Taming the Sun:
Innovations to Harness Solar Energy and Power the Planet

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GEORGETOWN UNIVERSITY

Bill Gates @BillGates

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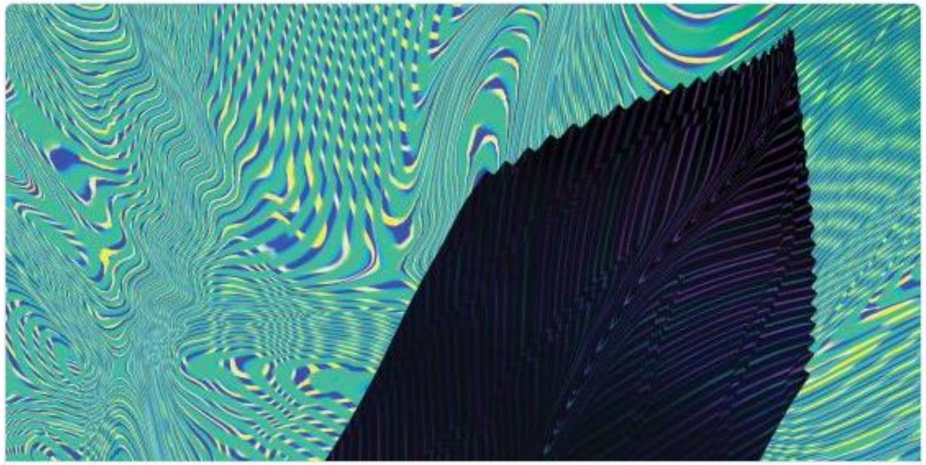
The sun is the most plentiful source of renewable energy we have -- and the race is on to harness its power.



The race to invent the artificial leaf

In this excerpt from his new book Taming the Sun, Varun Sivaram follows the research paths of two rival scientists determined to find a way to wring fuel out of thi...

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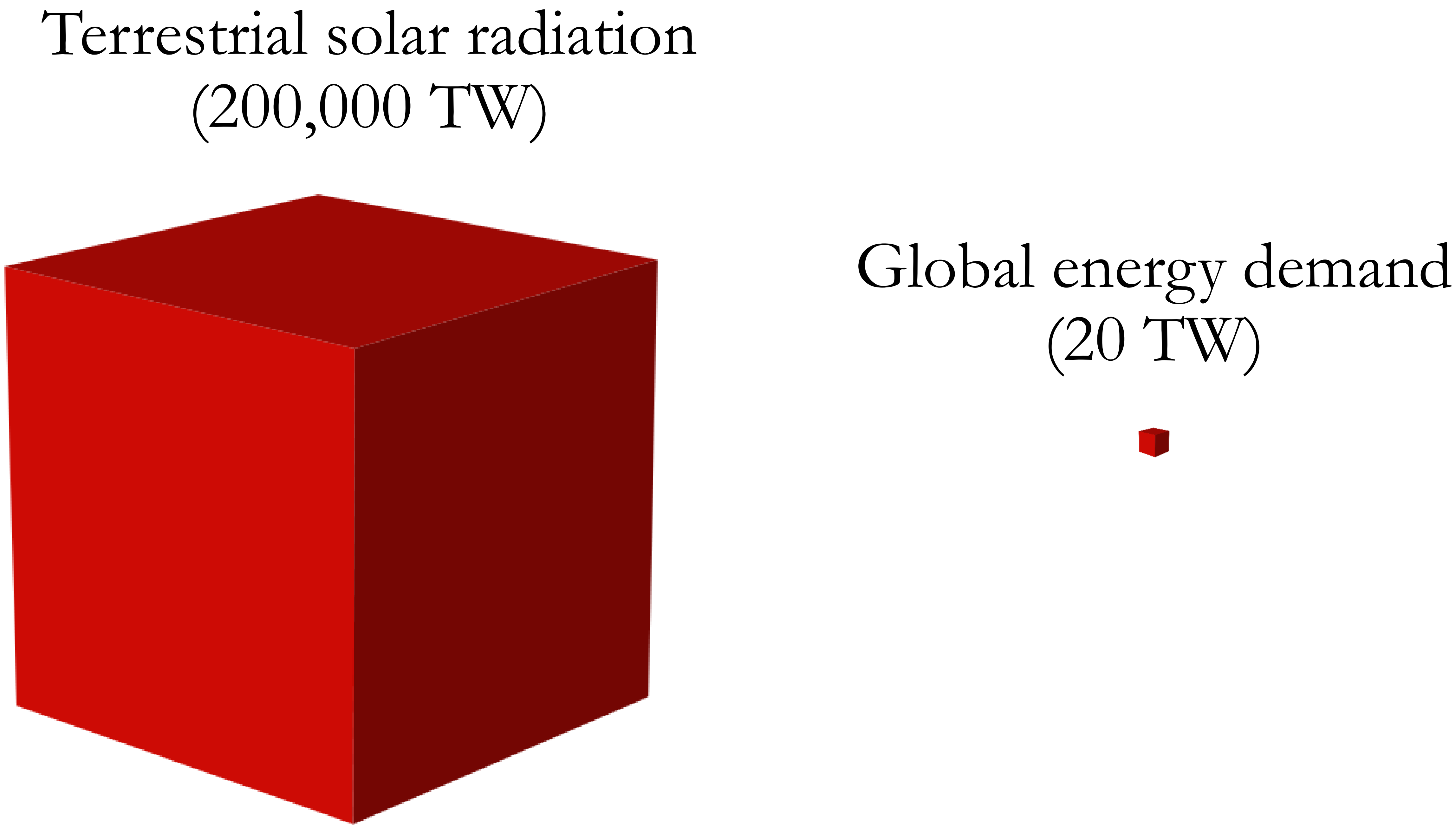
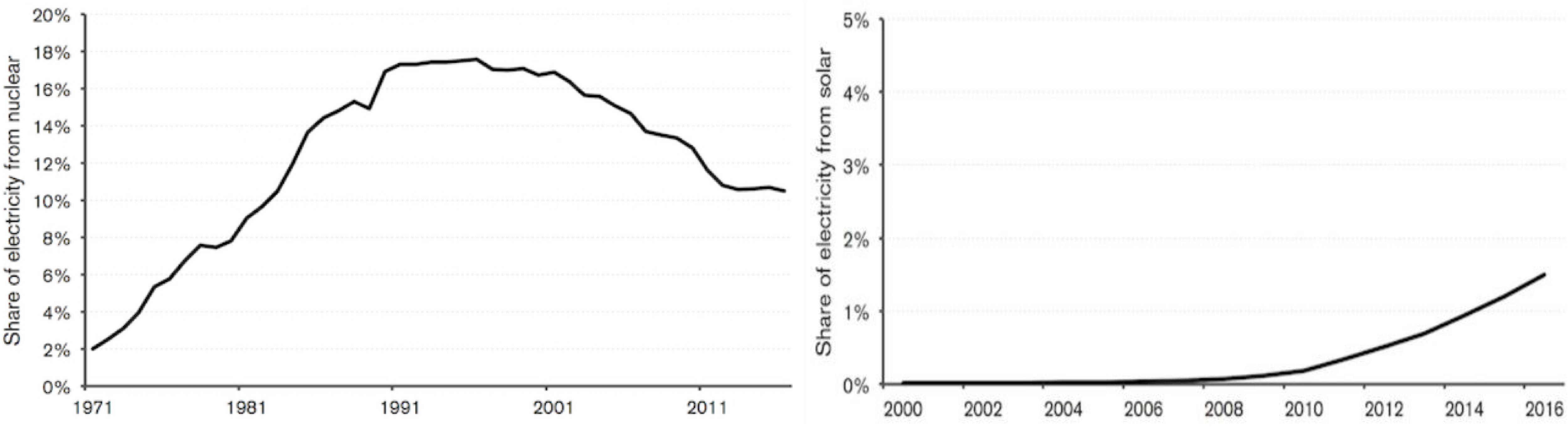
Part I: Playing the Long Game


Terrestrial solar radiation
(200,000 TW)
Global energy demand
(20 TW)

Solar has a boom coming; but so did nuclear before peaking



Panel A *plots the proportion of global electricity that was generated by nuclear energy in every year from 1970 to 2016.* ***Panel B*** *plots the proportion generated by solar energy.* ***Source****: World Bank, International Energy Agency, BP, International Renewable Energy Agency.*

In the last half-century, scientists have increased the percentage of the sun's energy that solar PV cells can convert into electricity

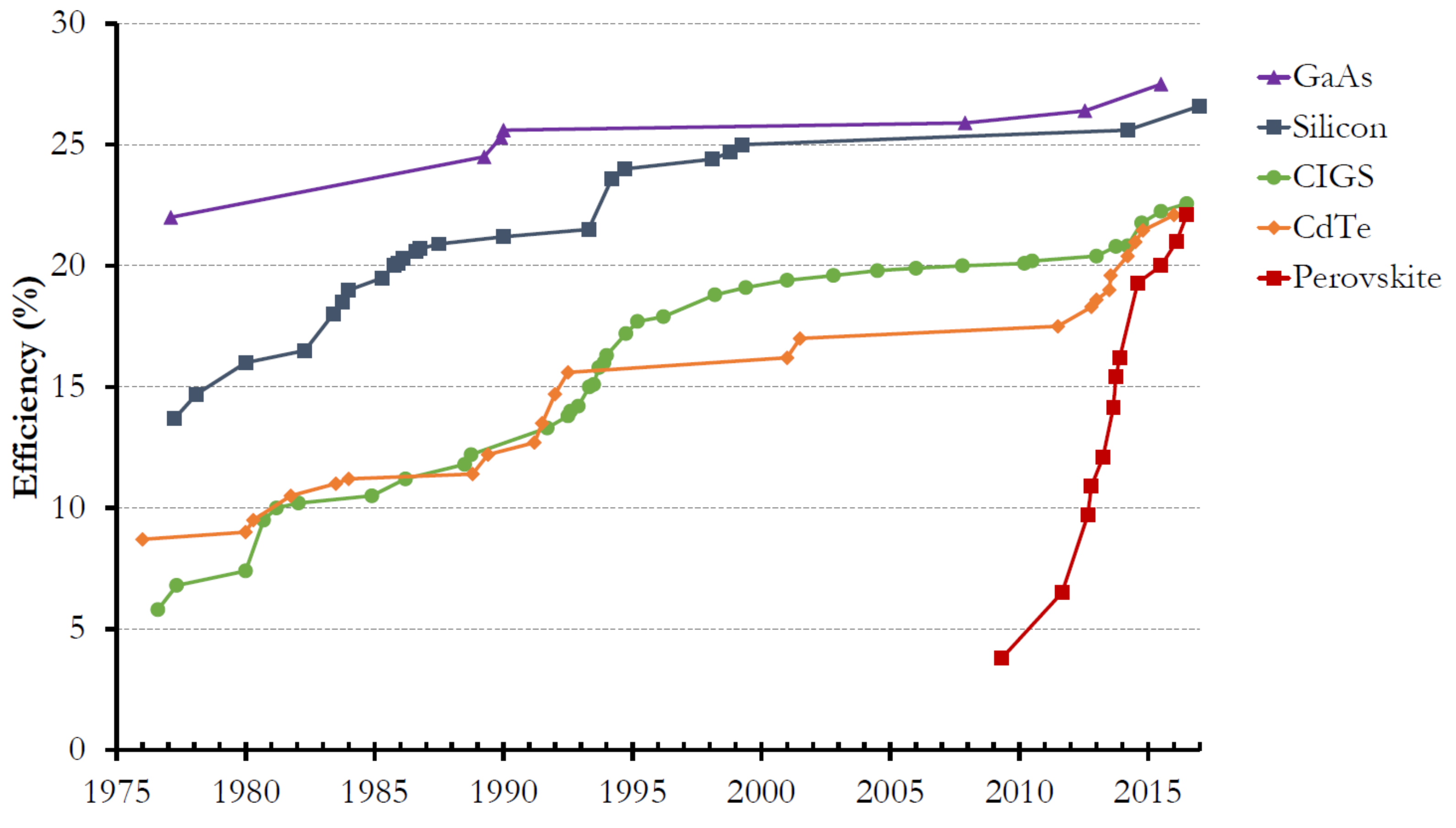


Figure 2.1
Efficiencies of various solar PV technologies. This chart plots the increase over time in the efficiencies of silicon and GaAs, which are traditional wafer technologies; CIGS and CdTe, which are thin films; and perovskite, an emerging solar technology (this technology is discussed in detail in chapter 6).
Source: NREL

