PROF. GREGORY NEMET

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UNIVERSITY OF WISCONSIN–MADISON

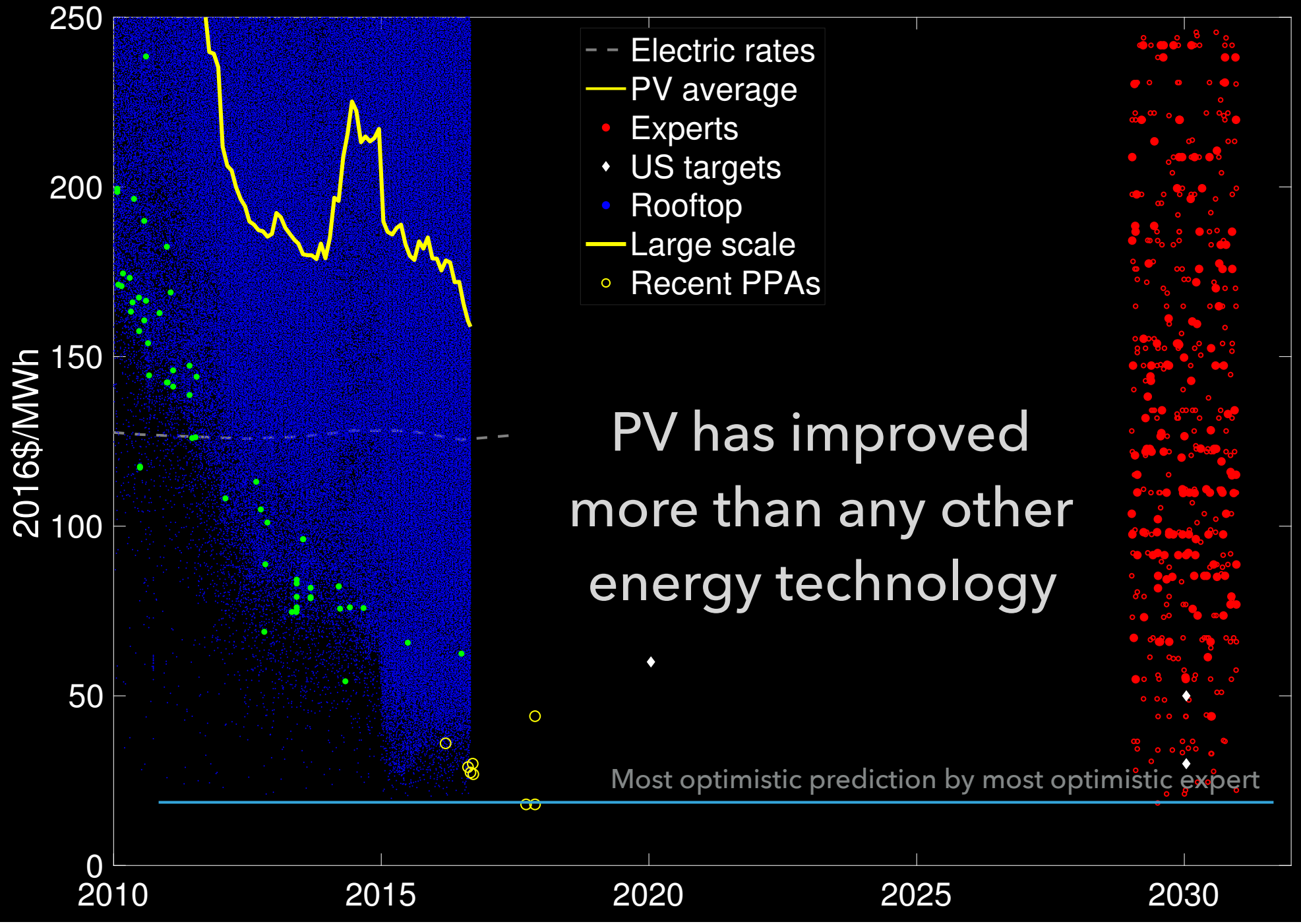
HOW SOLAR ENERGY BECAME CHEAP

A MODEL FOR LOW-CARBON INNOVATION

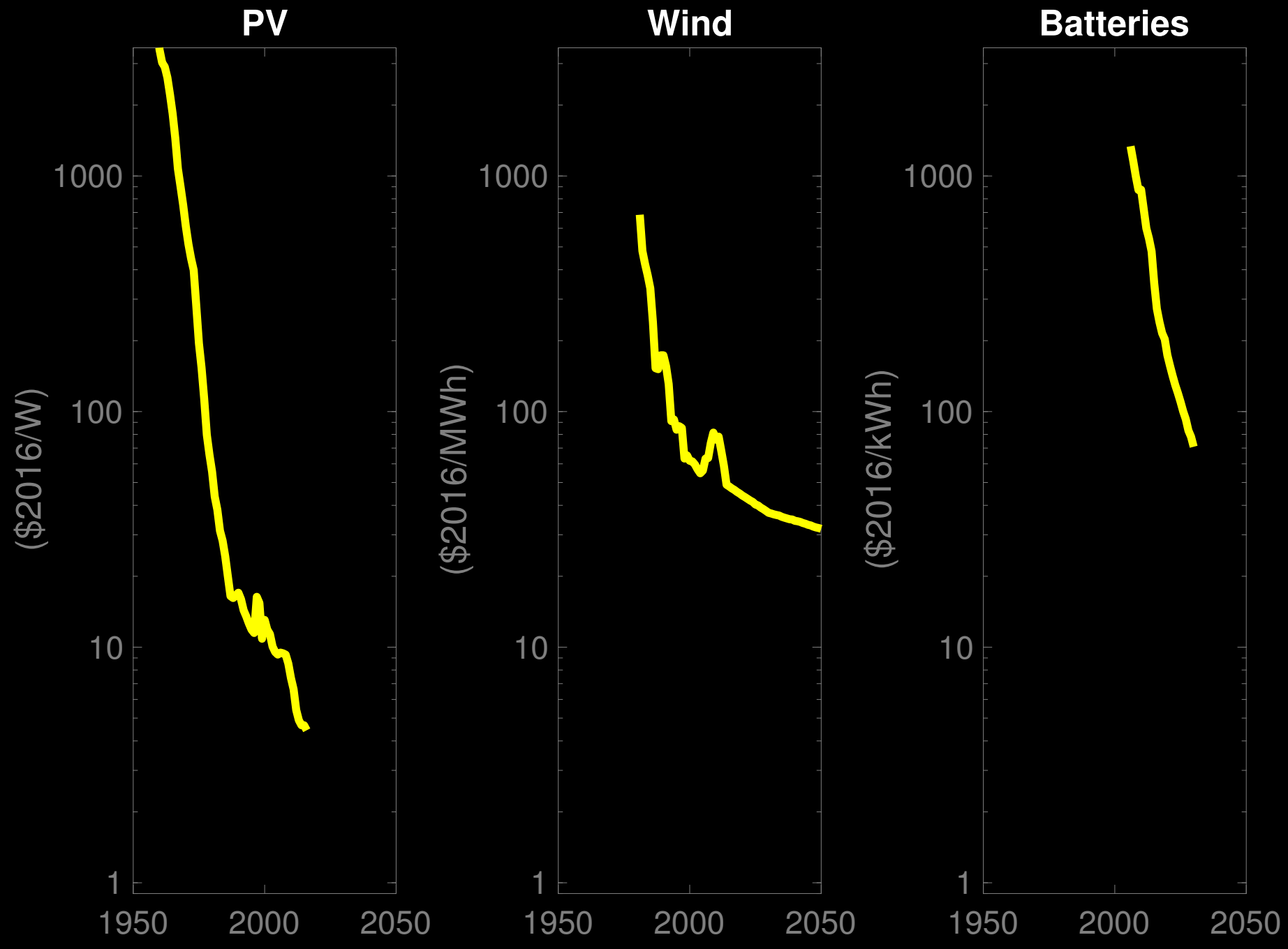
Gregory F. Nemet

earthscan from Routledge

PV IS NOW CHEAP...BEYOND EXPECTATIONS



LONG TERM COST REDUCTIONS



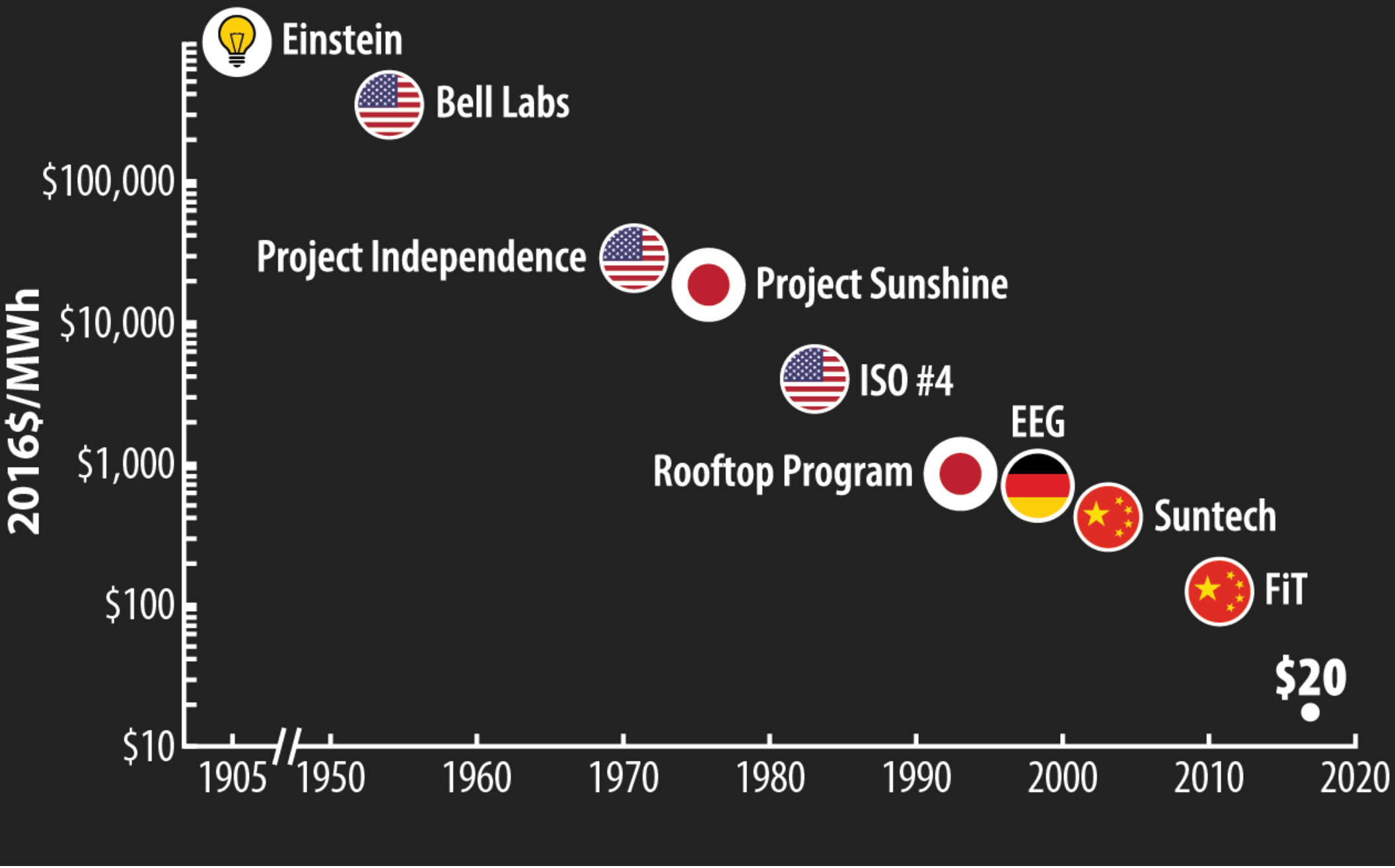
RESEARCH QUESTIONS

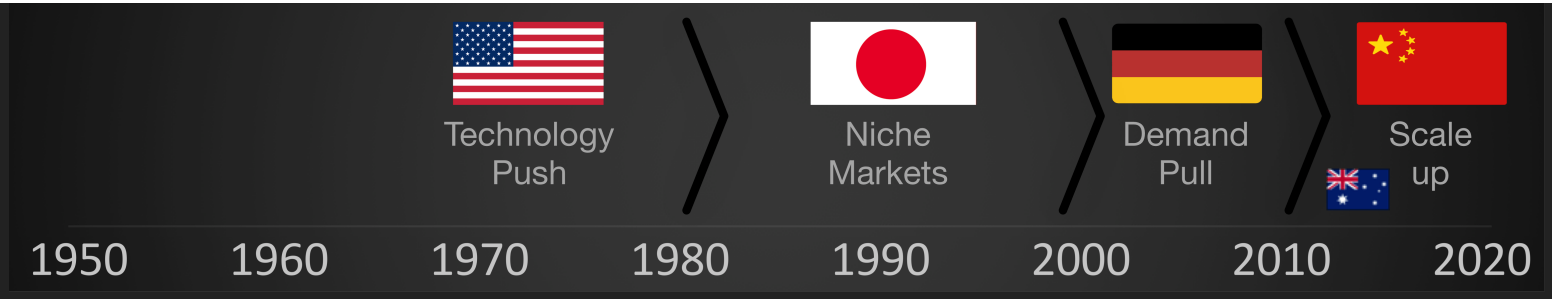
1. How did solar become cheap?
2. Why did it take so long?
3. How can it be a model

ANDREW CARNEGIE FELLOWS PROGRAM

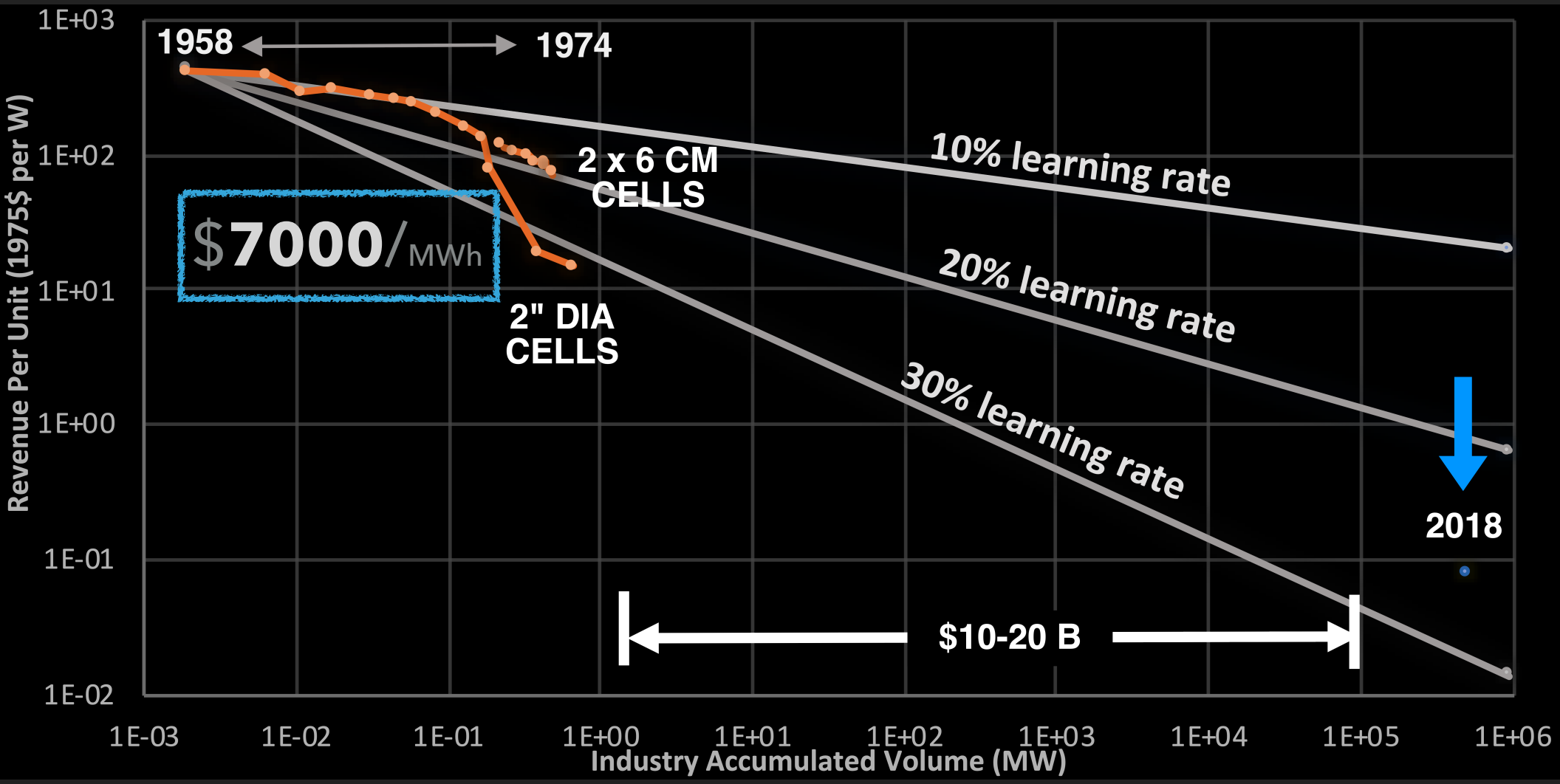
This study was made possible by a grant from Carnegie Corporation of New York. The statements made and views expressed are solely the responsibility of the author.

