Drivers of technological improvement in clean energy systems

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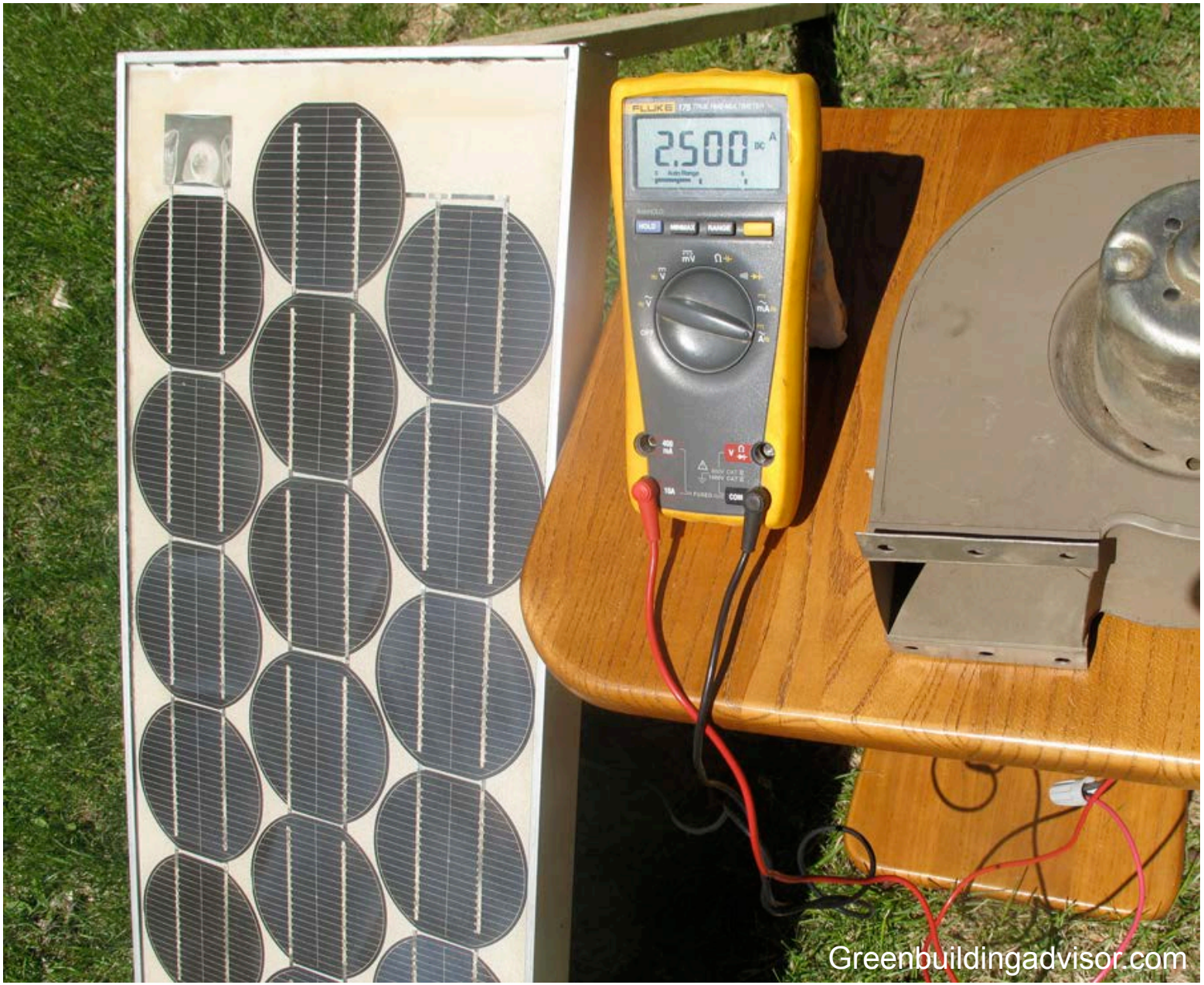
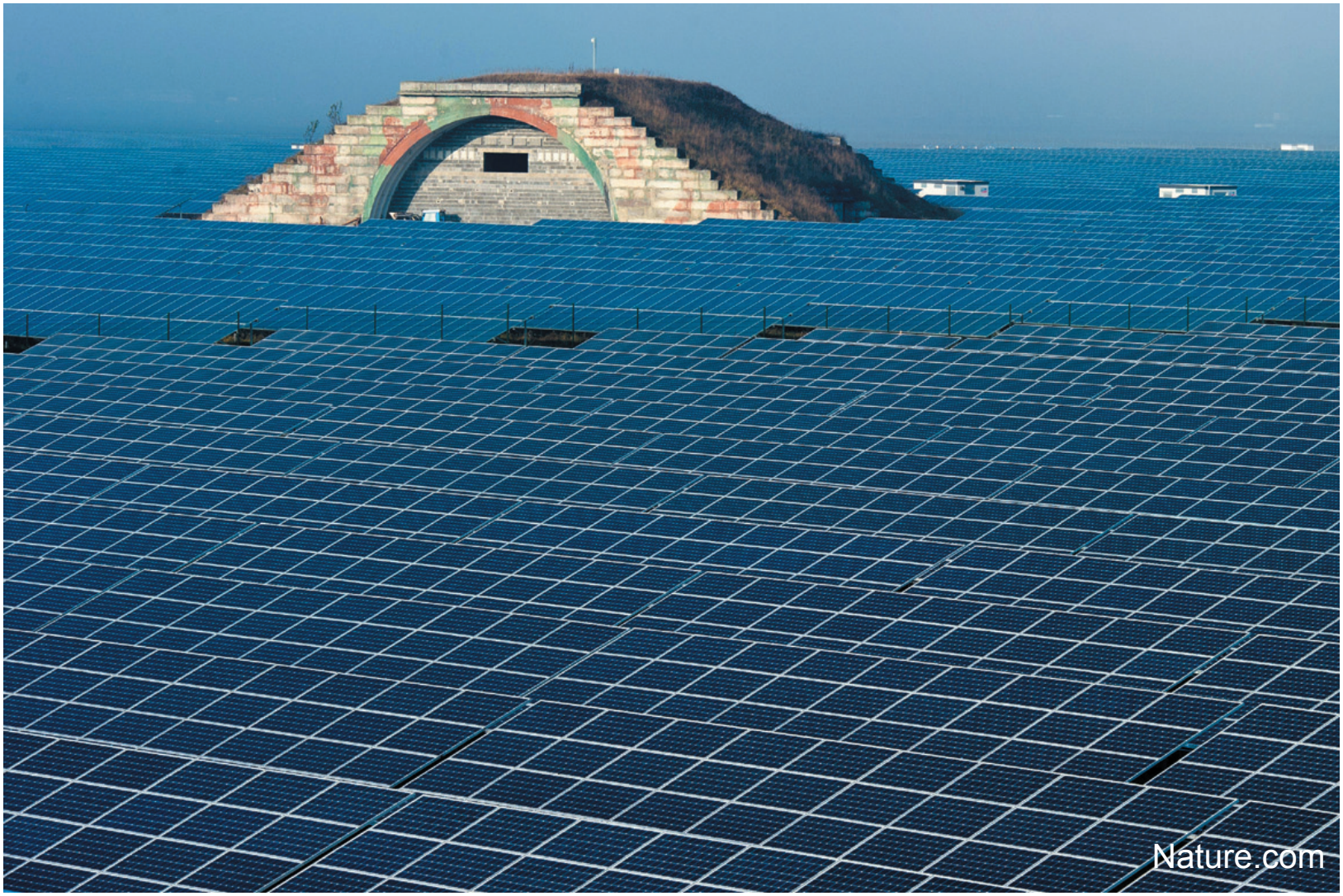


