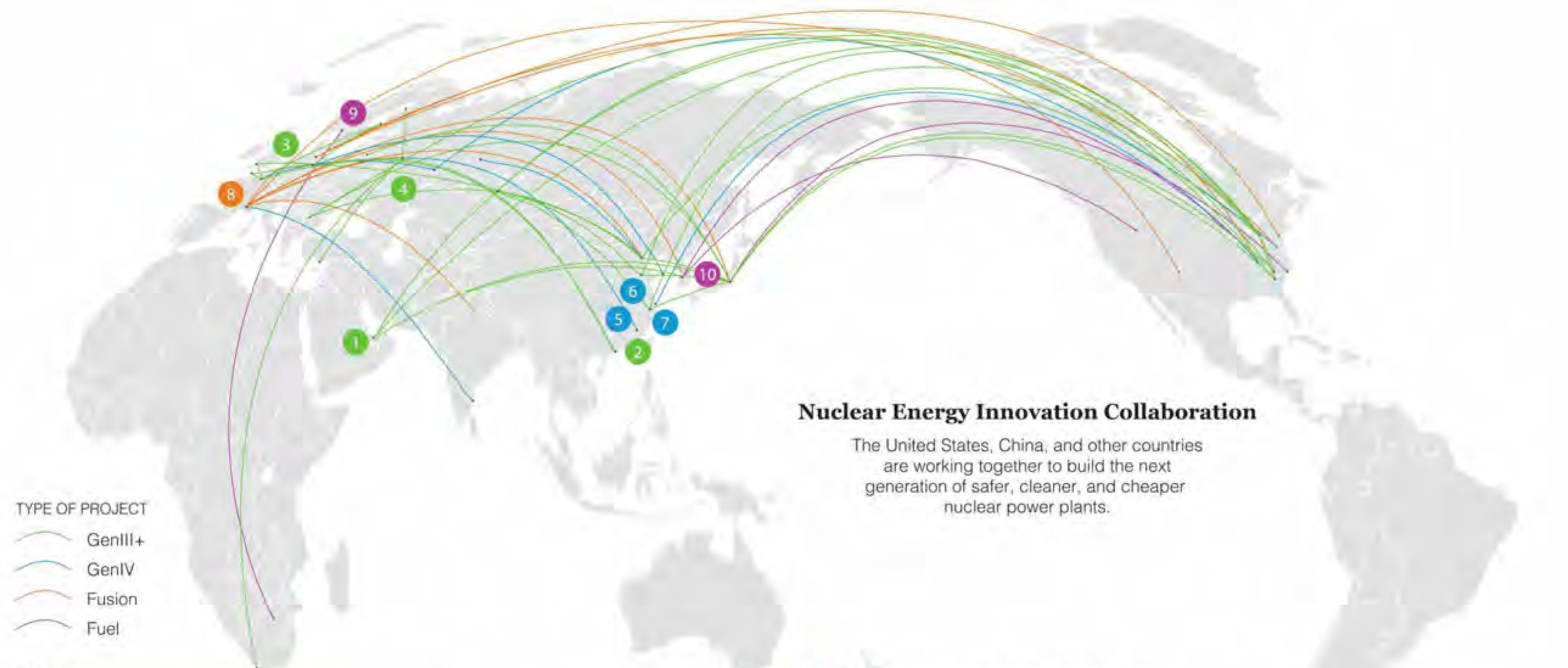
Countries have tried to do this by attracting the expertise of US firms. Mexico, for example, has opened up its oil and gas sector to foreign investment[50] in order to acquire the horizontal drilling and hydraulic fracturing techniques that can help it access one of the world's largest reserves of shale gas and tight oil.[51] And a Chinese energy company, Sinopec Group, paid Devon Energy (which had previously acquired Mitchell Energy, the firm that co-created the shale gas revolution with the US government) billions of dollars to work with it on fuel extractions projects, in the hope of gaining access to the US firm's expertise.[28,52] Other countries are enthusiastically exploring the possibility of shale gas production, including Argentina, South Africa, and Poland.[53]

NUCLEAR

Nuclear power is energy dense, provides reliable baseload power, and offers a range of highly advantageous end uses, such as the ability to generate large quantities of process heat for desalination and other industrial uses. Rising capital costs and systemic barriers to nuclear innovation over the past four decades have limited its ability to make a significant dent in fossil fuels' dominance.