MILESTONES 10-4

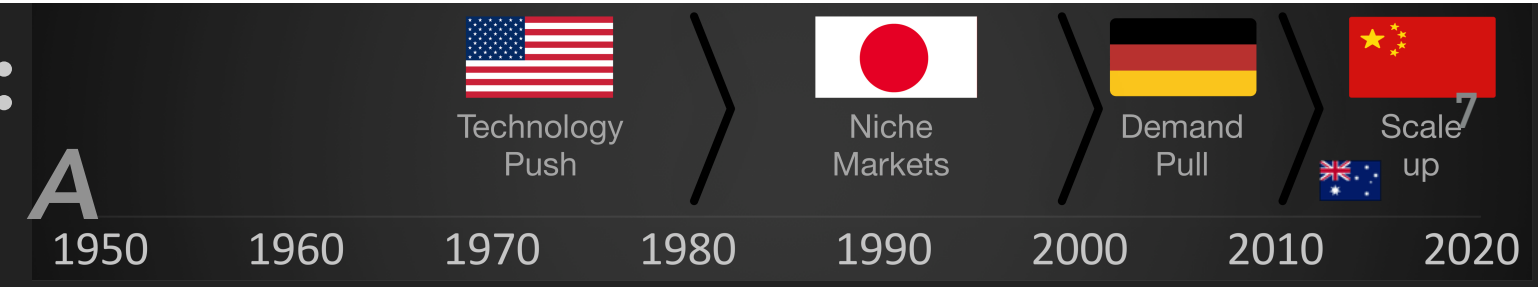




PROJECT INDEPENDENCE 1ST PV LEARNING CURVE



GERMANY: *CREATING A MARKET*

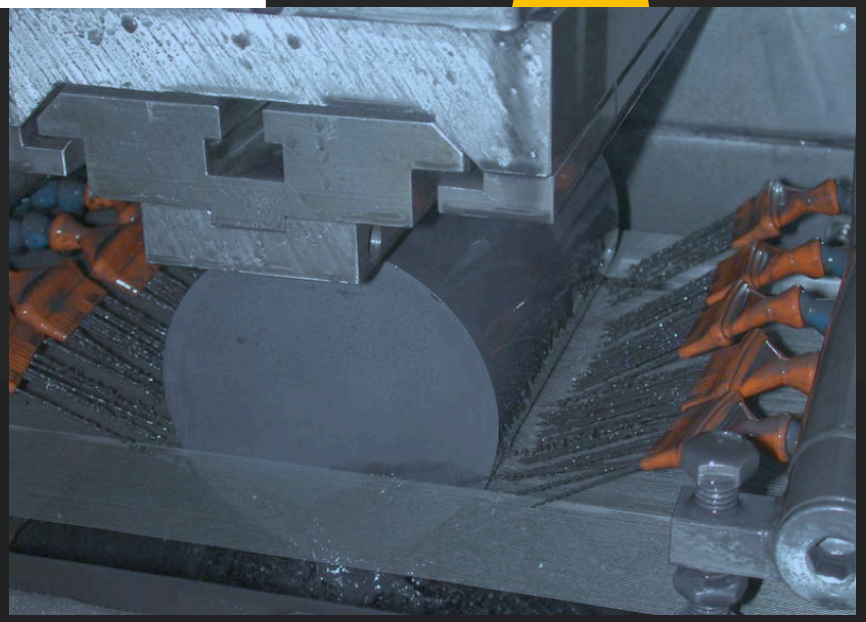


1. Policy window

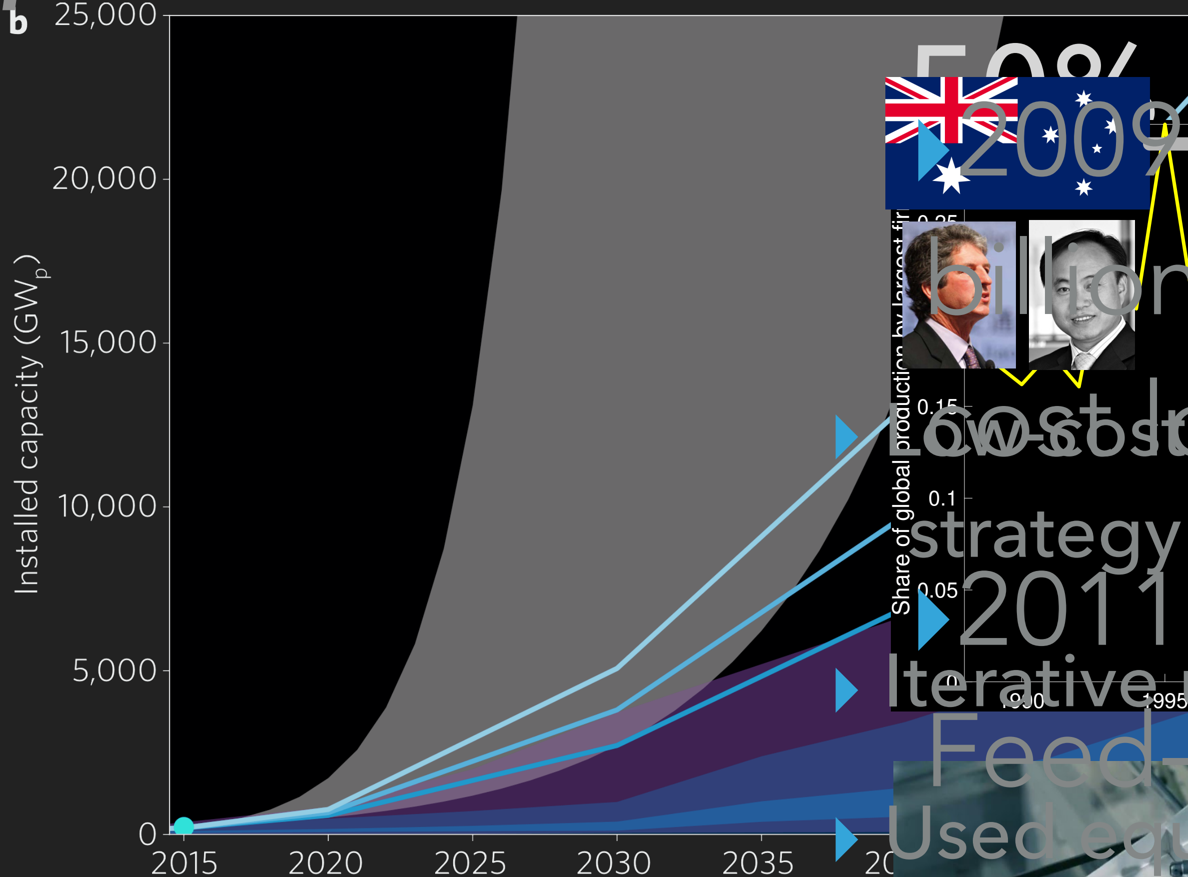
2. Policy diffusion

3. Demand Pull

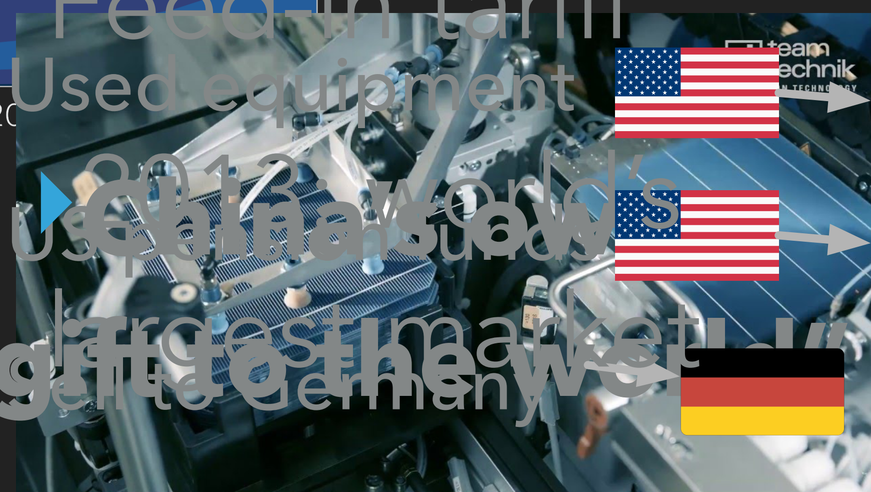
4. "Gift to the world"



CHINA:
MAKING IT CHEAP



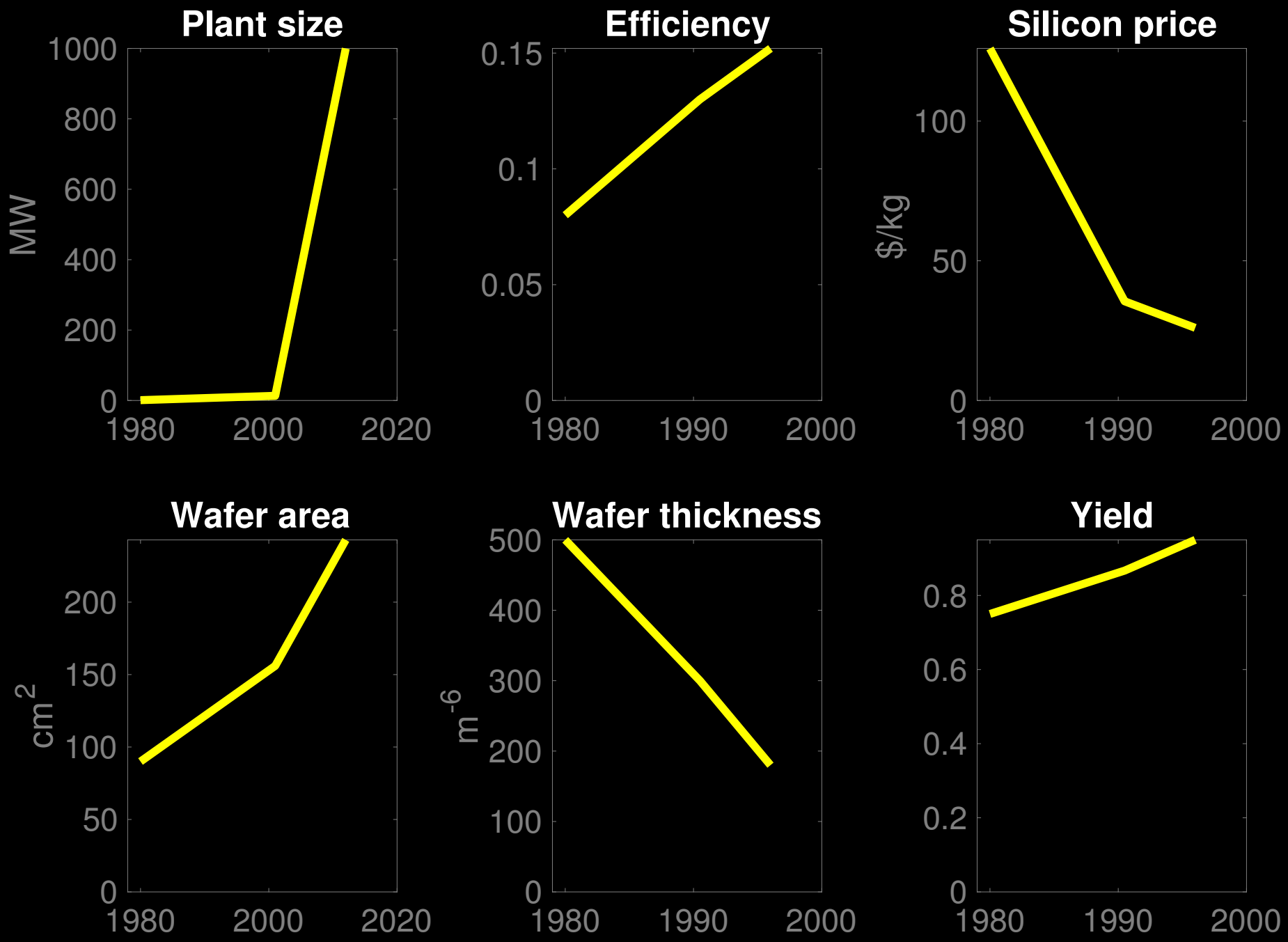
- 2009-10: $10s billions of low cost loans
- Low-cost expansion strategy
- 2011: Chinese
- Iterative upscaling
- Feed-in tariff
- Used equipment
- 2013: world's largest market
- China's own
- Sell to Germany

