HOW SOLAR ENERGY BECAME CHEAP
A MODEL FOR LOW-CARBON INNOVATION

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PV IS NOW CHEAP...BEYOND EXPECTATIONS

PV has improved more than any other energy technology

Most optimistic prediction by most optimistic expert
LONG TERM COST REDUCTIONS

PV

($2016/W)

1950 2000 2050

1000

100

10

1

1950 2000 2050

1000

100

10

1

1950 2000 2050

1000

100

10

1

Wind

($2016/MWh)

Batteries

($2016/kWh)

($2016/W)

($2016/MWh)

($2016/kWh)
RESEARCH QUESTIONS

1. How did solar become cheap?
2. Why did it take so long?
3. How can it be a model

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PROJECT INDEPENDENCE       1ST PV LEARNING CURVE

1958 $7000/MWh

2 x 6 CM CELLS

2" DIA CELLS

10% learning rate

20% learning rate

30% learning rate

2018 $10-20 B

Industry Accumulated Volume (MW)
GERMANY: CREATING A MARKET

1. Policy window
2. Policy diffusion
3. Demand Pull
4. “Gift to the world”
CHINA: MAKING IT CHEAP

2009-10: $10s billions of low cost loans

2011: Chinese Feed-in tariff

2013: World's largest market

"Gift to the West"

Cheap electricity

"China's own gift to the world"

Iterative upscaling

Low-cost expansion strategy
HOW DID SOLAR GET CHEAP?

CREATING TECHNOLOGY
- Scientific Understanding
- Evolving R&D Foci
- Knowledge Spillovers

BUILDING A MARKET
- Niche Markets
- Modular Scale
- Robust Policy Support

MAKING IT CHEAP
- Learning by Doing
- Iterative Upscaling
- Delayed System Integration
PV AS A MODEL FOR LOW-CARBON INNOVATION
### WE NEED MULTIPLE MODELS

<table>
<thead>
<tr>
<th>Technology type</th>
<th>Innovation model</th>
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<td>1. High-tech, iterative, disruptive</td>
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<td>4. General purpose</td>
<td>Micro-processors</td>
<td>Artificial intelligence</td>
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% ELECTRICITY FROM PV

- Germany
- Japan
- China
- US
- India

SHARE OF ELECTRICITY GENERATION

- 1950
- 1960
- 1970
- 1980
- 1990
- 2000
- 2010
- 2020

%
ACCELERATE INNOVATION

DACCS EXAMPLE

1st commercial
1957

Low cost
2017

Widespread adoption
2040

PV

Low cost
2076

Widespread adoption
2099

ClimeWorks

2017

Low cost
2017

Widespread adoption
2060

ClimeWorks

Low cost
2030

Widespread adoption
2060

Accelerated model
2017

Factor of 4 acceleration!

Negative emissions deployment in "likely" 2°C scenarios
ACCELERATE INNOVATION

DACCS EXAMPLE

Scale-up needed for 1% of emissions by 2025 vs PV actuals
PROF. GREGORY NEMET

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earthscan from Routledge
APPENDIX
### HOW TO ACCELERATE LOW-CARBON INNOVATION

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thousand peak kilowatts

- Solar photovoltaic case begins
- Tariffs announced
- Tariffs effective
REASONS FOR OPTIMISM

1. **technology** is improving
2. emerging **collective action**
3. learning from **policy experience**
4. success in **other areas**
5. **adaptation incentives** strong
6. **co-benefits**: local and immediate
7. **examples** of low-energy, high-HDI
8. **young adults**
BELL LABS 1954

The First PV Cell

Chapin, Fuller, Pearson

Solar Energy Converting Apparatus
1954

Components

- Scalf
  - High Purity Silicon
  - 1945
- Ohl
  - Light-sensitive Device
  - 1946
- Teal
  - Photoelectromotive Force Cells
  - 1947
- Ohl
  - Improved Light-sensitive Device
  - 1948
- Krkpatrick
  - Semiconductor Crystals
  - 1952
- Bell
  - Direct Current Reverse Power Controller
  - 1952
- Barton
  - Variable Impedance Device
  - 1951
- Sparks
  - Production of P-N Junction Semiconductor
  - 1953

Precursors

- Heydon et al., 1956
- Allen, 1912
- Flipp, 1935
- Blass, 1912
- Woodbridge, 1913
- Lunt, 1920
- Steiger et al., 1937
- Fless, 1909
- Bliss, 1912
- Rich, 1927
- Friedrich, 1937
- Barncy, 1949
- Hazel, 1925
- Lewis, 1933
- Boggart, 1937
- Waich, 1940
EVOLUTION OF NICHE MARKETS

- Total niche markets
- Rooftop
- Consumer products
- Other niches

SHARE OF WORLD PV INSTALLATIONS

1993 1995 1997 1999 2001 2003

- Technology Push
- Niche Markets
- Demand Pull
- Scale up
Feed in tariffs by year implemented
SOLAR PANELS ARE NOW EXTREMELY CHEAP
“Germany’s gift to the world”

- Feed in tariff: $400/MWh
- Surcharge: $0.20
- Installed capacity: 8,000 MW

Business
Cheap Renewables Shave $10 Trillion Off Cost to Curb Warming

By Brian Parkin
April 8, 2019, 10:00 PM CDT  Updated on April 9, 2019, 2:59 AM CDT

- Renewable energy group says wind and solar costs are plunging
- Abu Dhabi-based researcher calls for shift toward electricity
HOW TO SPEED UP INNOVATION
THE IRON LAW OF ENERGY POLICY:
Policymaking in energy always involves multiple objectives.

Cheap
- Affordability --> macro-economic shocks
- energy for the 2 billion

Clean
- health effects of air pollution --> damages from unstable climate

Reliable
- uninterrupted supply
- domestic/friendly sources --> negotiating on other issues
TRANSITIONS ARE SLOW

...and so is removing CO2
ENERGY TRANSITIONS ARE HARD

1. Want CHEAP, CLEAN, RELIABLE

2. Past transitions took decades

3. CO$_2$ in atmosphere for >100 yrs