Energy Innovation

Why We Need It and How to Get It

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Introduction

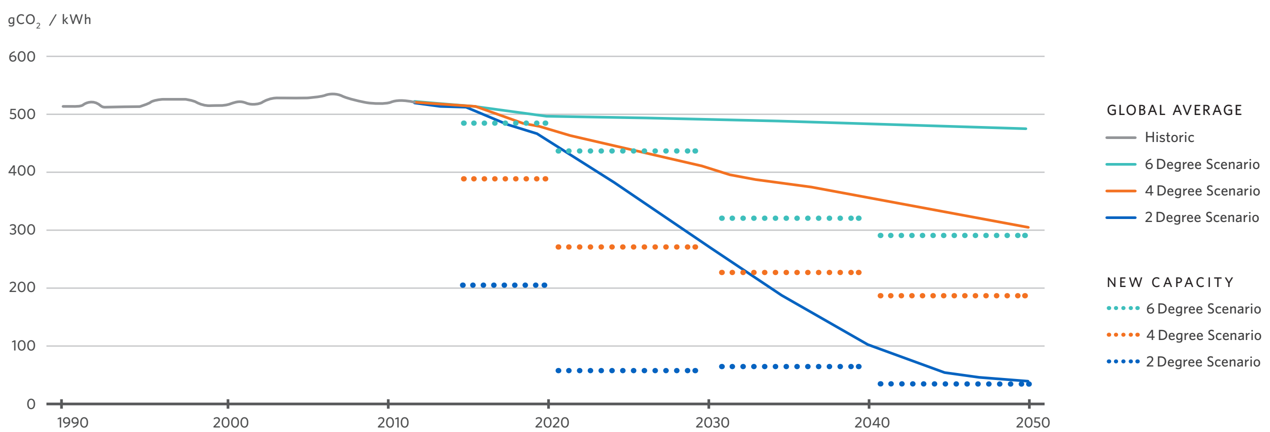
In 30 years the world will consume much more energy than it does today. This should be good news. Wherever access to reliable, affordable energy goes up, so does the quality of life. But today more than 1 billion people lack access to the most basic energy services. Energy keeps schools and businesses running, city lights shining, tractors plowing, and cars and trucks moving. Without plentiful energy, the poverty rate could not have dropped by more than half since 1990, and hundreds of millions of people would have been denied the opportunity to improve their lives. There would be no steel, fertilizer, cement, or many of the other materials that make modern life possible.

Of course, the world's growing appetite for energy is not unalloyed good news. More than 80 percent[1] of the energy we use today comes from fossil fuels, which produce greenhouse gases and drive climate change. Scientists generally agree that to limit warming to 2 degrees Celsius—essentially the least bad option—the world's biggest carbon emitters need to reduce emissions by 80 percent by 2050, and all countries need to essentially eliminate them by the end of the century.

By far the biggest source of emissions is the production of energy, which accounts for around two thirds of all greenhouse gases produced by human activity.[2] Although using energy more efficiently can help, the only way to dramatically reduce or eliminate global carbon emissions is to switch to sources that do not emit carbon.[3]

IMPACT OF REDUCING EMISSIONS ON GLOBAL TEMPERATURE RISE

The blue line shows how dramatically we need to cut emissions from energy production if we want to limit warming to 2 degrees Celsius.



Source: International Energy Agency

[1] Vaclav Smil, *Energy Transitions: History, Requirements, Prospects.*
[2] International Energy Agency, *Energy Technology Perspectives 2015.*
[3] The world will need to reduce emissions in other areas too, including manufacturing. For example, making steel and cement involves chemical reactions that produce carbon dioxide. Cattle produce methane, another greenhouse gas. Zero-carbon energy sources will not change these facts. But because energy represents such a large share of global emissions, there is no way to solve the climate problem without carbon-free energy. It is necessary but not sufficient.

Affordable, reliable energy would be a priority even if climate change were not a problem. It would help millions more people escape poverty and become more self-sufficient. It would ease international tensions, increasing global security and making more countries energy-independent. It would unlock new economic opportunities in a growing trillion-dollar industry. It would lessen the problems caused by the expensive and often dangerous work of extracting fossil fuels. It would reduce air pollution, which kills millions of people every year.[4] And it would stabilize energy prices, which will have an even bigger impact on the global economy as more people come to rely on energy in their daily lives.

