Evaluating storage technologies for solar and wind energy

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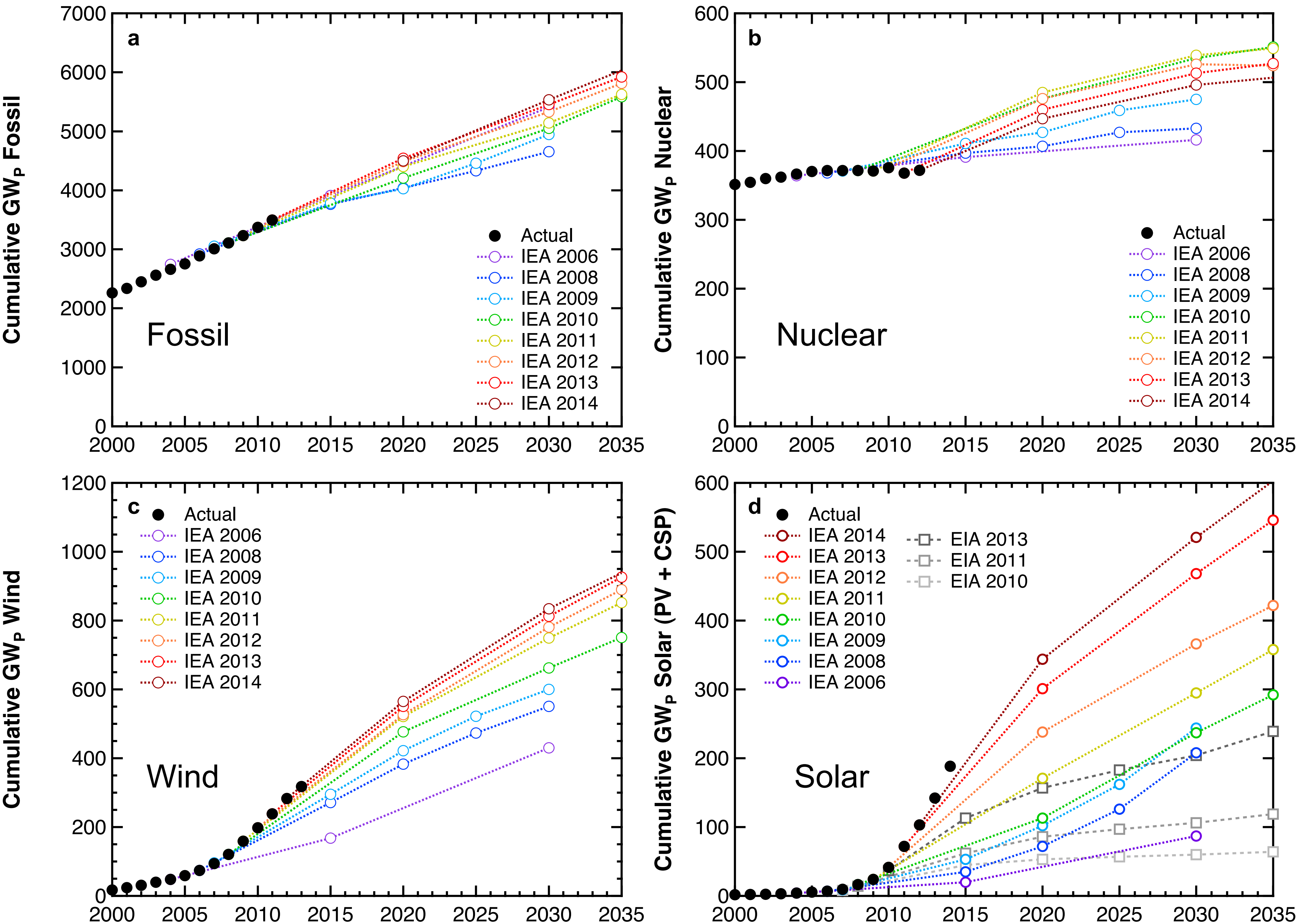
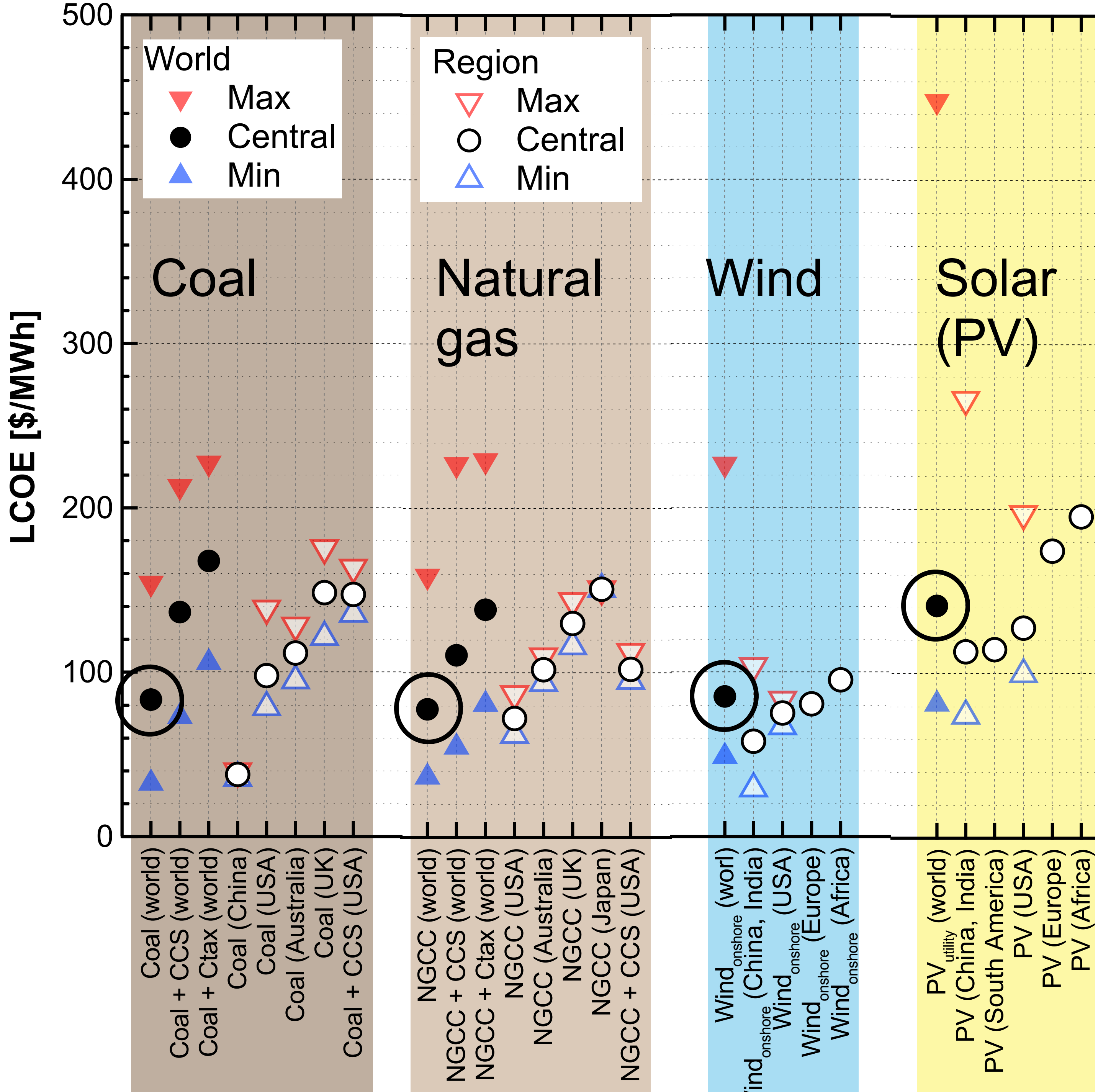