China drove down the cost of solar PV by manufacturing it en masse; now it's the world's biggest deployment market, fueling even more production

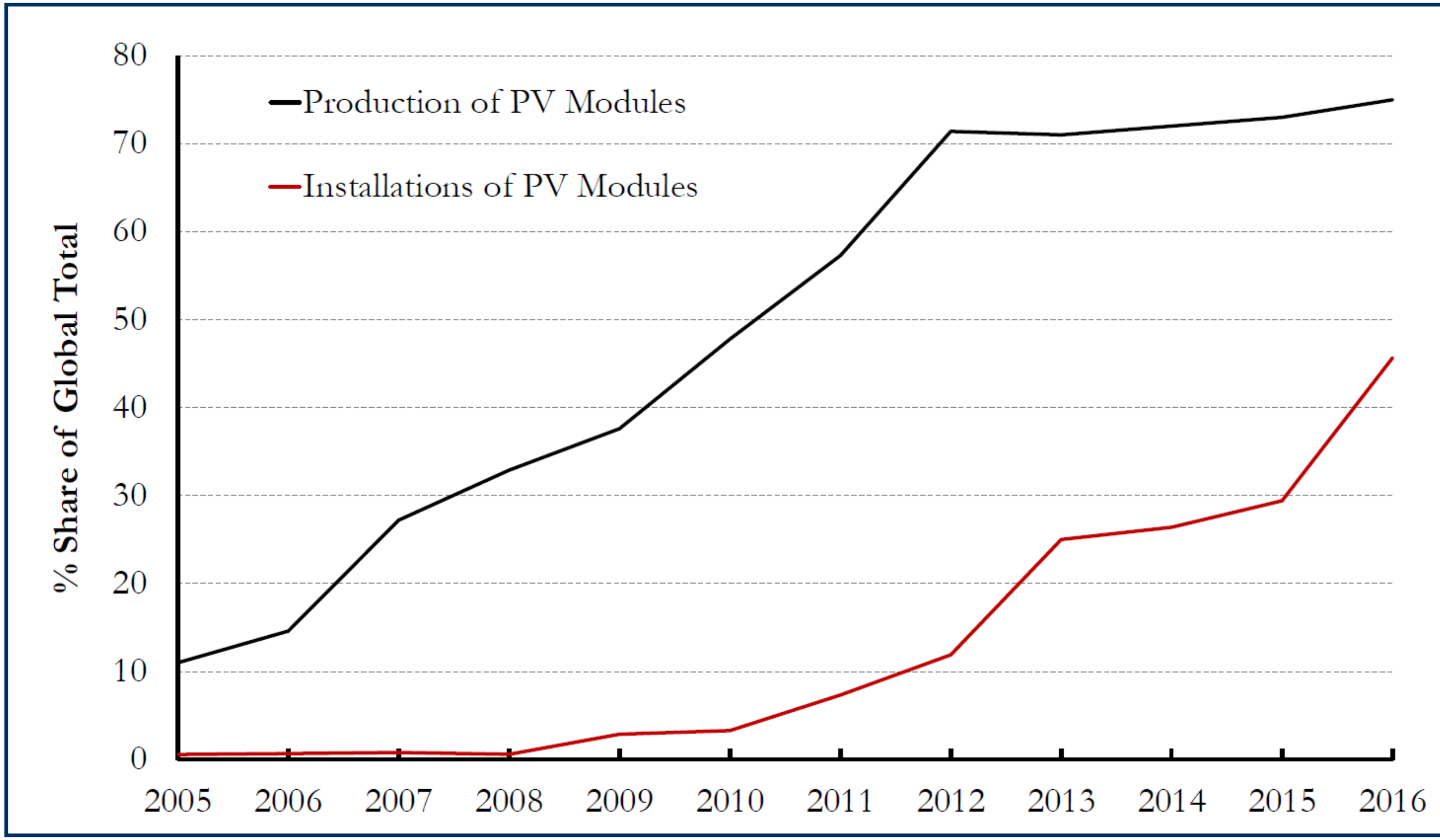


Figure 2.2
Comparison of China's rising domestic share of global PV panel production with its more recently rising domestic share of global solar PV installations

Source: Center for Study of Science, Technology and Policy; Fraunhofer Institute.

Around the world, the cost of electricity from utility-scale power plants has plunged and continues to fall (<2c/kWh in Saudi in 2017!)

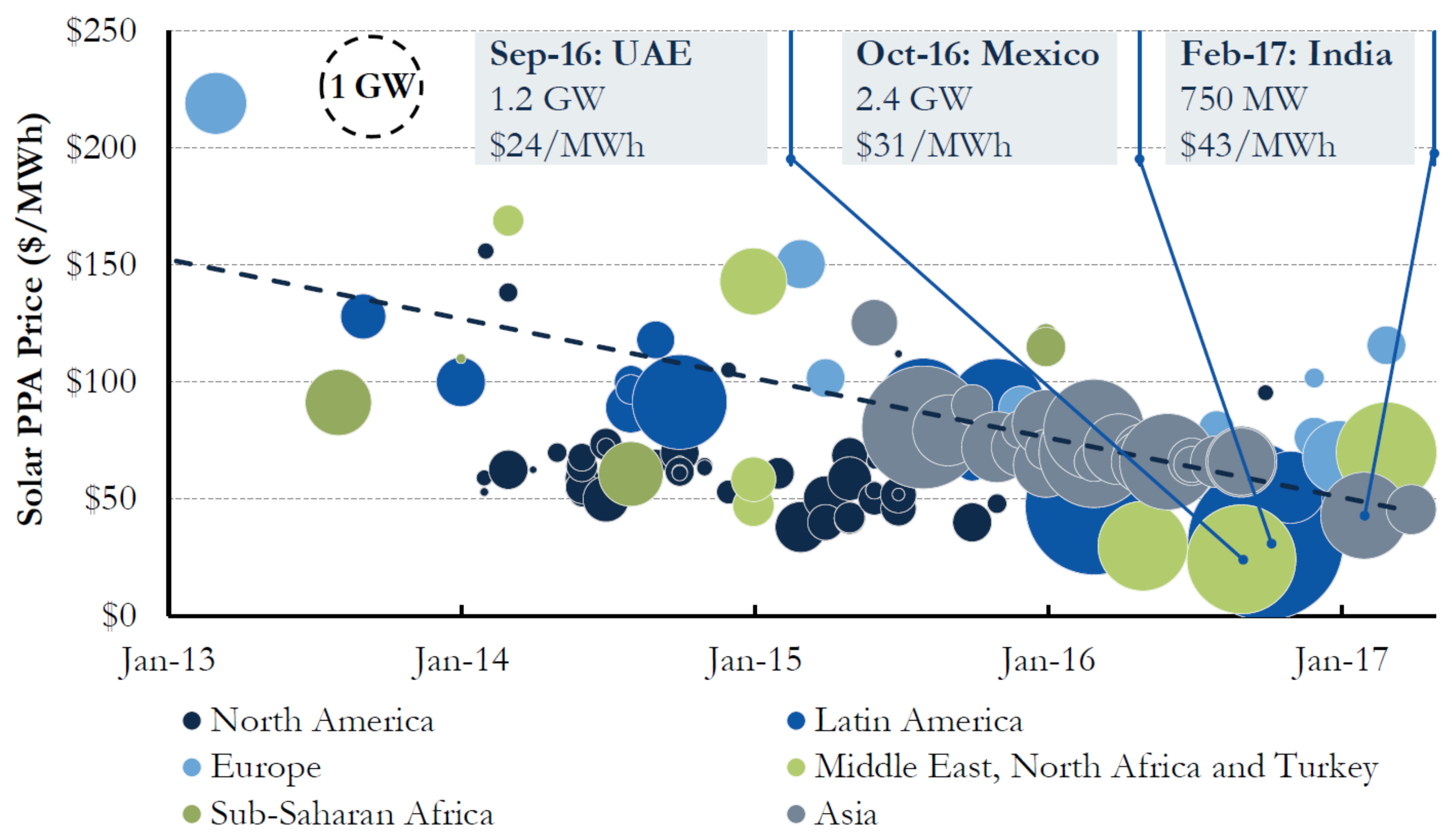


Figure 2.7
Each circle represents the price for which a developer of a utility-scale solar project has agreed to sell electricity through a PPA contract with a customer (for example, a utility that will buy the electricity and distribute it to homes and businesses). The size of each circle represents the power-generating capacity, in megawatts or gigawatts

Source: GTM Research (2017).

As a result, the amount of installed solar around the world is projected to grow by an order of magnitude by 2040.