Most of the growth in commercial nuclear power over the coming decades will occur in rapidly industrializing countries like China and South Korea, and Middle Eastern countries like Saudi Arabia and the United Arab Emirates. Indeed, 28 of the 67 reactors currently under construction in the world are being built in China.[54] By contrast, the dominant rich-world markets for nuclear power — including the United States, France, Sweden, and Japan — have either dramatically slowed their nuclear build-out or pursued a path of accelerated decommissioning, as in the case of Germany.[27] And nuclear is unlikely to be an option in poor nations that lack strong scientific, technical, and regulatory establishments.

In the 1960s, conventionally constructed thermal reactors became the "locked-in" dominant technology at the expense of other designs, including thorium-fueled, pebble-bed, gas-cooled, and fast reactors.[55] Five decades later, nuclear innovation is occurring with both conventional light-water reactors and next-generation reactors that use new coolant and fuel designs. For instance, the Chinese Academy of Sciences is currently building on research into a molten salt reactor (MSR), initiated and later discarded by the United States' Oak Ridge National Laboratory in the 1960s, with the aim of constructing a thorium-breeding MSR prototype in Shanghai by 2015. The US Department of Energy is collaborating on the project, which reportedly has a start-up budget of $350 million.[56] Bill Gates reportedly has been in talks with the China National Nuclear Corporation about developing his idea for a traveling-wave reactor.[57]



Nuclear Energy Innovation Collaboration

The United States, China, and other countries are working together to build the next generation of safer, cleaner, and cheaper nuclear power plants.

GENIII+

1 To build its first nuclear power plant, the **United Arab Emirates** contracted with Korea Electric Power Co. The contract (signed in 2009), which includes equipment from Westinghouse, marks the first international deal for **South Korea's** fledgling nuclear export industry. The first of these reactors will come online in 2017.

2 Westinghouse's AP1000 dominates the international GenIII+ market, with dozens of projects underway in the **United States, China,** and **Bulgaria**. Westinghouse has 4 AP1000s under construction along the coast of **China**, and the multinational corporation is close to signing a deal for up to 26 additional nuclear plants to be built throughout **China's** interior.

3 Paris-based Areva and Berlin-based Siemens collaborated to design the European Pressurized Water Reactor (EPR) reactor, a competitor of the AP1000, which is under construction in **Finland**, **France**, and **China**. Another two EPRs are planned for the **UK** with an expected commercial start date in the early 2020s.

4 **Russia's** VVER reactor series has long operated in **Armenia, Bulgaria, China, Czech Republic, Finland, Hungary, India, Iran, Slovakia, Ukraine, and Russia.** Their new GenIII+ design, the VVER-1200, is targeted to countries hoping to build their first nuclear power plants. **Russia** offers the lowest cost GenIII+ design, while also helping with financing, liability, and managing the fuel cycle, which companies like Westinghouse and Areva may not offer.

GENIV

5 Rosatom's BN-800 reactor (a sodium-cooled fast neutron reactor) began producing electricity in **Russia** in October 2014, and the state-owned company is also working with the China Nuclear Energy Industry Corporation on a project of the same design in **Sanming City, China** — making it the first fast reactor built for commercial export.

6 **China** is constructing a two-unit modular demonstration of a high-temperature gas-cooled reactor that will use a pebble bed fuel, the design of which was based on the German High-Temperature (HTR)-MODUL, which was never built in **Germany** due to antinuclear sentiment in the wake of Chernobyl. These reactors are scheduled to come online in 2017.