Trancik, Brown, Jean, Kavlak, Klemun, Edwards, McNerney, Miotti, Mueller, Needell, Technical Report, 2015



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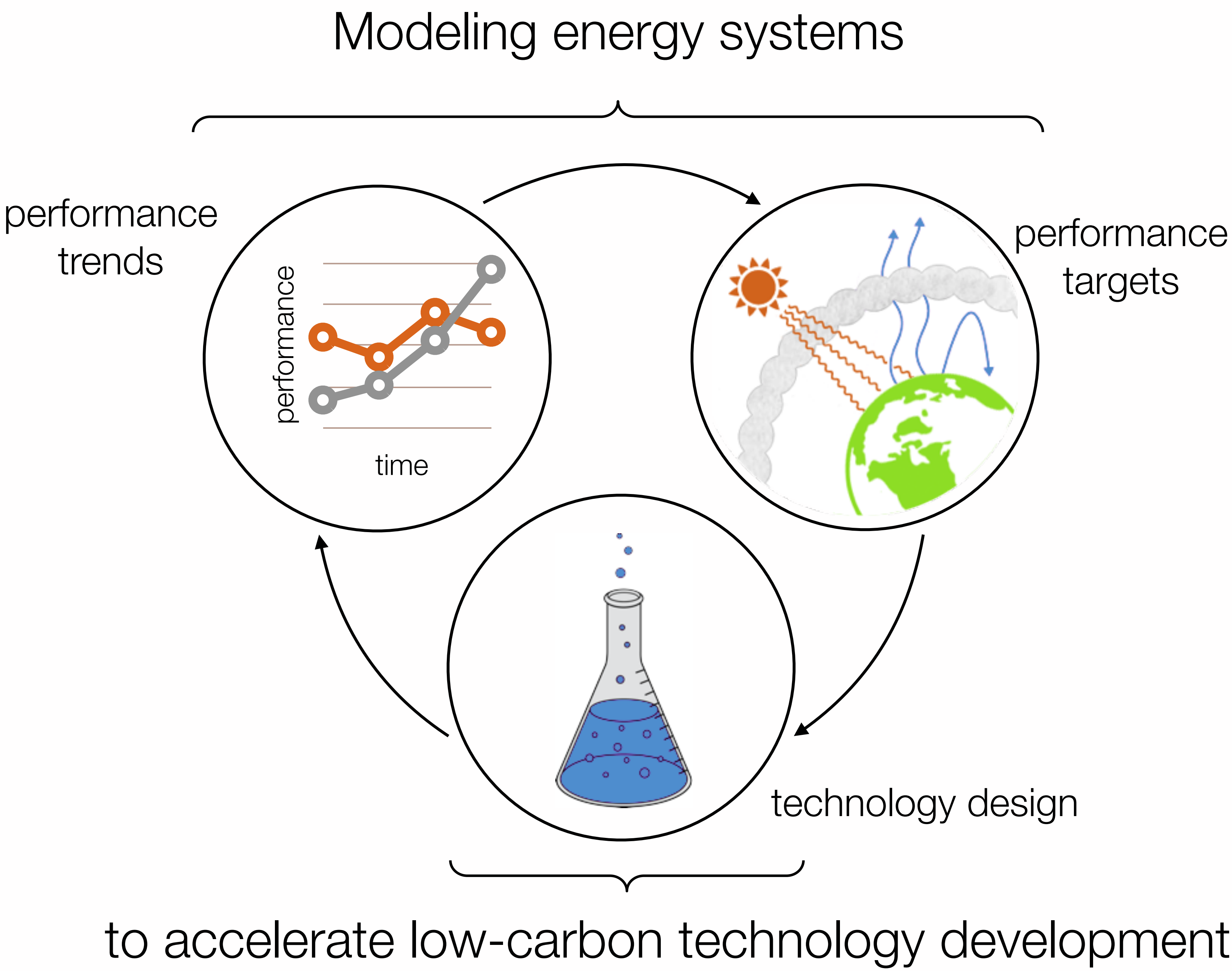
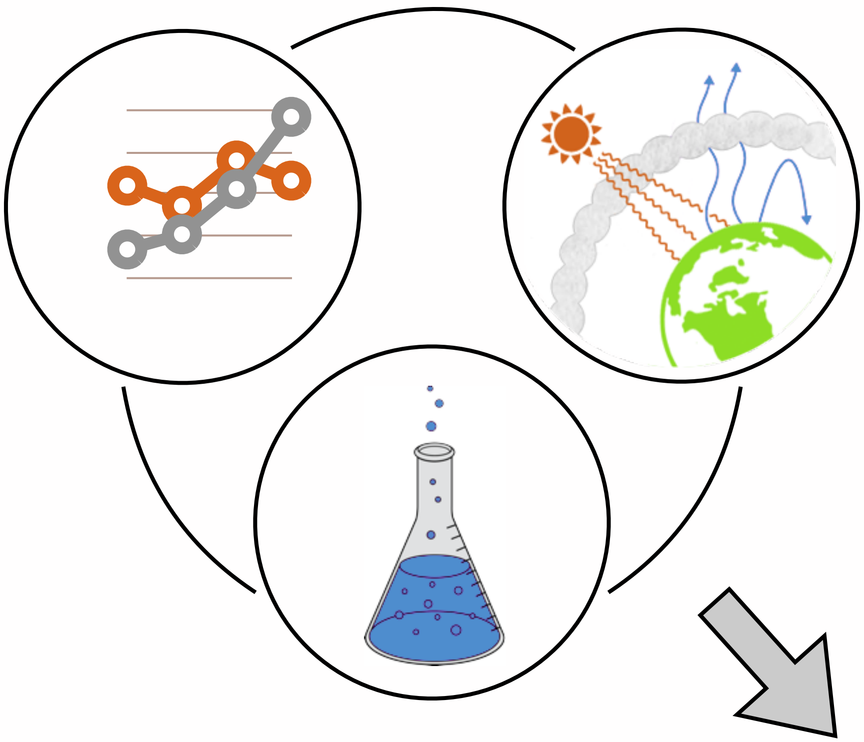

Modeling energy systems
performance trends
performance
time
performance targets
technology design
to accelerate low-carbon technology development



Fundamental insight + tools to inform decisions:
- engineers
- private investors
- policy makers (R&D, regulations)

Research areas

- Determinants of the rate of technological improvement
- Adoption potential of technologies evaluated against energy demand dynamics
- Emissions impacts of energy technologies evaluated against climate targets

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How much improvement needed in energy storage technologies?