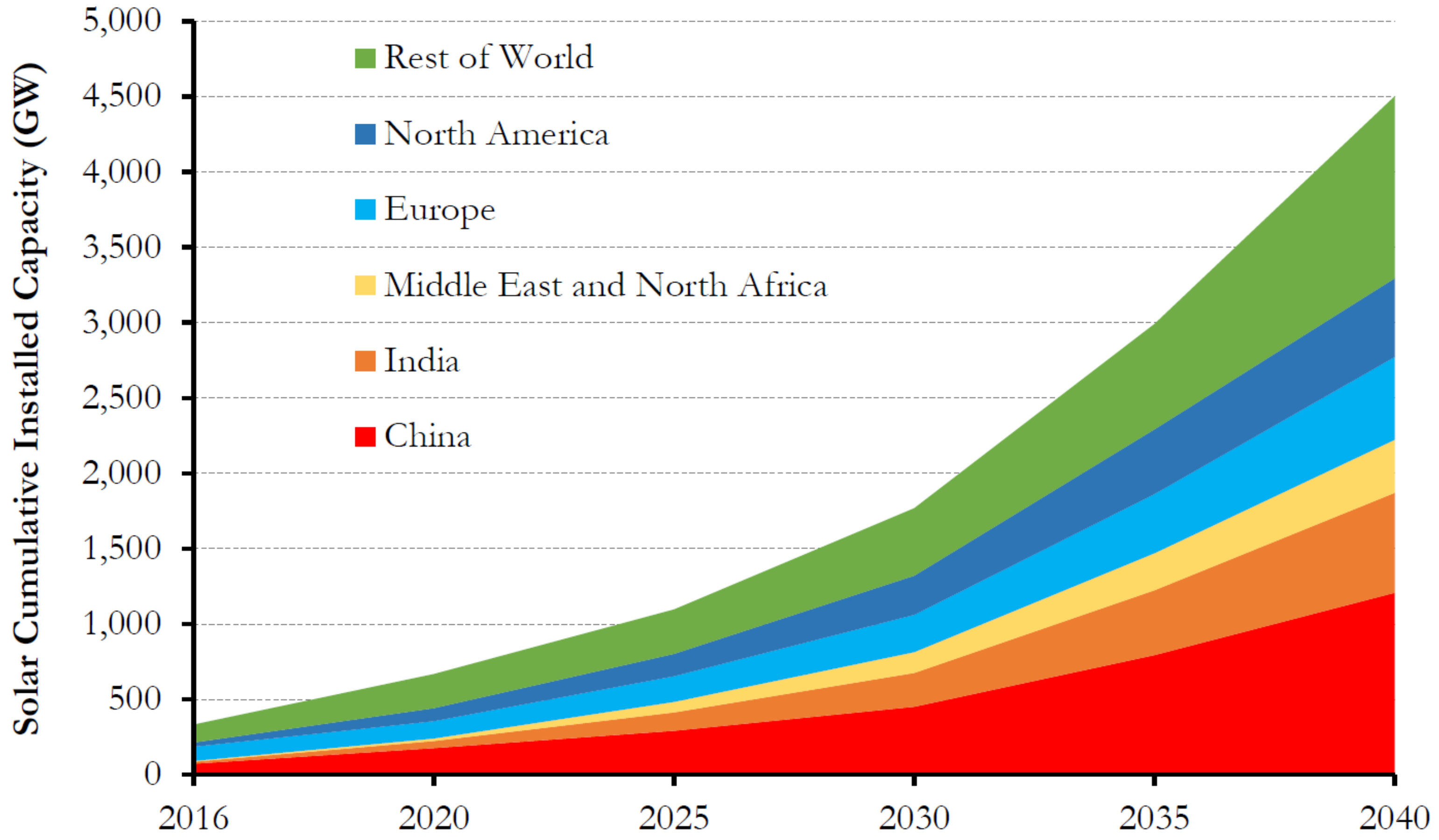


Figure 2.8
Projections for global solar deployment. This chart plots the expected growth in the installed solar PV capacity (measured in gigawatts) in major countries and regions around the world between 2016 and 2040.

Source: Bloomberg New Energy Finance (2017).

But at the penetration of solar needed—roughly one-third of global electricity by 2050—solar sharply undercuts its own value

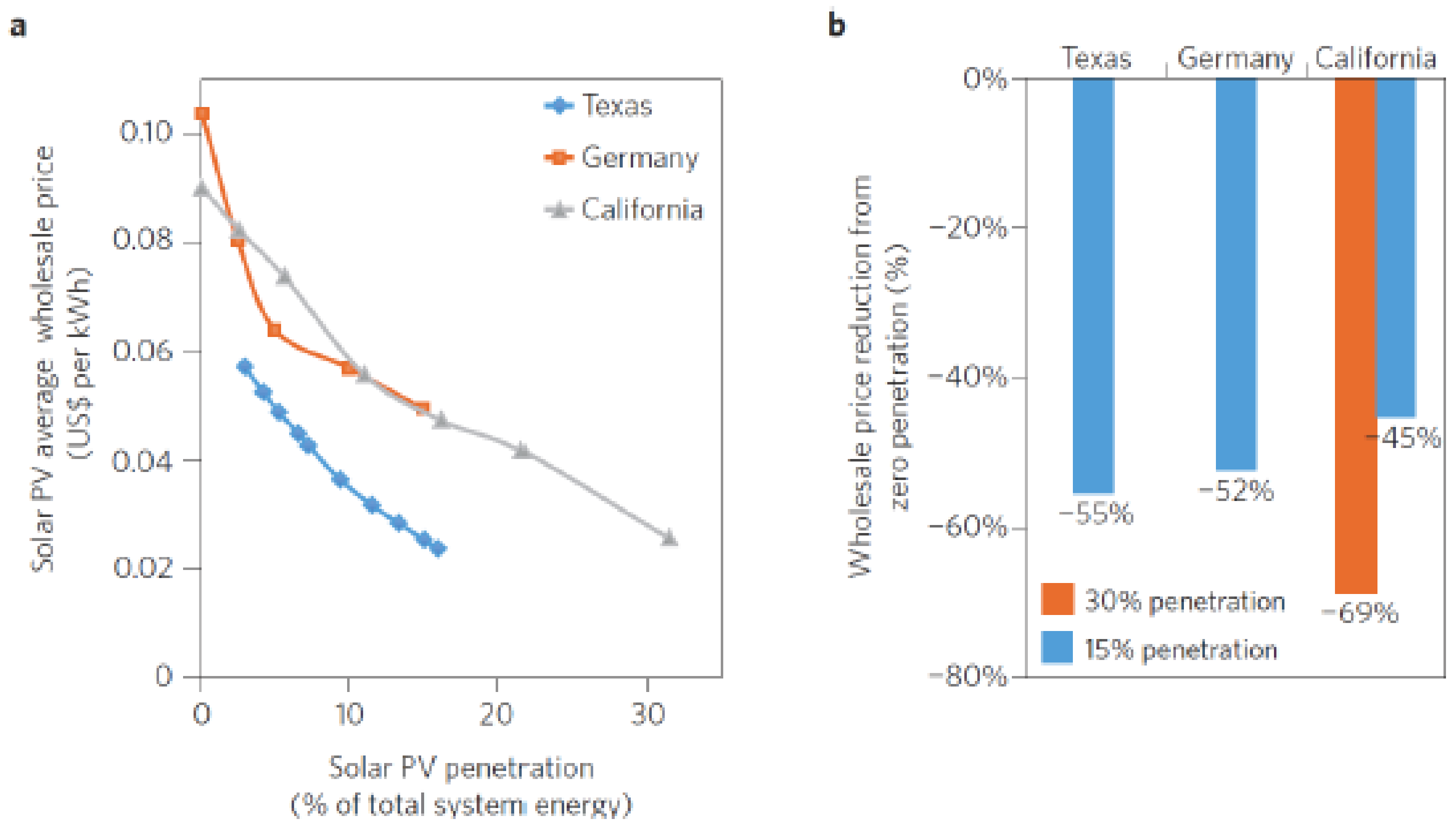
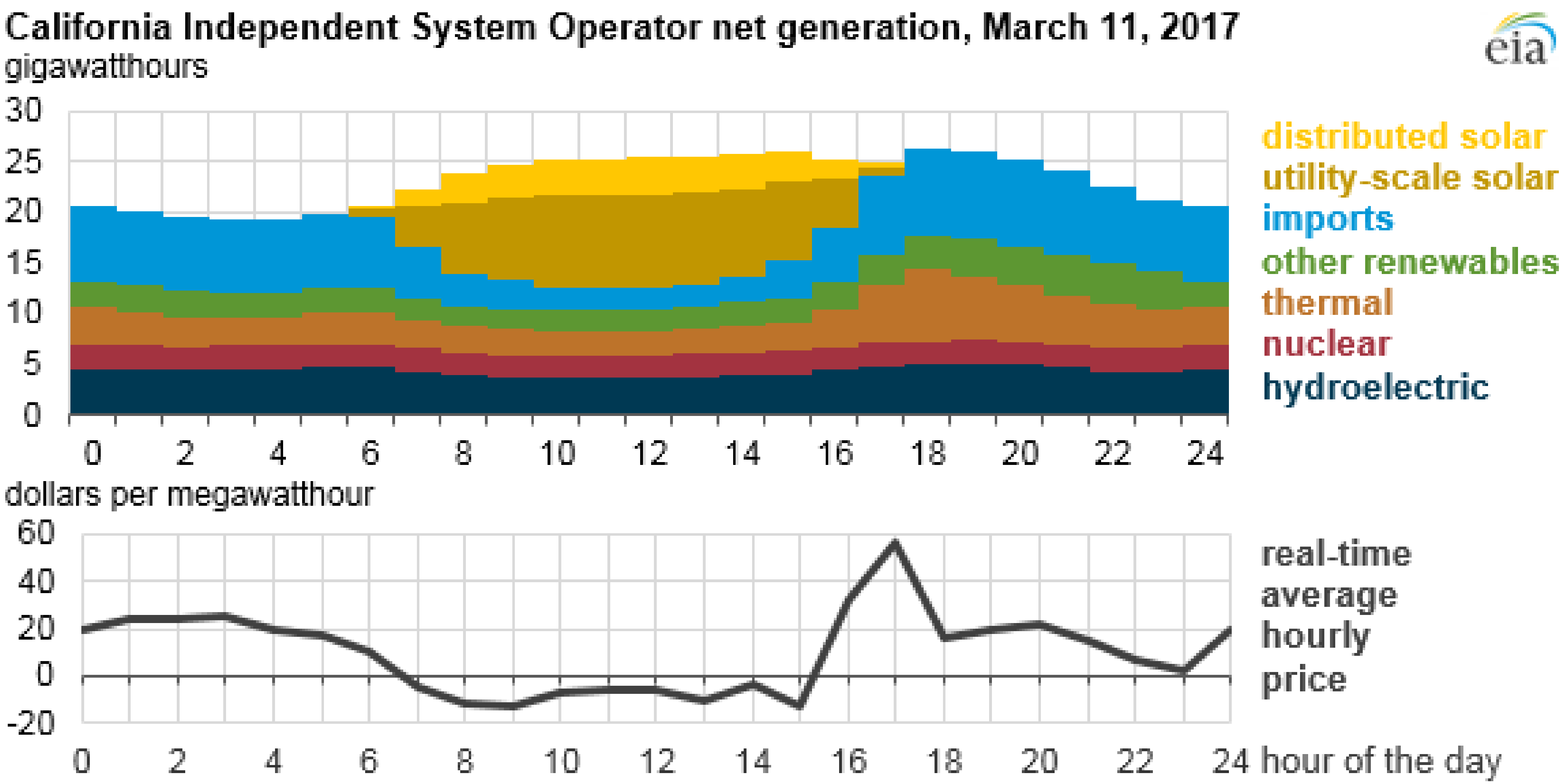


Figure 3.2
Panel (a) displays the results of three different simulations of power grids in different parts of the world that forecast the falling value of electricity produced by solar PV projects as the penetration of solar PV increases. Panel (b) plots solar PV value deflation at 15 percent and 30 percent solar PV penetration, compared with no penetration.