The opportunity is especially clear for developing countries. Their most immediate need is to keep their hospitals and schools running and help their economies grow. If forced to choose between energy that is clean and energy that is reliable and affordable, it is completely responsible to prioritize the health and welfare of their people today over the serious implications of an uncertain future with climate change. We need to resolve this dilemma by making energy reliable, affordable, and clean.

In other words, moving to new energy sources is both a wise response to the threat of climate change, and an opportunity to make the world more secure and more equitable.

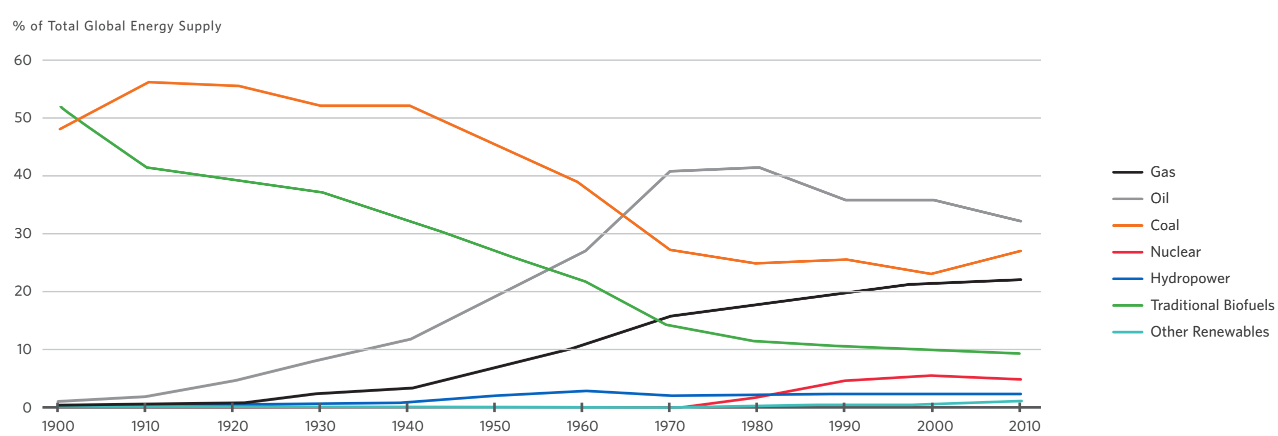
In this paper I make the case that, although we have made good progress on this front, the pace of progress needs to increase substantially. As the International Energy Agency (IEA) has written: "Recent trends reaffirm the need to accelerate energy technology innovation."[5] To get this acceleration, governments and the private sector should invest far more in clean-energy research, development, and deployment.

The work needs to start immediately. The history of energy transitions is clear: It takes years to develop new sources of energy, and decades to make them a significant part of our energy mix. Today, renewables account for less than 5 percent of the world's energy. It took four decades for oil to go from 5 percent of the world's energy supply to 25 percent. Natural gas took even longer.[6]

I believe we can make this transition faster, both because the pace of innovation is accelerating, and because we have never had such an urgent reason to move from one source of energy to another. Some critics argue that only governments can manage such a big transition. Others argue that only the private sector can create the innovations we need. Both sides have a point. Private companies will ultimately develop energy breakthroughs. But their work will rely on the kind of basic research that only governments can fund. The primary drivers of innovation are government research and high-risk private funding.

The IEA has called for both deploying "immediately available solutions" and developing "more complex solutions needed for long-term deep decarbonisation."[7] Most discussions

ENERGY TRANSITIONS TAKE DECADES



Source: Vaclav Smil

[4] World Health Organization (http://www.who.int/mediacentre/news/releases/2014/air-pollution/en/).
[5] International Energy Agency, *Energy Technology Perspectives 2015*.
[6] Vaclav Smil, *Energy Transitions: History, Requirements, Prospects*. The figure for renewables' current share of global energy does not include hydropower.
[7] International Energy Agency, *Energy Technology Perspectives 2015*.

about energy and climate focus only on the former. As important as those solutions are, we also need to focus on the latter—the breakthrough innovations that will ultimately solve the problem on a global scale. With the right investments, the world can get the tools to meet its growing energy needs while also cutting our carbon emissions to near zero.