- *Example 1:* Evaluate stationary storage cost structures against electricity demand, prices and resource availability

- *Example 2:* Evaluate mobile battery specific energy against personal vehicle travel patterns

Role of storage technologies for renewable energy

- Wind, solar resources are intermittent
- Storage can be used to:
  - Match renewables supply to demand
  - Increase renewable plant revenue

For background see:
D. Rastler, EPRI, Dec. 2010;
E. Hittinger, J.F. Whitacre, J. Apt, *J. Power Sources*, 206, 2012
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Evaluating storage techs for solar and wind energy

- How to compare diverse storage technologies on a single scale?

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

Moving beyond lists of attributes...

Storage technologies.

	L/A battery	Li-ion battery	NaS battery	VRB flow battery
Energy storage capacity (kW h)	⩽100	⩽10	⩽100	20–50
Typical power output (MW)	1–100	0.1–5	5	0.01–10
Energy density (W h/L)	50–80	200–500	150–250	16–33
Power density (W/L)	10–400	0	0	0
Discharge duration	Hours	Minutes–hours	Hours	2–8 h
Charge duration	Hours	Minutes–hours	Hours	2–8 h
Response time	<Seconds	Seconds	Milliseconds	<Seconds
Lifetime (years)	3–10	10–15	15	5–20+
Lifetime (cycles)	500–800	2000–3000	4000–40,000	1500–15,000
Roundtrip efficiency (%)	70–90%	85–95%	80–90%	70–85%
Capital cost per discharge ($/kW)	$300–$800	$400–$1000	$1000–$2000	$l200–$2000
Capital cost per capacity ($/kW h)	$150–$500	$500–$1500	$125–$250	$350–$800
Power quality			√	√
Transient stability	√			
Ancillary services				
Regulation		√	√	√
Spinning reserves	√	√	√	√
Voltage control		√	√	√

Castillo and Gayme, 2014

Evaluating storage techs for solar and wind energy

- How to compare diverse storage technologies on a single scale?
- At what costs do storage technologies add value to renewables?
- How do current devices compare to these targets?
- How to optimally improve future storage technologies?

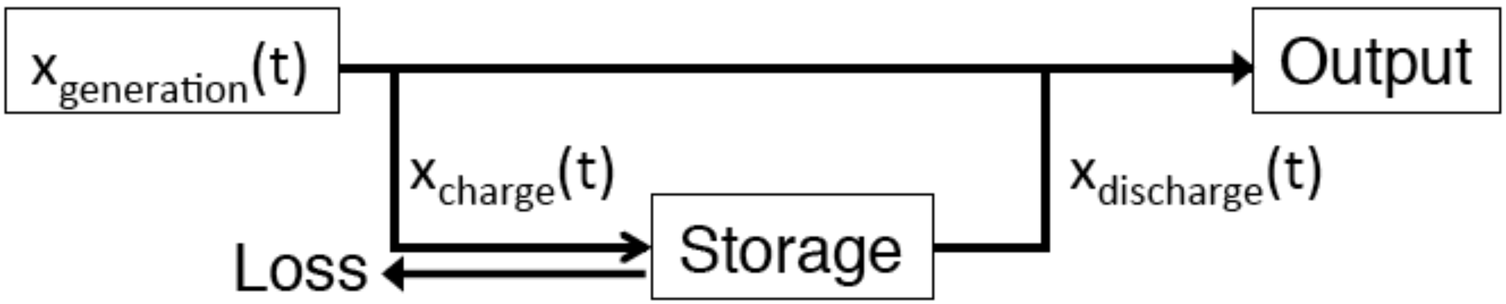
Braff, Mueller, Trancik, *Nature Climate Change* 2016

Consider three locations, two energy resources

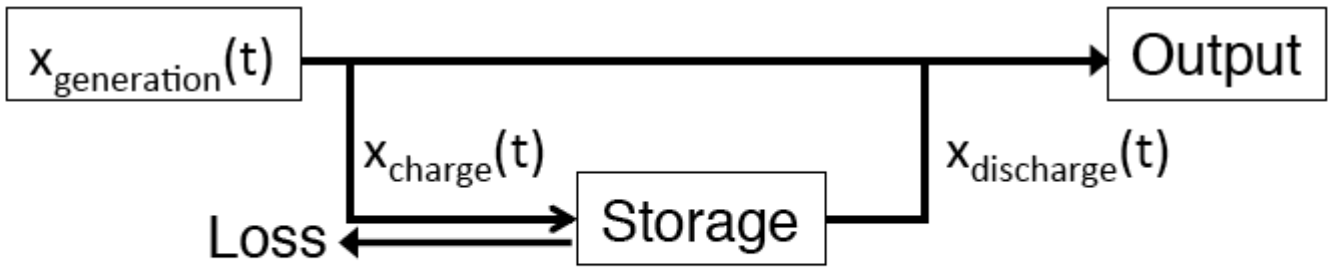
- Consider wind and solar at three sites:
    - Barnstable, MA
    - McCamey, TX
    - Palm Springs, CA

- Datasets:
    - Hourly real-time electricity pricing (ISONE, ERCOT, CAISO)
    - Hourly generation of solar and wind plants

Manage storage to maximize revenue



Manage storage to maximize revenue



revenue

wind, solar resource

$$R_{\mathrm{total}} = \max\left(\sum_{t=0}^{N} P(t)\left(x_{generation}(t) + x_{discharge}(t) - x_{charge}(t)/\eta\right)\right)$$

electricity price

subject to:

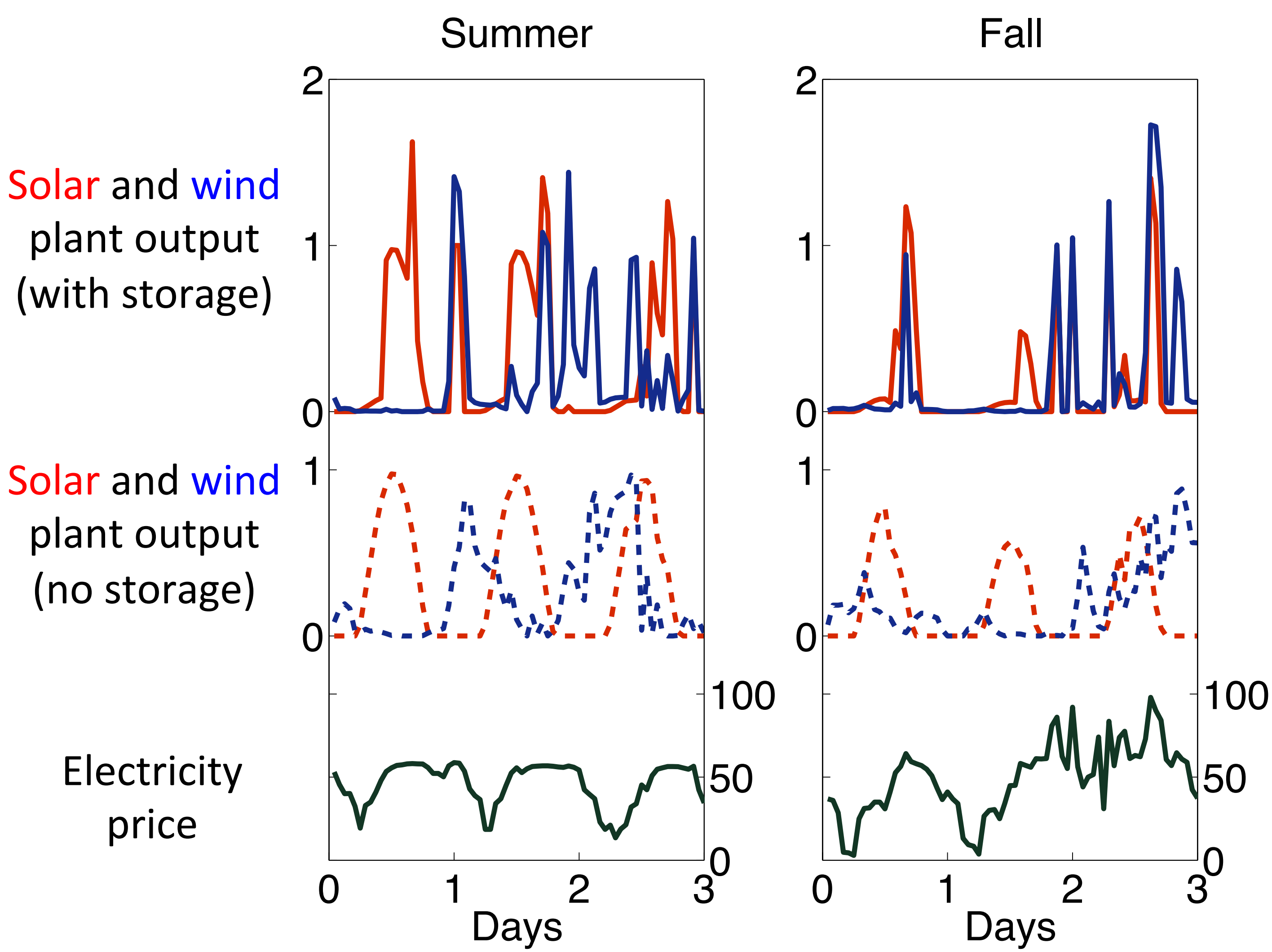
power capacity constraint

$$\begin{cases} 0 \leq x_{discharge} \leq \dot{E}_{max} \\ 0 \leq x_{charge} \leq \min(\eta x_{generation}(t), \eta \dot{E}_{max}) \end{cases}$$

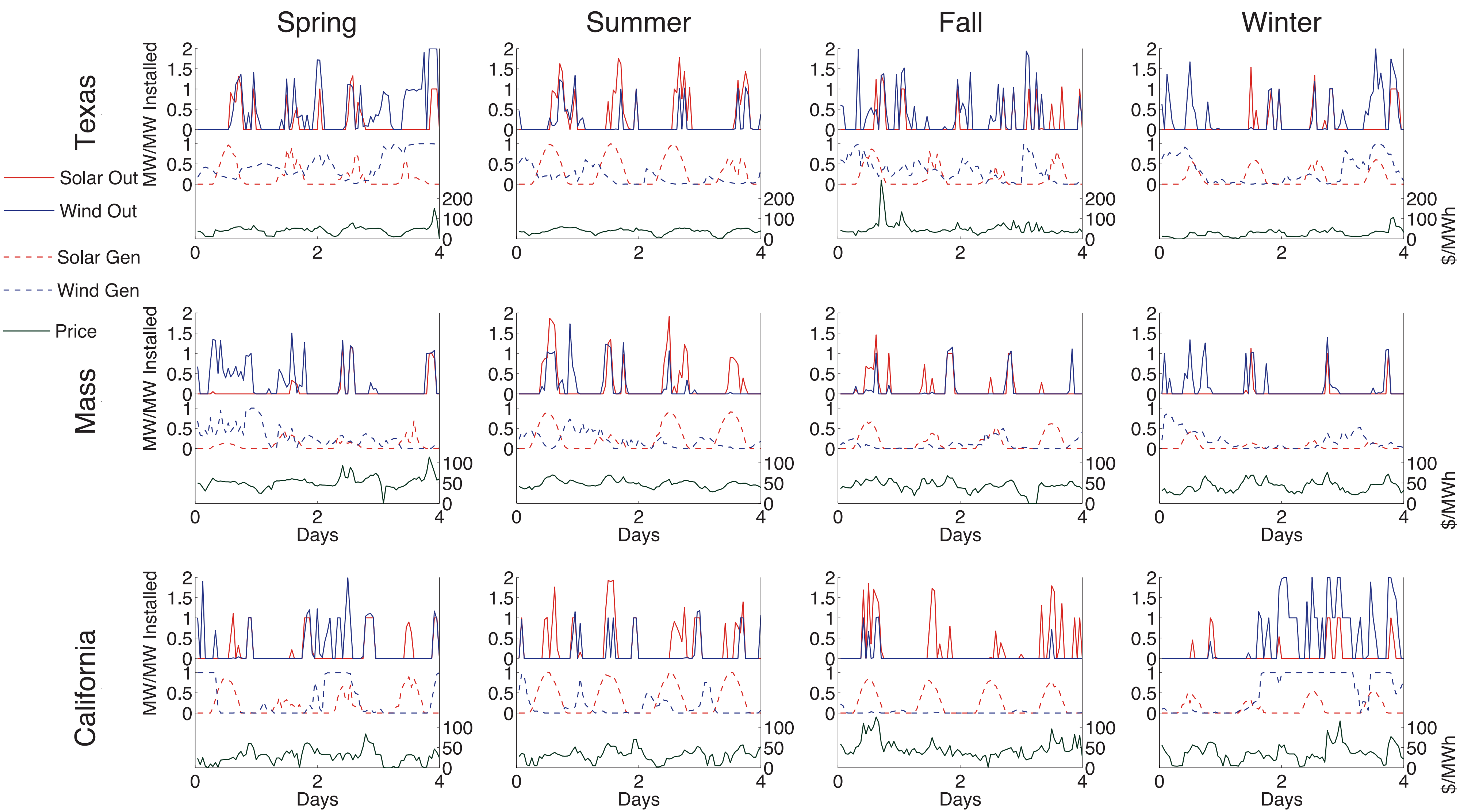
energy capacity constraint

$$\left\{ 0 \leq \sum_{t=0}^{N} (x_{charge}(t) - x_{discharge}(t)) \leq h\dot{E}_{max}. \right.$$