Source: Sivaram and Kann (2016).


California Independent System Operator net generation, March 11, 2017
gigawatthours
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imports
other renewables
thermal
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hour of the day
real-time average hourly price
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Part II: Teaching an Old Technology New Tricks

Chapter 4: Chasing Capital

Chapter 5: From Charity Case to Business Case

Solar needs far more capital than existing sources can provide; institutional investors are promising targets

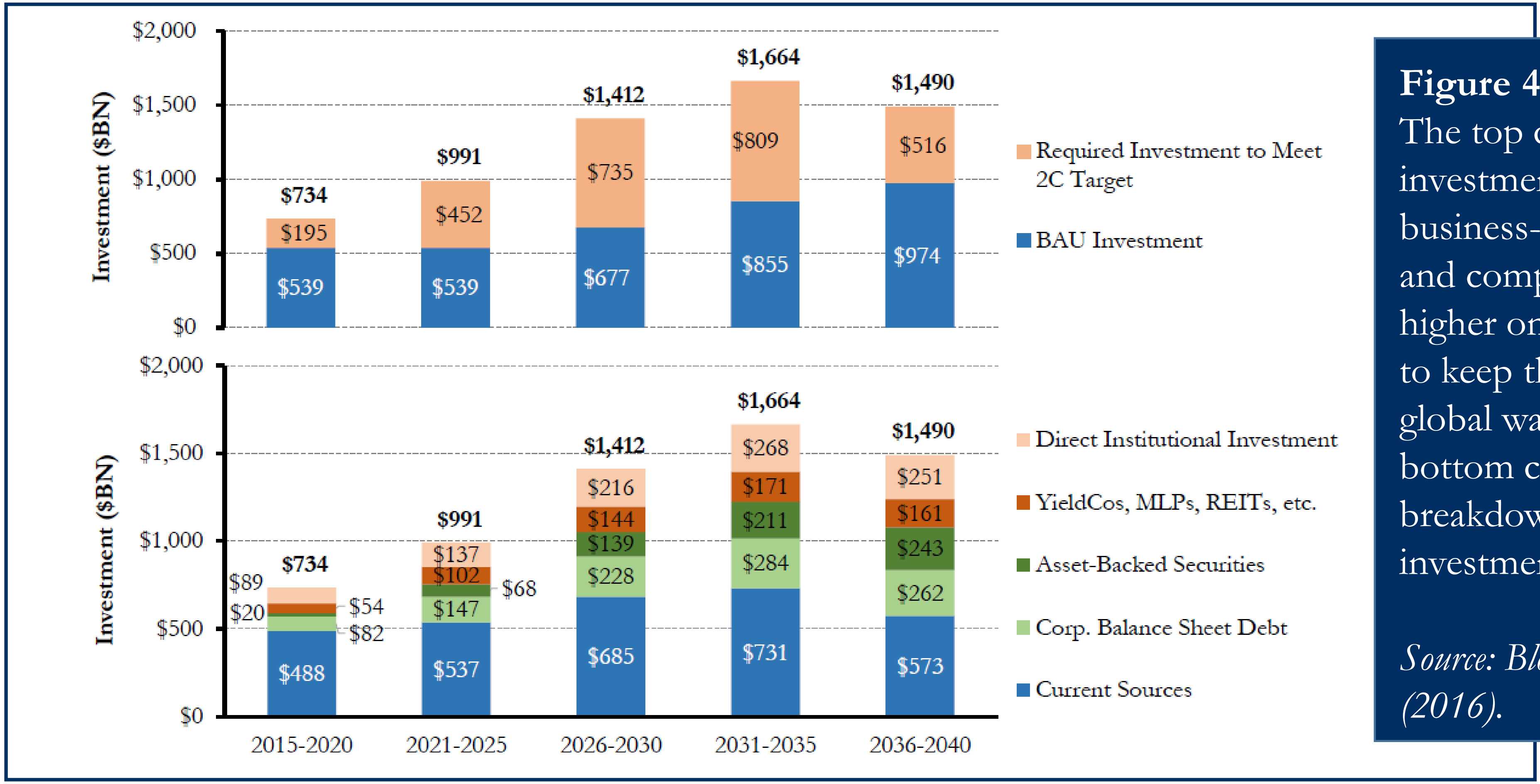


Figure 4.4
The top chart plots levels of investment in solar energy under a business-as-usual (BAU) scenario and compares those levels with higher ones needed through 2040 to keep the world on track to limit global warming to 2°C. The bottom chart provides a viable breakdown of these required investment levels by source.

Source: Bloomberg New Energy Finance (2016).

Over a billion people around the world lack access to electricity; most of them are in sub-Saharan Africa and South Asia

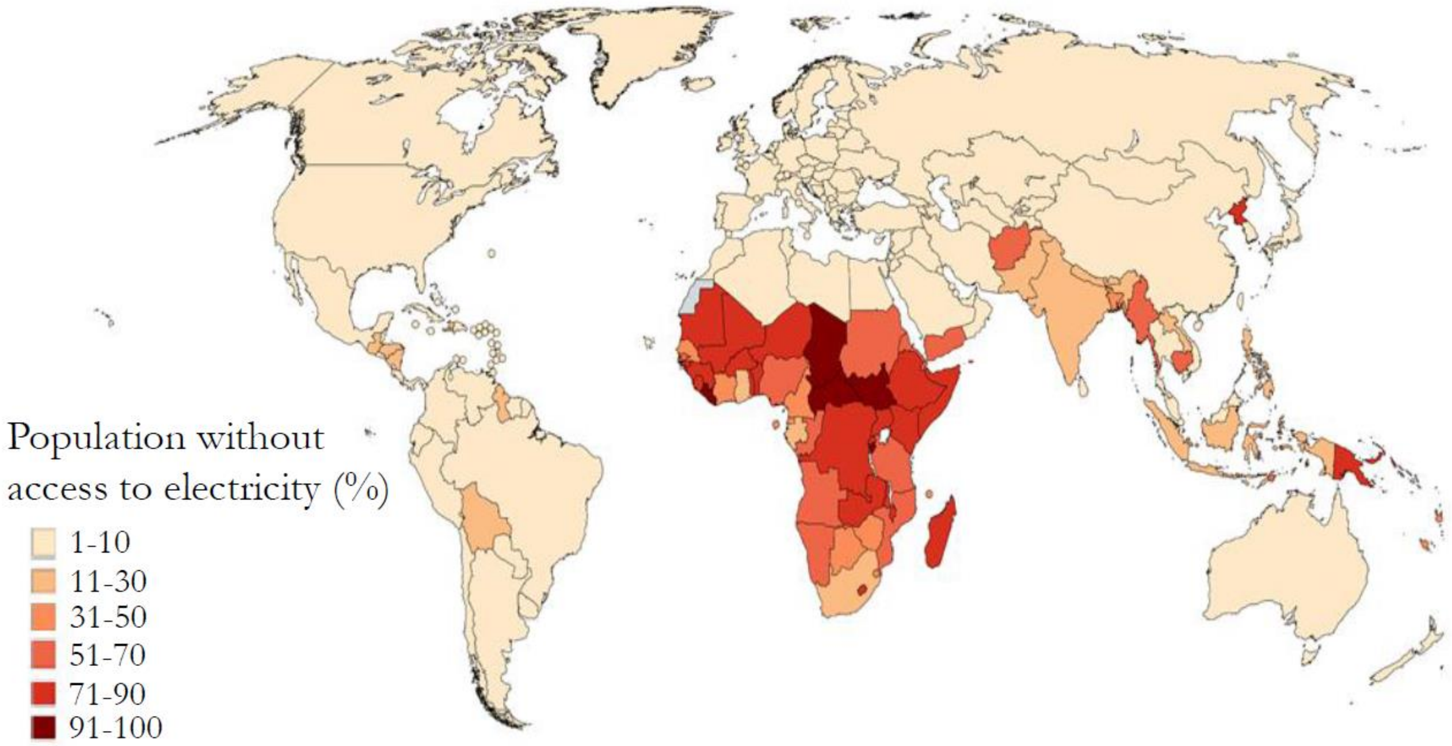


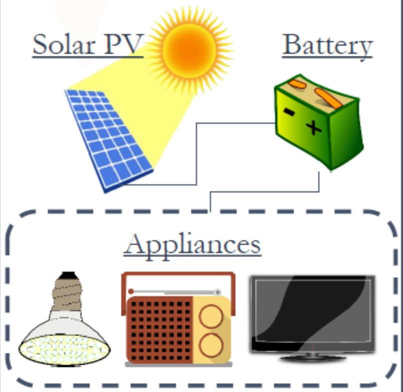
Figure 5.1

Global distribution of populations without acces to electricity.

Source: World Bank.

The Pay-As-You-Go business model brings off-grid solar systems within reach for unelectrified households. Fig 5.2 breaks it down:

1 Provider Installs Solar Home System

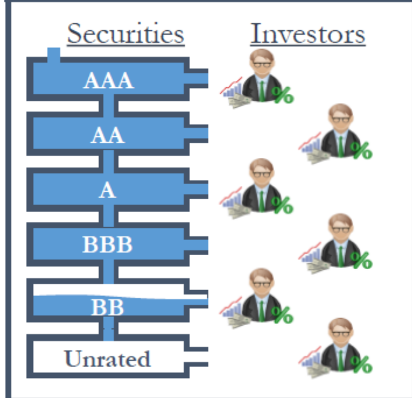


- Smaller systems (<20W) might charge phones, power 1–3 LEDs (e.g., M-KOPA)
- Larger systems (up to 300W) can power other appliances like a TV, radio, or fridge (e.g., Mobisol)

2 Customer Makes Mobile Payments

- Customer uses mobile money services, like M-PESA, to make ongoing payments for power
- Provider can remotely monitor, shut down system if customer fails to pay

3 Provider Securitizes Customer Leases



- Provider can package solar leases together and issue securities to investors to raise debt capital
- Can infer credit score from customer demographics, mobile payment history

4 Customer Pays Off and Owns System

- In most cases, customer can pay off lease (after, e.g., 3 years) and own the underlying SHS asset
- Customer then has a valuable asset against which to raise credit

Alongside the PAYG business model, the falling costs of an off-grid solar system's components are also driving increased adoption