7 Through a knowledge-sharing agreement that began in 2010, the Chinese Academy of Sciences enlisted the US Oak Ridge National Laboratory for two thorium molten salt reactor experiments based on research pioneered by the **United States** in the 1960s and 1970s. **China's** 2 MW solid-fueled molten salt reactor should begin operation in 2017, while the liquid-fueled experiment won't start until 2020 at the earliest.

FUSION

8 The International Thermonuclear Experimental Reactor (ITER) in **France** is one of the largest collaborative energy projects ever built, involving more than **30 countries** investing more than $50 billion. The first plasma is expected to be created in 2020.

FUEL

9 Thor Energy, co-owned by the **South African** company Steenkampskraal Thorium, has started testing its own solid thorium MOX fuel rods in **Norway**, which are designed to be used in existing light-water reactors.

10 While pioneered and then abandoned by **US** research labs, fuel pyroprocessing research at lab scale has continued in **South Korea**, which would like to begin larger scale demonstrations. Pyroprocessing technology is critical to fast reactors like GE-Hitachi's PRISM design, based on the Experimental Breeder Reactor (EBR-II) developed in the US by Argonne National Laboratory from 1964 to 1994, until Congress cut funding for the program.

Rapidly developing countries are leading the way on advanced reactor designs across the board. Russia has been operating sodium-cooled fast reactors since the 1980s, just started construction on an 800MW commercial design,[58] plans to construct the same reactor in China,[59] and is beginning work on two different lead-cooled fast reactor demonstrations. India and China are also operating their own experimental fast reactors and planning for larger demonstrations. China has begun construction on a 210MW high-temperature gas reactor.[60]

The US government could do more to facilitate international cooperation, governance and safety, and knowledge spillover. One example is the commercialization of fuel reprocessing. The United States and South Korea have cooperated on the development of civilian nuclear resources since the 1950s.[61] Nuclear currently provides around 40 percent of South Korea's electricity needs, and the country has recently become an exporter of nuclear technology.[62] However, proliferation concerns have made the United States reluctant to share research on reprocessing spent fuels, which has hindered South Korea's efforts to deal with waste disposal.[63] American leadership in reforming international governance regimes and coordinating other areas of research and demonstration would likely yield benefits not just to the countries actively involved in such projects, but also to future consumers of advanced nuclear technologies — the "late adopters" who can capitalize on early collaborative enterprises.

CARBON CAPTURE AND STORAGE

Despite enormous political efforts to the contrary, the world is becoming more, not less, dependent on its most carbon-intensive power source[64] — a strong testimony to both poor countries' desire to transcend poverty and the powerful path dependencies that govern technological innovation. China already burns as much coal as the rest of the world combined. By 2030, the developing Asia-Pacific region, led by China, is expected to double its electricity demand to consume more electricity annually than all the affluent OECD countries put together. The Asian Development Bank projects that 83 percent of these energy needs will be met with coal.[10, 65]

Its commitment to greener growth notwithstanding, China is building out the energy system that will meet this tremendous demand in substantial part by exploiting coal, its largest and cheapest energy resource.[10] In the past decade alone, China has invested many

Carbon Capture and Storage Innovation

Governments and industry collaborate on carbon capture technologies with an aim towards producing power while capturing and storing emissions underground.

OXY-FUEL COMBUSTION CAPTURE

1. Compostilla - **Switzerland**-based multinational Foster Wheeler is a major investor in this project in northwest **Spain**. The European Commission provided 180 million euros to the project as part of Europe's economic recovery strategy.
2. Datang Daqing - **France**-based Alstom and **China**-based Datang collaboration on CCS power plant demonstration in China.