Why We Need Energy Innovation

The past decade has seen remarkable progress in zero-carbon sources, especially solar photovoltaic (PV) and wind. The cost of solar PV cells has dropped by nearly a factor of ten. There is no question that these technologies can play an important role in the world's zero-carbon energy mix; the IEA has estimated that wind and solar PV could cut the world's annual emissions from electricity generation 22 percent by 2050.[8]

Why not 100 percent? One reason is that solar PV and wind power are intermittent sources. Customers still need energy even when the sun is not shining and the wind is not blowing.

Today that requires maintaining a parallel system powered by fossil fuels. On bright summer days, the two systems together generate so much electricity that the price drops below zero—utilities pay others to take their product. At night, on the other hand, the only source is electricity from fossil fuels. Because energy companies have to recover their capital costs and they are not getting any return during the day, they either raise the price of energy at night, or they slowly go bankrupt.

It would help solve this problem if we could store lots of solar or wind energy and then use it on cloudy or still days. Another option would be to deploy these resources wherever sun and wind are plentiful and connect them to other places using a high-voltage grid. These options are being used today in some places, but we need to make them cheaper and improve their performance.

For example, with today's technology, it is not economical to store mass amounts of solar or wind energy for use on cloudy, windless days. Depending on the type of battery used, it costs between 30 cents and 80 cents to store a kilowatt-hour of electricity.[9] Given that the price of electricity averages around 10 cents per kilowatt-hour in the United States,[10] these storage costs would at least triple the price of electricity, even if the electricity itself were generated for free. The European Union, where prices average 20 cents per kilowatt-hour, and India, where they range from 2 to 15 cents, would see similarly dramatic increases.[11]

Today's batteries also have a far lower energy density—that is, they store much less by weight—than fossil fuels. Coal provides 37 times more energy per kilogram than the best lithium-ion batteries available today. Gasoline provides 60 times more.[12] This explains not only why electric cars have a shorter range than ones that run on hydrocarbons, but also why there are not electric airplanes, freight trucks, or cargo ships. Any battery big enough to power these vehicles would be prohibitively heavy.

If we are going to take full advantage of the benefits of solar PV, wind, and batteries—especially if they are going to power factories, skyscrapers, and other large consumers of energy—we need innovative ways to stitch them together into a reliable, affordable system.

These technologies could be one path to a zero-carbon future, but they are not the only one. Given the scale of this challenge, we should be exploring all potential avenues. Doing so is a job for both the public and private sectors.

The Case for Government Investment

Government-funded research programs have produced many of the innovations that define modern life. For example,

[8] International Energy Agency, *Energy Technology Perspectives 2015*.
[9] Based on the capital cost of the battery, amortized over its useful life.
[10] U.S. Energy Information Administration (http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_6_a).
[11] Eurostat (http://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&language=en&pcode=ten00117&plugin=1); Government of India, Department of Economic Affairs (https://data.gov.in/resources/state-wise-average-rate-electricity-domestic-and-industrial-consumers/download).
[12] Based on energy density of 0.2 kilowatt-hours per kg for batteries. Gasoline and coal statistics are drawn from *Energies: An illustrated Guide to the Biosphere and Civilization*, by Vaclav Smil.

during the Cold War, the U.S. Department of Defense developed computer networks that could survive a nuclear attack. Today that same technology helps run the Internet. Private companies have made the Internet a hub of global commerce and communication, but it would not exist without early government investments in computer chips and communications technology. The digital revolution, which has empowered people around the world, owes a considerable debt to federally funded research.

Government investments also strengthen the academic institutions that are the birthplace of so much innovation. It is no accident that the world's top computer science schools—Stanford, Carnegie Mellon, MIT—are based in a country whose government has made big investments in that field. Nor is it an accident that the United States, which has invested heavily in biological research, produces an outsize share of the world's innovation in health and medicine.

Similarly, research funded by the U.S. government has defined the state of the art in energy production since World War II. Early advances in wind and solar technology were developed with federal money. And energy research offers a strong return on investment. The Department of Energy found that the $17.5 billion (adjusted for inflation) it spent on research between 1978 and 2000 provided a yield of $41 billion. A study by the OECD found a strong link between increased funding for R&D and a rise in high-value patents for clean-energy technology.[13]

If investments in energy research are so valuable, why not simply let the market guide them? The answer is that the energy industry differs from other industries in some crucial ways.