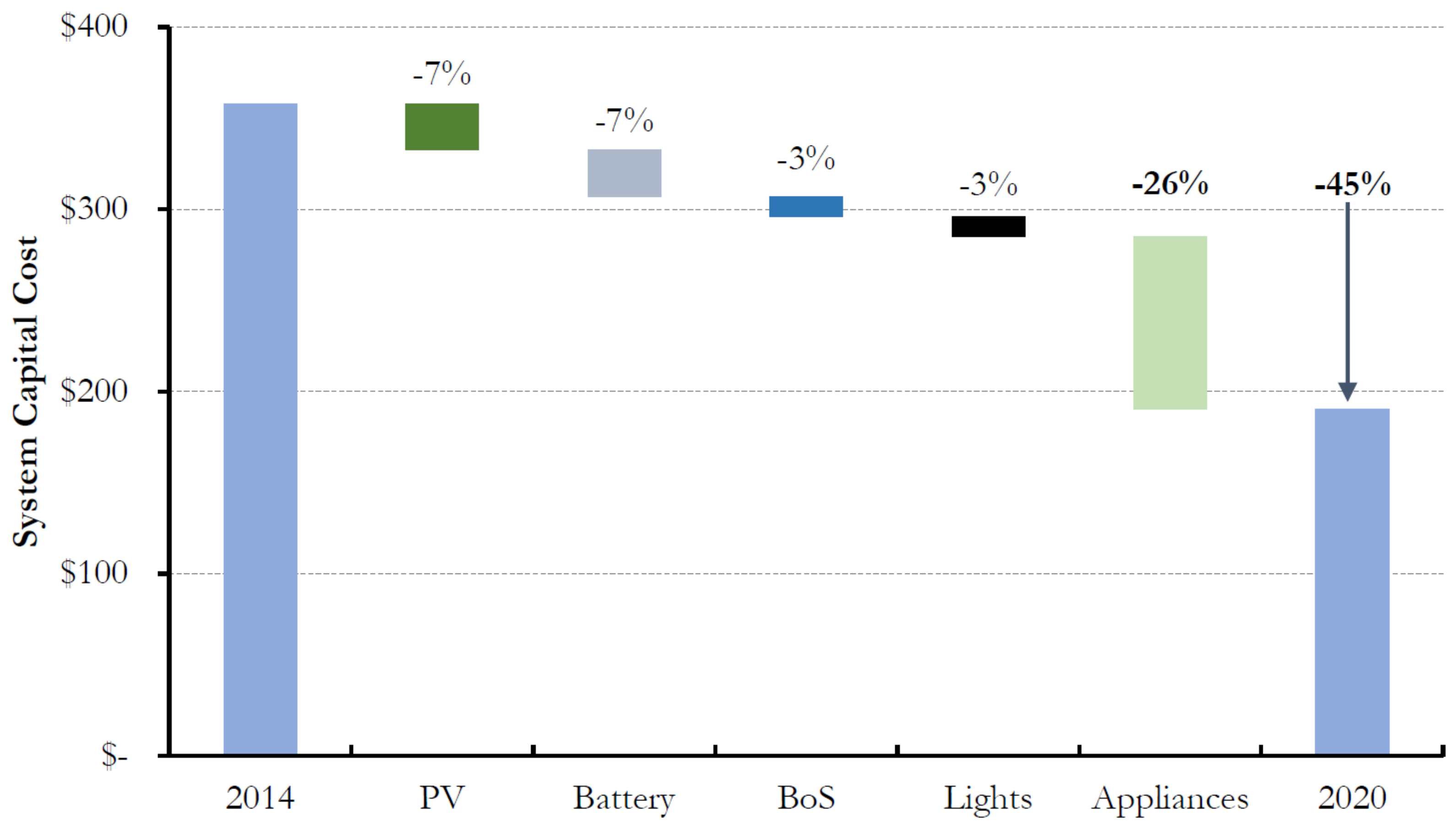


Figure 5.3
Current and forecast cost of a solar home system (SHS). Comparison of the total capital cost of an off- grid SHS powered by a 25 W PV panel in 2014 with that of an equivalent system in 2020, breaking out the cost savings by system component.

Source: Bloomberg New Energy Finance (2016).

Governments can help by coordinating efforts to expand central grids and deploy off-grid solutions; uncertainty deters investment

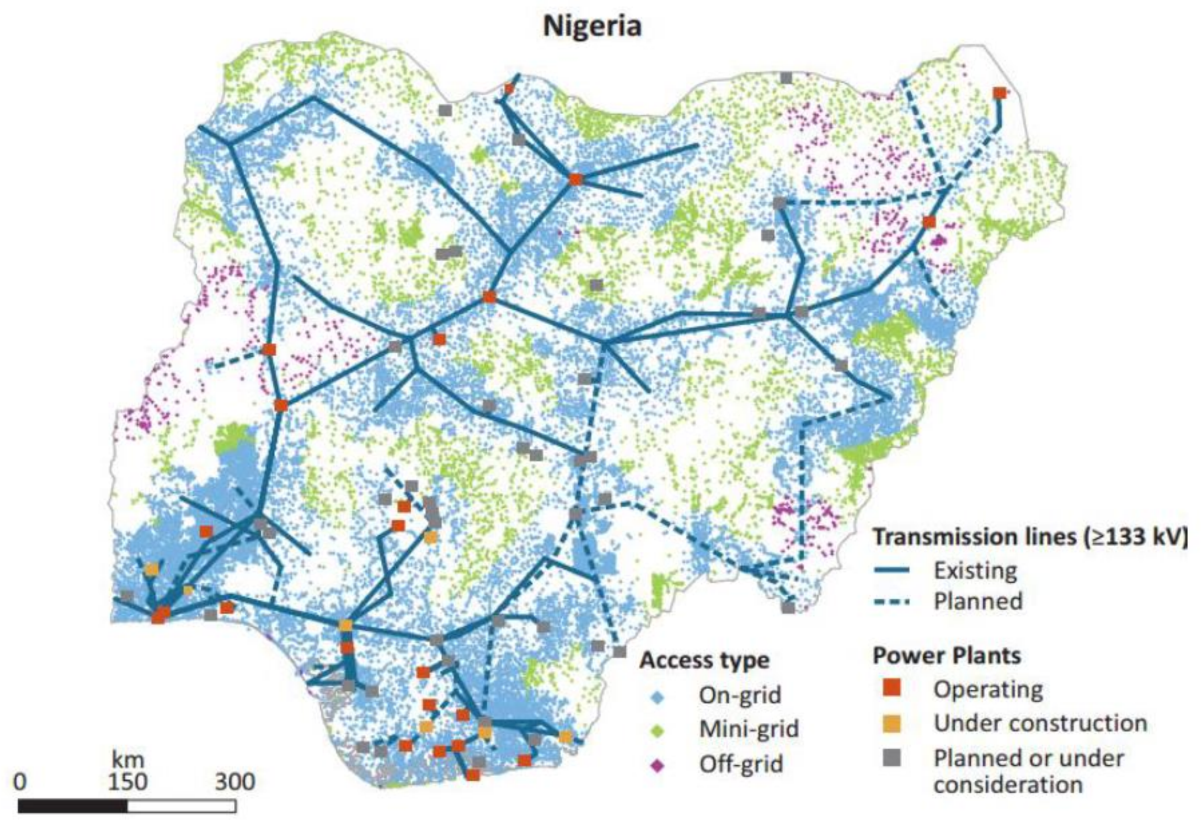
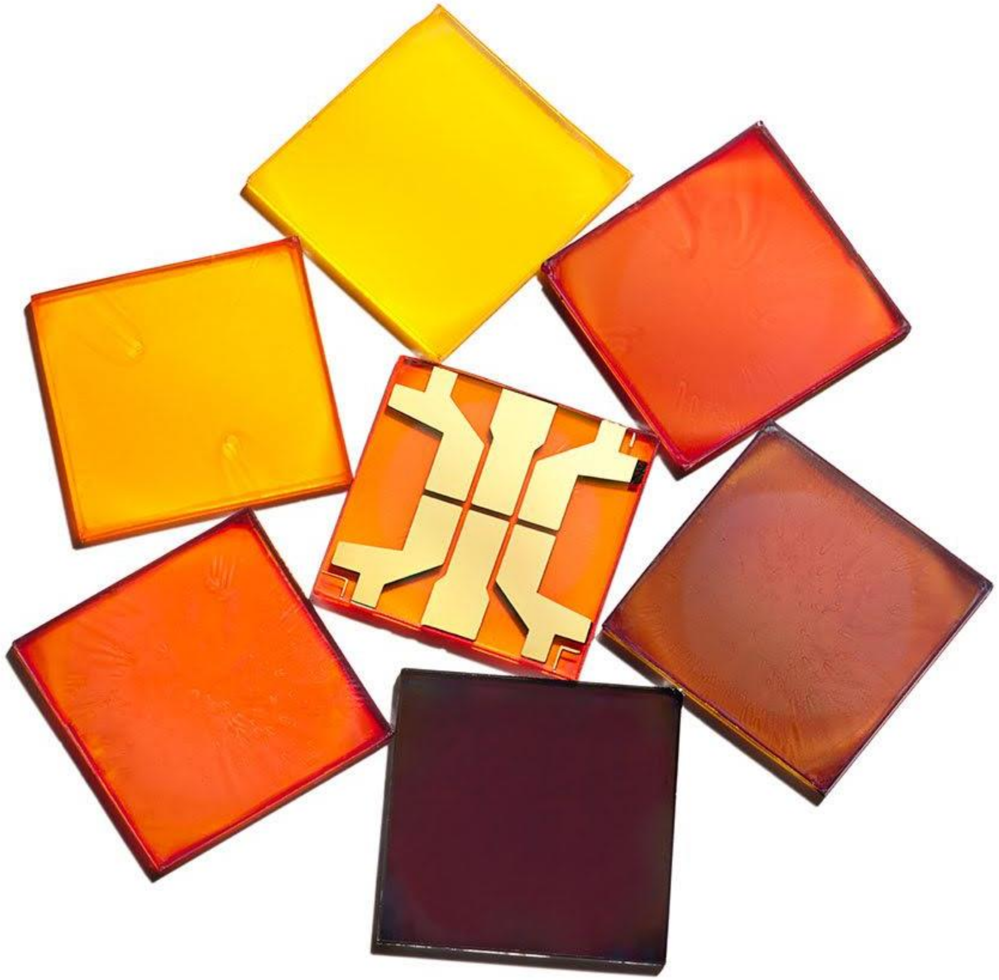


Figure 5.4
This map depicts the optimal deployment of different strategies to achieve universal electrification in Nigeria. The dark gray regions are areas where the main grid currently operates or could feasibly be extended. The light gray regions are remote, possibly sparsely populated areas where it does not make economic sense to extend the main grid. And the black areas are targets to deploy microgrids (likely powered by solar), which could initially provide energy access without the main grid, but to which he main grid might ultimately connect.

Source: Mentis et al. (2015).

