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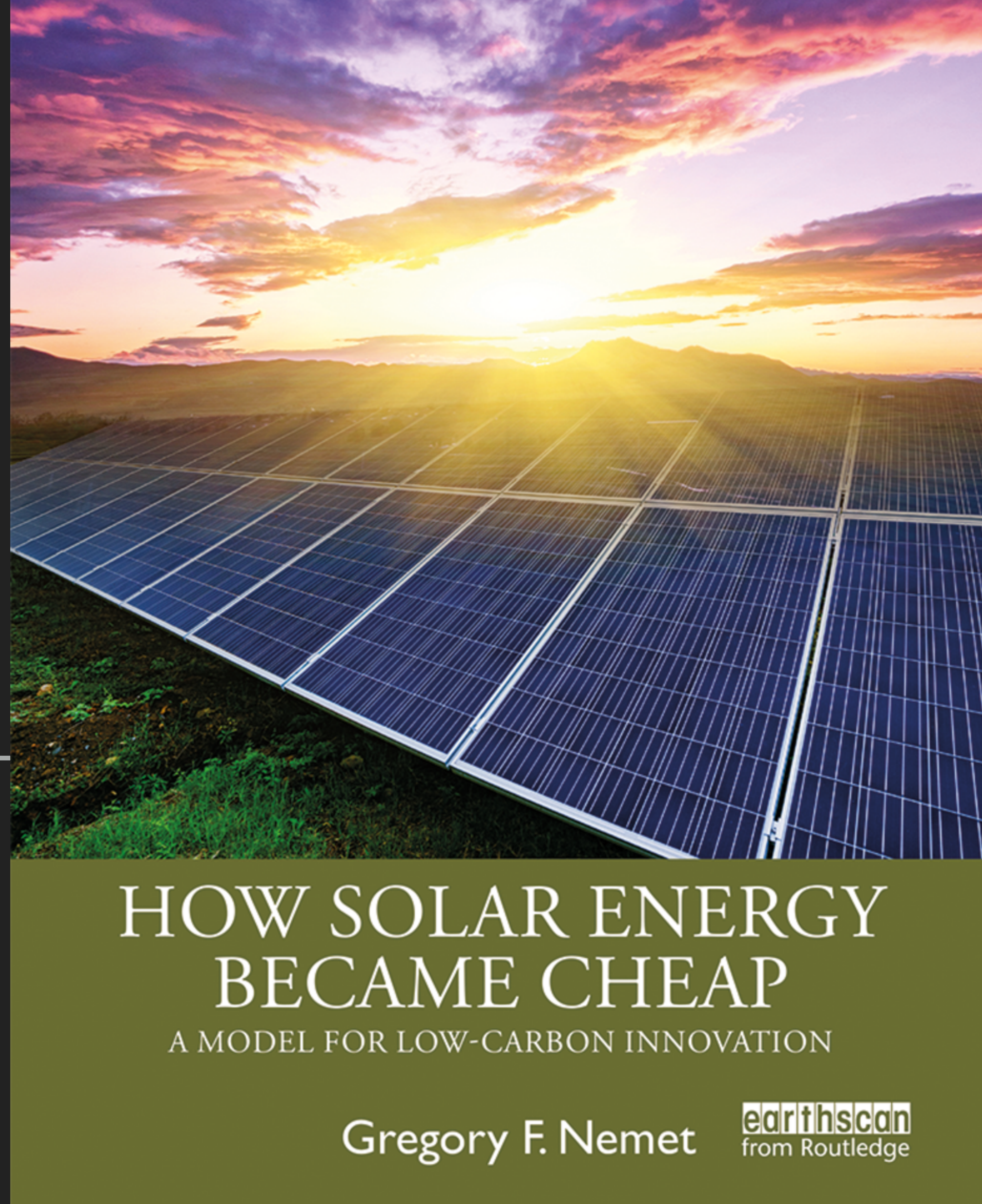
