Taming The Sun

Taming The Sun: Innovations To Harness Solar Energy and Power The Planet

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## Prelude

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Part I Playing the Long Game

# Part I Playing the Long Game 1

## 

# Two Futures 3

### A Brighter Future

### The Sky’s The Limit

### Everybody’s Doing It

* It doesn’t help that the paths toward each future start out looking deceptively similar-both involve today’s solar PV panels surging in popularity over the next decade or two-so it’s not obvious which path the world is on right now.
* Still supplied less than 2 percent of the world’s electricity through 2016, that rapid growth has convinced governments that solar is on track to solve their most intractable na)

### New Delhi, India

* Prime Minister Narendra Modi has hailed, solar as the “Ultimate solution to India’s energy problems.”19
  + As soon as he entered office in 2014, he announced an audacious target for solar power: by 2022, India would install gigawatts (GW;
* The tumbling costs of solar PV-which fell by three- ་ between 2010 and 2017-will enable India to keep installing more of it
* Most of the planned solar expansion will be in the form of utility” scale solar projects-massive solar farms sit in the sunniest areas that are cheapest to build thanks to economies of scale. But over a third of the target is reserved for rooftop solar panels
* A last sliver of the target is small, off-grid setups in rural villages having limit or no connectivity to the main power grid
* growth, and it has scrapped plans for new coal power plants. Pinned its hopes on solar to clear india‘s air.
* Replace household diesel power generators that cause urban smog.
* Depends on a wildly wildly optimistic extrapolation of solar’s future growth. From 2012 to 2016, roughly 100,000 households gained access to electricity thanks to off-grid solar systems-but over 50 million households remained in the dark
* For solar to deliver what the government expects out of it, today’s red-hot market will have to government expects out on,
* India has historically struggled to maintain its ailing power grid. If t
* May not be up to the task of transmitting power from faraway solar farms to growing cities or absorbing the swells and sags of unreliable solar power.
* Scrambling in search of other sources of cheap power to sustain its economic growth.
* Electric vehicles remain comparatively marginal.

## Rokkasho, Aomori Prefecture, Japan

* Construction costs, Rokkasho is finally set to open
* Energy security ever since the oil shocks of the 1970s.
* Prepares to start recycling tours have been shuttered. As a result, a desperate Japan is now looking to urgently ramp up its supply of solar power to achieve energy self-sufficiency
* Policymakers unveiled an ambitious plan to secure 70 percent of the
* Needs from domestic sources Dу 4030. Ine centerpiece vy UI LA :
* Disaster struck just a year later. In 2011, an earthquake and resulting tsunami caused three nuclear reactor meltdowns at Fukushima-daiichi
* To restart its nuclear plants, Japan must subject each reactor to a rigorous review process and withstand grassroots legal challenges-through the end of 2016, it had managed 4 restart only four of nearly fifty reactors
* Thanks to generous public subsidies, Japan’s solar market ballooned to become the third-biggest in the world in 2016.³
* Power utilities have meaningful energy security to Japan. Large quantities of intermittent solar power, and that the need for storage is growing.
* Of advanced solar energy technologies.34 And
* Japan is enthusiastic about setting up a nationwide hydrogen economy to Slash fossil fuel imports and instead run its industries and vehicles off a fuel that could one day be produced from sunlight.

## Mexico City, Mexico

* “How did Mexico manage to contract for some of the lowest-cost solar power in the world?»
* “We did it without government sweeteners. We ran an open auction, and solar beat out every other source including natural gas, plain and simple.”
* Hydropower supplies a majority of the region’s power needs; the dependence rises to as much as 70 percent in countries, such as Brazi
* Yet climate change is inflicting droughts that depleting reservoirs from Santiago to Sao Paolo; it’s also melting the Andean glaciers that supply the mighty rivers of the Amazon, 35 As a result, region faces chronic shortages of hydropower in the future.
* In Chile, a boom in solar installations led to a glut of power in the afternoon. As a result, the price installations led to a glut of power in the afternoon.
* Free makes it impossible to repay the cost of constructing a solar PV plant, matter how cheap that cost is.
* Prospective electricity customers could sharply deteriorate as more of it comes online. And if solar’s growth stalls in Latin America, consistent with the first future, the region could suffer from chronic power shortages as climate change wreaks havoc on hydropower plants.
* Most in the region are simply content to ride the wave of cheap solar, although I did get the sense that a wary few are waiting for the other
* “When the charity is so great, even a saint remarked to me