Part III: Reinventing Solar

Chapter 6: Revolution by Evolution
Chapter 7: Stashing Sunshine



Source: Plamen Petkov

Layering a perovskite right on top of a silicon cell can boost its efficiency, because now there are two semiconductors with complementary bandgaps

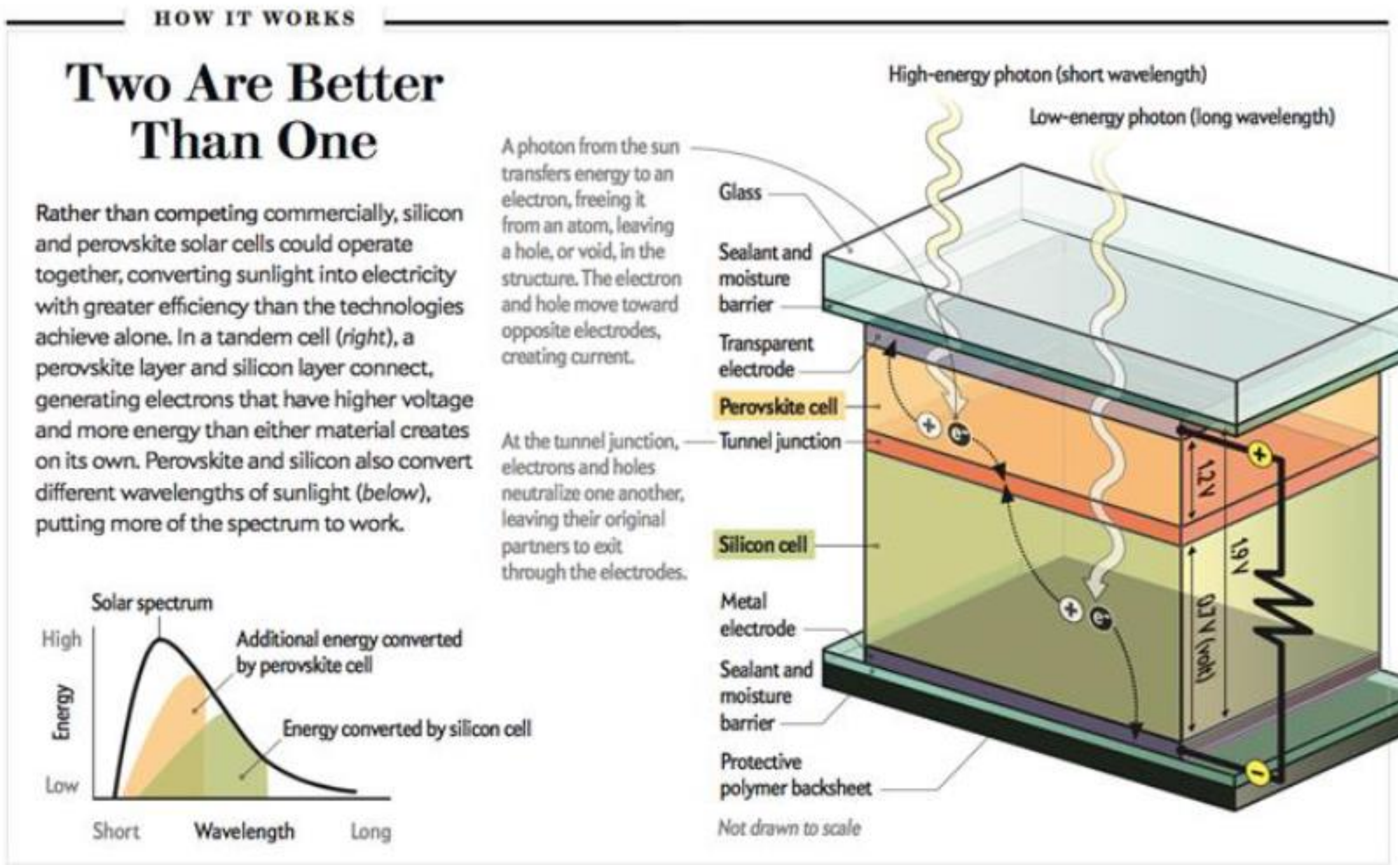


Figure 6.2

How a tandem perovskite/silicon cell works.

Source: Image reprinted with permission from Sivaram, Stranks, and Snaith (2015).

Layering emerging and conventional technologies (and maybe switching entirely to emerging tech) could boost PV panel efficiency to 35% by 2050

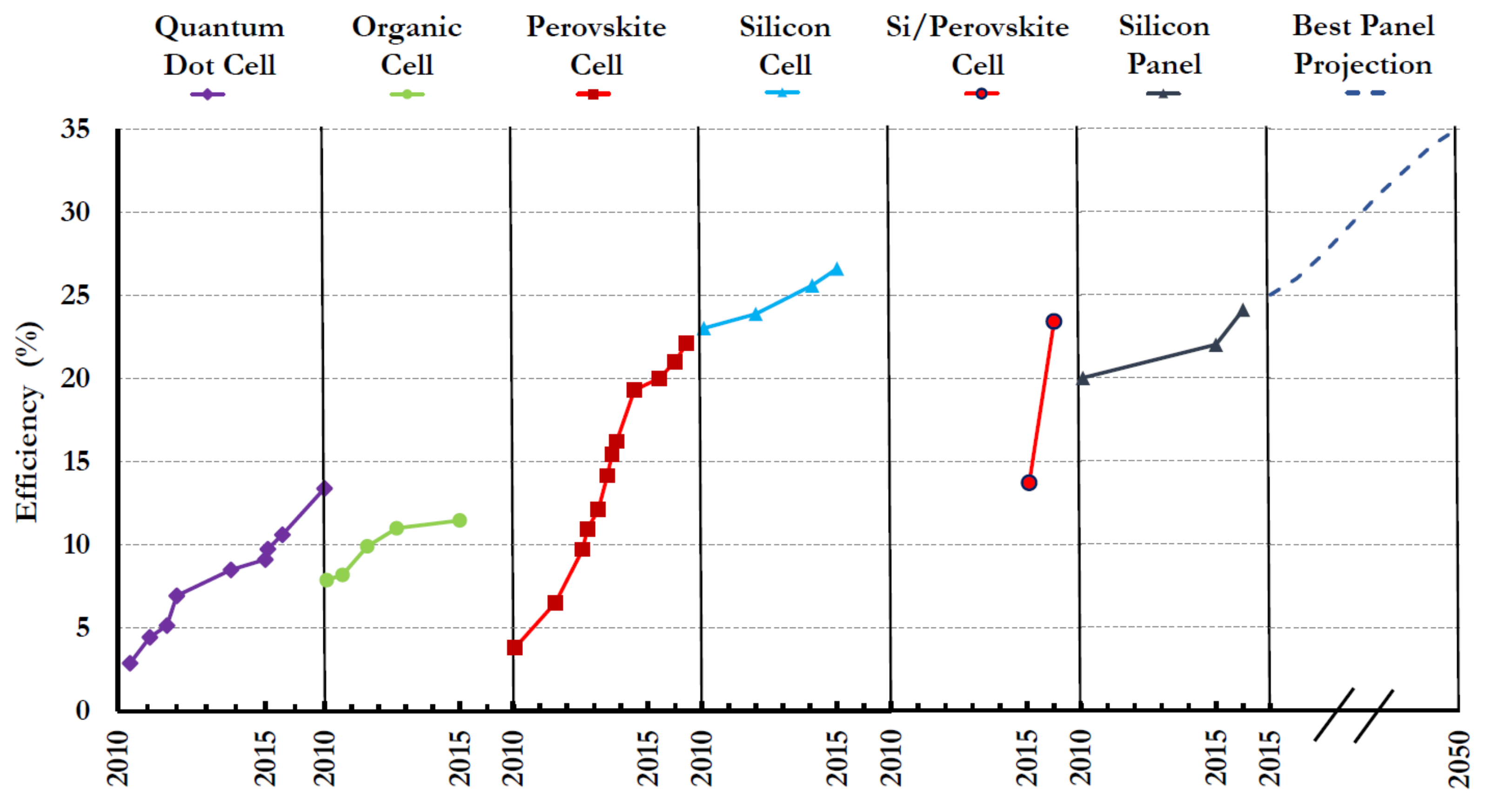
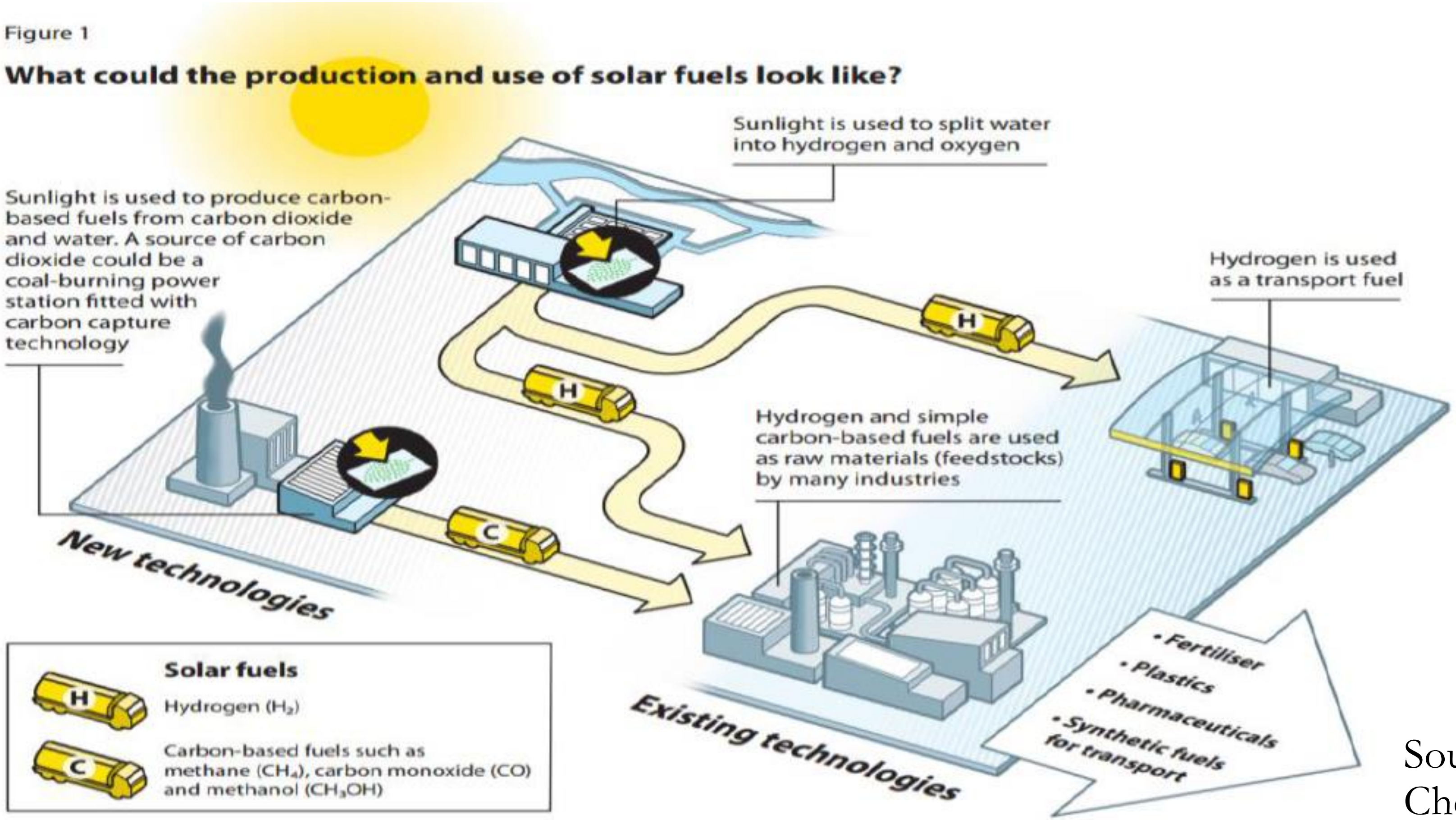


Figure 6.3
Comparison of solar PV efficiency across different technologies. The first six panels chart the progress in record efficiencies for solar cells and panels made of different materials. The rightmost panel projects the efficiency for the best, commercially available solar panel

Source: NREL; Albrecht and Rech (2017).