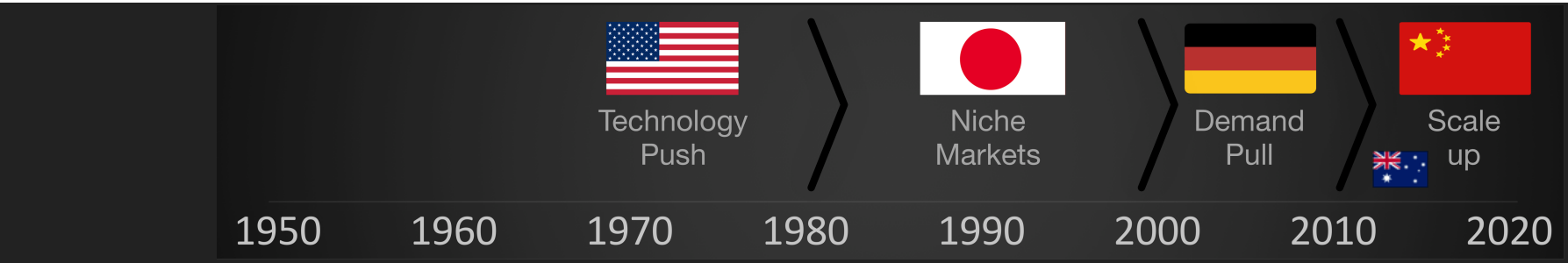


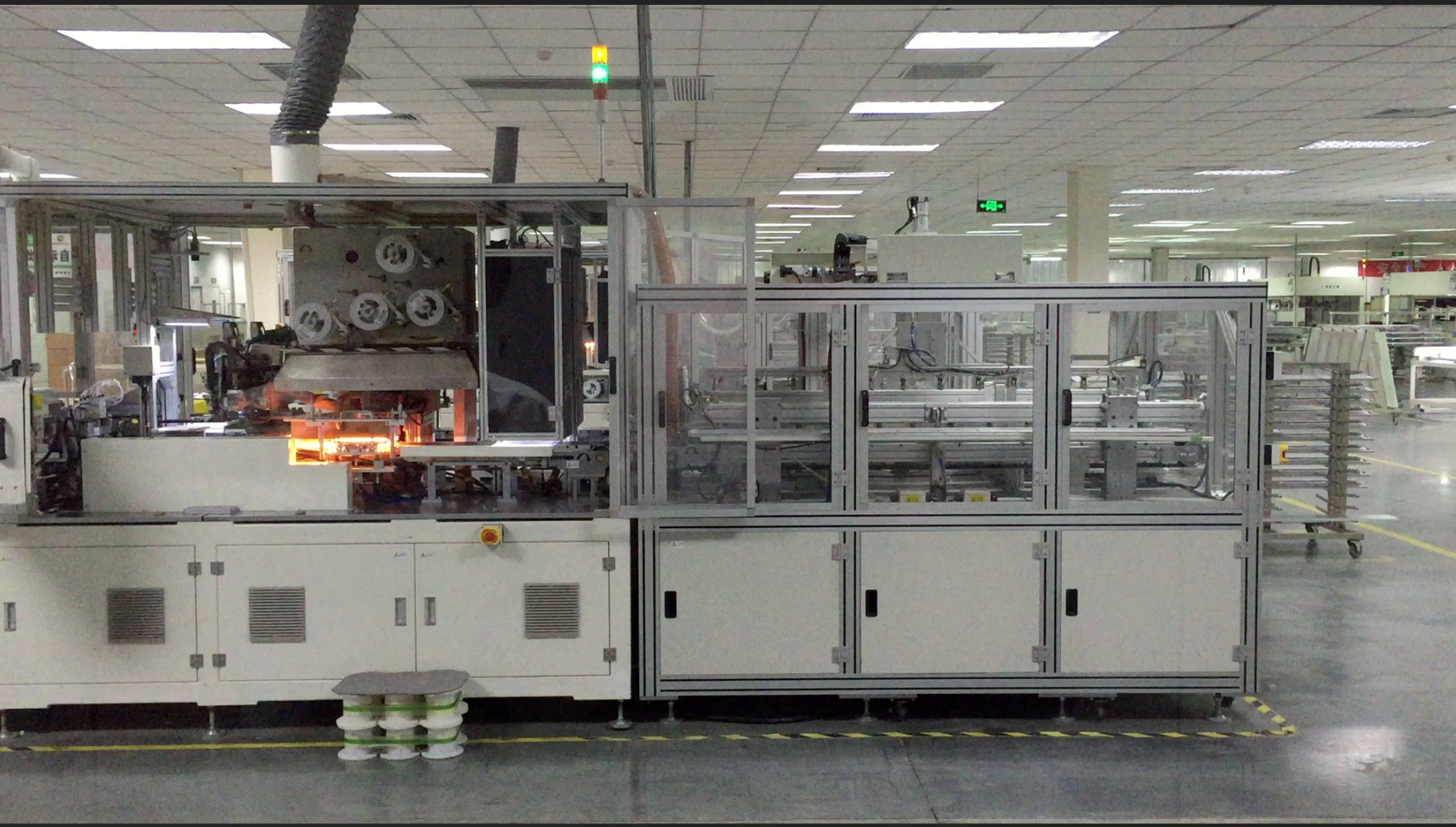
“gift to the world”

2017-> **cheap electricity**

IMPROVEMENTS IN PV MANUFACTURING



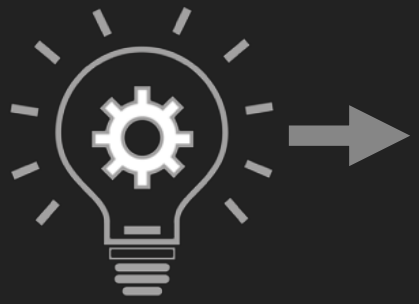

Technology Push
Niche Markets
Demand Pull
Scale up
1950
1960
1970
1980
1990
2000
2010
2020



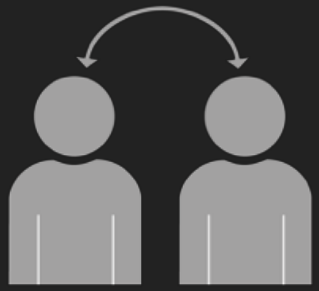
HOW DID SOLAR GET CHEAP?

CREATING TECHNOLOGY

SCIENTIFIC UNDERSTANDING

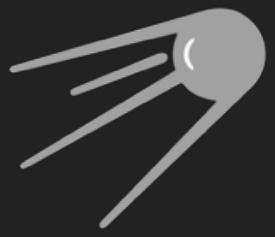


EVOLVING R&D FOCI



KNOWLEDGE SPILLOVERS

BUILDING A MARKET



NICHE MARKETS

MODULAR SCALE

ROBUST POLICY SUPPORT

MAKING IT CHEAP

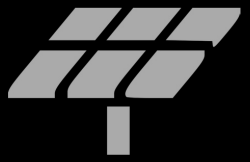
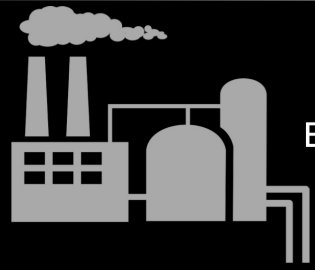
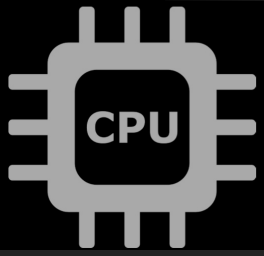
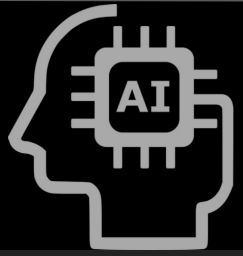
LEARNING BY DOING

ITERATIVE UPSCALING

DELAYED SYSTEM INTEGRATION

PV AS A MODEL FOR LOW-CARBON INNOVATION

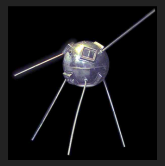
WE NEED MULTIPLE MODELS

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
1957



Low cost
2017

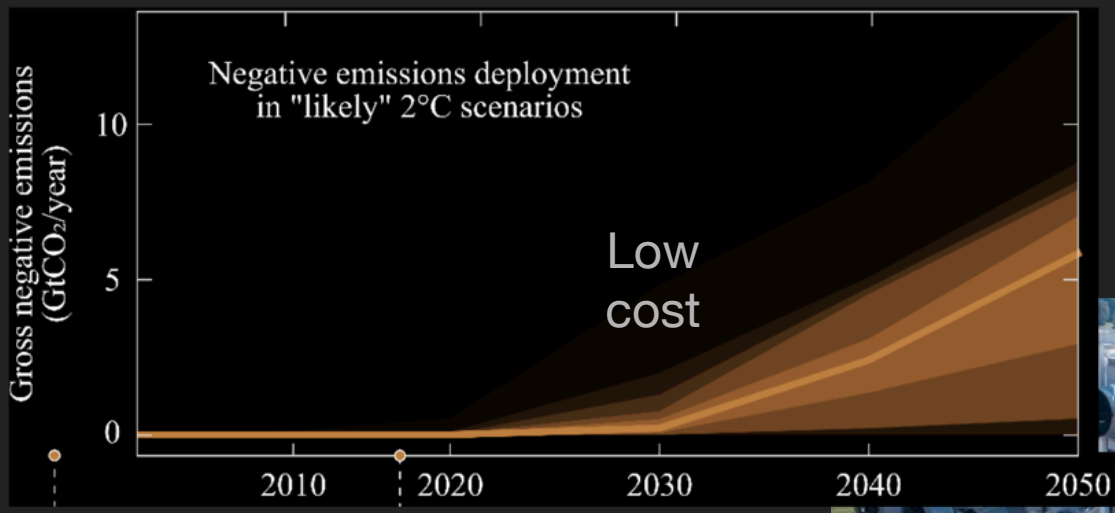
Widespread adoption
2040

DACCS

ClimeWorks
2017

Low cost
2076

Widespread adoption
2099



Widespread adoption

Accelerated model

ClimeWorks
2017

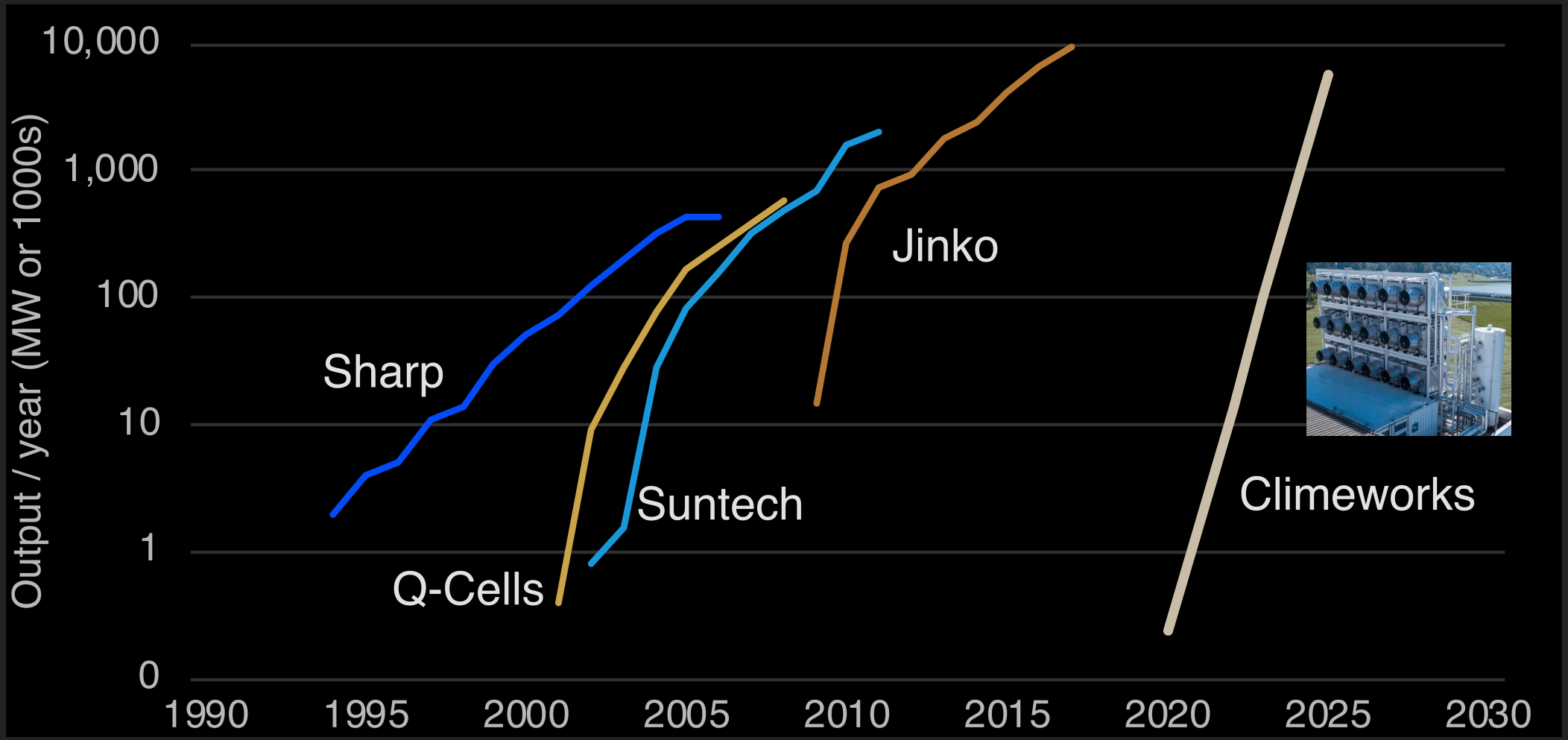
Low cost
2030

Widespread adoption
2060

Factor of 4 acceleration!