## Dubai, United Arab Emirates

* The Middle East Electricity Summit slide after slide detailing solar coatings on skyscrapers, slower rates of climate change, and cheap power for the developing world were met with Yawns from the audience. I
  + -notably Saudi Arabia—a way to burn less oil and gas at home and sell more of it abroad.
  + Whose economies depend mostly on gas to generate power and sell it at a deep discount to domestic customers, encouraging wasteful consumption at home and foregoing export revenue
  + Saudi Arabia has big plans for solar PV.
  + The kingdom consumes over one-quarter of the oil that it produces
  + Offsetting some of the pain from slowing global demand for Saudi oil.
  + Even Saudi Arabia could find a silver lining in second future, in which solar power would challenge fossil fuel dominance.
  + There will be winners and losers. But there will be far i more winners and many more prizes to go around if the world can realize second future, not the first.

## We‘ve Seen This Movie Before

* The gap between solar’s promise and today’s realities. Commission, predicted that within a generation, nuclear power would be “too cheap to meter.
  + What went wrong? One explanation is that accidents, activists, and ascending costs have plagued nuclear, stymying plans for new reactors across the developed world.
  + Hard to imagine a solar farm melting down and inciting a political backlash, and the costs of solar PV have steadily fallen and look set to continue doing so.
  + Advanced designs that could be cheaper, more efficient, and meltdown proof have remained on the drawing board for decades
* The last half-century, researchers and companies have brought silicon PV panels near their theoretical performance limits, in some cases converting over 20 percent of the sun’s energy to electricity
  + Gains are wrung from incremental optimization of TF manufacturing lines and supply chains, not breakthroughs in the lab¸‹³
  + Worryingly little investment in innovation.
  + Firms in Asia, which dominate the industry, invest less than a penny from every dollar of revenue into R&D of new technologies.
* If countries to build out their power grids and otherwise invest in ways to
  + Solar could hit a ceiling sooner rather than later.
* The cost of batteries to store that power is falling in parallel, thanks in part to demand for electric vehicles.
* Combined cost of solar panels and batteries might be cheaper than any fossil fuel alternative by 2030.
  + Neither technological change nor beefed-up power grids will be necessary for solar to continue growing.
* But what if they’re wrong?
* Energy transitions take a very long time.
* To coal to oil-have each taken roughly a half-century, as If
* Here will be no opportunity for another do-over.

## Switching Tracks

* Targeted policy interventions to promote innovation are politically tractable and would yield outsize returns.
* Absent a decision to lay the groundwork needed to reach the second future now, the ride to a solar future could run out of steam.
* Financial and business model innovation
  + Solar industry could gain access to massive ɔools of low-cost investment to deploy solar on an unprecedented scale.
* Off-grid solar has been slow to take off. Now, a new crop of entrepre
* Without much more support from the public and private sectors, academic researchers will struggle to bring their technologies to market.
* Will struggle to bring their technologies to market. World's energy systems to fully take advantage of abundant, but unreliable, solar PV output.
  + Shaking up sluggish industries and marshalling political courage, change-averse power utilities need to be reformed before they will proactively equip electricity grids to cope with fluctuating solar power.
* take steps to advanced technological and systemic innovation, which is not proceeding as quickly as financial and business model innovation.
* Trump administration,
  + Erection of sweeping trade barriers to protect domestic manufacturers
    1. Would likely fail to encourage innovation and instead would dampen the U.S. solar market and probably incite trade retaliation from China.
    2. 1 further damage U.S. credibility on energy and climate issues—and
  + Abandoning a leadership role in male transition to clean energy would be a grave mistake
    1. R&amp;D into futuristic solar materials-may not pay off for years, the work has to be done now to ensure that the technology is ready when it is needed.
  + ૩ acts now and inspires partners around the world to follow suit, its leadership could unlock the most abundant source of energy on Earth for generations to come.