Solar (photovoltaic) panel from the 80s

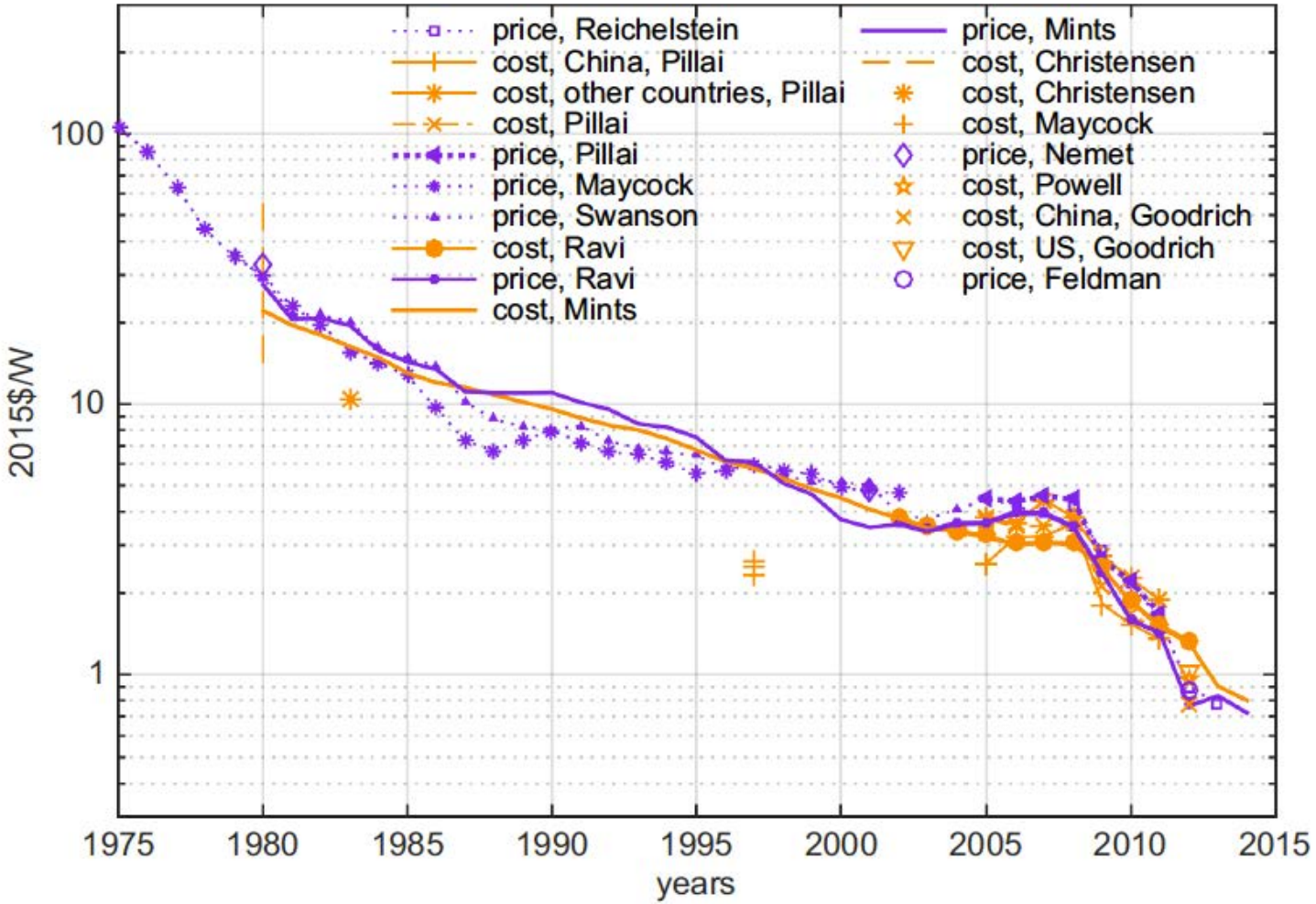


Solar energy today

1977 Volvo electric vehicle

Electric vehicles in 2016: Tesla Model S

Example: Photovoltaics (solar) modules cost decline



Kavlak, McNerney, Trancik, *Energy Policy* 2018.

Why did photovoltaics module costs fall?

Government policy drivers of PV modules' cost decline?

- 60% research and development funding and 30% market-stimulating policies?

or

- 30% research and development funding and 60% market-stimulating policies?

Approaches to modeling technology costs and innovation

- Correlational analysis of technology innovation trends

e.g. Nagy et al. 2013, Koh and Magee 2008, McDonald and Schrattenholzer 2001.

Approaches to modeling technology costs and innovation

- Correlational analysis of technology innovation trends
- Static engineering models

e.g. Fu et al. 2016, Seel et al. 2014, Goodrich et al. 2012, Powell et al. 2013, Jones-Albertus et al. 2016

Approaches to modeling technology costs and innovation

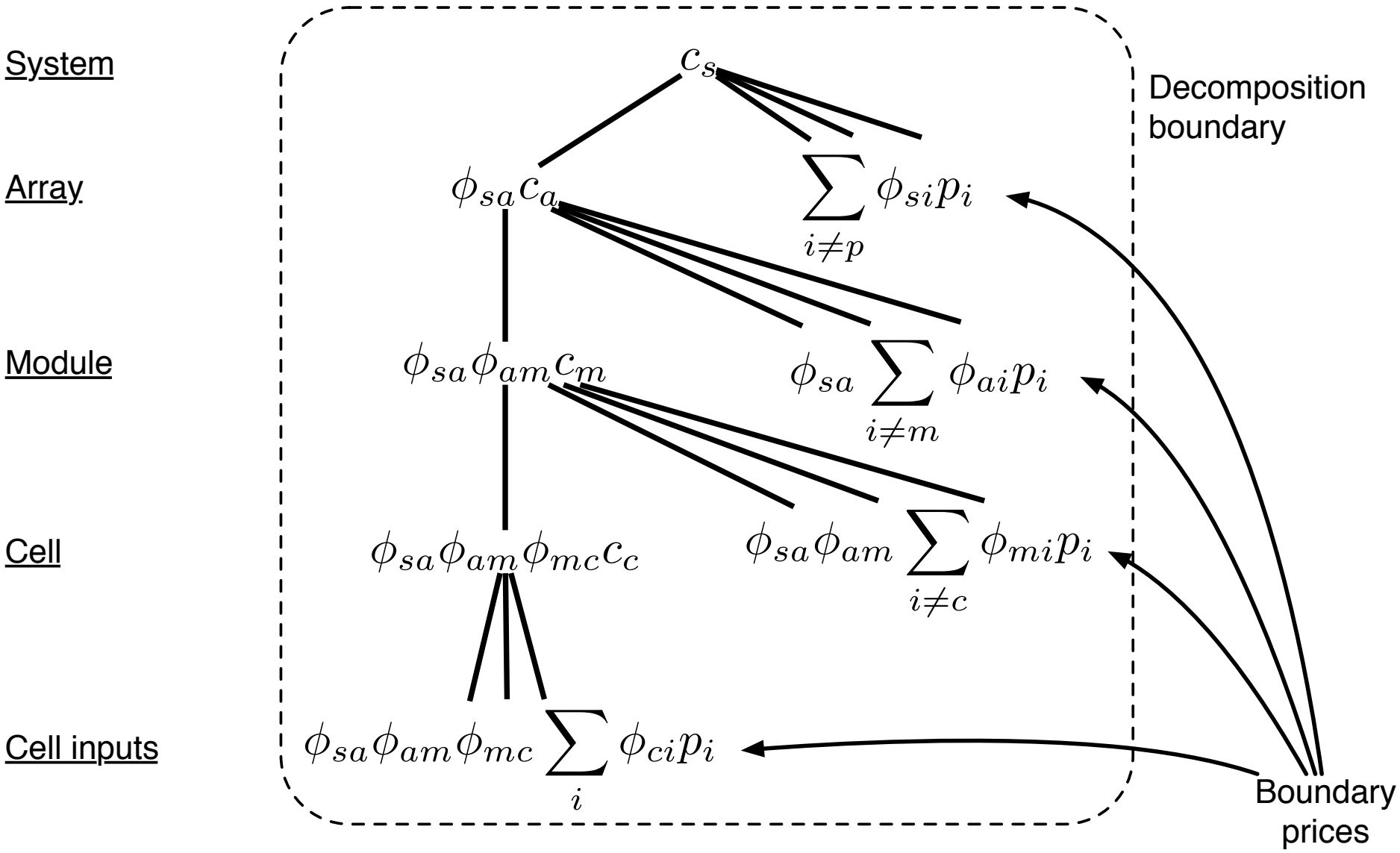
- Correlational analysis of technology innovation trends
- Static engineering models
- Dynamic, mechanistic models of technological change

Three-step process to identify cost change drivers

- Develop cost equations
- Derive cost change equations (‘low-level mechanisms’)
- Identify key human efforts, strategies (‘high-level mechanisms’)

Kavlak, McNerney, Trancik, *Energy Policy* 2018.