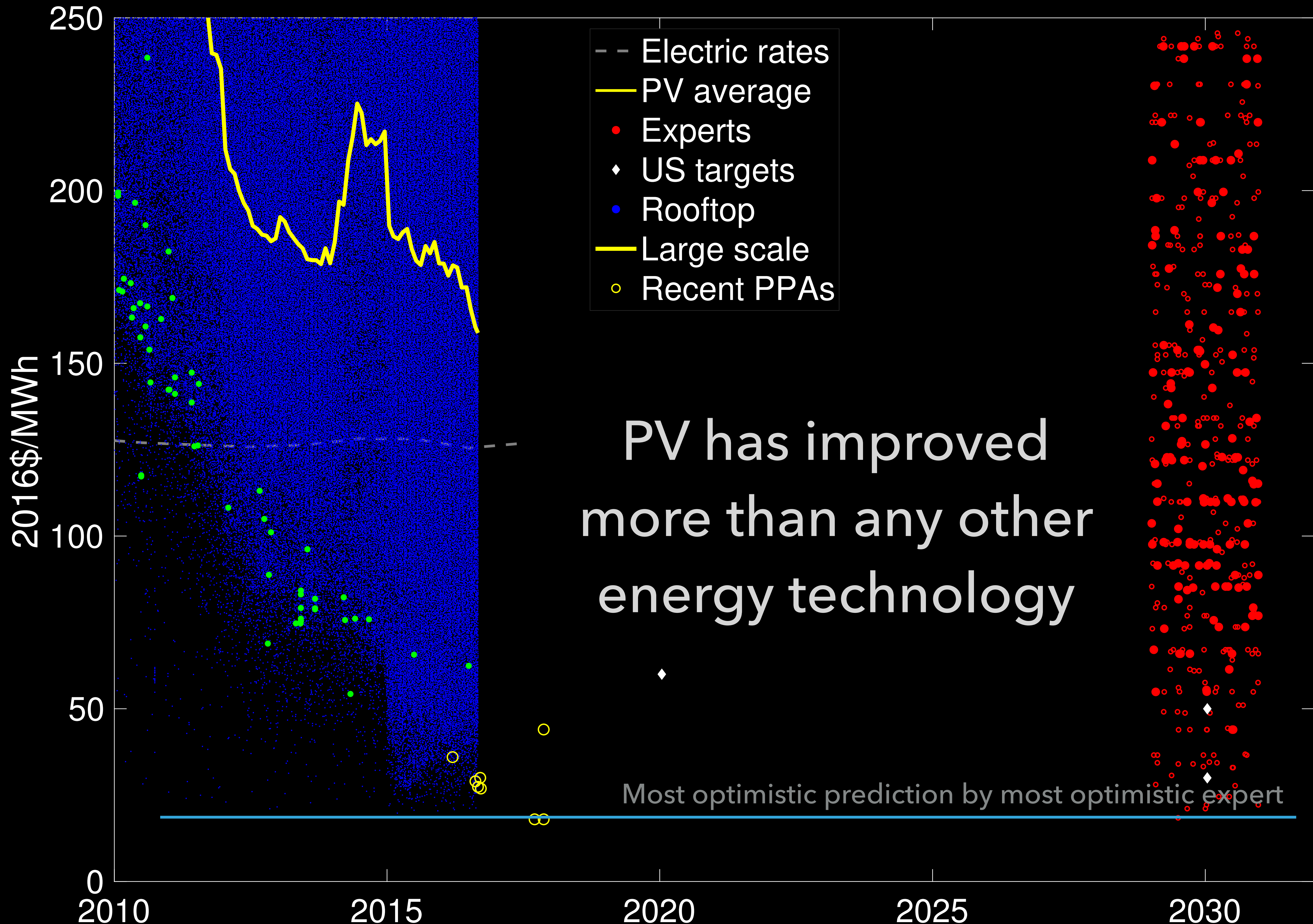
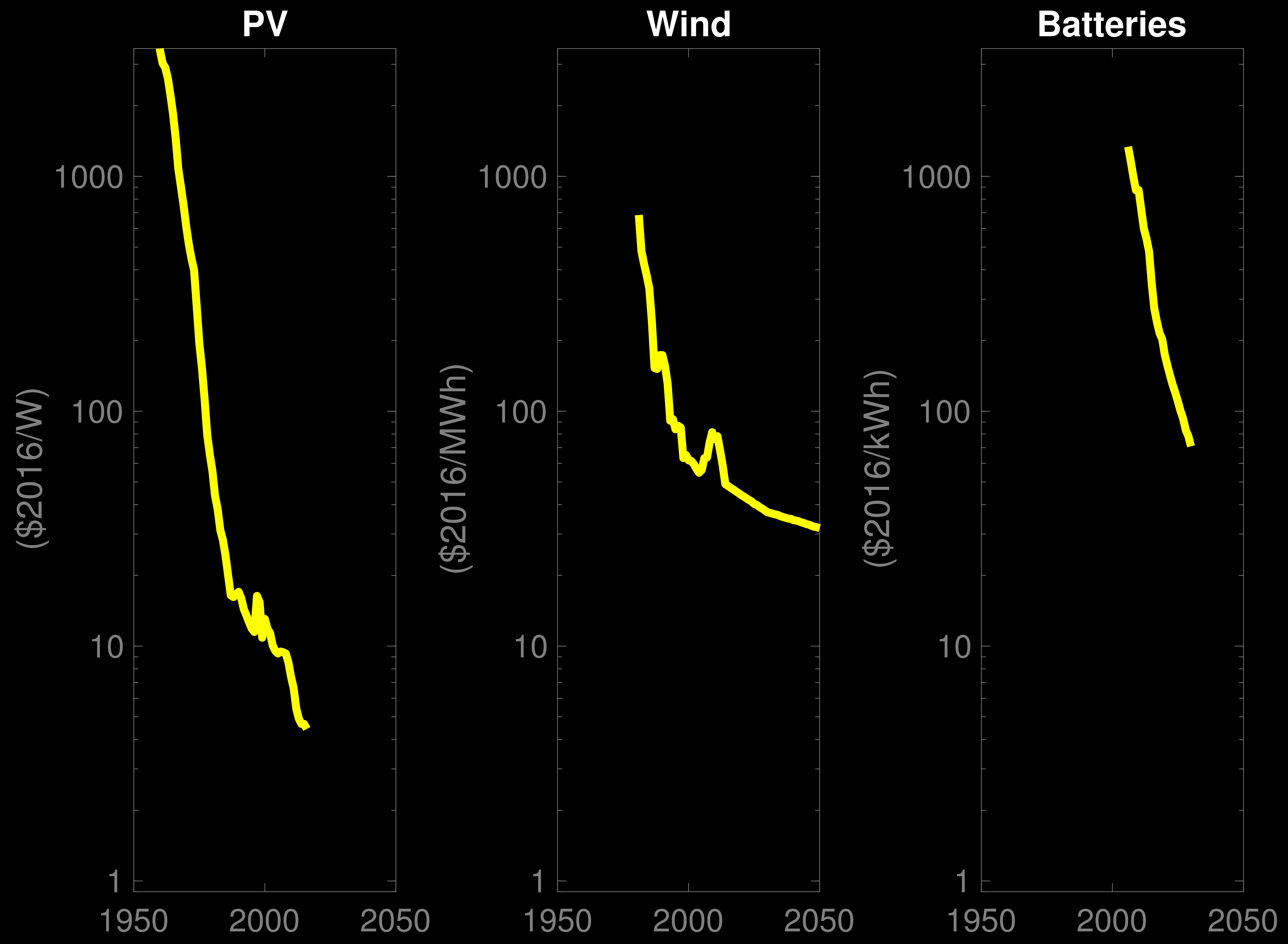