PRE-COMBUSTION CAPTURE (GASIFICATION)

3. TharPak - Consortium of **American** companies and multinationals financing a coal plant with CCS in the Thar region of **Pakistan**.
4. GreenGen - Peabody Energy (headquartered in **St. Louis, Missouri**) is a major investor in this northern **China** project.
5. Dongguan - KBR (headquartered in **Texas**) and the Southern Company (headquartered in **Atlanta, Georgia**) are providing the IGCC technology for this CCS project in southern **China**.
6. Kemper - Southern Co. and Shenhua signed a deal to share technology and knowledge related to the Kemper coal gasification plant in **Mississippi**. Work will include other government agencies and universities as well.

POST-COMBUSTION CAPTURE

7. Boundary Dam - Saskatchewan Power Corporation and **Japan**-based Hitachi collaborated on one of the world's first and largest CCS power plants, that became active in fall of 2014.
8. Porto Tolle - **Norway**-based multinational Aker Solutions is a major investor in this project in northern **Italy**. The European Commission provided 100 million euros as part of Europe's economic recovery strategy.
9. Getica - The Global CCS Institute (headquartered in **Australia**) provided AU$2.5 million towards this project planned for operation in 2015 in **Romania**.
10. Taweelah - Masdar in partnership with BP.
11. **Korea** CCS 1&2 - are being developed by the Korea Carbon Capture and Sequestration research Center, which has an agreement with Scottish Carbon Capture and Sequestration (SCCS), the largest CCS R&D center in the **United Kingdom**.

hundreds of billions of dollars in its "coal-based quest for modernity."[66] The size of China's coal endowment and its need to exploit this resource to meet the needs of its people in the absence of other inexpensive, large-scale power options means that putting a dent in global emissions from the energy sector will depend on the construction of efficient coal power plants equipped with carbon capture and storage (CCS) in China.

The dependence on coal-based electricity generation shared by China and the United States also represents an opportunity for creating new models of international collaboration on energy innovation. To this end, the Clean Air Task Force's (CATF) Asia Project provides a platform for Western technology developers to collaborate with Asian partners.[67] Through workshops, conferences, and briefings in the United States and China, CATF helps bring about joint business ventures that leverage both countries' extensive experience with coal. For example, Chinese firms have estimated significantly lower costs for capturing emissions[68] — an example of the "China price" for energy innovation — and US companies have experience with using carbon dioxide for enhanced oil recovery (EOR) and storage in geologic formations.

Partnerships that build on knowledge exchanges, such as the series of recent US-China energy pacts,[69] and the potential financing offered by the New Development Bank (or BRICS bank),[70] lower technology costs and speed deployment. Such efforts are also vital for bridging cultural and communication divides that have hindered effective international cooperation and have for decades been the undoing of the "technology transfer" model.[6]

The climate and development communities have for the most part refused to acknowledge that the world is irrevocably committed to fossil energy, including coal, for the foreseeable future.[71] This state of denial is self-defeating and continues to hamper efforts to drive down the costs of CCS through demonstration and operation not just in the United States,[72] but more importantly in countries that require assistance in building out their energy sectors. For example, relieving Pakistan of its crippling energy poverty by exploiting the country's Thar coal deposits — a project which integrates a range of advanced carbon capture technologies — has received no support from the US Agency for International Development (USAID), despite the fact that the USAID considers energy sector development in Pakistan a "top assistance priority."[73, 74] Development of mining and power generation in the Thar region has finally begun with the backing of Chinese banks, but whether the project will ultimately incorporate CCS is unclear.[75] Regardless of the merits of any particular plan, a soft-energy framework restricted to nonfossil energy impedes progress in CCS, despite the fact that the world will depend on coal for decades to come.[65]

SOLAR PHOTOVOLTAICS (PV)