DACCS EXAMPLE

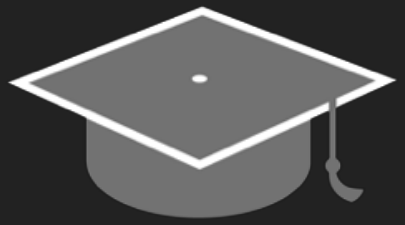
Scale-up needed for 1% of emissions by 2025 vs PV actuals



ACCELERATE INNOVATION

TECHNOLOGY PUSH

CONTINUOUS R&D

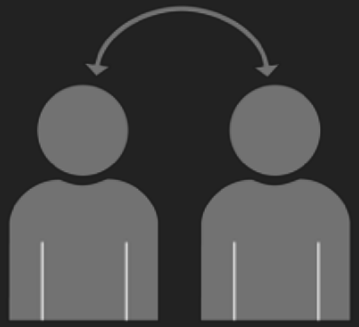


TRAINED WORKFORCE

PUBLIC PROCUREMENT

KNOWLEDGE FLOWS

CODIFY KNOWLEDGE



KNOWLEDGE SPILLOVERS

GLOBAL MOBILITY

DEMAND PULL

ROBUST MARKETS

DISRUPTIVE PRODUCTION

POLITICAL ECONOMY

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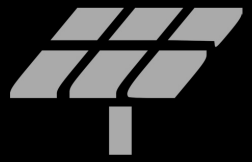
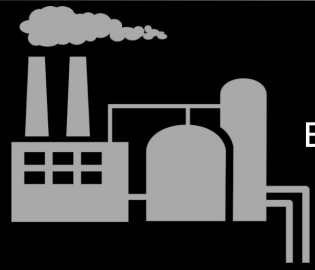
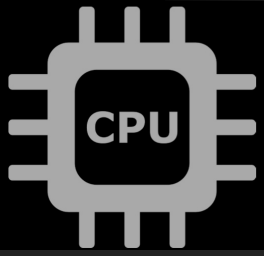
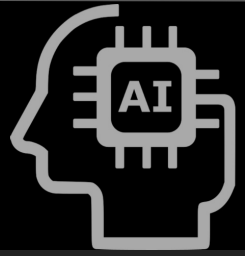
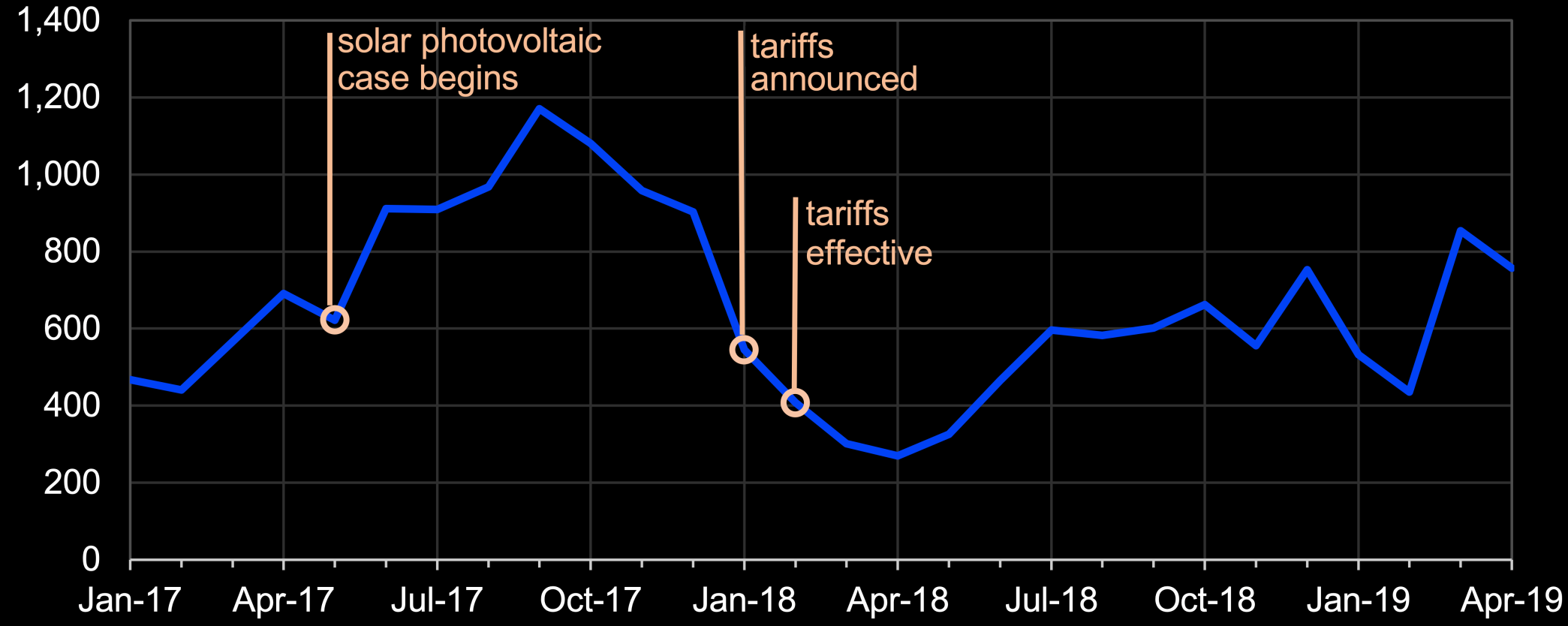
APPENDIX

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

Monthly U.S. imports of solar photovoltaic modules (2017-2019)
thousand peak kilowatts



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

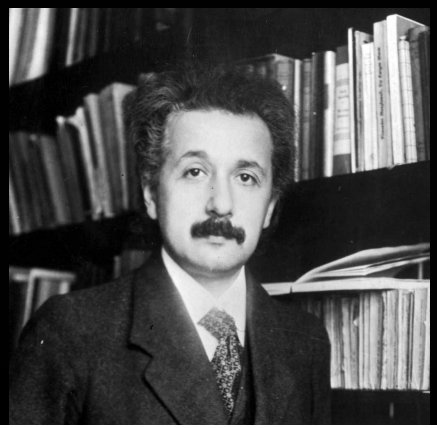
The First PV Cell

Chapin, Fuller, Pearson

Solar Energy Converting Apparatus
1954

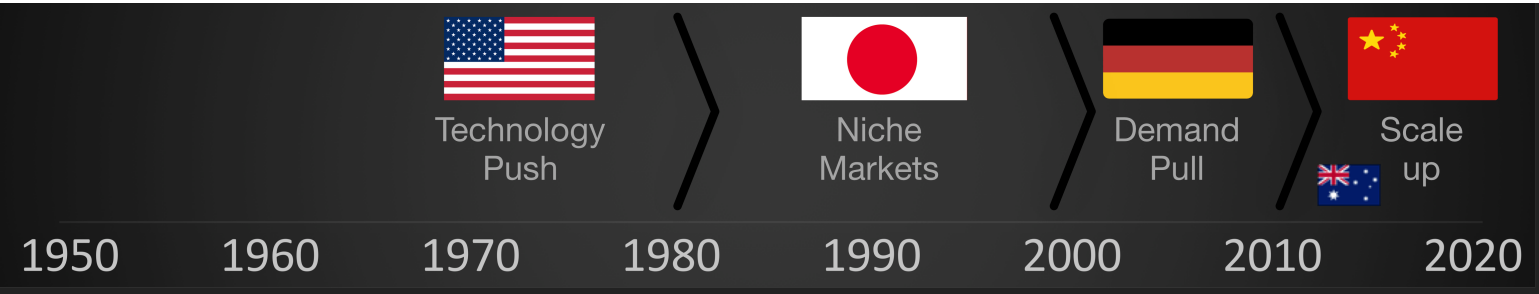
Components

- Scaff — High Purity Silicon — 1943
- Ohl — Light-sensitive Device — 1946
- Teal — Photoelectro-motive 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