PV IS NOW CHEAP...BEYOND EXPECTATIONS



PV has improved more than any other energy technology

LONG TERM COST REDUCTIONS

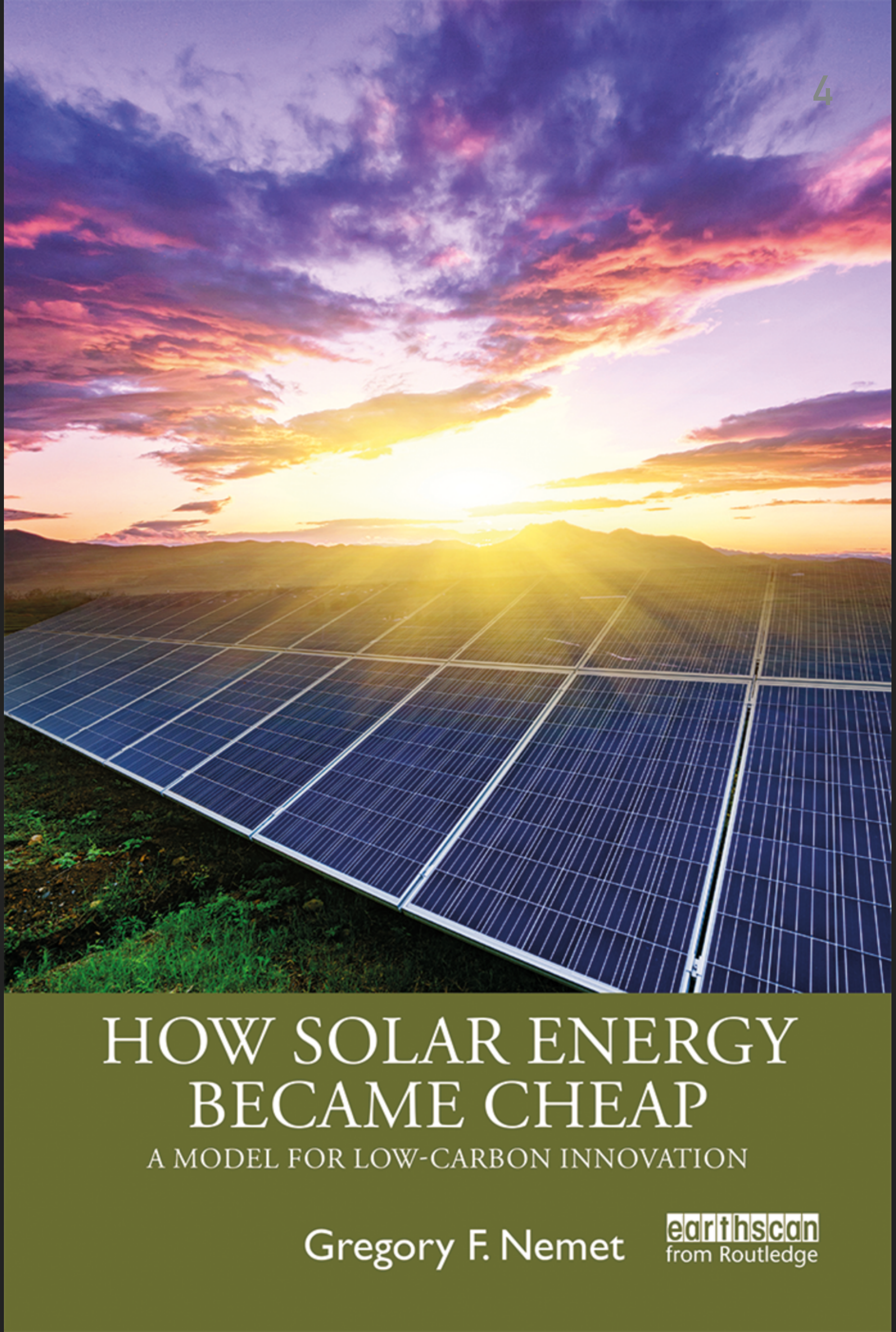


RESEARCH QUESTIONS

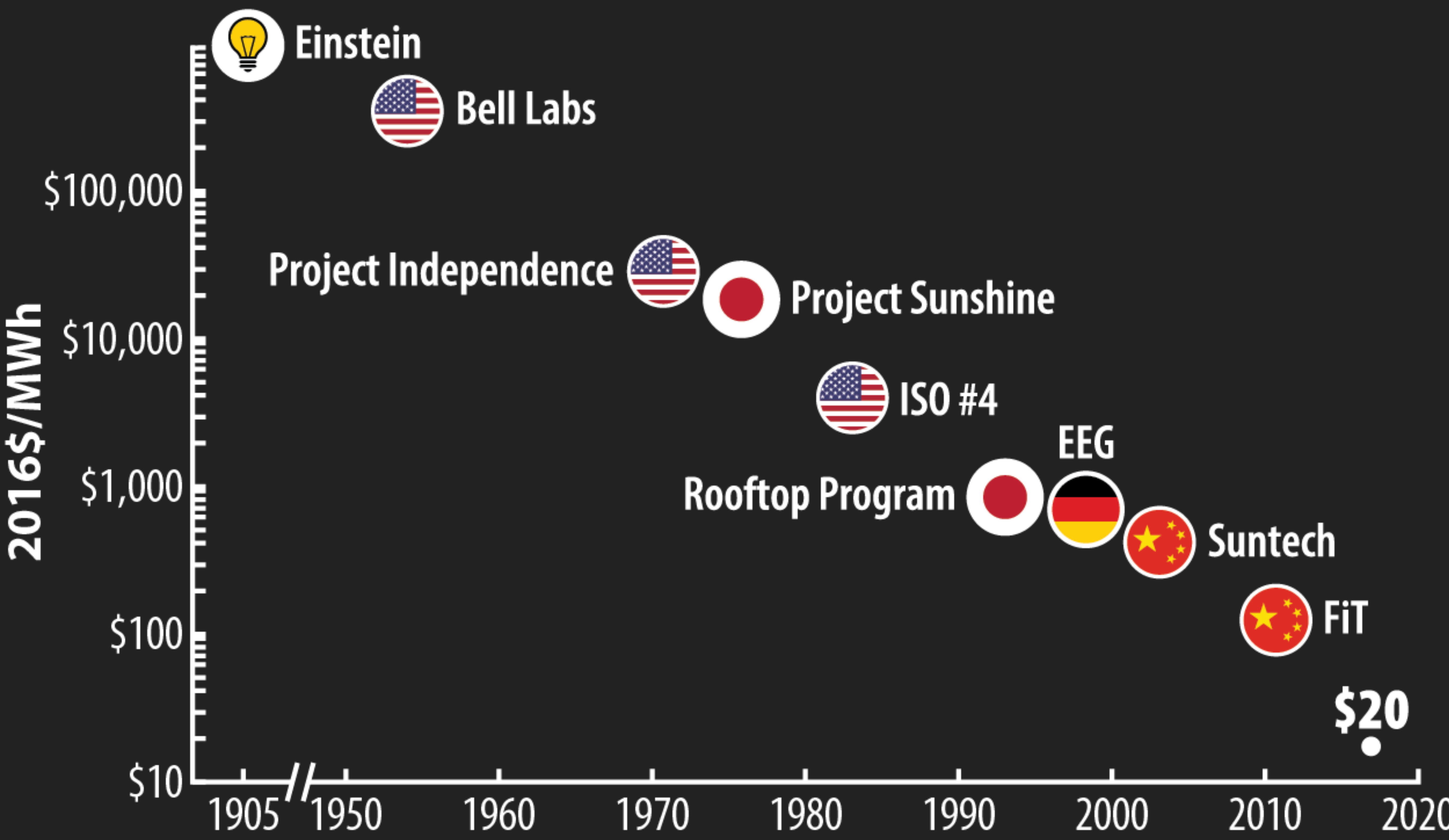
1. How did solar become cheap?
2. Why did it take so long?
3. How can it be a model