The last several decades have witnessed a remarkable reduction in the cost of solar photovoltaics (PV), declining by a factor of 100 over the past 50 years.[76] Extremely high early costs for solar PV found a niche market in satellite application and experienced marked cost improvements thereafter, most notably through R&D improvements in electrical conversion efficiency of PV systems, manufacturing scale, and technological "learning" in response to local markets and public deployment policies.[77, 78] Solar experts have emphasized the "chain-linked innovation" of R&D, production support, and market formation that, combined, enabled solar PV to reach its current status.[76, 79]

The recent dramatic cost declines in solar PV cells and modules are effectively the result of international technology interaction: Western deployment regimes paired with aggressive Chinese industrial policy and the pursuit of solar PV manufacturing dominance.[4] Policies like the US federal investment tax credit for solar (ITC) and European feed-in tariffs provided the demand that Chinese solar manufacturers sought to supply, through aggressive national and regional state subsidization of solar production capacity. However, the policies that interacted to drive these cost declines also resulted in international solar trade wars, as Western governments – including Germany and the United States – accused Asian solar producers of flooding the market to gain an unfair competitive edge. How this supply-side dispute will be resolved is not yet clear.[80] And whether countries like the United States and Japan experience a slowdown in the deployment of solar PV similar to that of Spain and Germany also remains to be seen.[81, 82]

In the meantime, more and more emerging economies are taking advantage of the price decline in PV by fostering solar markets of their own. From Asia to the Middle East to Latin America, the market for solar plants is becoming similar to the market for upstream solar manufacturing: "truly global."[76] The leading manufactures of global PV – including the United States' First Solar, China's Yingli and Trina, Canada's Canadian Solar, Germany's SolarWorld, Japan's Sharp Electronics, and others – are increasingly exporting their panels for us in large solar farms in emerging economies. Development and finance of new solar capacity is increasingly international as well, with firms like

MANUFACTURING

1. **China** dominates solar PV production, with 7 of the 10 largest manufacturers in the world.

POWER PLANTS

2. Amanecer - This 100-megawatt plant is the largest solar PV plant in **Latin America**.
3. Gujarat - This project in **India** will be Asia's largest solar power park hub.
4. Longyanxia Dam Solar Park - This **Chinese** plant will be the world's largest solar-hydro power station.
5. Topaz Solar Farm - At 550 megawatts, this **San Luis Obispo** plant is the largest photovoltaic plant in the world.
6. Latin America: **Brazil, Argentina**, and other Latin American countries are aggressively jumping into the solar PV market, with a total of 6,000 megawatts of solar under development.
7. **Saudi Arabia** has planned 16,000 megawatts of solar PV capacity to be deployed over the next 20 years, as well as 25,000 megawatts of solar thermal.
8. **German** renewables firm Juwi is developing several large PV power plants in **South Africa** under an MOU between the German and South African governments.

R&D INITIATIVES

9. Solar Energy Center - A collaboration between the **US** Department of Energy National Renewable Energy Laboratory (NREL) and the **Indian** Solar Energy Center (SEC) to test new manufacturing techniques for thin-film solar PV.
10. ArtESun - The goal of ArtESun is to develop advanced organic solar cell technologies. This is a collaboration among top research groups and industries within **Belgium**, **Germany**, **the UK**, **Spain**, **France**, **Finland**, and **Canada**.
11. Solar & Photovoltaics Engineering Research Center (SPERC) - In spring of 2014 a 5-year MOU was signed between ZSW in **Germany** and KAUST in **Saudi Arabia** to develop advanced thin-film solar technology.
12. IEA Photovoltaic Power Systems Programme - One of the International Energy Agency's several R&D Agreements, established in 1993, dedicated to pursuing advanced solar technologies.