Photovoltaics cost decomposition



Kavlak, McNerney, Trancik, *Energy Policy* 2018.

Cost equation

$$C_m\left(\frac{\$}{module}\right) = \underbrace{\frac{n_{cw}n_{mc}}{y_m y_c y_w}\sum_i \phi_{wi}p_i}_{\text{wafer costs}} + \underbrace{\frac{n_{mc}}{y_m y_c}\sum_{i\neq w}\phi_{ci}p_i}_{\text{non-wafer cell costs}} + \underbrace{\frac{1}{y_m}\sum_{i\neq c,w}\phi_{mi}p_i}_{\text{non-cell module costs}}$$

usage price

where

n_{mc}	number of cells per module
n_{cw}	number of wafers per cell
y_w	yield at wafer manufacturing
y_c	yield at cell manufacturing
y_m	yield at module manufacturing
ϕ_{wi}	quantity of input i per wafer
ϕ_{ci}	quantity of input i per cell
ϕ_{mi}	quantity of input i per module
p_i	price of input i.

Kavlak, McNerney, Trancik, *Energy Policy* 2018.

Reduced form cost equation

$$C\left(\frac{\$}{W}\right) = \frac{\alpha}{\sigma A \eta y}\left[Av\rho p_s + cA + p_0\left(\frac{K}{K_0}\right)^{-b}\right]$$

PV module cost

silicon cost

other materials costs

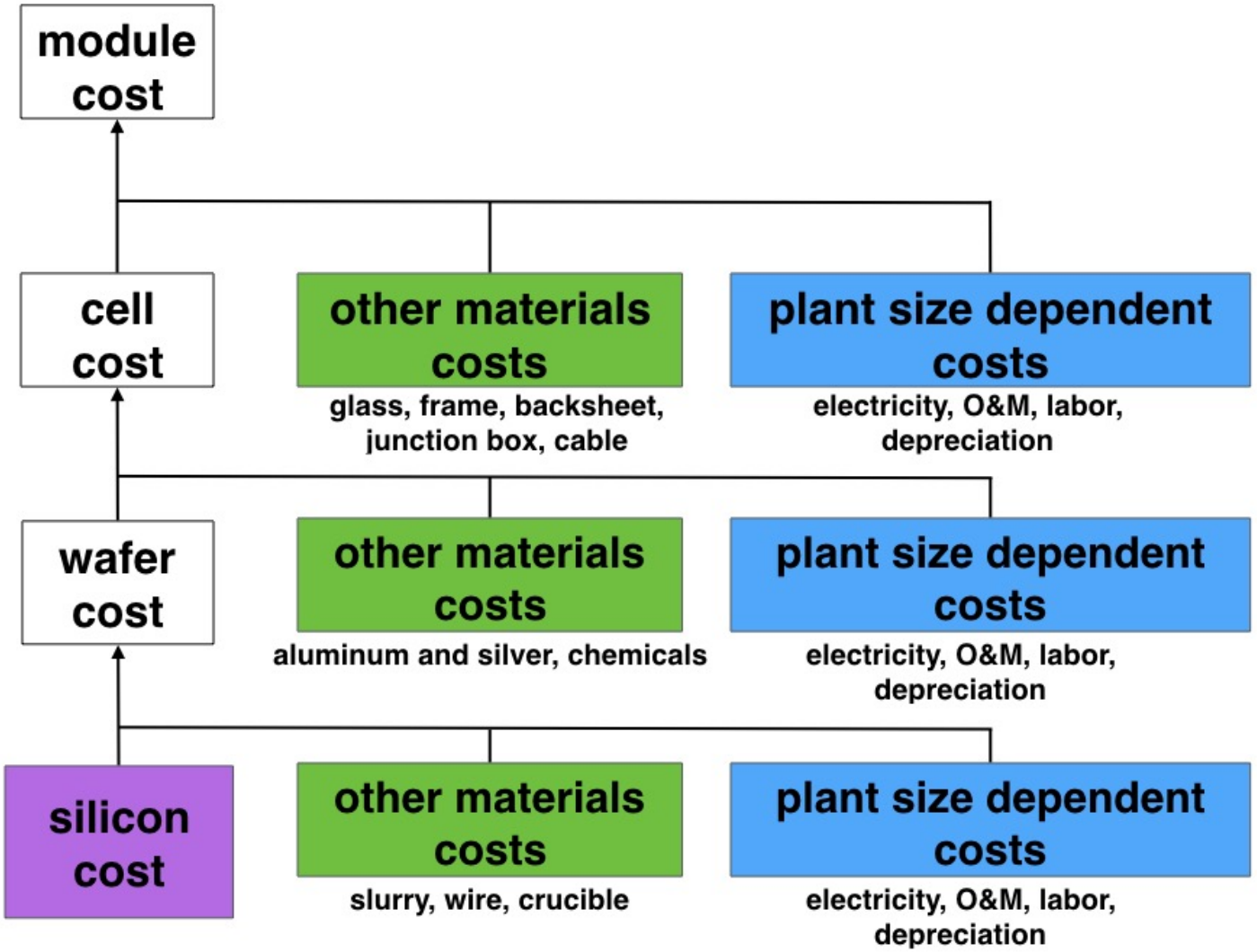
plant size-dependent costs

Key low-level mechanisms

- Module efficiency
- Yield
- Wafer area
- Silicon usage
- Silicon price
- Manufacturing plant size

Kavlak, McNerney, Trancik, *Energy Policy* 2018.

Photovoltaics cost decomposition



Kavlak, McNerney, Trancik, *Energy Policy* 2018.; Inspiration from Nemet, *Energy Policy* 2006

Photovoltaics component cost *change* equations

$$\Delta C_z(t_1, t_2) \approx \sum_i \widetilde{C}_i \ln\left(\frac{g_{iz}(r_z^2)}{g_{iz}(r_z^1)}\right)$$