# 2. Coming of Age 27

* Exhilarating time to be in solar. Al Gore’s documentary An Inconvenient Truth had captivated the country. Investors were juiced at the prospect of red-hot market growth, running
* Nanosolar, the culture was infectiously optimistic. Around team lunches, we would dream about shipping cheap solar coatings to every corner of the developing world and carpeting remote
* Then the sky came crashing down. The price of PV panels plunged between 2008 and 2013, it fell 80 percent-and a flood of cheap Chinese silicon panels washed away nearly the entire crop of American start-ups.
* Nanosolar’s case, the firm scaled up manufacturing before it ironed out the kinks in its technology, and when the deluge of Chinese panels arrived, Nanosolar was in no position to compt
* Unchallenged dominance in the production solar panels; it also became the world’s largest market for their deployment.
* As Japan and Germany took the lead from the United States in supporting their domestic solar industries, solar PV started to gain traction in the early years of the twenty-first century.
* Industry is finally in the ascendant, it lost a vital element when Silicon Valley’s start-ups failed.
  + Upstream manufacturing to downstream deployment, firms are laser-focused on cutting costs rather disrupting the current order. T
  + Not at all conducive to the innovation the industry needs to pursue to brighten solar’s long-term prospects.

### Three Millennia to Get Going

* The silicon solar panel was invented more than sixty years ago, it is a newcomer in the context of humanity’s millennia-old quest
  + Over 3,000 years ago, the Chinese used yangsui, or “burning mirrors, focus sunlight to kindle a fire-the oldest-known human use of solar energy
  + In the first century BCE, the Romans invented the heliocaminus, a glass room that used the greenhouse effect to warm public baths,
* The next level of sophistication was to convert sunlight into mechanical work.
* Augustin Mouchot, a French mathematics professor, made the most
  + Driving a heat engine, generating electricity, and producing portable fuels.
  + In 1879, he figured out how to convert solar radiation into electricity by reflecting sunlight to heat the junction of two metals soldered together, generating an electric current. He used this electricity to split water into its constituent atoms-oxygen and hydrogen-ir ~intending to store the hydrogen as fuel.
* Search-but he succeeded in inspiring modern uses of solar energy. Heating \_
  + Substantial savings over using coal or gas to heat their water.
  + Has been eclipsed by the explosive growth of solar-generated electricity
* Progress in converting solar energy into heat and storing that heat inspired concentrated solar power industry. N
  + Built-in heat storage so that the plant can generate electricity around the clock »

### From Selenium to Silicon

* In 1839, when the French physicist Edmond Becquerel discovered the photovoltaic effect. He immersed silver chloride in an acidic solution, illuminated it, and connected it to two electrodes, between which an electric voltage developed.
* Forty years later, an English engineer, Willoughby Smith, discovered that selenium, a material known today as a semiconductor, became more conductive when exposed to light. Rese
* Charles Fritts, from building the first solar panels out of selenium and installing them on a New York City roof in 1884.
  + Two more decades before Albert Einstein finally solved the mystery and explained how light was turning into electricity. In a 1905 paper that time would win him the Nobel Prize in physics, |
    1. Light was composed of tiny packets-or photons-of energy.13 So
    2. A photon had enough energy to knock an electron out of its customary orbit around the nucleus of an atom in a metal or semiconductor, and that electron could then move freely.
    3. Energy of a photon depends on its color. Blue and violet photons have the highest energies the rainbow; red photons have the lowest.
       1. Only some colors are energetic enough to Kick electrons out of their orbits.
       2. In 1953, Gerald Pearson and Calvin Fuller-researchers at Bell Laboratories who had helped invent the silicon transistor, the building block of the modern computer realized that their device was highly sensitive to light. So they recruited Daryl Chapin, who was looking for a way to power remote telephone installations, and the trio built the first silicon solar PV cell.
          1. Just 2.3 percent efficient

### Peddler on the Roof

* Timing couldn’t have been worse.
* Overshadowed by an even more heralded clean energy technology: nuclear power.
* In 1953, President Dwight D. Eisenhower delivered his “Atoms for Peace” speech to the United Nations General Assembly, laying out his vision for “universal, efficient, and economic usage” of nuclear power
* (R&amp;D) funding necessary to drive the cost down was not forthcoming because all eyes were on nuclear. During the 1950s, U.S. government funding for solar R&amp;D was limited to $100,000 per year, whereas nuclear power received over $1 billion a year.
  + Solution to keep satellites operating indefinitely
  + Crumbs enabled a few firms to invest in developing increasingly efficient solar panels because it was crucial to extract as much energy as possible from the limited number of panels that could be sent into space.
* Advantage of solar over petroleum fuels or batteries was its low maintenance-you could leave a solar panel out for a decade or more and it could be trusted to generate power every day. That made it attractive for settings where routine maintenance was impractical.
* Oil companies invested substantially in solar power at its outset. In addition to Exxon, the U.S. oil firms Mobil, Arco, and power at its outset. In addition
  + Powering offshore platforms or service stations; the firms’ versatile engineers were well suited to advancing the technology:
  + Many also lost money on it, nearly every firm left the sector.
* A big boost in the 1970s from the U.S. government as America reeled from spiking oil prices.
  + The Carter administration shepherded incentives for solar power through Congress.
  + Increased support for R&amp;D, tax credits of up to 30 percent to install solar panels and water heaters, and regulations requiring power utilities to purchase power from independent generators like solar farms.
* 1988, President Ronald Reagan and his administration had led Congress to slash R&amp;D funding for photovoltaics by 75 percent compared with its 1980 peak¸²
  + Funding only basic science research, rather than applied and demonstration projects
  + The withdrawal of government support simply drove American companies out of the market.
* 2000, Germany passed landmark legislation that offered substantial incentives for new solar installations-a guaranteed premium price, or feed-in tariff, for which the owner of the installation could sell solar power to a utility over the next twenty Years.
  + Energiewende (energy transition)-