US-based SunEdison developing a 100-megawatt plant in Chile,[83] Germany's KfW financing a 150-megawatt plant in India,[84] and two Russian banks financing a 105-megawatt plant in Ukraine.[85]

Solar PV's progress is substantial and ongoing. But as solar expert Greg Nemet described in a 2012 case study charting PV's decades of progress, "Despite this achievement, the technology remains too expensive compared to existing electricity sources, such that widespread deployment depends on substantial future improvements."[76] To date, the increasingly globalized deployment of solar PV still depends largely on concerted government efforts. The International Energy Agency expects that solar PV will contribute a relatively minor portion of global electricity production in 2050 without major improvements made to a range of technologies, including storage and transmission, as well as to business models and policy.[86]

Fortunately, there are encouraging efforts and investments being made toward innovation in advanced and next-generation solar PV technologies, including organic PV and thin-film. Several countries are pursuing a brand of solar industrial policy via public-private partnerships in advanced solar PV innovation. These include a partnership between Merck and the German government in pursuit of breakthroughs in organic PV,[87] JA Solar's partnership with the Chinese Academy of Sciences,[88] and the Brazilian Technology System's (SIBRATEC) investments in solar innovation initiatives.[89] There are also many budding international collaborative efforts being made towards next-generation solar innovation. Key among these is the IEA's 29-member Photovoltaic Power Systems Programme, which includes the United States, China, Germany, Malaysia, Mexico, Turkey, and others.[90] Other promising activity includes an MOU in thin-film research between research institutes in Germany and Saudi Arabia,[91] and a partnership between the US Department of Energy and India's Solar Energy Center.[92]

CONCLUSION: CLEAN, CHEAP ENERGY IS A GLOBAL PUBLIC GOOD

In *The Post-American World,* Fareed Zakaria observed that the rise of large developing powers like the BRICS (Brazil, Russia, India, China, and South Africa) augured the relative, but not absolute, decline of the West.[93] Many wealthy developed nations, with their strong scientific and engineering institutions, have an interest in engaging "the rise of the rest" for geopolitical, economic, and environmental reasons. This line of reasoning applies well to energy innovation. Just as US-pioneered solar and nuclear energy technologies are benefitting China today, next-generation versions of those technologies could benefit the United States — and the world — in the future.

Clean energy innovation should thus be recognized as a public good and a shared responsibility. Treating energy-climate innovations as a public good like national defense, public health, adequate food supplies, or a safe air transportation network, where governments routinely invest billions of dollars to advance specific technologies that solve particular problems,[13] offers new avenues for public investment in promising energy technologies and technology portfolios.

There is a long history of effective international collaboration on innovation for global public goods. One of the most well-known and most successful was the creation and funding of international agricultural research centers by the philanthropies and governments behind the Green Revolution.[94] More recently, developed and developing countries, along with philanthropy and the private sector, have worked together in novel partnerships to accelerate biomedical innovations to address health challenges ranging from AIDS to malaria to tuberculosis.[95] Like innovation collaborations around agriculture and health, innovations in energy technologies benefit all nations involved and thus can be justified by states and societies as worthy of shared investment.

The influence of the low-energy development model has distracted attention from the urgent need to mobilize these public-private energy innovation projects, not just for renewables, but also for CCS and nuclear power, which have historically failed the litmus test of environmental correctness.[96] But a consensus of experts, Nobel Prize winners, and respected international leaders have over the last decade called for a greater public and private sector commitment to improving low- and zero-carbon technologies.[97] Bill Gates and others have emphasized the multiple benefits from energy innovation. "If you gave me only one wish for the next 50 years — I could pick who is president, I could pick a vaccine … or I could pick [an energy technology] that's half the cost with no carbon emissions — this is the wish I would pick," Gates said. "This is the one with the greatest impact."[98]

Due to rising technological complexity and the cost of innovation, a strong public role is essential.[13] While in 1858, two industrialists could break rock and produce the first oil in North America,[69] today not even the world's richest man, Bill Gates, can pioneer a new nuclear technology without the support of the Chinese state.[99] New energy technologies — whether solar, batteries, nuclear, or biofuels — require increasingly specialized knowledge, integration with ever larger and more complex infrastructures, and industrial capacities that span many sectors, nations, and institutions. In this context, the role of the state may be rising. Today's cheap solar panels were the result of massive public Chinese investments at both the national and local levels.[6] Elon Musk required a half-billion dollars in taxpayer subsidies to achieve the highly regarded (yet still extremely expensive) Tesla Model S electric vehicle, not to mention the billions of dollars of investments by Japanese and American governments in the necessary precompetitive research and development over the previous 20 years.[100]