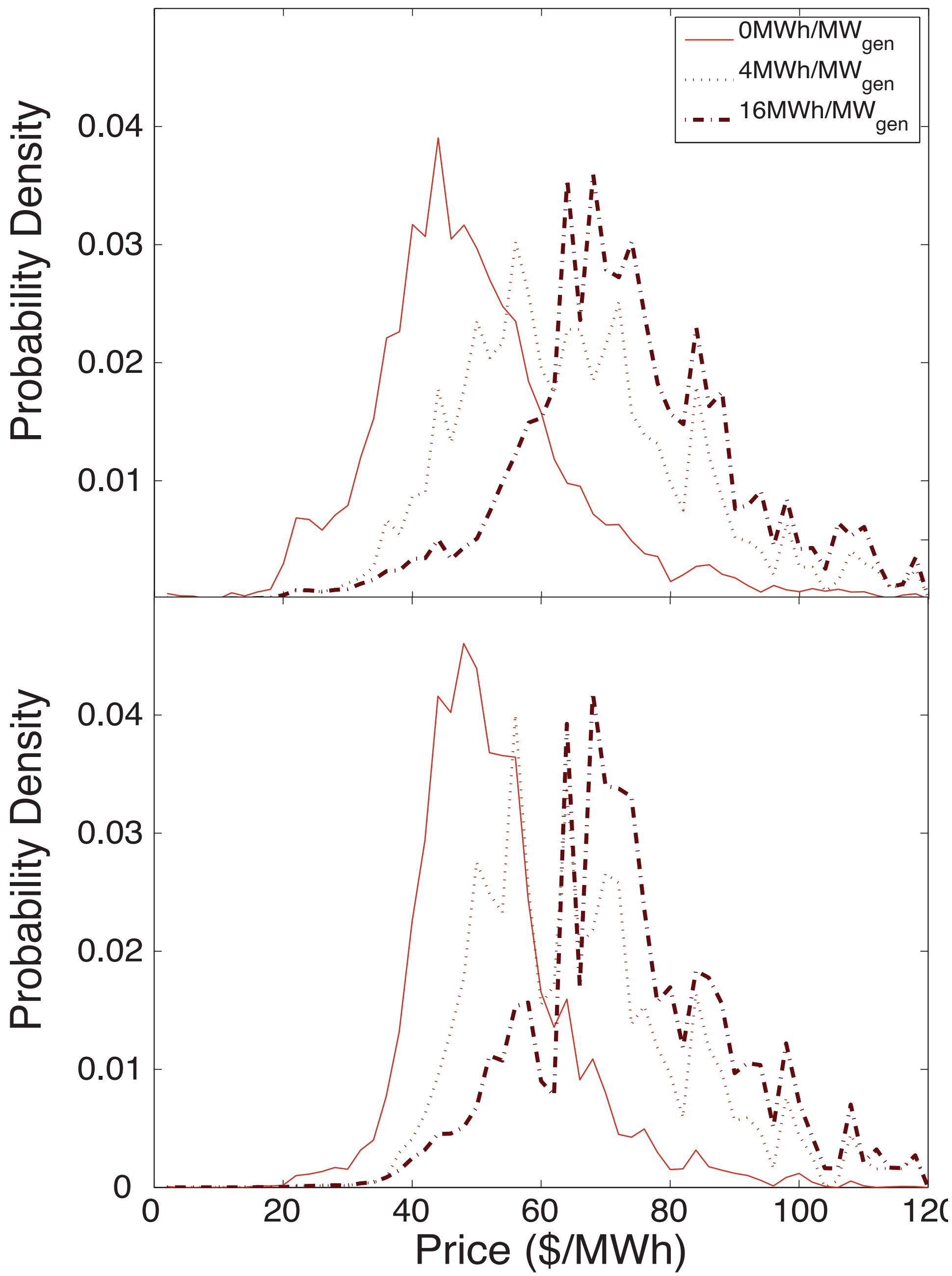
Managing storage to maximize revenue



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



Spring
Summer
Fall
Winter
Texas
Mass
California
MW/MW Installed
$/MWh
Days
Solar Out
Wind Out
Solar Gen
Wind Gen
Price



MA solar

MA wind

Balancing the cost and benefit of storage

- Value of energy storage

annual revenue

$$\chi = \frac{R_{\text{total}}}{CRF(C_{\text{gen}} + \dot{E}_{\max}(C^{\text{power}}_{\text{storage}} + hC^{\text{energy}}_{\text{storage}}))}$$