Total cost change due to variable z

Factor change induced in C_i by a change in z

Representative value of cost component C_i in time period t_1, t_2

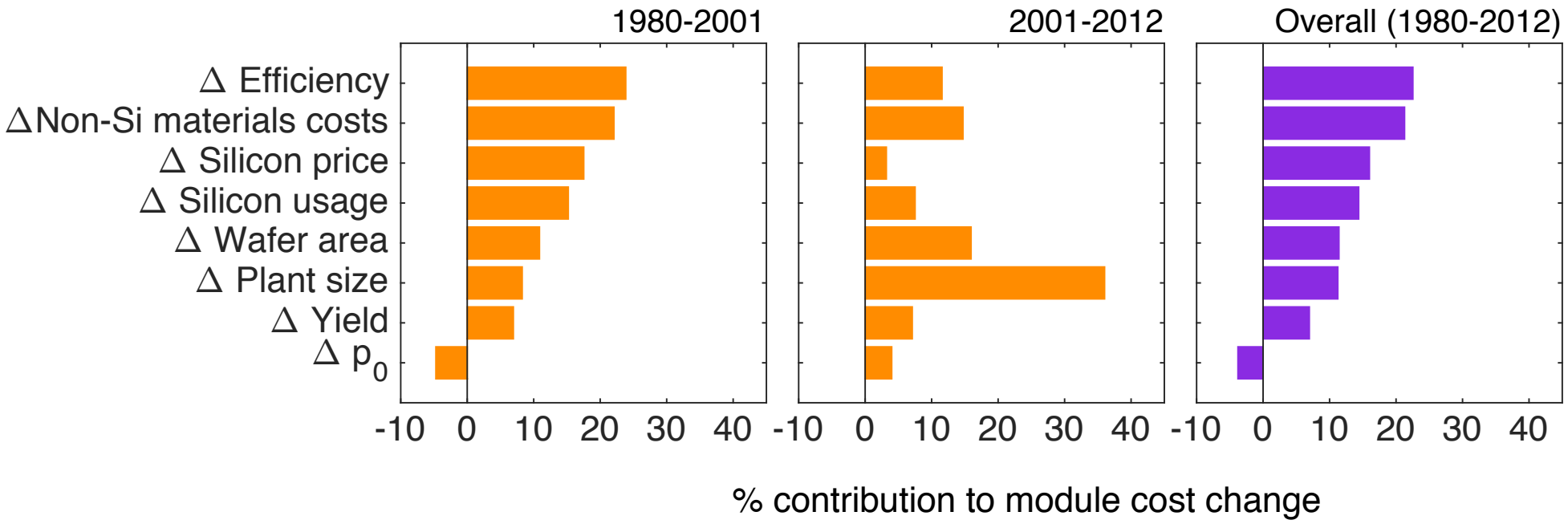
$$\widetilde{C}_i = \frac{\Delta C_i}{\Delta \ln C_i}$$

Example: Cost change due to changes in module efficiency

$$\Delta C_\eta = \sum_{i=1}^{3} \widetilde{C}_i \ln\left(\frac{(\eta^2)^{-1}}{(\eta^1)^{-1}}\right) = -\sum_{i=1}^{3} \widetilde{C}_i \ln\left(\frac{\eta^2}{\eta^1}\right)$$

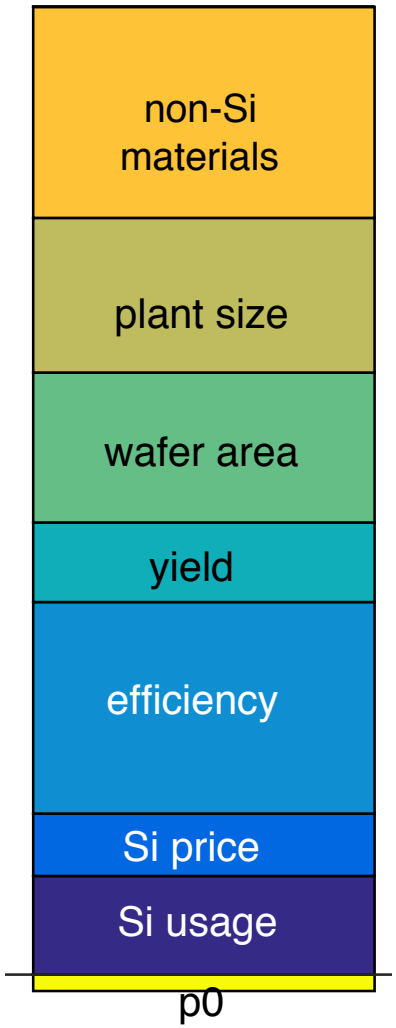
Kavlak, McNerney, Trancik, *Energy Policy* 2018.

Low-level mechanisms of cost reduction



Mechanisms of cost reduction

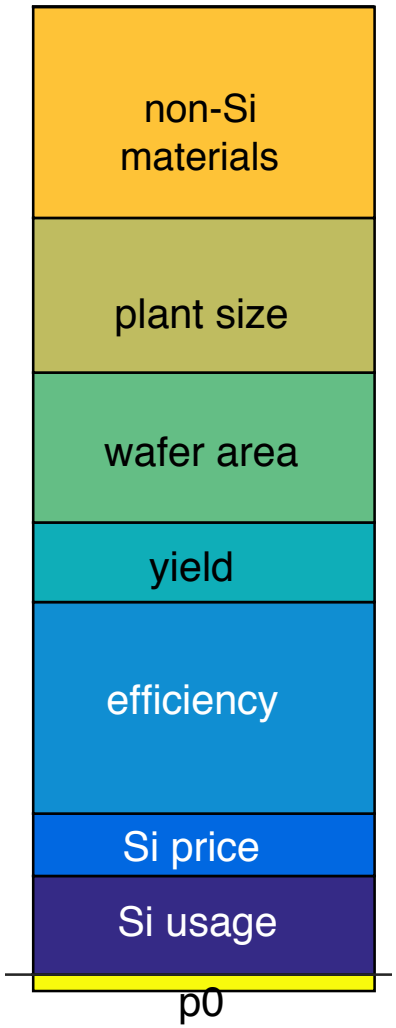
Low-level mechanisms



Kavlak, McNerney, Trancik, *Energy Policy* 2018.

Mechanisms of cost reduction

Low-level mechanisms



High-level mechanisms

Identify high-level mechanisms

Research and development (R&D)

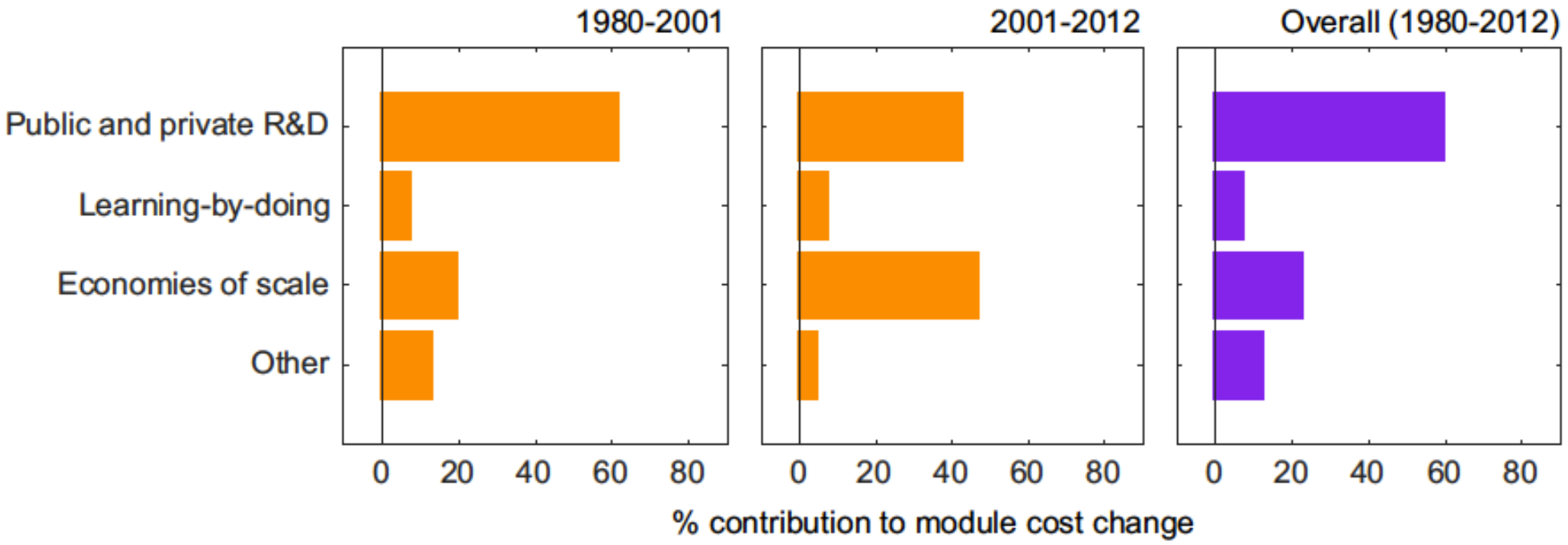
Learning-by-doing

Economies of scale

Other e.g. spillover

Kavlak, McNerney, Trancik, *Energy Policy* 2018.