ANDREW CARNEGIE **FELLOWS** PROGRAM

This study was made possible by a grant from Carnegie Corporation of New York. The statements made and views expressed are solely the responsibility of the author.

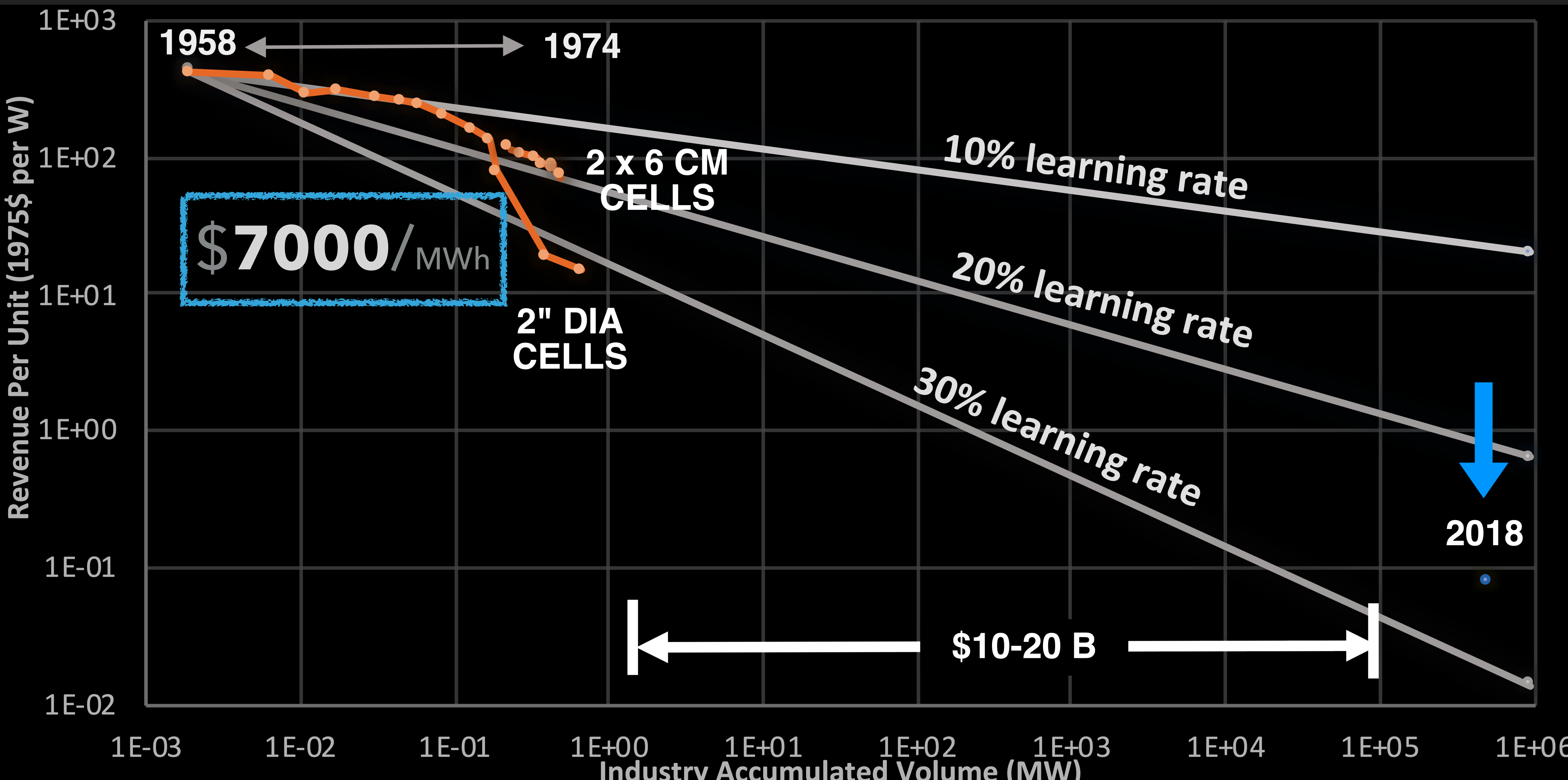


MILESTONES 10-4



PROJECT INDEPENDENCE

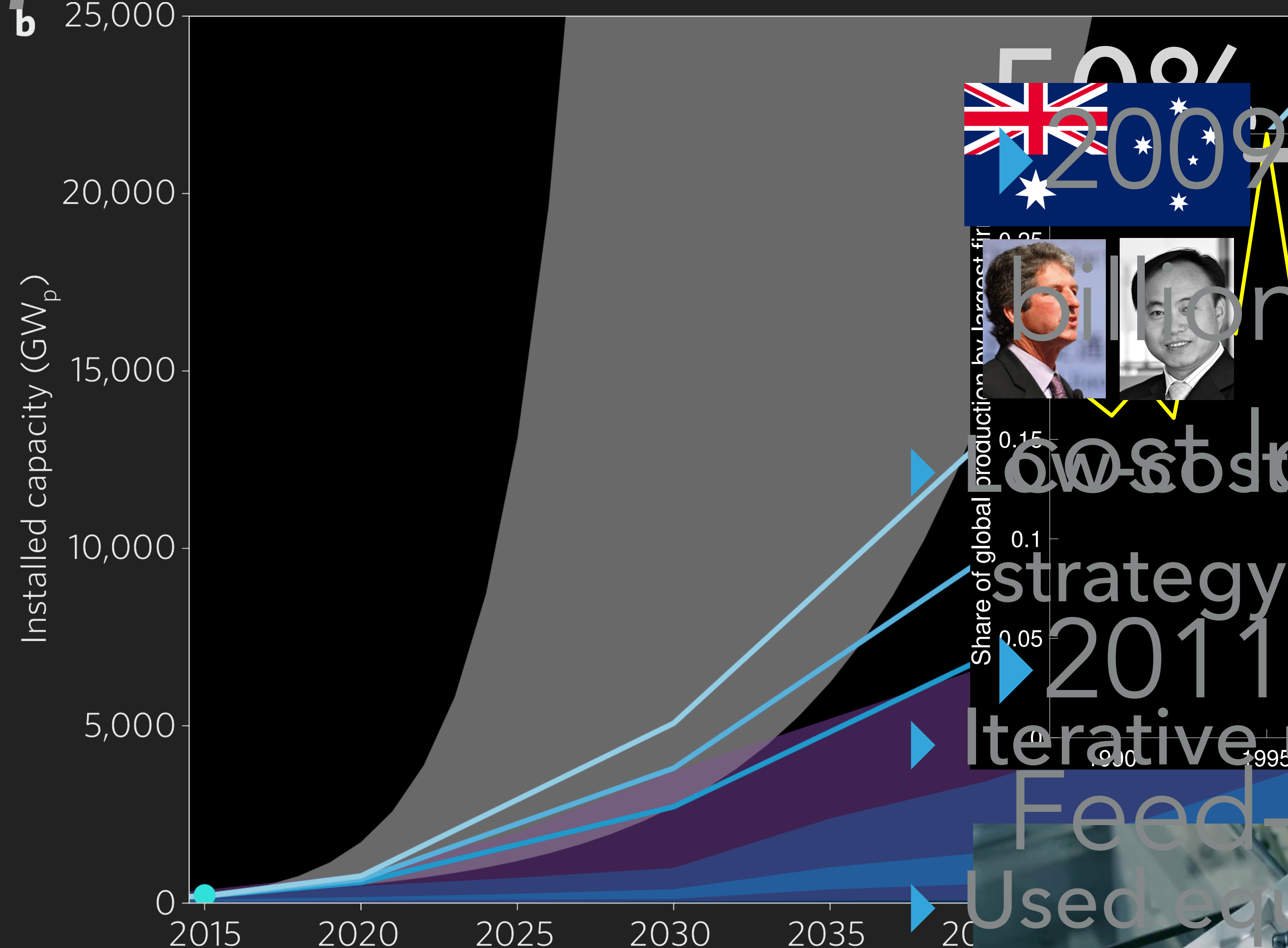
1ST PV LEARNING CURVE



GERMANY: *CREATING A MARKET*