annualization factor

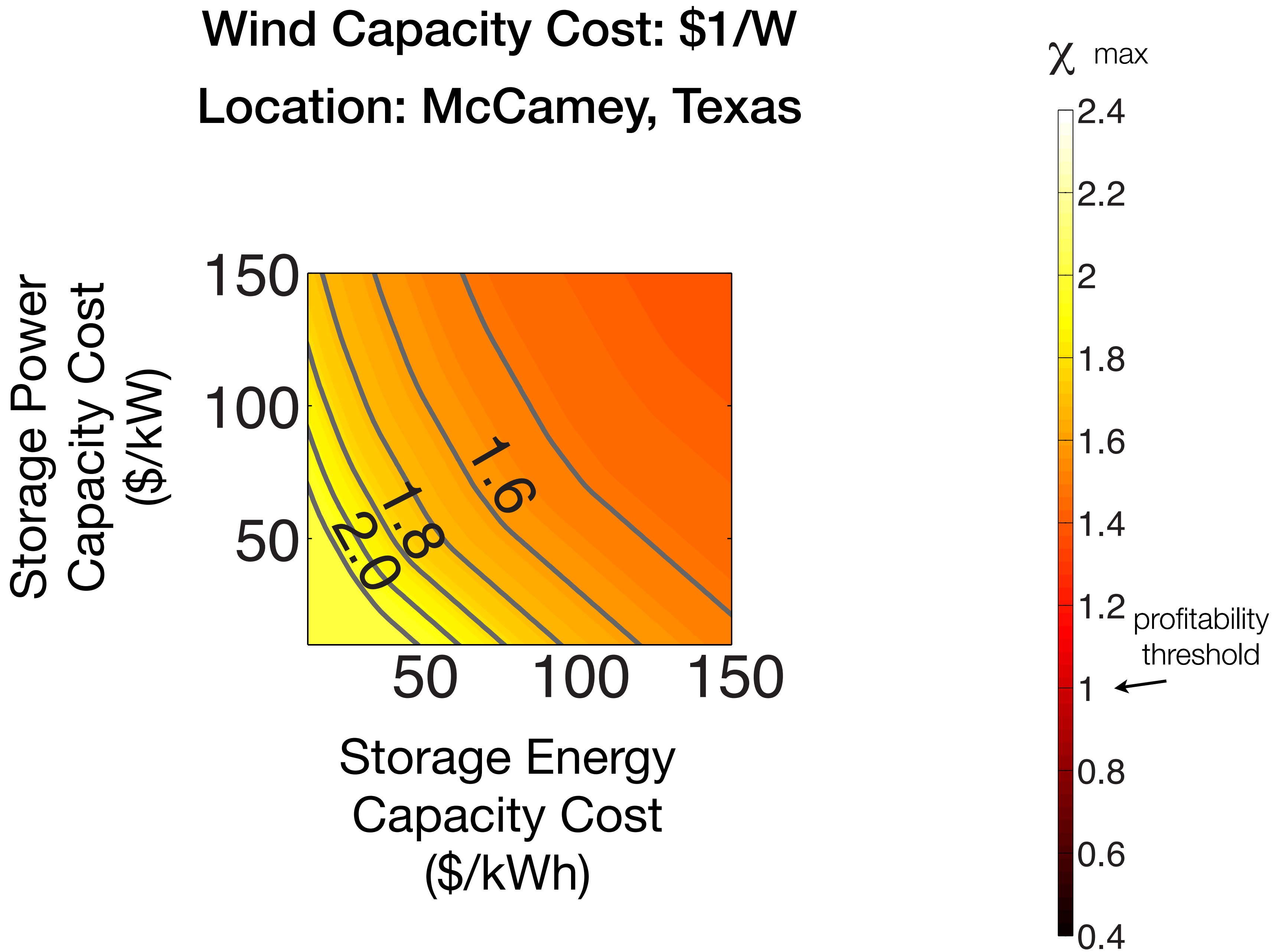
wind, solar cost

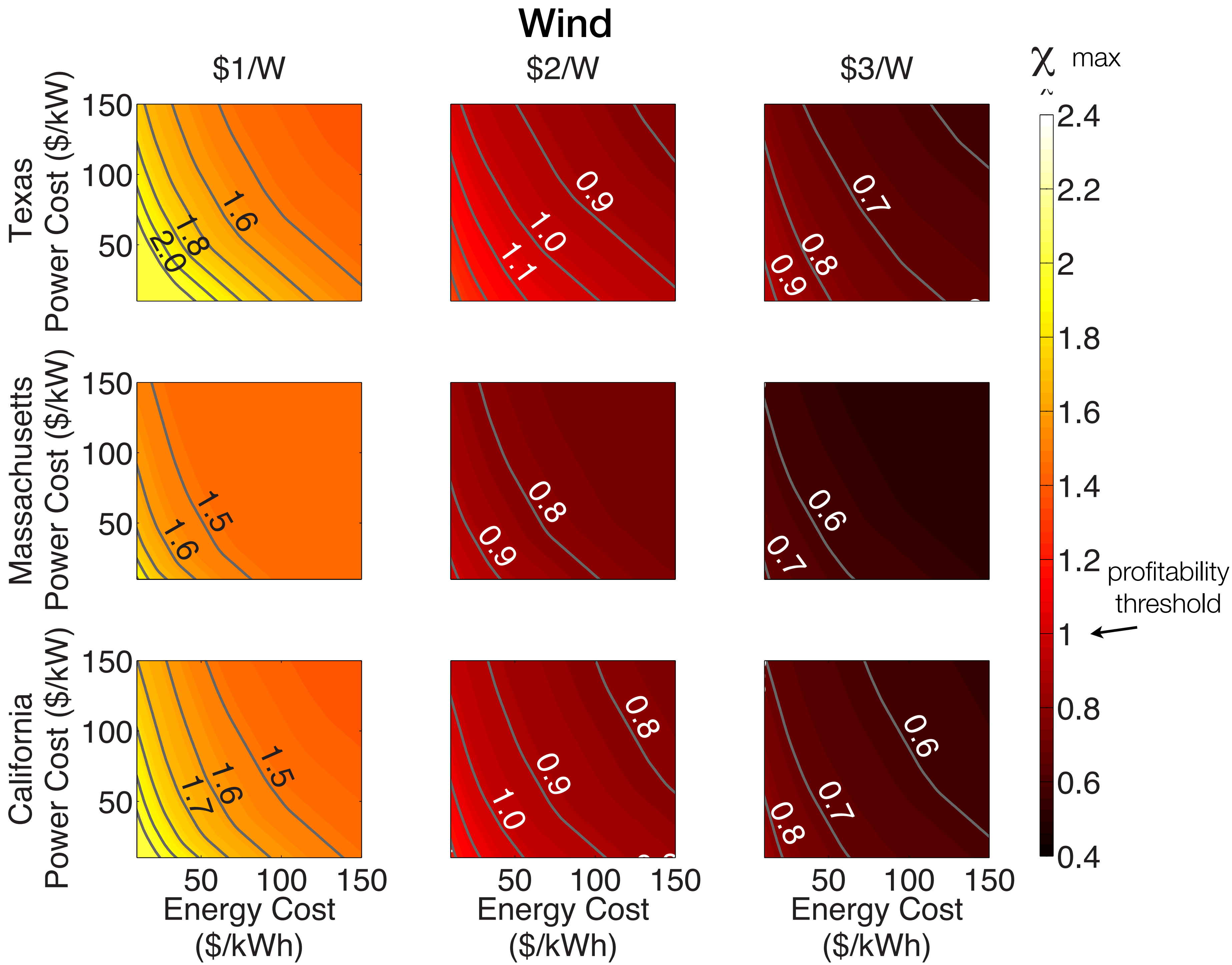
storage power

hours

storage cost

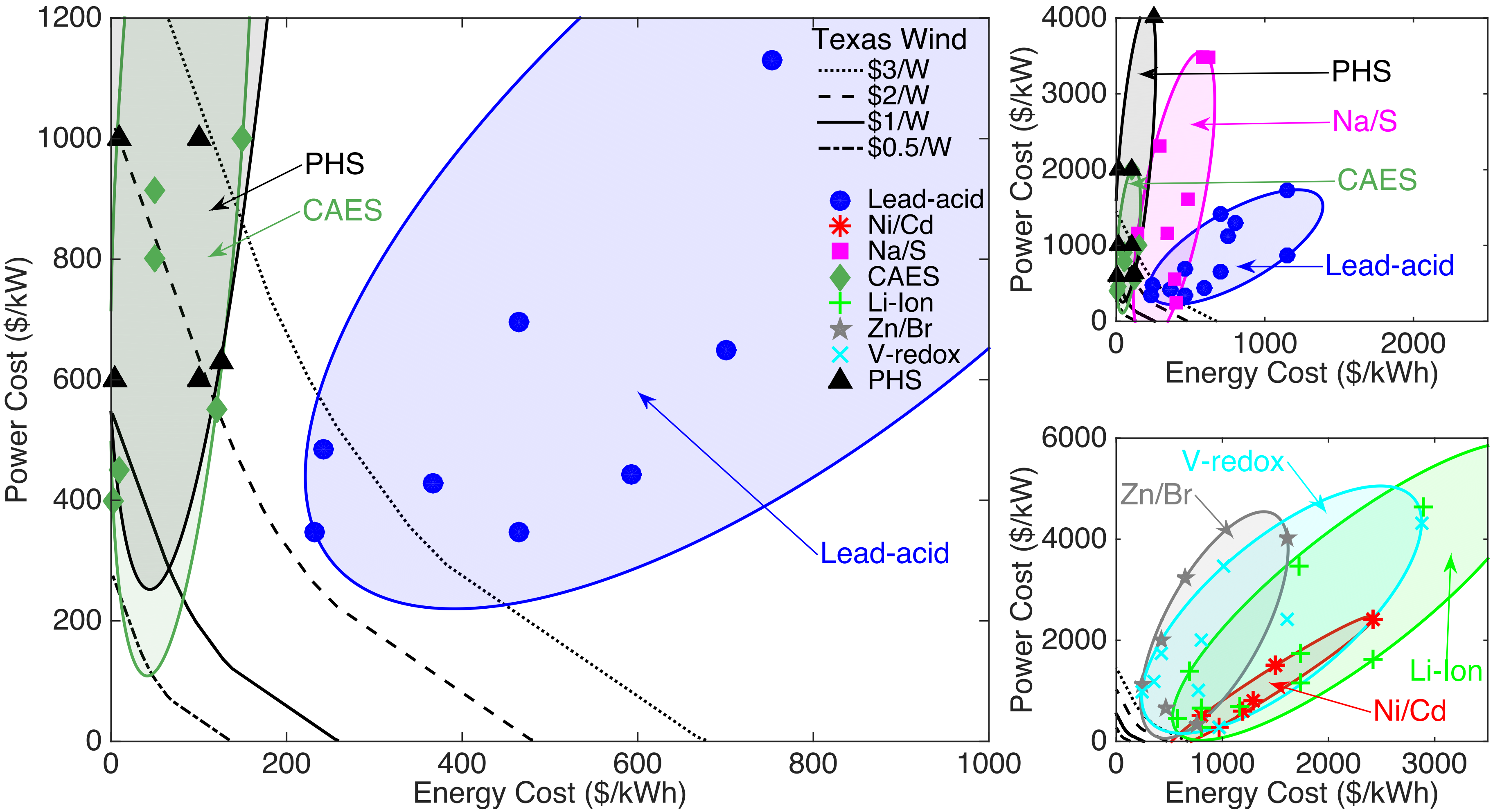
- Storage system sized to maximize chi


Wind Capacity Cost: $1/W
Location: McCamey, Texas
Storage Power Capacity Cost ($/kW)
150
100
50
1.6
1.8
2.0
50
100
150
Storage Energy Capacity Cost ($/kWh)
χ max
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
profitability threshold



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

Storage technologies compared to value-adding cost thresholds