High-level mechanisms of cost reduction

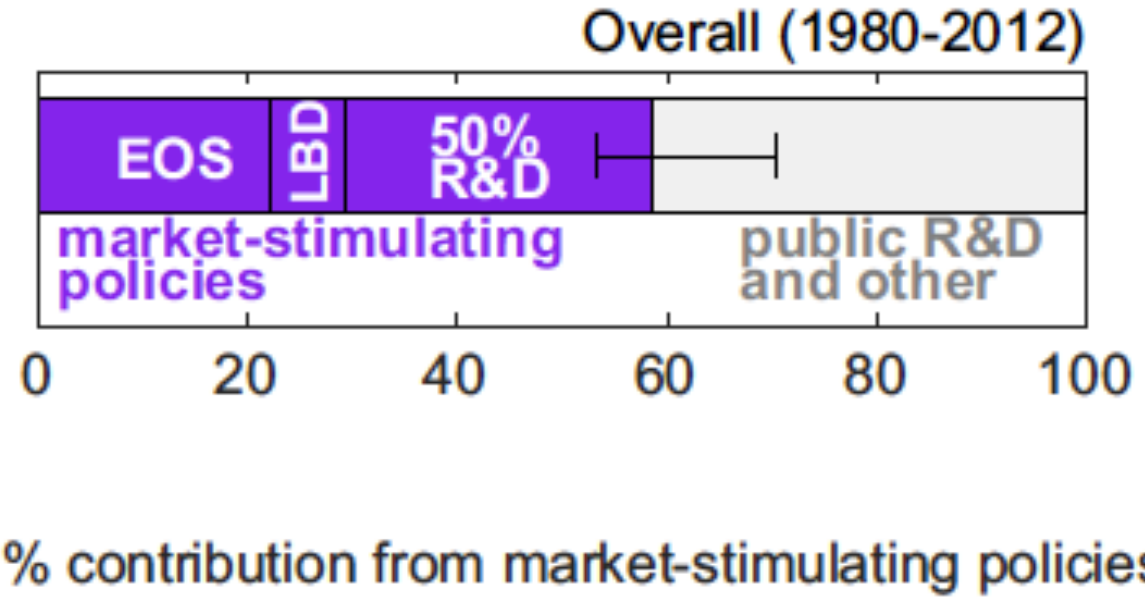


EOS=economies of scale

LBD=learning by doing

Kavlak, McNerney, Trancik, *Energy Policy* 2018.

Government policy contributions to cost reduction



Kavlak, McNerney, Trancik, *Energy Policy* 2018.

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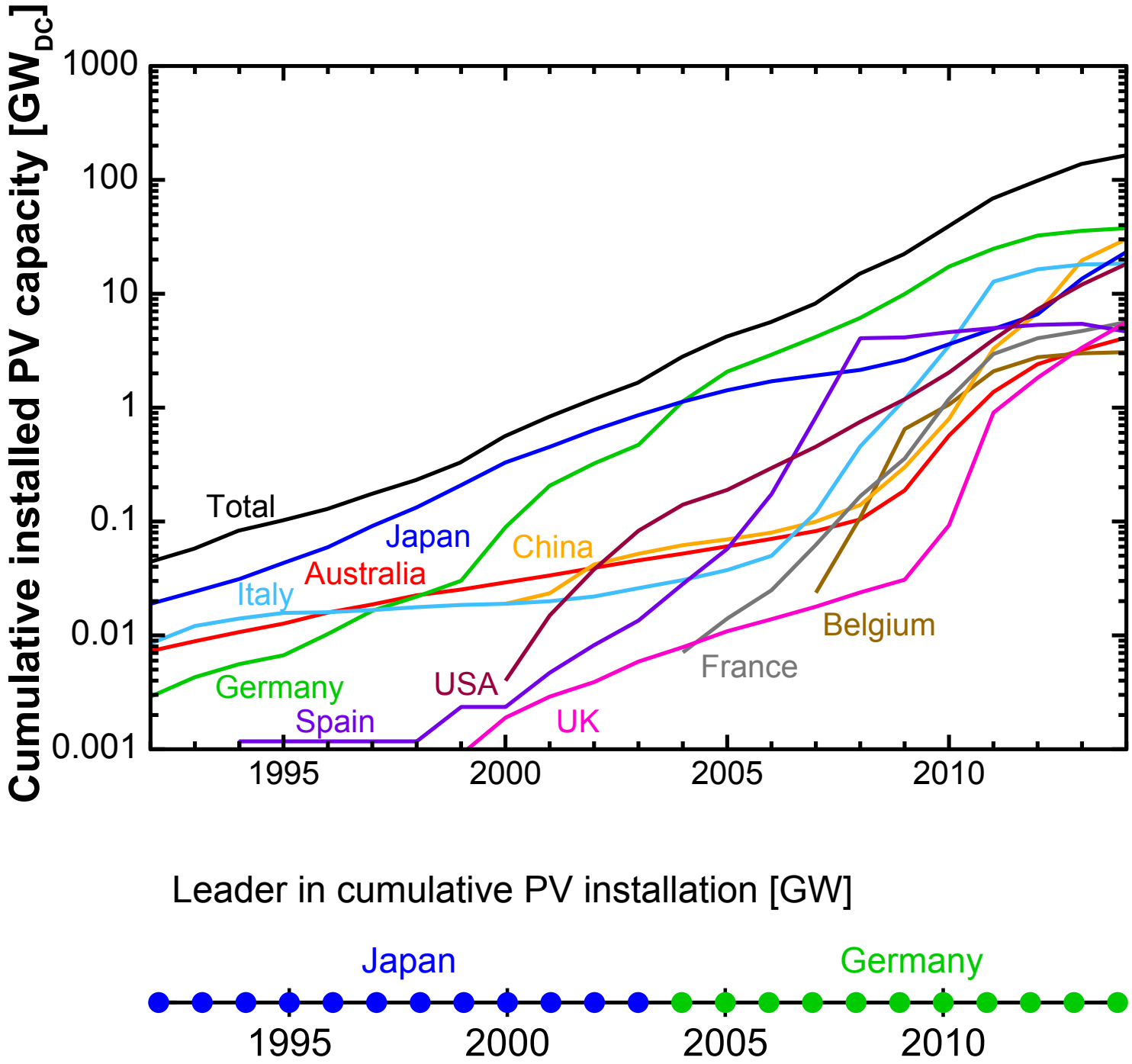
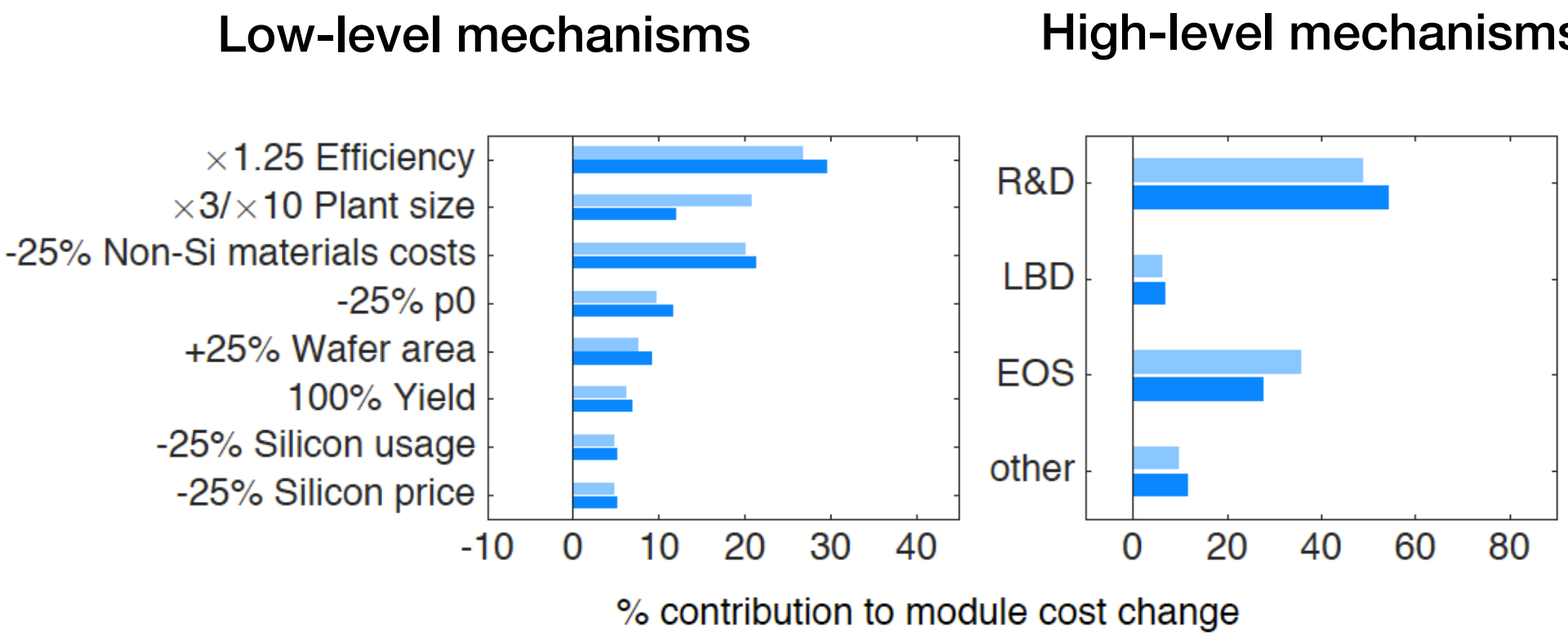