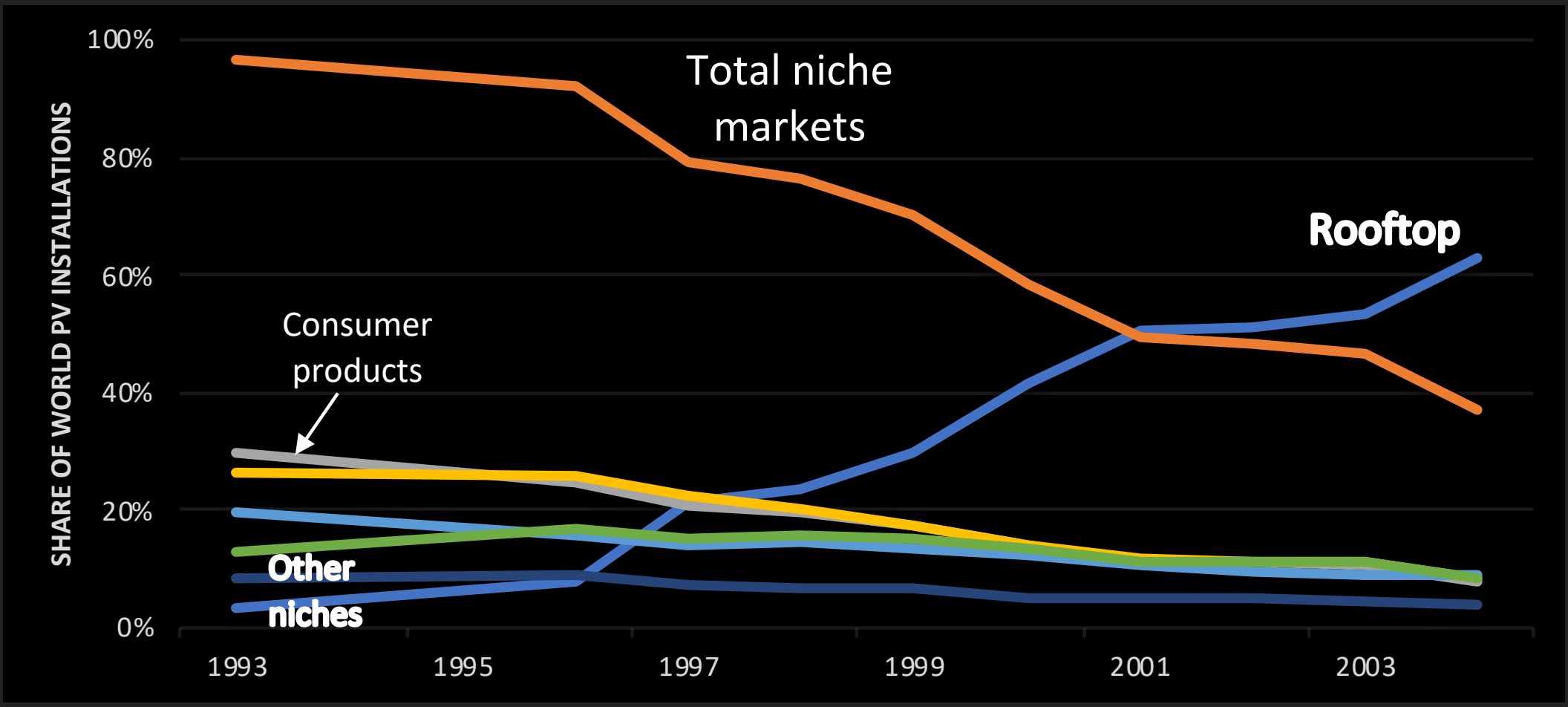


- Allen, 1912
- Rupp, 1935
- Heyroth et al., 1936
- Riss, 1909
- Bliss, 1912
- Woodbridge, 1913
- Lunn, 1920
- Seeger et al., 1937
- Hoffman, 1939
- Richards, 1943
- Richards, 1950
- Rickets, 1927
- Friedrich, 1937
- Rack, 1949
- Barney, 1949
- Hazelett, 1925
- Lewis, 1933
- Boggett, 1937
- Welch, 1940