Most technology companies know within a couple of years whether a given innovation will pay off. Pharmaceutical companies work on roughly the same time scale. But energy research can take decades to pay off, because it takes so long to adopt new technologies. Rudolf Diesel invented his engine in the late 19th century, but the diesel engine did not become commonplace until well after his death in 1913.

This time lag between invention and impact helps explain why the energy industry tends to invest less in research, development, and deployment than other industries do. American pharmaceutical companies put 20 percent of their revenues into these activities. For IT and semiconductor companies, the number is around 15 percent of revenues. For energy firms, it is 0.23 percent.[14]

RESEARCH & DEVELOPMENT

How much do U.S. industries invest in R&D?

% of Revenue (2010)

INDUSTRY	INVESTMENT IN R&D
PHARMACEUTICAL	20%
INFORMATION TECHNOLOGY	15%
ENERGY	0.23%

Source: International Energy Agency, *Global Gaps in Clean Energy R&D* (2010)

This is why governments play an indispensable role in supporting energy research. The field will become only more important in the years ahead. As the world's need for energy continues to grow, bright people with new ideas will flock to the places that support efforts to make cheap, reliable, clean energy. Any country that wants to lead the world in innovation and energy independence should be doubling down on this research.

How much are governments investing today? The United States spends more on energy research than any other country, so its federal budget is a good proxy. In the chart below, the first two columns show total spending and the U.S. research budget in three sectors: energy, health care, and defense. The third column shows the ratio of government research to total spending in each sector.[15]

The contrast is striking. The ratio of government R&D to total spending in energy is 0.4 percent. In health, the ratio is more than twice as high. In defense, it is more than 22 times higher.

	TOTAL U.S. SECTOR SPEND (2013)	U.S. GOV R&D SPEND (2013)	RATIO OF R&D TO TOTAL SECTOR SPEND (2013)
ENERGY	$1.4 TRILLION	$5.3 BILLION	0.4%
HEALTH CARE	$2.9 TRILLION	$31 BILLION	1.1%
DEFENSE	$640 BILLION	$69.8 BILLION	11%

[13] International Energy Agency, *Global Gaps in Clean Energy R&D* (2010).
[14] International Energy Agency, *Global Gaps in Clean Energy R&D* (2010).
[15] Figures in the table were drawn from the U.S. Energy Information Administration (http://www.eia.gov/totalenergy/data/annual/pdf/sec1_13.pdf and http://www.eia.gov/state/seds/data.cfm?incfile=/state/seds/sep_sum/html/sum_ex_tx.html&sid=US), Centers for Medicare and Medicaid Services (https://www.cms.gov/Research-Statistics-Data-and-Systems/Statistics-Trends-and-Reports/NationalHealthExpendData/NationalHealthAccountsHistorical.html), Belfer Center for Science and International Affairs at Harvard University (http://belfercenter.ksg.harvard.edu/publication/24065/doe_budget_authority_for_energy_research_development_demonstration_database.html), and U.S. Bureau of Economic Analysis (http://www.bea.gov/industry/xls/io-annual/GDPbyInd_GO_NAICS_1997-2014.xlsx). "Sector spend for defense" is the U.S. defense budget.

To make the point another way: In the United States, consumers spend more on gasoline in a week than the government spends on clean-energy research in a year.[16]

Some countries are stepping up to this challenge and investing more in clean-energy research. Through Mission Innovation (www.mission-innovation.net), more than 10 governments have committed to significant increases. I am confident that the money can be put to good use quickly, thanks to the outstanding university and laboratory systems that already exist in the United States and other countries. There is research capacity to spare—it has lacked only the necessary funding.

The Role of Markets

Private-sector efforts are the flip side of government research. Energy is already a trillion-dollar market, and clean energy could one day be a multi-trillion-dollar market. But private investors are reluctant to get into the field, for the same reason that energy companies tend to under-invest in R&D: Breakthroughs can take decades to play out and their inventors see relatively little reward. Although the profit motive is not entirely absent, it is muted because investors have little incentive to take risks. Promising concepts and viable products are separated by a Valley of Death that neither government funding nor conventional investors can bridge completely.

A key part of the solution is to attract investors who can afford to be patient, and whose goal is as much to accelerate innovation as it is to turn a profit. I am joining with a number of other investors who are fortunate enough to be in this position.