Trancik, Brown, Jean, Kavlak, Klemun, Edwards, McNerney, Miotti, Mueller, Needell, Technical Report, 2015

Why did photovoltaics module costs fall?

- Efficiency, yield and other low-level mechanisms responsible (many possible knobs to turn)
- R&D and economies of scale dominant high-level mechanisms
- Market expansion policies played a critical role in reducing costs

Prospective assessment of PV module cost reduction



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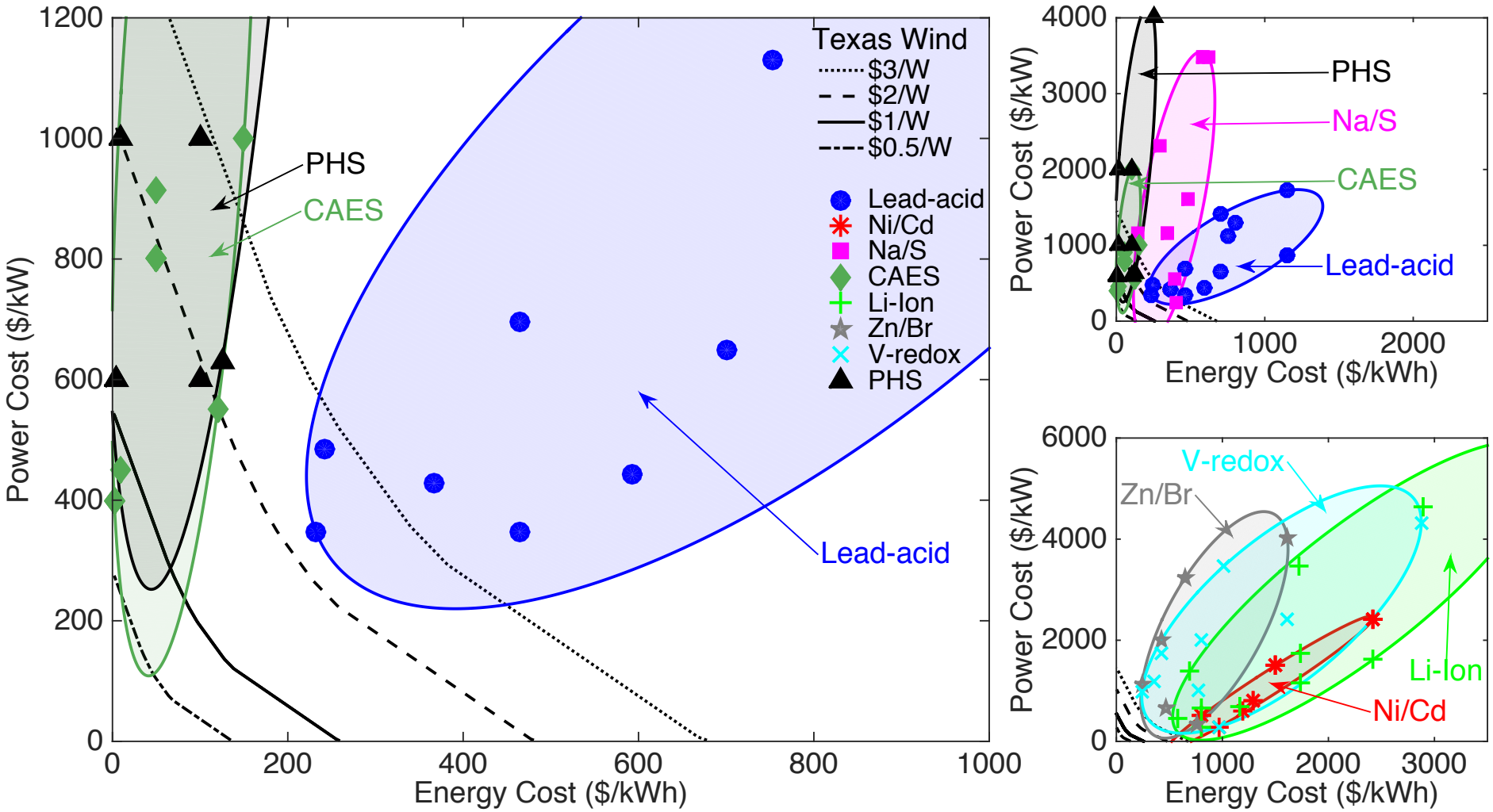
Kavlak, McNerney, Trancik, *Energy Policy* 2018.