Precursors



EVOLUTION OF NICHE MARKETS



Technology Push → Niche Markets → Demand Pull → Scale up

1950 1960 1970 1980 1990 2000 2010 2020

経済産業省
Ministry of Economy, Trade and Industry

$20
$15
$10
$5
$0
$/W

New Sunshine Program

Price

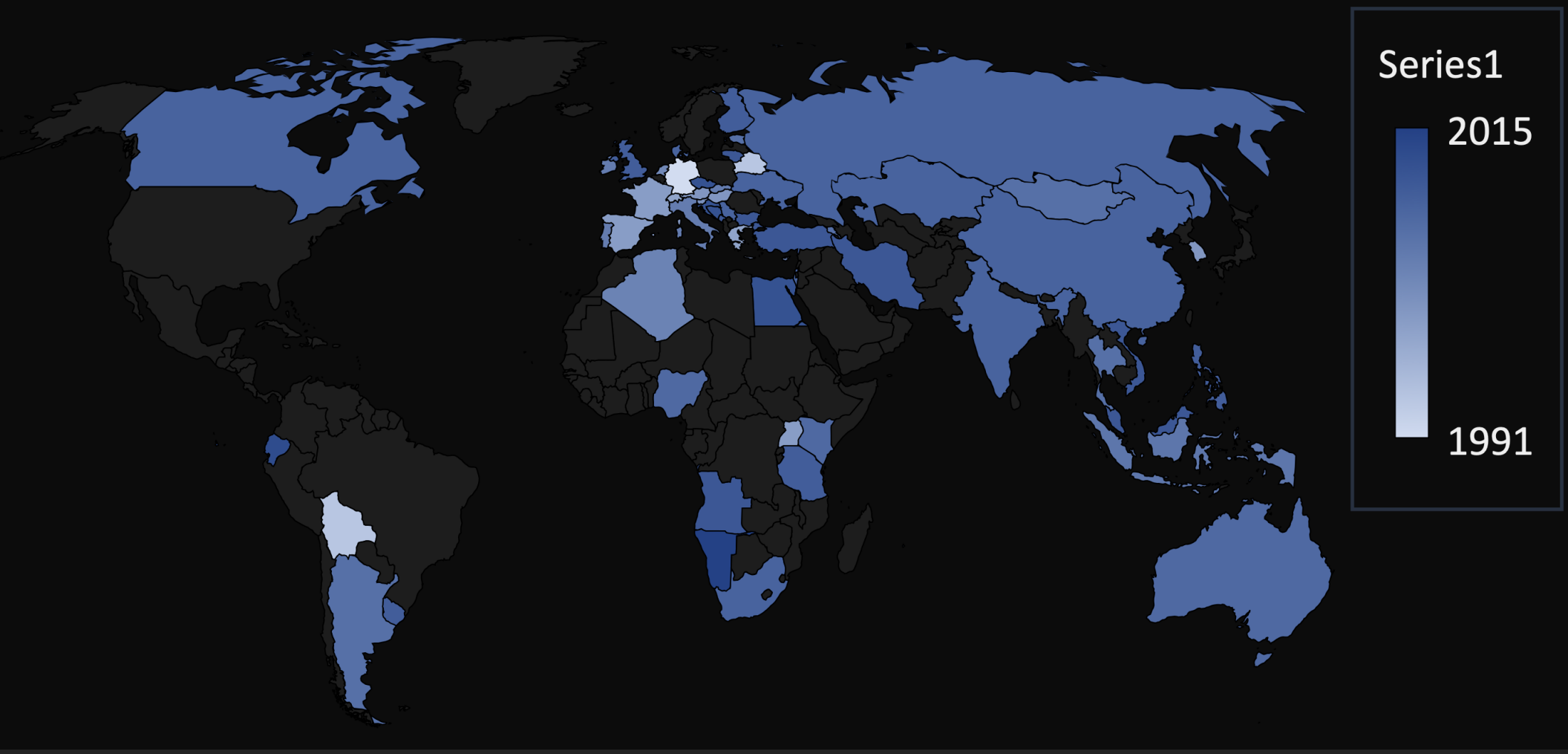
Subsidy

$800/MWh

1990 1995 2000 2005 2010

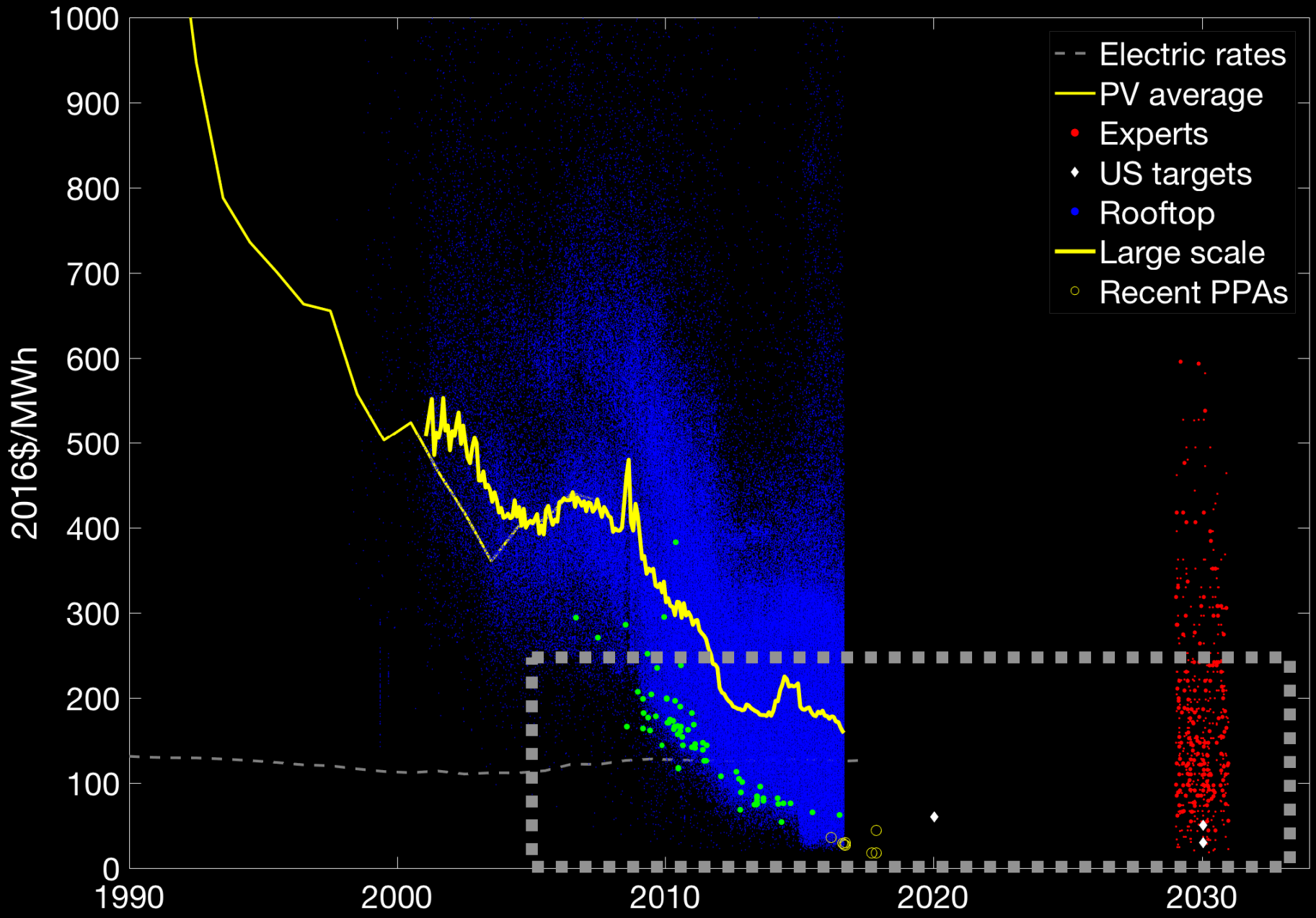
POLICY DIFFUSION