We are creating the Breakthrough Energy Coalition (www.breakthroughenergycoalition.com), a global, private investment group which intends to help promising approaches cross the Valley of Death—to take the risks that allow companies to get innovation out of the lab and into the marketplace. We will focus on early-stage companies that could make reliable zero-carbon energy available to everyone. Some of these companies will fail. We expect the successful ones to attract large amounts of traditional capital investments as they are demonstrated and deployed.

Over the next year, we will be analyzing potential investments, creating vehicles to support this effort, and expanding the pool of investors who join us. In the meantime, we have agreed on five principles that will guide our work. We will:

1 INVEST EARLY
We will take a flexible approach to early-stage work, providing seed, angel, and Series A investments, with the expectation that once these investments are de-risked, traditional commercial capital will invest in the later stages.

2 INVEST BROADLY
Because it is too early to tell which paths to a clean-energy future will succeed, we will support a wide range of approaches in a number of sectors: electricity generation and storage, transportation, industrial use, agriculture, and energy system efficiency.

3 INVEST BOLDLY
We will look for novel technologies as well as ways to make existing technologies dramatically cheaper, more efficient, or more scalable. We will require a credible pathway to scaling up rapidly—providing affordable energy to the greatest number of people without overburdening essential resources.

4 INVEST WISELY
This effort requires a deep understanding of complicated science and technology as well as public policy. We will work with leading public and private institutions and energy experts to guide our decisions.

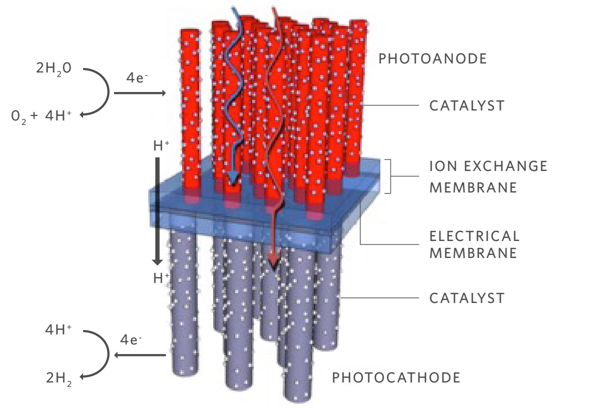
5 INVEST TOGETHER
Because so many breakthroughs rely on government research, we will focus our investments on countries that commit to expanding their funding for research on clean, affordable, reliable energy. The countries that have come together in the Mission Innovation initiative are showing great leadership on this issue.

[16] According to the U.S. Energy Information Administration (http://www.eia.gov/tools/faqs/faq.cfm?id=23&t=10), Americans used more than 374 million gallons of gasoline per day in 2014. At an average of $2.50 / gallon, this works out to more than $6.5 billion per week.

Promising Research

As an investor, I have been involved with many companies working on promising energy solutions. I wish there were many more to choose from. There should be hundreds if not thousands of companies around the world exploring different approaches.

Below I give three examples of promising technologies I have learned about. Researchers are exploring other exciting ideas too; I am mentioning these only to illustrate a few types of ideas that deserve support. None of them is likely to be ready to deploy for at least a decade, if they even get that far. But they show how ingenious researchers throughout the United States and around the world are developing ideas that could solve the energy problem. The faster governments and investors accelerate research, the faster we can make the transition to clean, affordable, reliable energy.



Solar chemical cells would use sunlight to make fuel.
They work much the same way a plant uses photosynthesis to convert sunlight into carbohydrates. The simplest application involves cells that use sunlight to generate enough energy to split water, producing oxygen and hydrogen gas. The hydrogen can be used directly as fuel or in commercial processes like making fertilizer.

Source: California Institute Of Technology

SOLAR CHEMICAL

The Opportunity
Solar photovoltaic technology uses photons to generate electricity from sunlight. Solar thermal uses mirrors to channel heat from the sun. Solar chemical takes a different approach, using solar energy to create fuel.

It works much the same way a plant uses photosynthesis to convert sunlight into carbohydrates. The simplest application involves a kind of club sandwich of cells: a series of catalysts separated by a membrane, and surrounded by light-absorbing material on the top and bottom. These cells use sunlight to generate enough energy to split water, producing oxygen and hydrogen gas; the hydrogen can be used directly as fuel or in commercial processes like making fertilizer. Another approach uses water, carbon dioxide, and sunlight to create hydrocarbons—making it possible to produce and burn fuels with no net gain or loss of carbon dioxide in the atmosphere.