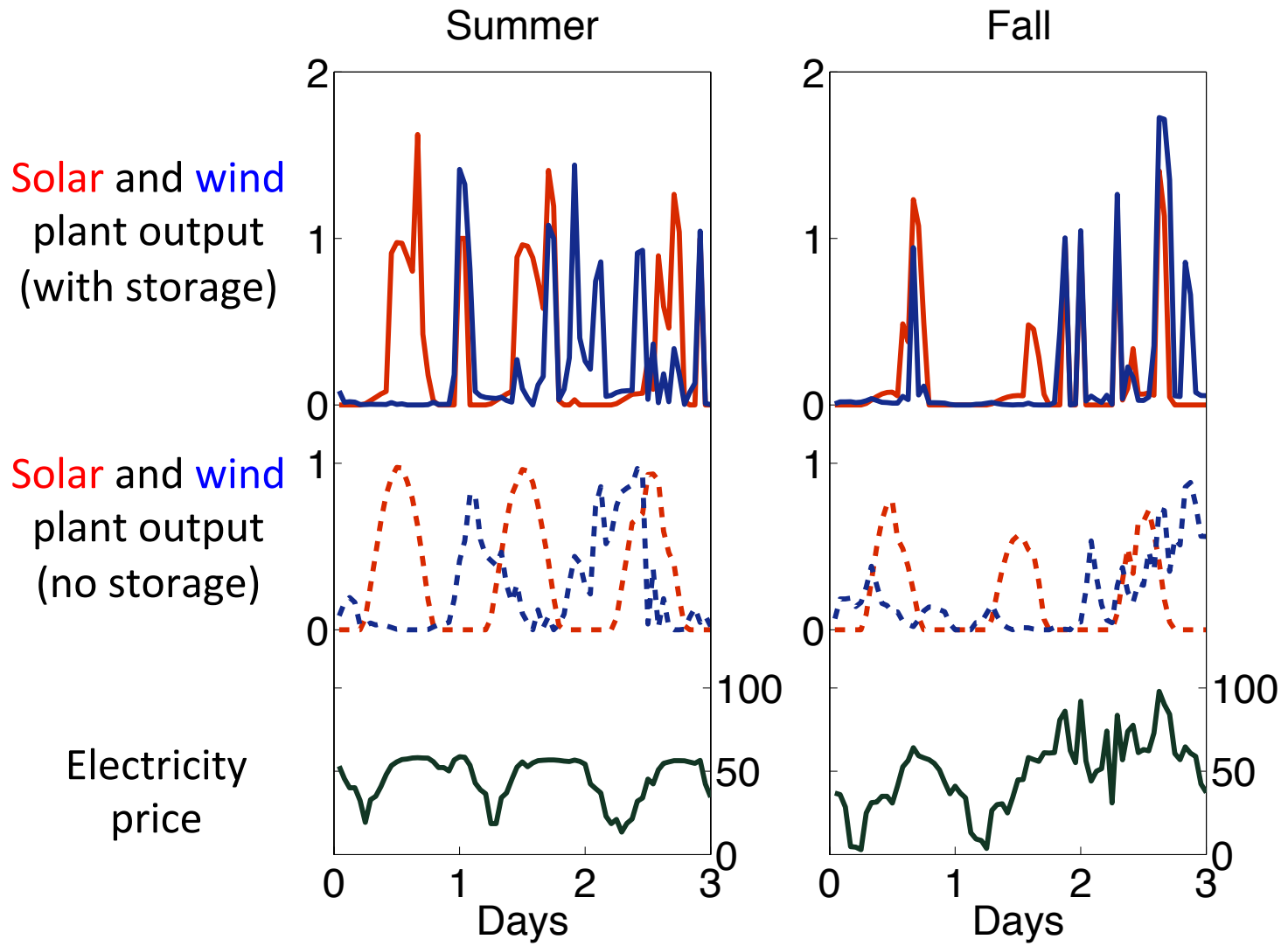
Profitability of storage technologies for solar and wind energy



PHS: pumped hydro storage
CAES: compressed air energy storage

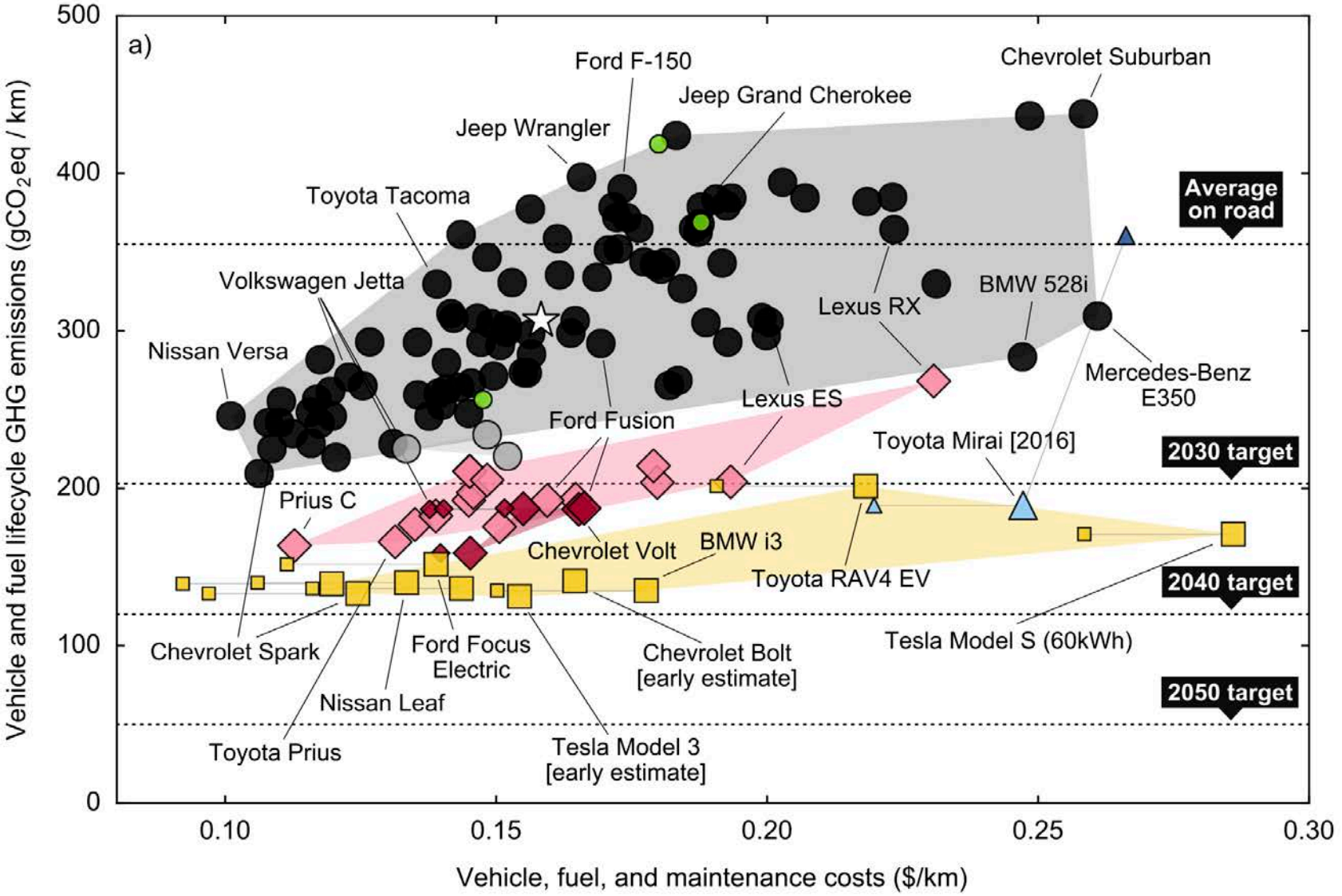
Braff, Mueller, Trancik, *Nature Climate Change* 2016

Profitability of storage technologies for solar and wind energy



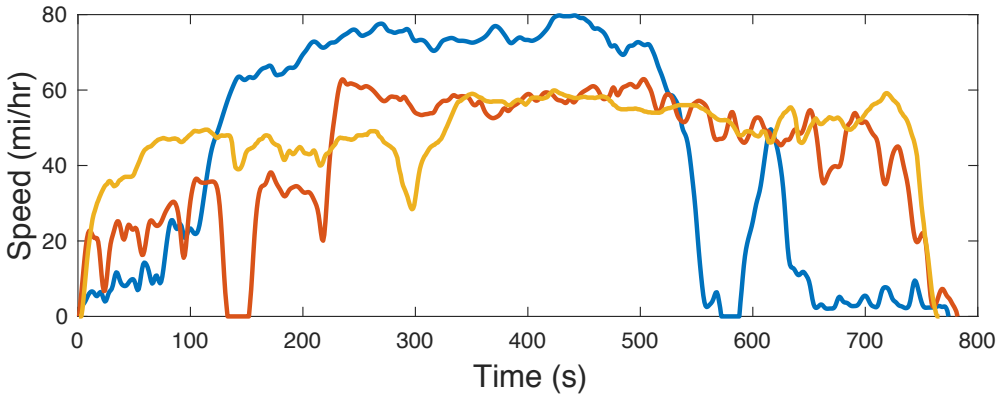
Braff, Mueller, Trancik, *Nature Climate Change* 2016