A range of solar fuels (incl. hydrogen and even carbon-containing fuels created using waste CO_2) can fuel transport, industry, and more



Source: Royal Society of Chemistry

Part IV: Putting It All Together

Chapter 8: Is Bigger Better?
Chapter 9: No Silver Bullet
Chapter 10: A Solar City upon a Hill

The cost of lithium-ion batteries is falling as more are produced—mirroring silicon solar PV—suggesting that pairing the two is the ultimate solution

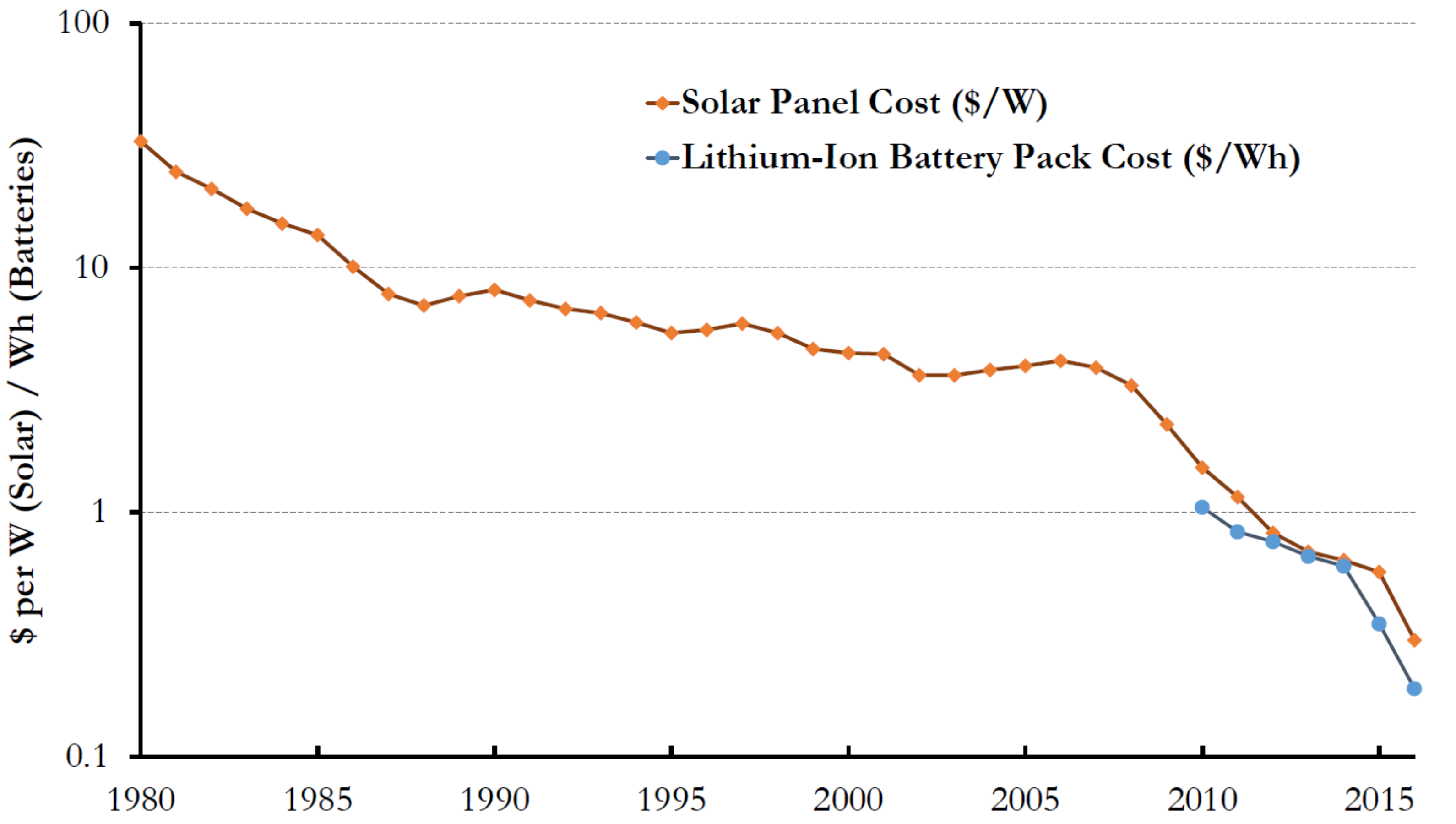


Figure 9.1
This chart plots the falling cost of a solar PV panel, expressed in dollars per watt of power-generating capacity; and that of a lithium-ion battery pack, expressed in dollars per watt-hour of energy-storage capacity.

Source: Bloomberg New Energy Finance, industry reports.

A power system with super-cheap Li-ion batteries ($150/kWh installed system cost) and $0.25/W solar would still require a majority of non-solar electricity

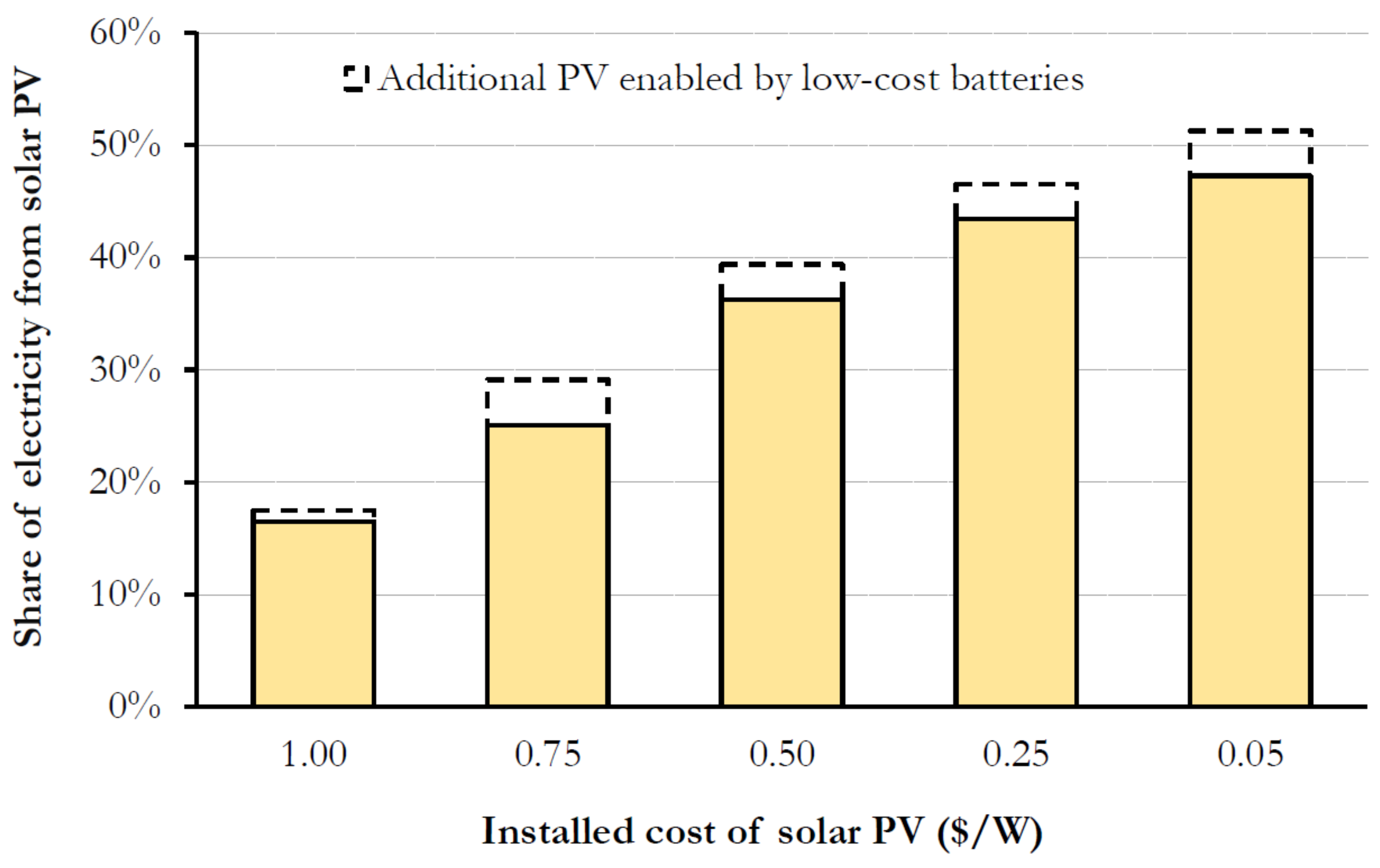


Figure 9.4
For each of the assumptions of the installed cost of solar PV along the x-axis, the filled bars represent the proportion of total electricity that solar PV would generate. The dotted extensions above the bars illustrate the additional amount of electricity that would be economical to generate with solar PV if a fully installed battery system cost only $150/kWh. (This is a simulation of the Texas grid)

Source: Brown, Jenkins, Sepulveda, & Sivaram (2017).

