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

Gregory F. Nemet
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

Wind

Batteries

($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

$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

- 2000-08: Scrappy startups
- 2009-10: State support
- 2011-: Compete, automate
- 2017-: Cheap electricity

- 0 0.05 0.1 0.15 0.2 0.25 0.3

Share of global production by largest firm

- 50%

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

- 2011: Chinese Feed-in tariff

- 2013: World's largest market

- "Gift to the West"

- China's own gift to the world

- Low-cost expansion strategy

- Iterative upscaling

- Used equipment

- US pension funds

- Sell to Germany

- 2012 world’s largest market for solar technology
IMPROVEMENTS IN PV MANUFACTURING

- **Plant size**
  - 1980: 0 MW
  - 2000: 1000 MW
  - 2020: 2000 MW

- **Efficiency**
  - 1980: 0.05
  - 1990: 0.1
  - 2000: 0.15

- **Silicon price**
  - 1980: 100 $/kg
  - 1990: 50 $/kg
  - 2000: 0 $/kg

- **Wafer area**
  - 1980: 100 cm²
  - 2000: 200 cm²
  - 2020: 300 cm²

- **Wafer thickness**
  - 1980: 0.2 m
  - 2000: 0.1 m
  - 2020: 0.06 m

- **Yield**
  - 1980: 0.2
  - 2000: 0.6
  - 2020: 0.8
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>
<th>Low-carbon target</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. High-tech, iterative, disruptive</td>
<td>Solar PV</td>
<td>Direct air capture</td>
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<td>2. Low-tech, small, distributed</td>
<td>Green revolution</td>
<td>Soils</td>
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<tr>
<td>3. Large, system integration intensive</td>
<td>Chemical plants</td>
<td>BECCS</td>
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<td>4. General purpose</td>
<td>Micro-processors</td>
<td>Artificial intelligence</td>
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ACCELERATE INNOVATION

DACCS EXAMPLE

ClimeWorks 1st commercial 1957

Low cost 2017

Widespread adoption 2040

Widespread adoption 2099

DACCS 2017

Low cost 2076

Widespread adoption 2099

PV

Accelerated model 2017

Low cost 2030

Widespread adoption 2060

Factor of 4 acceleration!

Negative emissions deployment in "likely" 2°C scenarios

Gross negative emissions (GtCO₂/year)
Scale-up needed for 1% of emissions by 2025 vs PV actuals
ACCELERATE INNOVATION

TECHNOLOGY PULL
CONTINUOUS R&D
TRAINED WORKFORCE
PUBLIC PROCUREMENT

KNOWLEDGE FLOWS
CODIFY KNOWLEDGE
KNOWLEDGE SPILLOVERS
GLOBAL MOBILITY

DEMAND PULL
ROBUST MARKETS
DISRUPTIVE PRODUCTION
POLITICAL ECONOMY
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