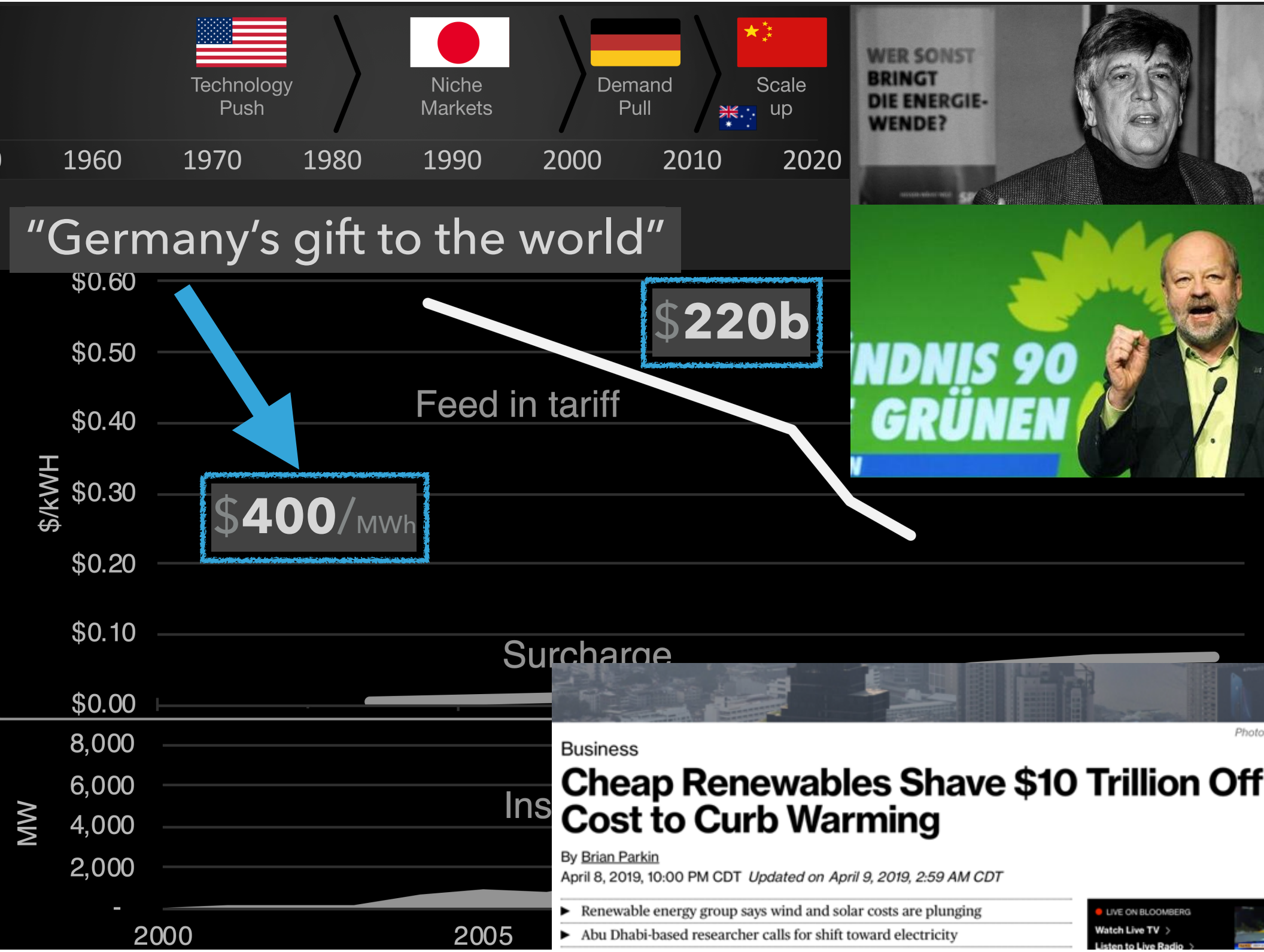
Feed in tariffs by year implemented

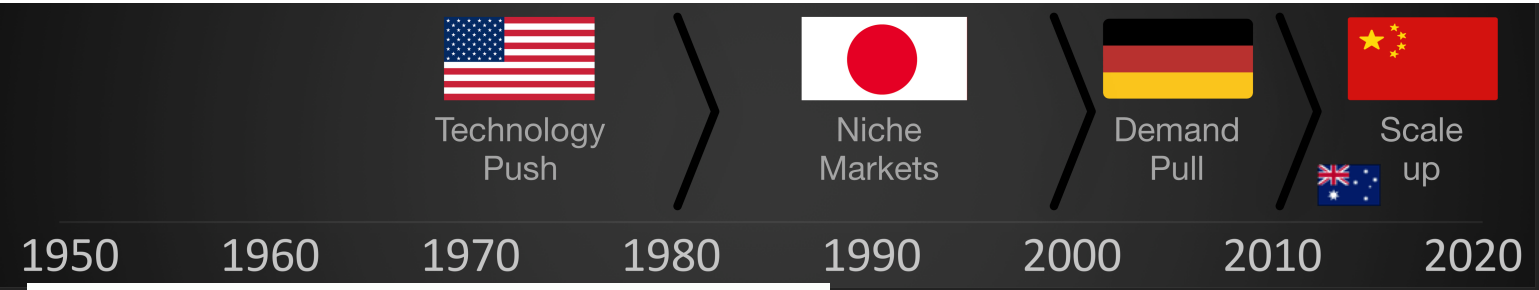


SOLAR PANELS ARE NOW EXTREMELY CHEAP

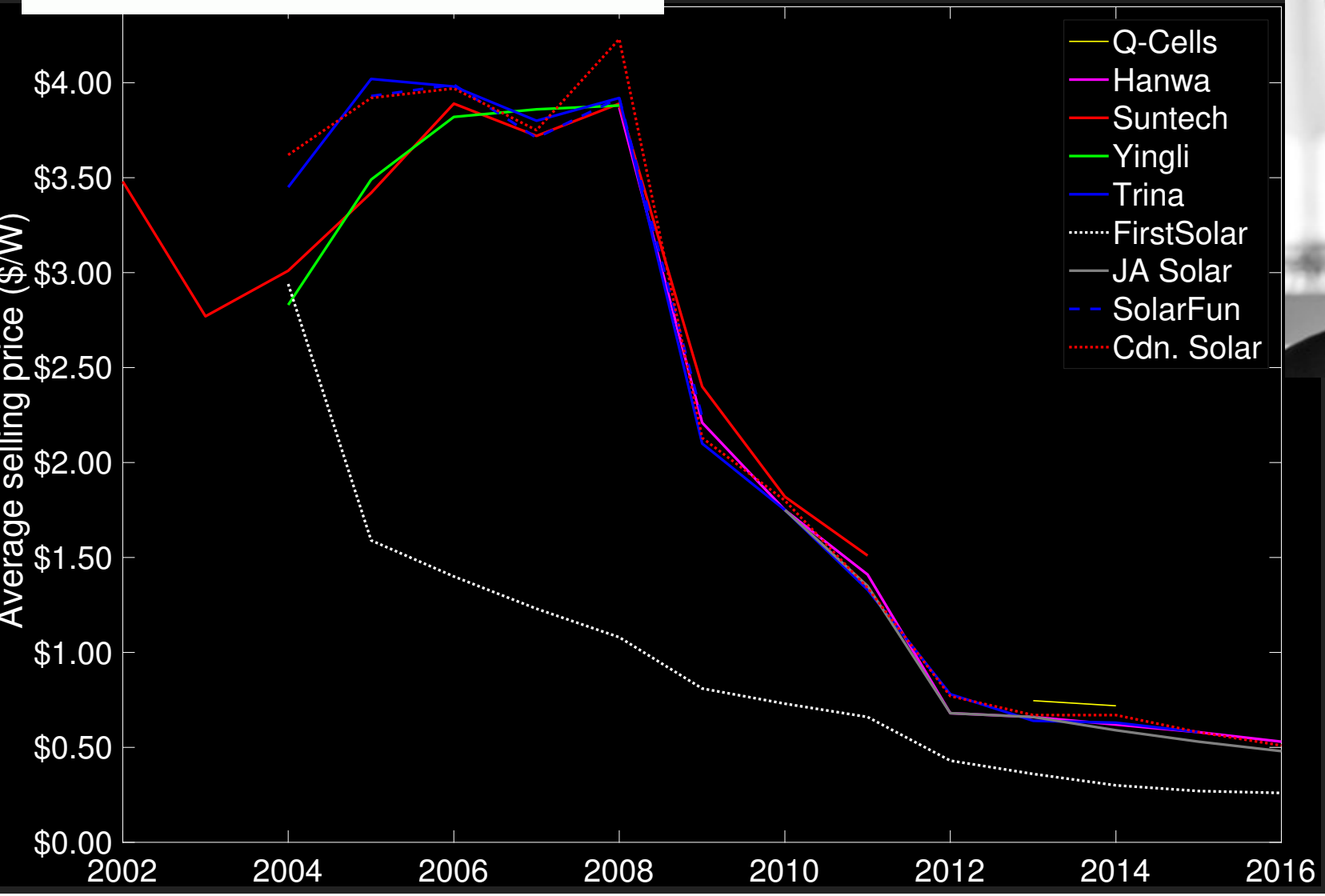
PV COSTS

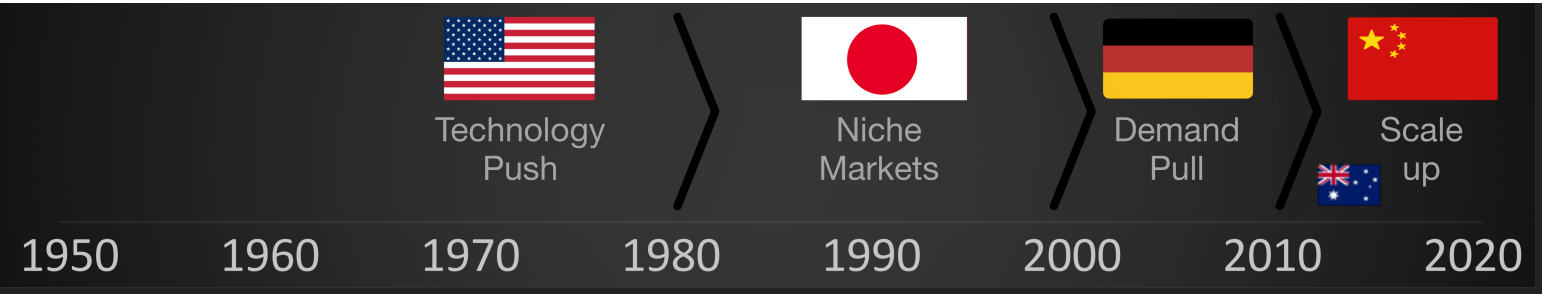

1000
900
800
700
600
500
400
300
200
100
0
2016$/MWh
1990
2000
2010
2020
2030
Electric rates
PV average
Experts
US targets
Rooftop
Large scale
Recent PPAs