1. **Policy window**
2. **Policy diffusion**
3. **Demand Pull**
4. **"Gift to the world"**

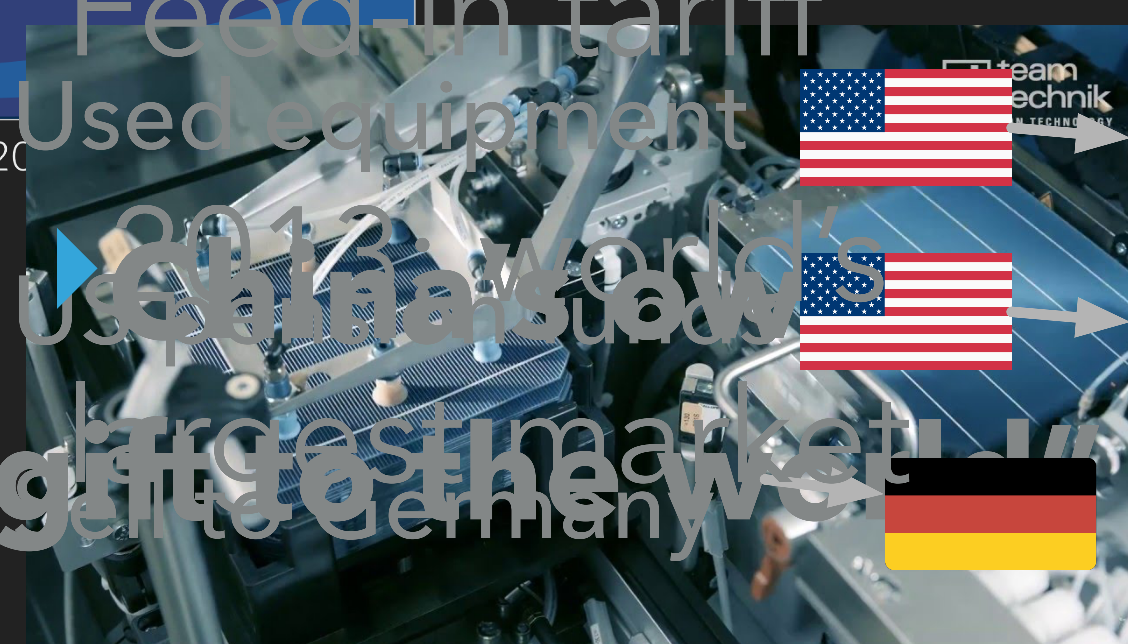
CHINA: *MAKING IT CHEAP*



- 2009-10: $10s billions of low cost loans
- Low-cost expansion strategy
- 2011: Chinese
- Iterative upscaling
- Feed-in tariff
- Used equipment
- 2013: world's largest market
- US…
- Sell to Germany