Cost and emissions of vehicle powertrains (see carboncounter.com)

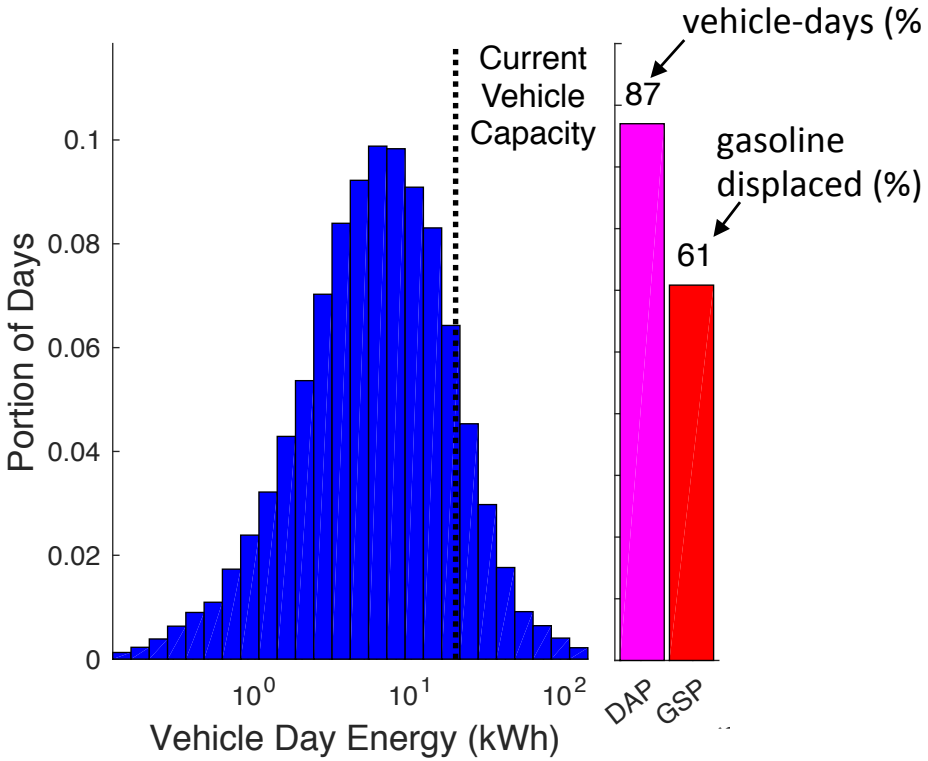


Miotti, Supran, Kim, Trancik, *Environmental Science & Technology* 2016; carboncounter.com

Daily adoption potential of electric vehicles



Based on driving patterns across all U.S. cities and millions of drivers….



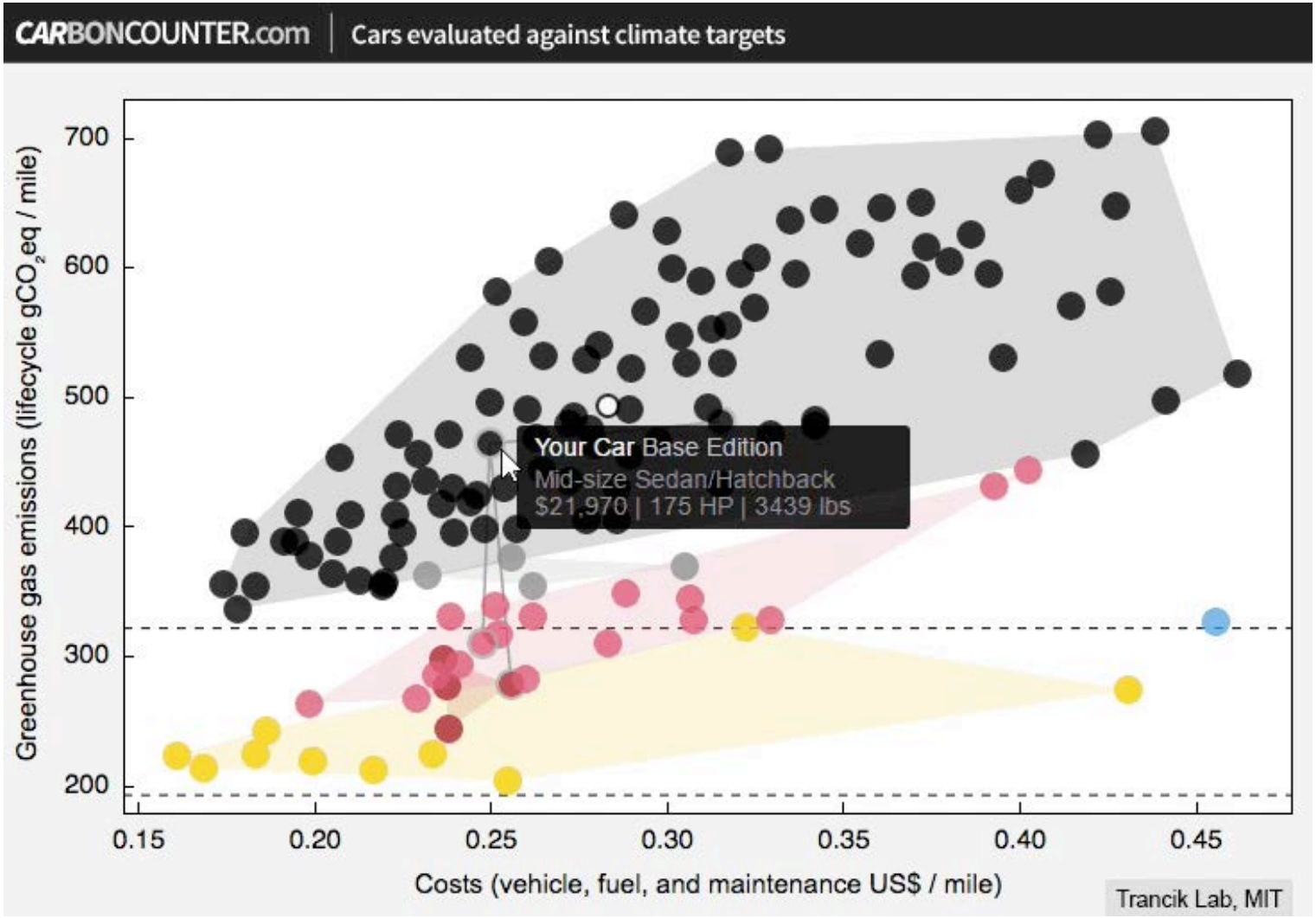
~90% of vehicles can be replaced by a low-cost electric vehicle on an average day, even if only nighttime charging is available.

This number is remarkably similar across diverse cities, from Houston to New York.

Needell, McNerney, Chang, Trancik, *Nature Energy* 2016

Website: trancik.mit.edu

Thanks to the US DOE's Solar Energy Evolution and Diffusion Studies for funding this research.


CARBONCOUNTER.com | Cars evaluated against climate targets
Greenhouse gas emissions (lifecycle gCO2eq / mile)
700
600
500
400
300
200
Your Car Base Edition
Mid-size Sedan/Hatchback
$21,970 | 175 HP | 3439 lbs
0.15
0.20
0.25
0.30
0.35
0.40
0.45
Costs (vehicle, fuel, and maintenance US$ / mile)
Trancik Lab, MIT