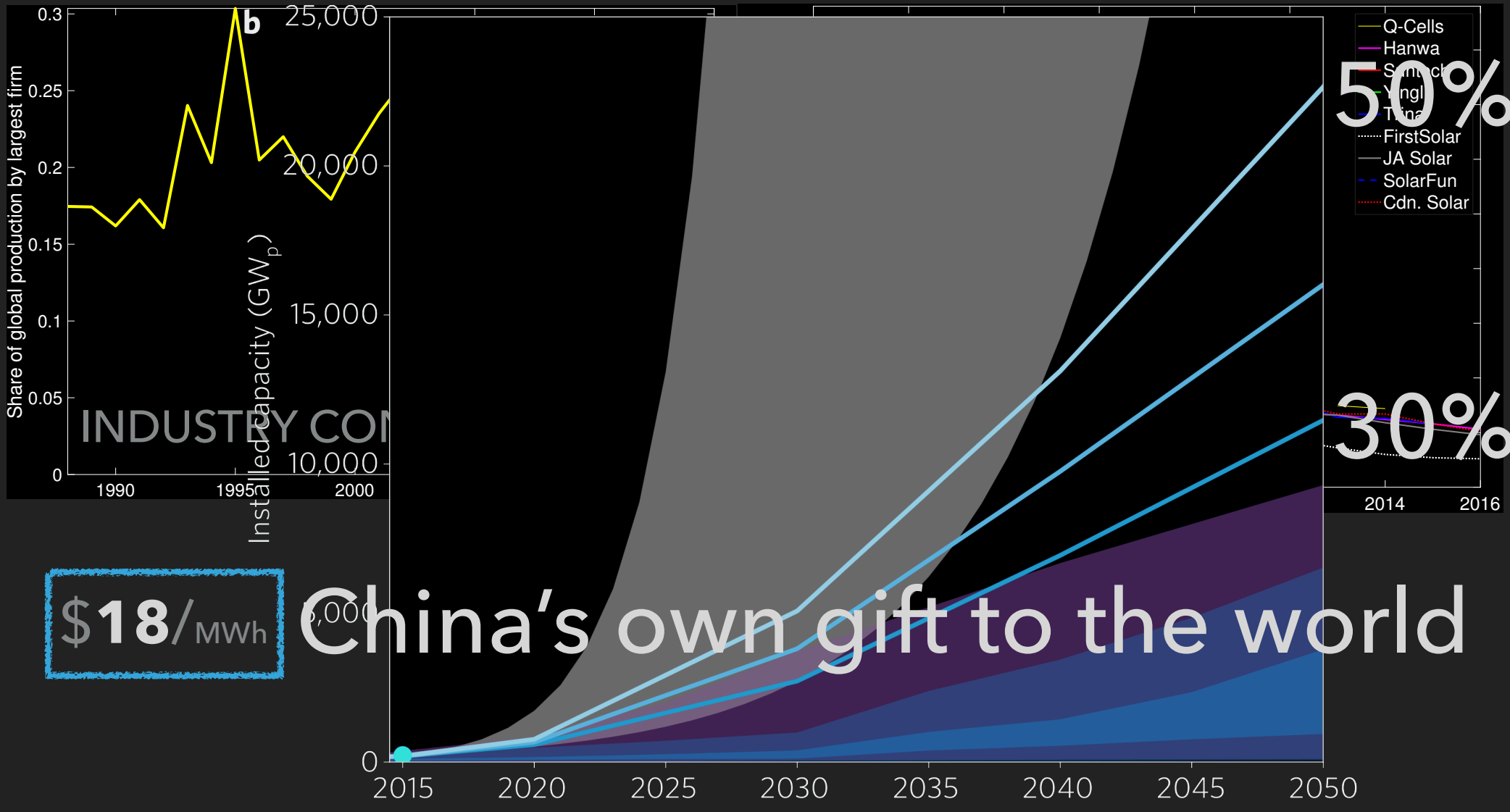

Technology Push
Niche Markets
Demand Pull
Scale up
1960
1970
1980
1990
2000
2010
2020
"Germany's gift to the world"
$0.60
$0.50
$0.40
$0.30
$0.20
$0.10
$0.00
$/kWH
$220b
Feed in tariff
$400/MWh
Surcharge
8,000
6,000
4,000
2,000
-
MW
Ins
2000
2005
WER SONST
BRINGT
DIE ENERGIE-
WENDE?
NDNIS 90
GRÜNEN
Photo
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
LIVE ON BLOOMBERG
Watch Live TV
Listen to Live Radio


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

SUNTECH


Average selling price ($/W)
$4.00
$3.50
$3.00
$2.50
$2.00
$1.50
$1.00
$0.50
$0.00
2002
2004
2006
2008
2010
2012
2014
2016
Q-Cells
Hanwa
Suntech
Yingli
Trina
FirstSolar
JA Solar
SolarFun
Cdn. Solar





Creutzig, F., P. Agoston, J. C. Goldschmidt, G. Luderer, G. Nemet and R. C. Pietzcker (2017). "The under-estimated potential of solar energy to mitigate climate change." Nature Energy **2**: nenergy2017140.

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

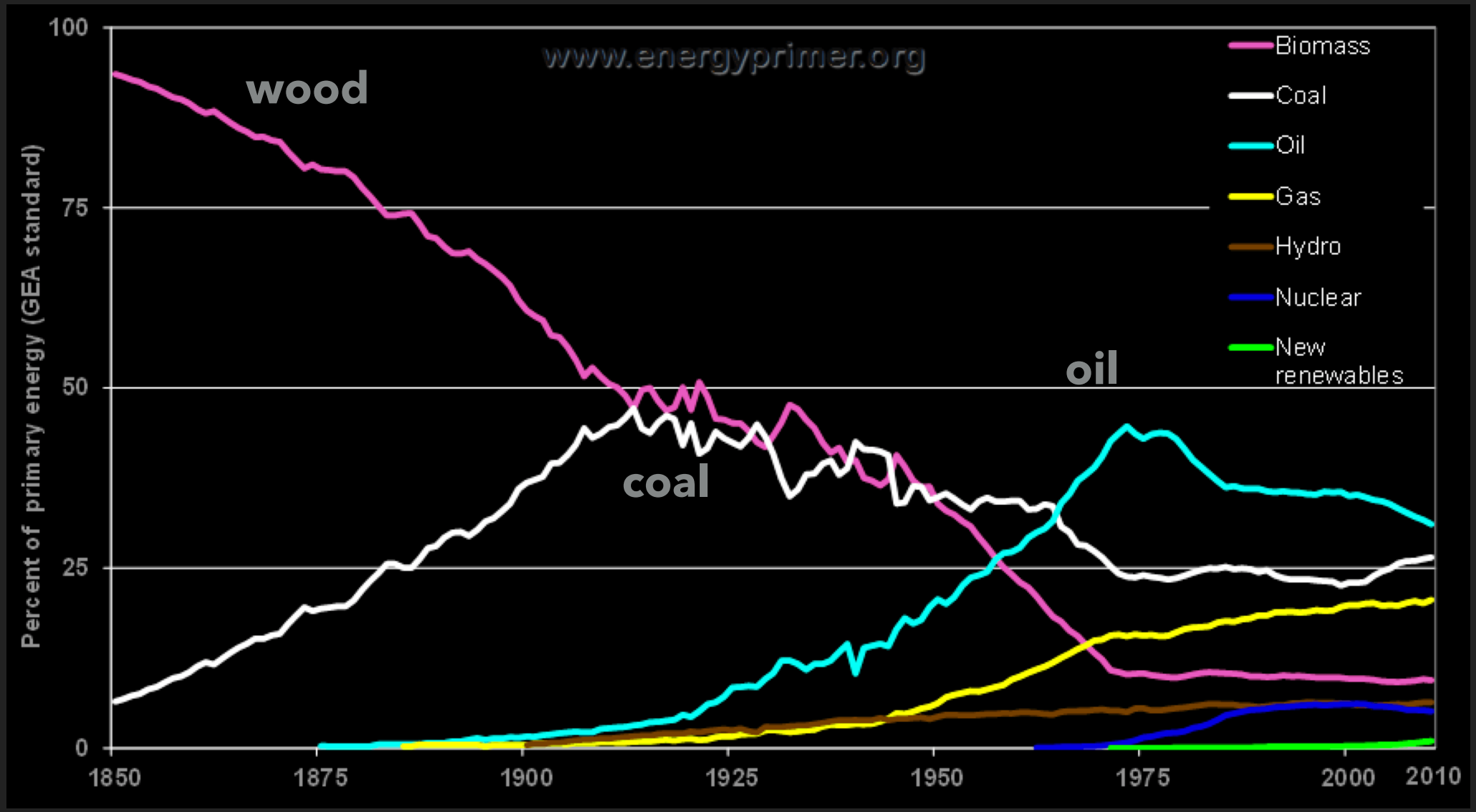
Clean

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

RESEARCH TEAM

Travis
Shoemaker

Atiya
Siddiqi

Rohan
Rao

Jiaqi
Lu

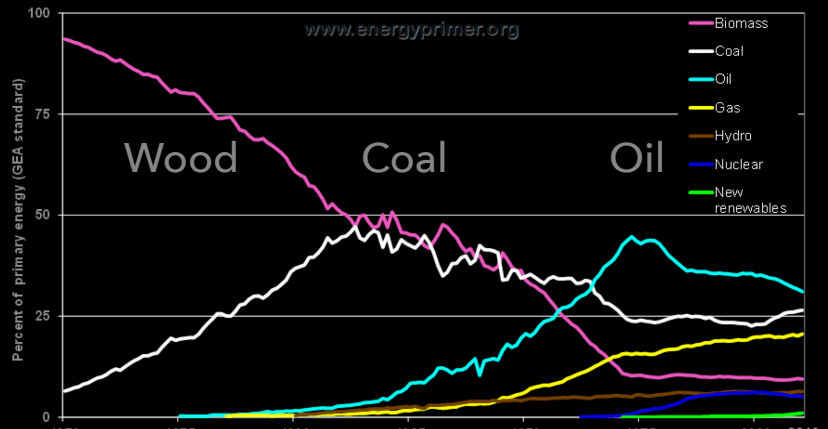
Andy
Lick

Mikhaila
Calice

ENERGY TRANSITIONS ARE HARD

1. Want CHEAP, CLEAN,RELIABLE

2. Past transitions took decades



1850 2010

3. CO_2 in atmosphere for >100 yrs