### Sunburned in Silicon Valley

* Scientists had long considered silicon a less than ideal material for a solar cell that was in use mostly out of convenience.
* A particularly thick chunk of silicon is needed to absorb the same amount of light that a thin slice of other materials can
  + Silicon absorbs more colors of light than other materials, but this broad absorption sacrifices much of the energy contained in blue and ultraviolet photons.
* Producing high-purity silicon, in which the atoms are arranged in perfect, crystalline order and are thus most efficient converting sunlight to electricity, requires expensive equipment, wastes a of silicon, and results in brittle wafers that break easily
* In 1967, was not a different material, known as “amorphous silicon,” which could be used to make flexible, thin photovoltaic films
  + Half as efficient as traditional crystalline ce
  + Never took off the way its backers had hoped, hough it did carve out a niche as the material of choice for flexible or sortable applications such as pocket calculators.
* Highest-performance solar cells today use GaAs and its cousins in multijunction solar cells-in lab, these can exceed 40 percent efficiency.
  + Not make much of a commercial impact on the terrestrial solar market not make much of a commercial
  + Serious competition to silicon came from two thin-film materials—cadmium telluride (CdTe) and copper indium gallium (di)selenide (CIS)——
    1. The early 2000s, the American firm First Solar managed to rapidly ramp up production of CdTe panels, which were less efficient than silicon but also less costly to produce.
       1. 2006 valued at a (then) eye-popping $400 million. A Silicon
       2. Exotically, Solyndra planned to transform flat solar panels into cylindrical tubes that could absorb light from every direction. That vision earned it a whopping $1 billion in private investment, along with a $500 million loan guarantee in 2008 from the Barack Obama administration.
* Then silicon suddenly stopped being precious. A
  + From over $400 per kilogram (kø) in 2008 to $50/ko in 2010. 3.3
* Investor expectations for these companies were likely | unrealistic from the beginning.
  + The start-ups had to develop new material customize the machinery to make those materials, design a new solar product, and cultivate a market for that product. They had to do it all within three to five years because of the way that venture capital funds were structured to pay back their investors
  + A costly mistakes, like racing to build expensive factories before they could reliably produce small batches of efficient

### China and Silicon: The Dream Team

* III roots in the work of a scientist out Australia. That scientist, Professor father of photovoltaics.
  + One of the best labs in the world.
  + Green’s students would take that technology with them and create the Chinese solar companies that would take over the global industry
  + COMSAT figured out how to carve microscopic pyramids on the surface of silicon solar cells to ensure that incoming light rays bounced around instead of being reflected away and were ultimately absorbed. These cells were known as “black cells”
  + Over 25 percent efficiency by th
  + PERC
  + 1982, Arco offered a five-year warranty for its solar panels; by the 1990s, BP offering a twenty-year warranty.
* Panel’s power could be sold for many more years, panel meant that me paner’s power co panel’s up-front cost.
  + Just as powerful for the competitiveness of solar PV as increasing the just as powerful for the competitiveness of
  + Industry pioneer Dick Swanson tel an old Stanford classmate: T. J. Rodgers, CEO of Cypress Semiconductor, a
  + Chinese producers invested heavily in making their facto ries more efficient than foreign facilities and wringing every last cent out of their supply chains.
  + Subsidies poured in from the central and provincial governments to depress the cost of raw materials, energy, land, and components.”
    1. Free-flowing stream of low- to no-cost loans defer any need for profits i.
  + In Spain, incentives sometimes cover the cost of solar installation, and by 2009, the share of solar in Spain’s power mix was the highest in the world.
    1. China built up massive production overcapacity all along the solar supply chain, fr
    2. European countries reeling from the Great Recession yanked their solar subsidies.
    3. All-out price war to win scarce customer demand.
* China has shifted the focus of its public policies away subsidizing the production of solar panels to funding their deployment home
* When the dust settled from the global industry upheaval, China had emerged as the world’s largest producer and consumer of solar PV, almost all of which is made of silicon. That dominance is unlikely to be challenged anytime soon.