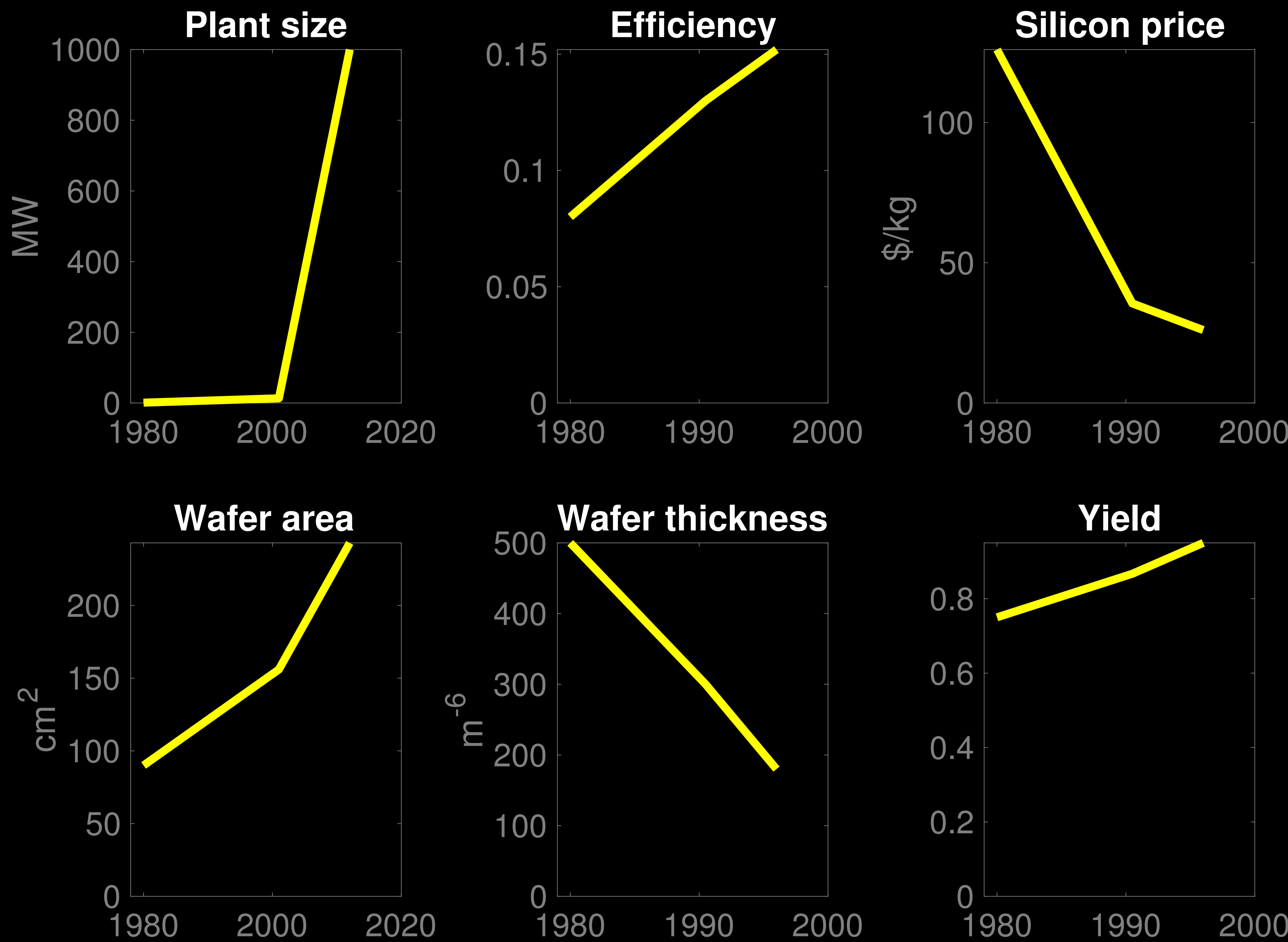
China's low

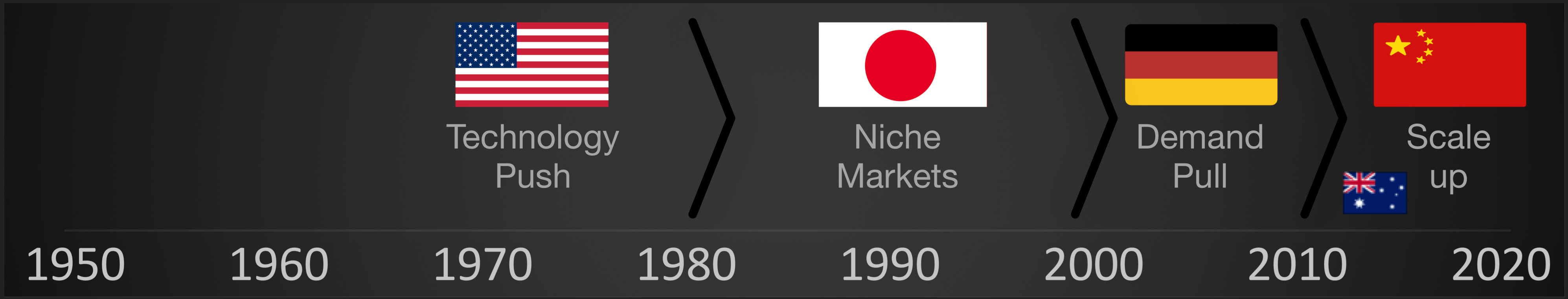
"gift to the west"