PHS: pumped hydro storage
CAES: compressed air energy storage

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

Evaluating storage techs for solar and wind energy

- Storage today can add value to wind and solar in some locations
- Cost improvement needed for wide-spread profitability
- Optimal cost improvement trajectories relatively location invariant
- Cost targets can inform industry and government tech strategies

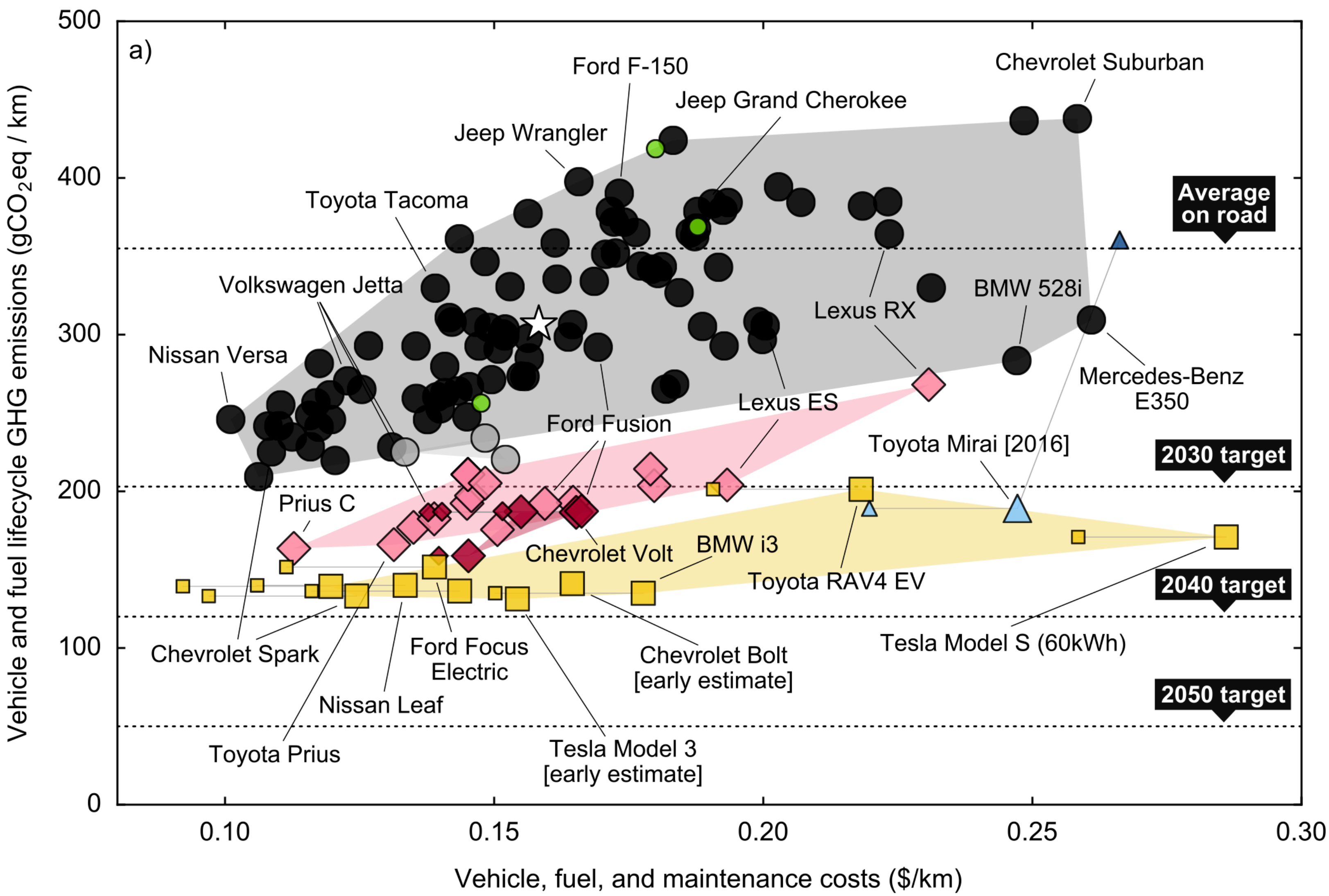
Braff, Mueller, Trancik, *Nature Climate Change* 2016

How much improvement needed in energy storage technologies?