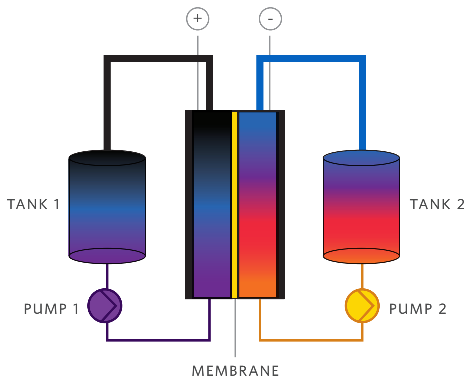
Solar chemical would put us on a path to decarbonizing both the electricity and transportation sectors. It would also help a lot with the storage problem, because the world is already very good at storing fuels and moving them around in pipelines, oil tankers, and other infrastructure.

The Challenge
The technology is still in its first generation. One challenge is that researchers need to develop a light-absorber—the top piece of bread in the club sandwich—that will work under the same conditions as all the other pieces.

FLOW BATTERIES

The Opportunity
The current gold-standard in storing electricity is the lithium-ion battery. Some researchers are focused on optimizing this technology, which has important applications including in cars. Another promising storage technology that deserves more investment is called a flow battery. Rather than using self-contained cells, as lithium-ion batteries do, flow batteries use a rechargeable liquid electrolyte inside two pairs of tanks—two receiving tanks and two holding tanks. While the battery is being charged, the liquid flows from the receiving tanks to the holding tanks, through a radiator-like set of fins that charge the liquid with energy. Energy is released when the liquid flows out of the receiving tanks, back through the fins and into the holding tanks. The tanks could be as small as a fish tank or as large as a swimming pool; the larger the tank, the more energy it would hold.

While flow batteries would be impractical for personal devices (imagine a cell phone the size of a fish tank), their scale could prove very useful for large industry. Another advantage is that, unlike lithium-ion batteries (whose capacity falls by half after 1,500 charges), a flow battery could last for decades and the rechargeable electrolyte liquid could last indefinitely.



Flow batteries would last longer and store more energy than today's batteries.
They use a rechargeable liquid electrolyte inside two pairs of tanks—two receiving tanks and two holding tanks. Energy is stored and discharged by moving the liquid between the tanks. These batteries can be as small as a fish tank or as big as a swimming pool, making them more attractive for industrial use than today's batteries.

The Challenge

Many working prototypes use vanadium, a relatively rare element, as the active electrolyte. Future systems will need to use a more easily available electrolyte before they are commercially feasible.

SOLAR PAINT

The Opportunity

Although the cost of solar panels is coming down quickly, installing and maintaining them remains expensive. The idea behind solar paint is to make solar power much cheaper and easier to install. Almost any surface could be transformed into a cheap solar panel: rooftops, walls, cars, cell phones, and more. It involves applying a conductive layer, then a white base layer, and finally a light-sensitive dye on top—this is what generates the electricity—and applying heat to cure the paint. In theory, anyone could do this; it would be almost as straightforward as painting a wall in a house.

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Source: NDnano, University of Notre Dame

The Challenge

Researchers are trying to refine the light-sensitive dyes that generate electricity. The most efficient dyes come from a family of chemicals called perovskites, and they convert about 20 percent of solar energy into electricity—a higher rate than all but the most efficient solar panels currently on the market. Unfortunately, these dyes contain lead, which is poisonous. (The United States has banned lead-based paints from houses and public buildings.) Researchers will need to develop a non-toxic dye that is efficient, stable, and readily applied by anyone, anywhere there is sunlight.

Conclusion

It is hard to overstate the impact that clean, affordable, reliable energy will have. It will make most countries energy-independent, stabilize prices, and provide low- and middle-income countries the resources they need to develop their economies and help more people escape poverty—all while keeping global temperatures from rising more than 2 degrees. I am optimistic that the next 15 years can bring the big breakthroughs we need to accomplish all of these things.

This is a fantastic opportunity. It is also an unmistakable challenge. Humans have changed their energy diets before, but never as rapidly as we need to today. Moving this fast is unprecedented, which is all the more reason to start now.