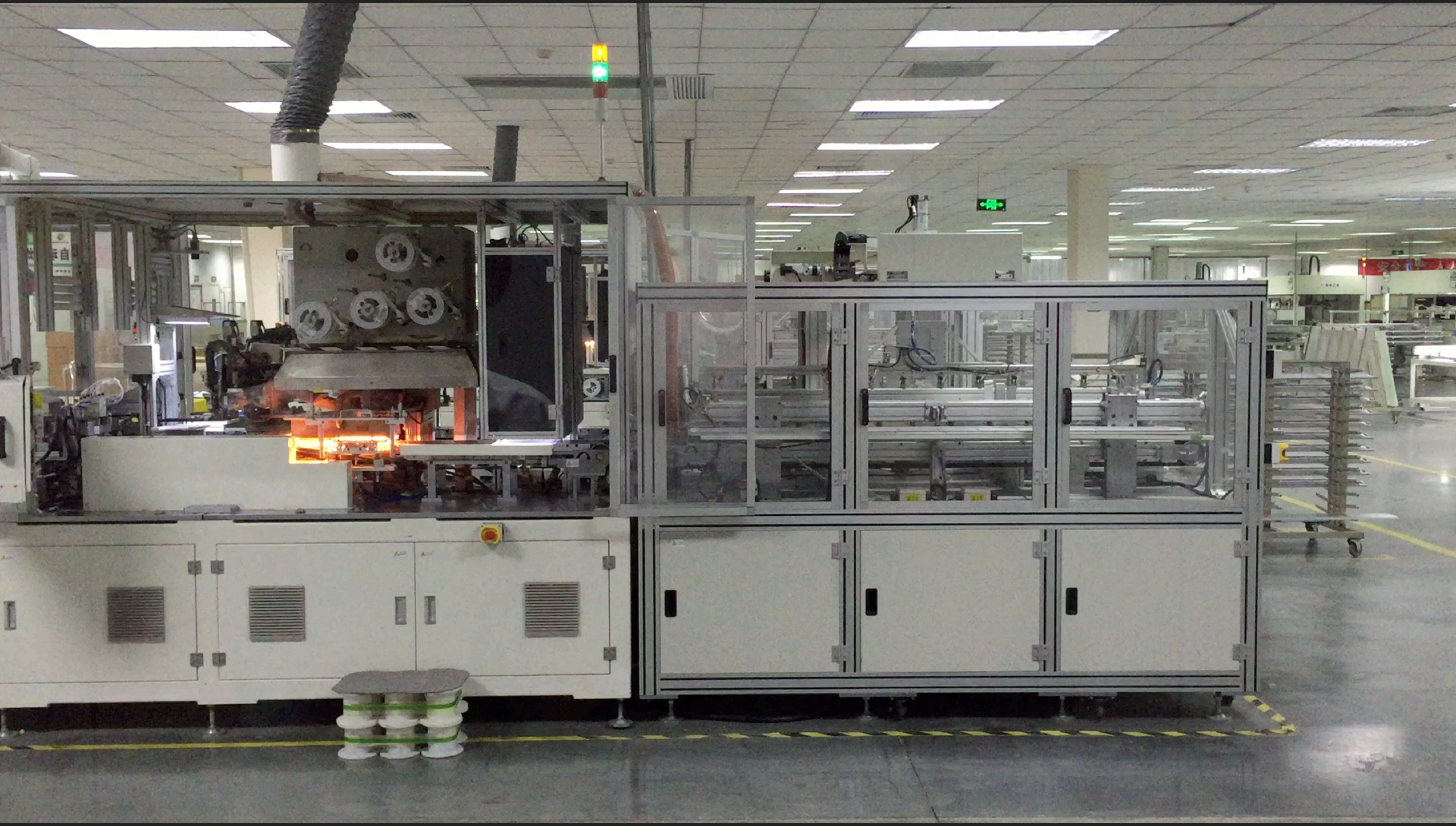


2017-> **cheap electricity**

IMPROVEMENTS IN PV MANUFACTURING




Technology
Push
Niche
Markets
Demand
Pull
Scale
up
1950
1960
1970
1980
1990
2000
2010
2020



HOW DID SOLAR GET CHEAP?

CREATING TECHNOLOGY → BUILDING A MARKET → MAKING IT 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

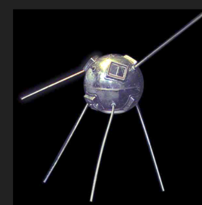
Technology type	Innovation model	Low-carbon target
1. High-tech, iterative, disruptive	Solar PV	Direct air capture
2. Low-tech, small, distributed	Green revolution	Soils
3. Large, system integration intensive	Chemical plants	BECCS
4. General purpose	Micro-processors	Artificial intelligence