### State of the Industry

* Throughout all the upheaval, bankruptcies, and price swings of recent decades, the solar industry and market has grown consistently and rapidly
  + Solar panel costs have regularly fallen as total solar production risen by roughly 20 percent for every doubling of cumulative production
  + Paul Maycock at at the U.S. Department of Energy (DOE)
* Performance improvements have stopped driving declining costs. Rather, those declines have happened because firms have achieved economies of scale from mass production,
  + Gained experience and devised clever ways to install solar more cheaply.
* Downstream deployment of solar are being squeezed as well, partly from intensifying competition and partly because of a global decline in incentive payments for solar power.
  + Mandates to require utilities to procure a certain share their power from renewable sources such as solar power. Two, they have subsidized the construction of solar installations, for example through tax credits that reduce solar’s up-front cost.
* Replacing feed-in tariffs,
  + With reverse auctions, in which developers bid against one another to offer the lowest price for which they will agree to sell solar power for the next fifteen to twenty years.
  + developers can sell their power, squeezing their profits
  + Is fiscally prudent for Germany, but disastrous for the profit margins of solar developers.
* New Energy Finance projects that by 2040, the cost of solar PV will plummet two-thirds, and as a result, solar will account for 17 percent of total electricity generation
  + If Bloomberg’s forecast is right, solar will grow by more than 1,500 percent through 2040, and more than 40 percent of that growth will occur in China and India, which are
* The scarcity of profits and recent upheaval in the industry has instilled in firms a conservative, low-risk approach to the future. In
* The reality is that the average efficiency of a silicon solar panel will increase each year for the next decade simply as more producers switch from low- to high-purity silicon and to more efficient cell architectures that have already been invented. Al il Companies are already using drones to aerially monitor the operations of solar farms and cut down on labor costs.
* Industry spends on average just 1 percent Yet the tact remains that the
* Dearth of innovation should be deeply worrying to anyone hoping for a solar-powered future.

# 3. Blocking the Sun 55

* 9:45 a.m. on March 20, 2015, electricity grid operators in Germany scanned the heavens, praying for clouds.
  + Ordinarily would provide a quarter of the country’s peak daytime power, would be knocked offline by a total solar eclipse before rushing right back online ¹
  + Germany was determined to confront the eclipse.
  + Grid operators prepared for months to recruit every manner of generator-coal, natural gas, biomass, nuclear, and hydroelectric &gt;wer plants-assembling a backup fleet with twice as much reserve capacity as normal.
* The much mused, “What we see as a crisis [today] will be a daily phenomenon in 10 years.
* Much more solar is on the way, bringing with it wild swings in power output that could increase the risk of blackouts.
  + To supply a quarter
    1. Produced at full output
    2. N 7 percent of Germany’s annual electricity
* Extensive preparation should be a warning sign that managing the rise of solar could be expensive for utilities and fraught with peril.
  + Invested in a fleet of expensive backup plants to maintain grid reliability.&gt;
  + $20 billion in building transmission lines, upgrading local distribution grids, and installing smart grid technology.
* Germany is better equipped than less wealthy countries,
  + Countries will confront dizzying costs and complexity if
  + Choice but to try, however. To limit catastrophic climate change, the world is likely going to need solar power to provide at least a third of all electricity by midcentury.
  + Will lead to challenges even more daunting than those of the past.
* Abandoning subsidy-driven models of financing solar power, 1 need to unlock vast pools of private capital to ramp up solar deployment
* Rise could be its own undoing. As the cost of generating solar power steadily falls, the value of consuming that electricity could fall even faster as more of it connects to the grid.
  + Would strain power grids around the world, req requiring costly solutions
    1. So-called “value deflation” could plunge solar’s value below gently falling cost of producing it, thereby undermining the economic benefits of adding more solar power. Then
    2. Solar’s current economic appeal would turn out to be a mere illusion-a poor predictor of solar’s future prospects.