A hybrid grid, with a long-distance superstructure and networked microgrids at the local level, could best integrate distributed and centralized clean energy

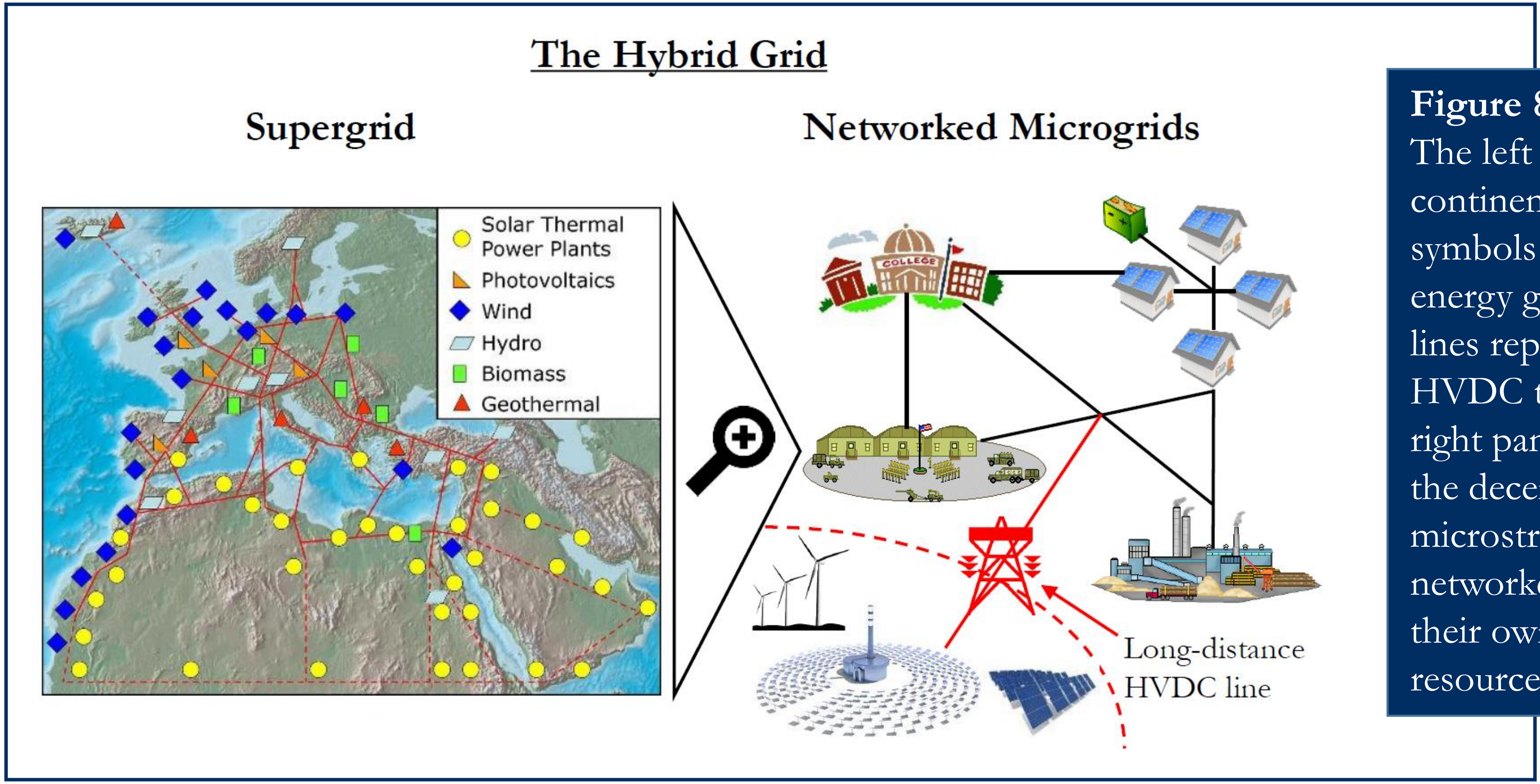


Figure 8.4
The left panel represents a continent-sized supergrid. The symbols represent renewable energy generators, and the lines represent long-distance, HVDC transmission lines. The right panel zooms in to reveal the decentralized microstructure, consisting of networked microgrids with their own distributed energy resources

China is on track to surpass U.S. in public clean energy research, development, and demonstration (RD&D) funding by 2020

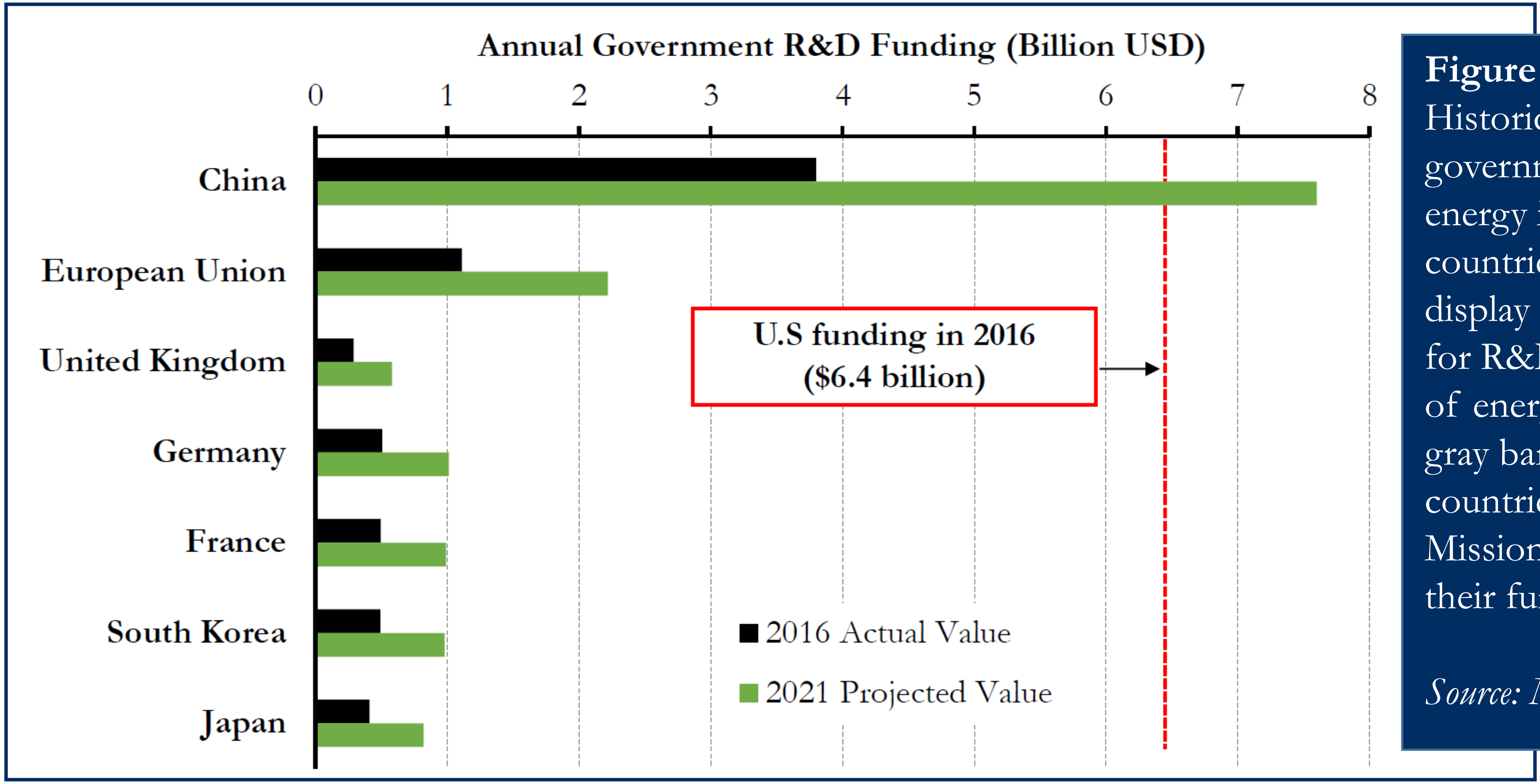
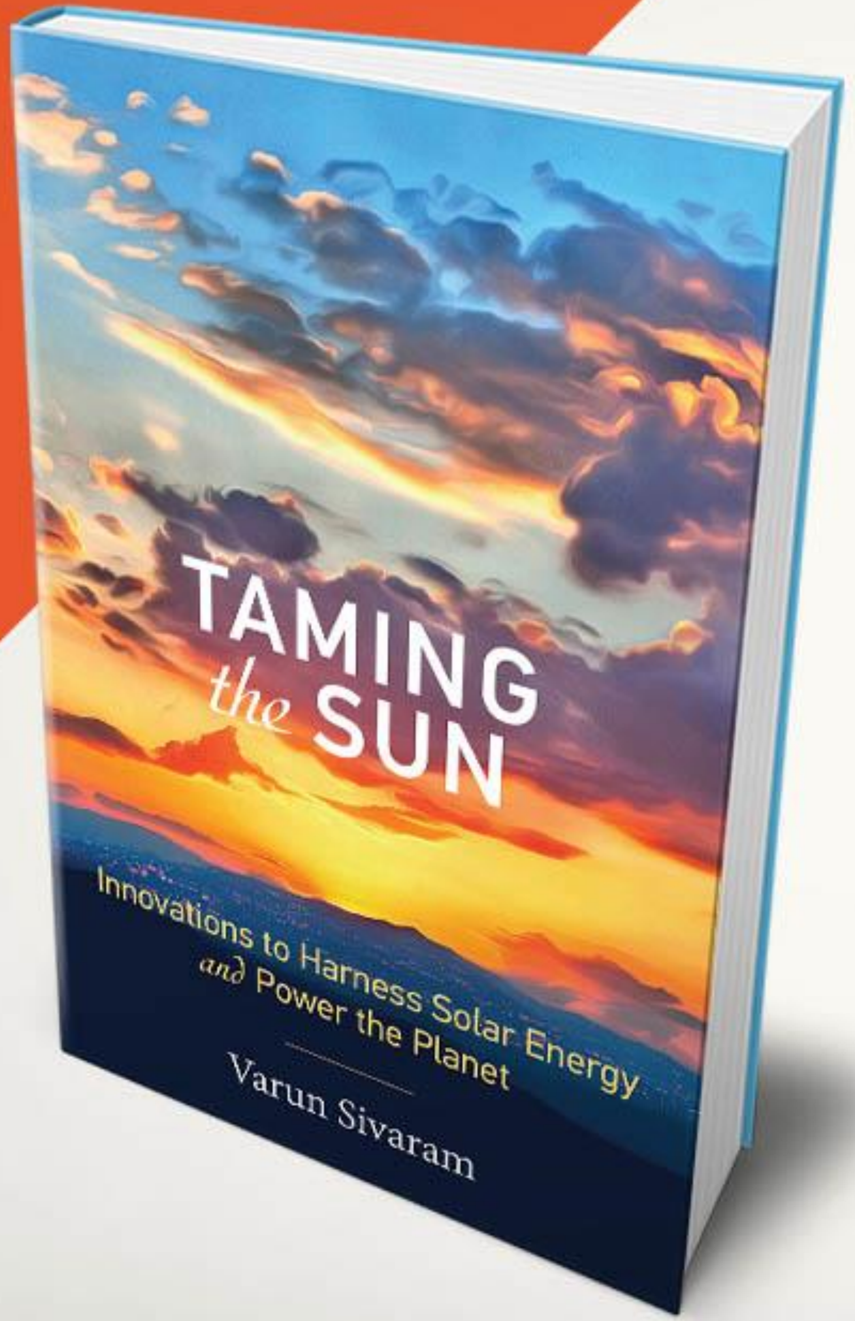


Figure 10.1
Historical and projected government funding for energy innovation in top countries. The black bars display current public funding for R&D and demonstration of energy technologies. The gray bars correspond to countries' commitments under Mission Innovation to double their funding levels.

Source: Mission Innovation



"To understand the history and the future of solar energy...*Taming the Sun* is the book to read ...the authoritative, balanced, and comprehensive text that the field has been waiting for."

—Arun Majumdar, Professor and Co-Director of the Precourt Institute for Energy, Stanford University; Former Founding Director of ARPA-E and U.S. Undersecretary of Energy

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