Governments have multiple roles to play. Probably the most notable aspect of fracking's development was the close collaboration between public institutions and private firms. Rather than keeping the private sector at arm's length — as is often considered best by economists wary of corporate capture — the US Department of Energy (DOE) developed gas research programs in which gas companies were explicitly asked to contribute.[101] One such program, the Eastern Gas Shales Research Program, is credited for pioneering horizontal drilling for shale gas.[30] DOE was also responsible for approving the funding and research efforts of the Gas Research Institute (GRI), an industry consortium tasked with developing new energy technologies. Working closely with the private sector, and providing technical expertise that complemented the practical experience of private sector firms, the state played a decisive role in developing the technology without spending vast sums of money.[102]

On the face of it, the fracking case is yet another challenge to the common presumption that the role of the state in energy innovation is to fund "basic science" and stand back while the private sector develops the technologies.[103] For one thing, in this case the government's most important role seems to have been as network builder, coordinating research and development with multiple actors in the field, not in laboratories unconcerned with economic considerations under the guise of basic or "pure" science.

Unfortunately, the lessons of the fracking revolution for clean energy innovation remain largely unknown to policy makers. While local environmental consequences of natural gas production must be addressed, these concerns have obscured the most significant aspects of the shale revolution, namely that public-private collaboration over three decades has rapidly reduced US emissions and may prove to reduce carbon intensity globally.[104] This collaboration should be a model for US philanthropies as well as nation-states, which to date have been overly focused on the low-energy paradigm and expanding the small-scale deployment of largely intermittent renewables.[105]

Whether or not nations increase their investment in innovation, they can still pursue visionary energy innovation collaborations, as the US collaboration with China on nuclear demonstrates. Recognizing that the United States was unlikely to demonstrate advanced salt-cooled nuclear reactors, the Oak Ridge National Laboratory agreed to share this information with the Chinese government in 2010.[106] A case can be made that the DOE and US firms should compete with the Chinese government and Chinese firms to create the best new nuclear reactor, and step up both public and private efforts. But barring a radical and unlikely increase in US nuclear innovation efforts, China will lead the global race for both development and deployment of advanced nuclear reactors.

To catalyze, augment, and legitimate such public support, philanthropy can play a pivotal role. In the 1940s, the Rockefeller and Ford Foundations made investments in international agricultural innovation that were pivotal in catalyzing the Green Revolution.[107] More recently, the Bill and Melinda Gates Foundation (along with several others) has been crucial in accelerating innovation to meet urgent global public health challenges.[108] Philanthropies and the organizations they fund have long time horizons and the ability to set ambitious programs that transcend national boundaries, technology classes, and economic sectors, without succumbing to short-term political pressures.

A good first step for philanthropies would be to develop comprehensive "maps" of important programs, public and private, across the globe as a basis for strategic investments in partnerships that can make crucial contributions to scalable, inexpensive, low-carbon energy in the near- to medium-term. As our brief case studies are meant to show, partnerships that bring together different innovation capacities within and between nations, that foster trust between partners, and that reflect and emerge from the realities of existing energy systems and markets, can be key to accelerated innovation. And such partnerships can be fostered without enormous new government investments.

Behind two decades of political stalemate on climate are national and economic interests that cannot be transcended as long as the priority is to reduce energy consumption and pay more for energy. When the focus is reversed, and governments, industry, and philanthropies collaborate to provide the global public good of abundant, clean, cheap energy, climate policy will win far higher levels of public support. Embracing high-energy innovation is the best way to address our shared energy and climate challenges.

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