% ELECTRICITY FROM PV

DACCS EXAMPLE

1st commercial — Low cost — Widespread adoption

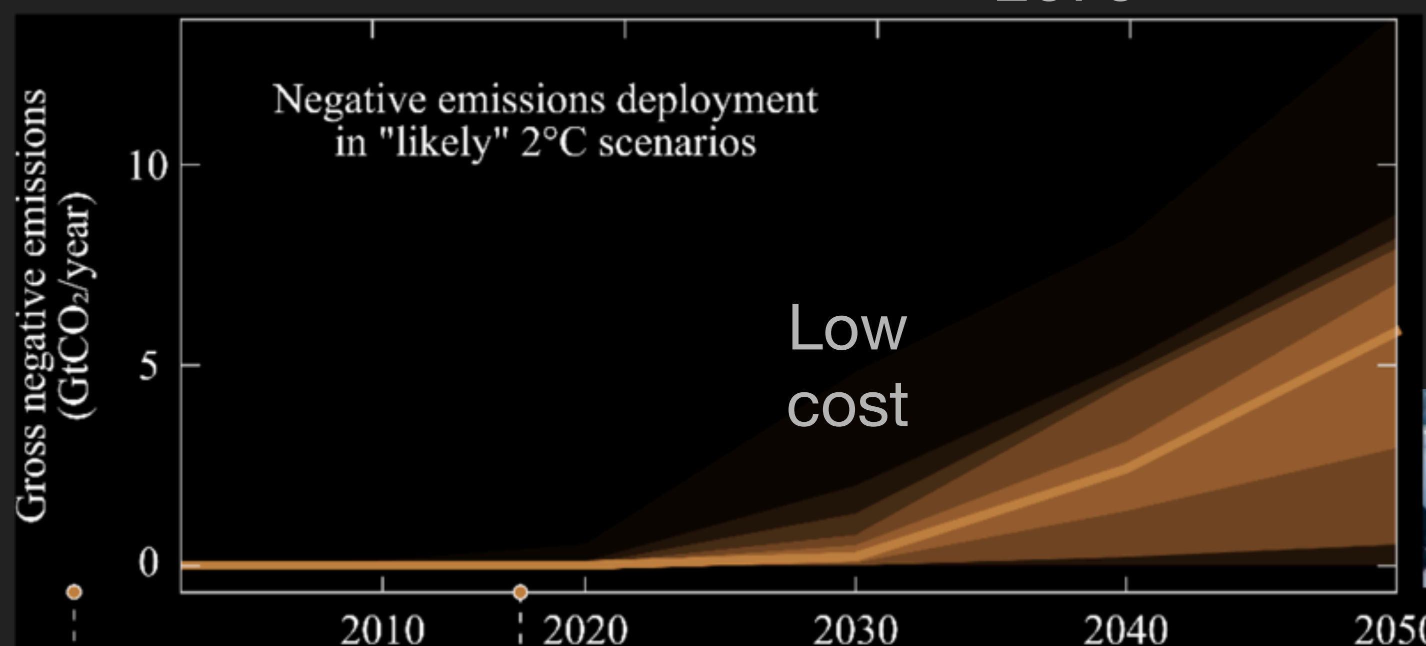
1957 — 2017 — 2040



DACCS

ClimeWorks — Low cost — Widespread adoption

2017 — 2076 — 2099



Widespread adoption

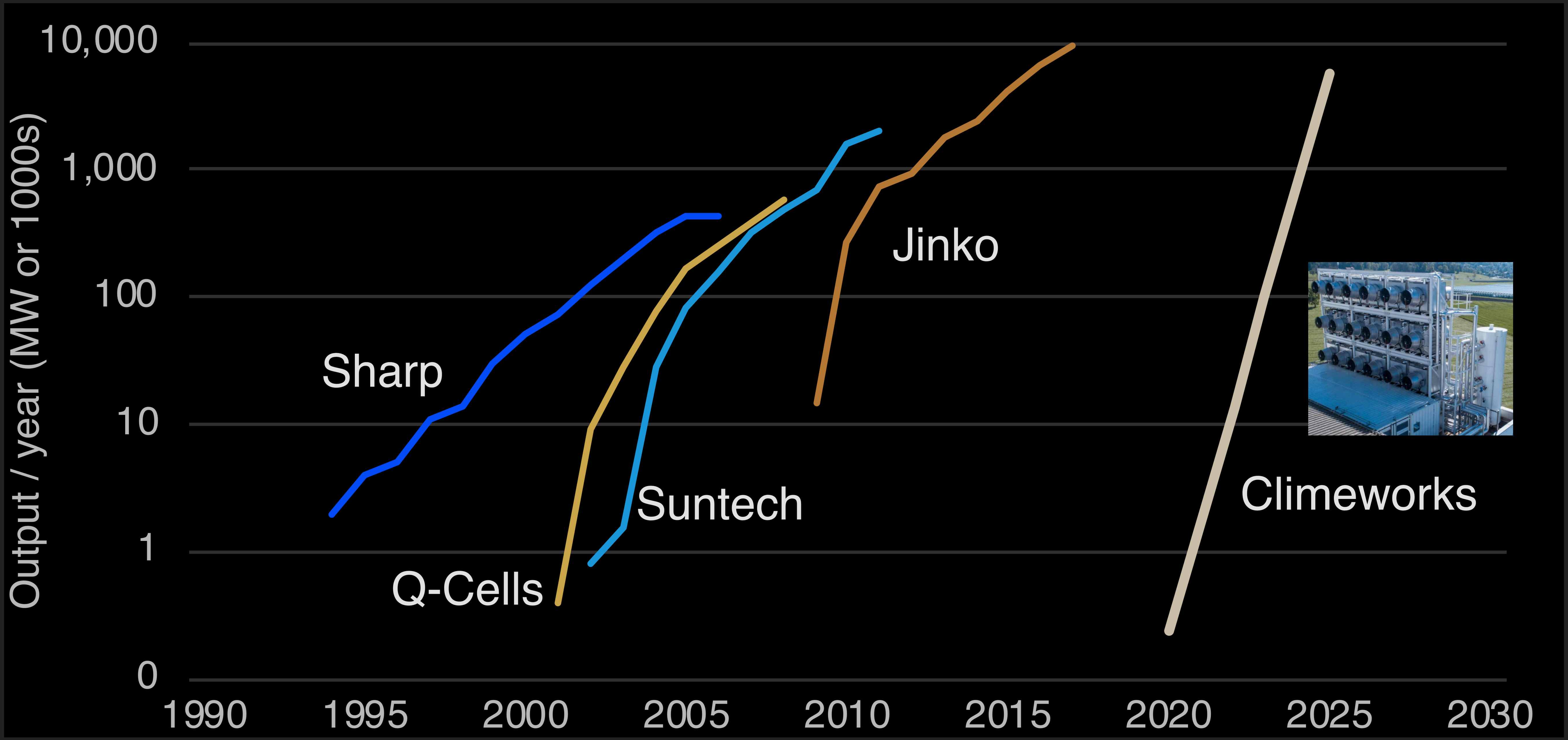
Accelerated model

ClimeWorks — Low cost — Widespread adoption

2017 — 2030 — 2060

Factor of 4 acceleration!

Scale-up needed for 1% of emissions by 2025 vs PV actuals



ACCELERATE INNOVATION

TECHNOLOGY PUSH

- 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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