- *Example 1:* Evaluate stationary storage cost structures against electricity demand, prices and resource availability

- *Example 2:* Evaluate mobile batteries against personal vehicle travel patterns

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



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

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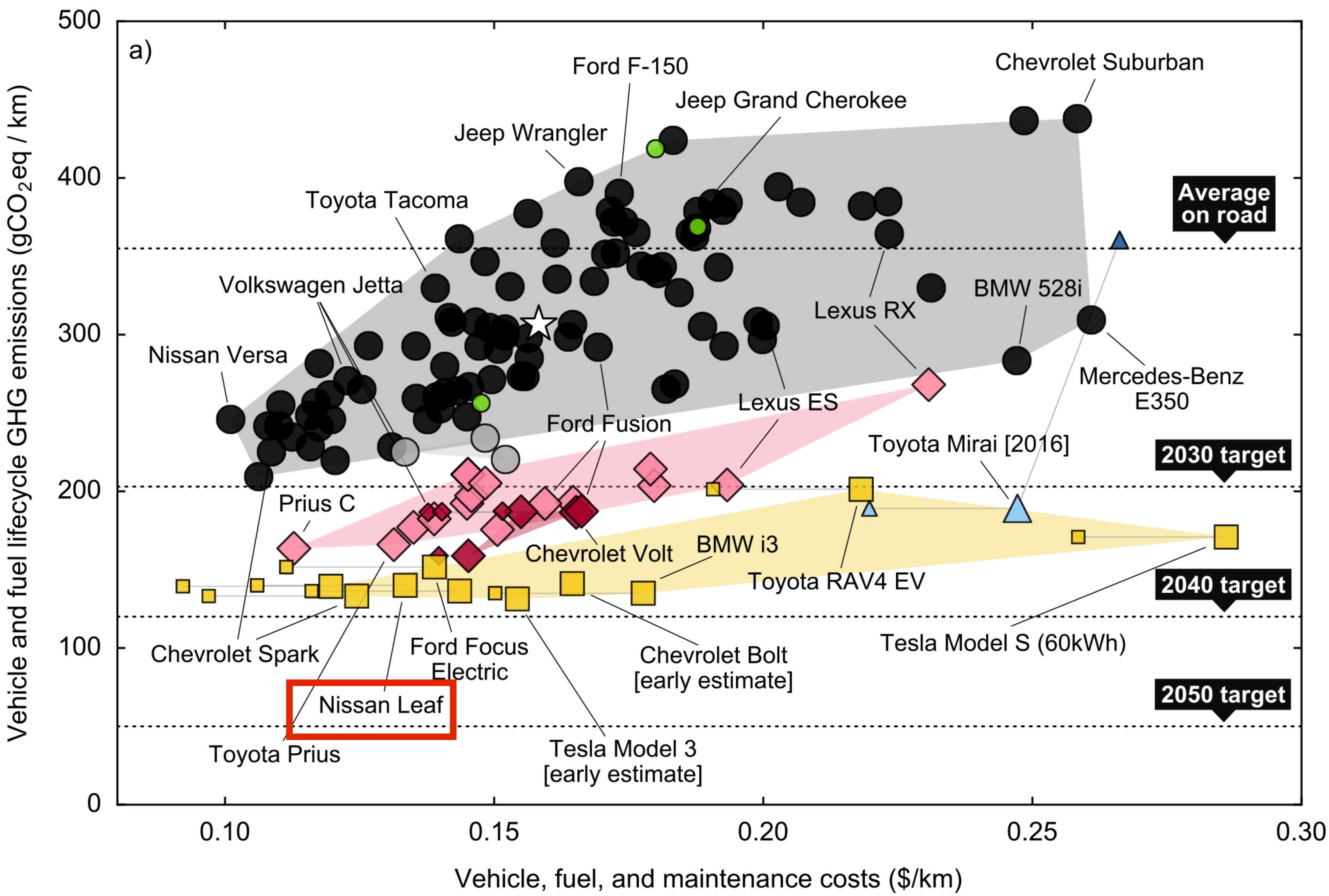
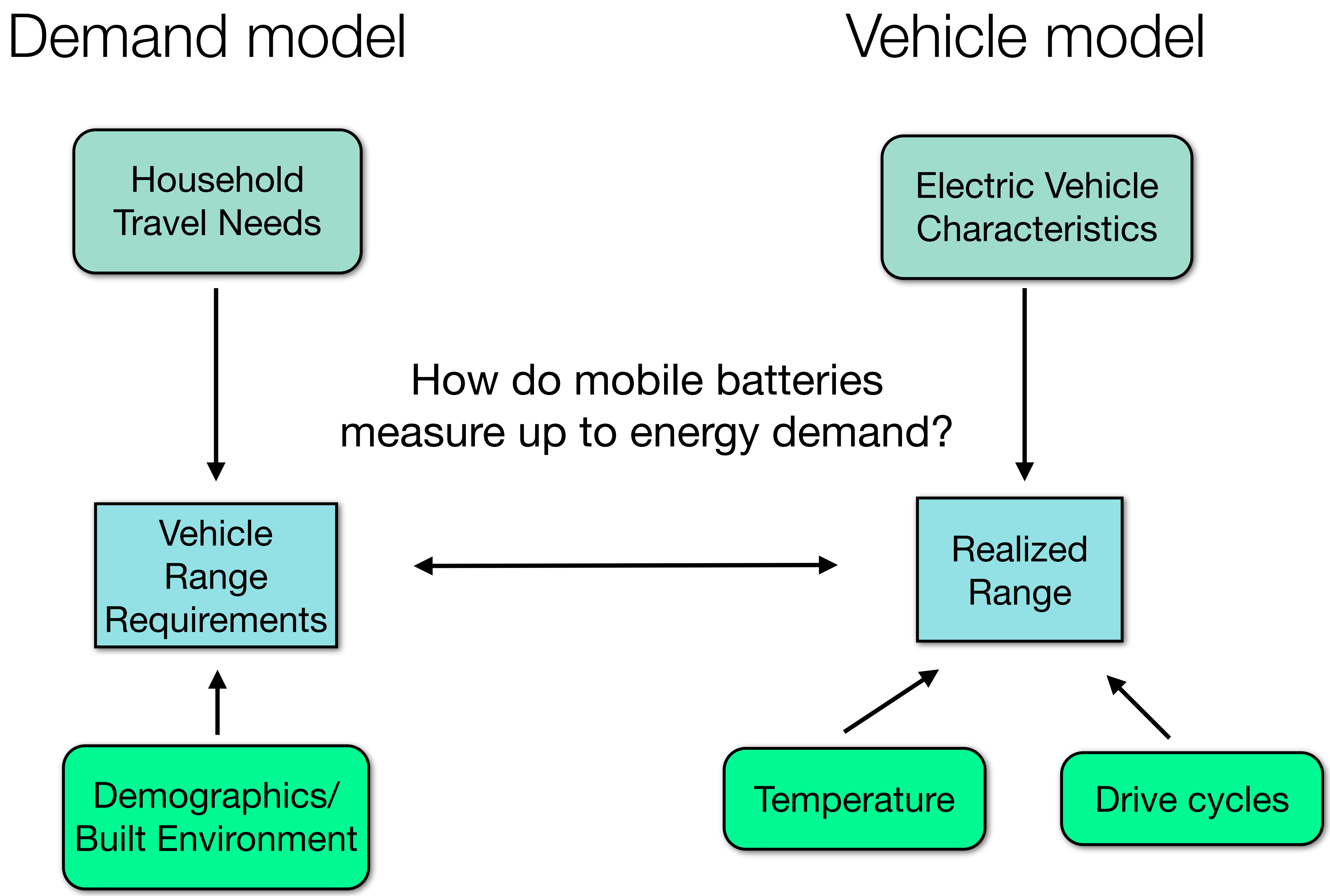


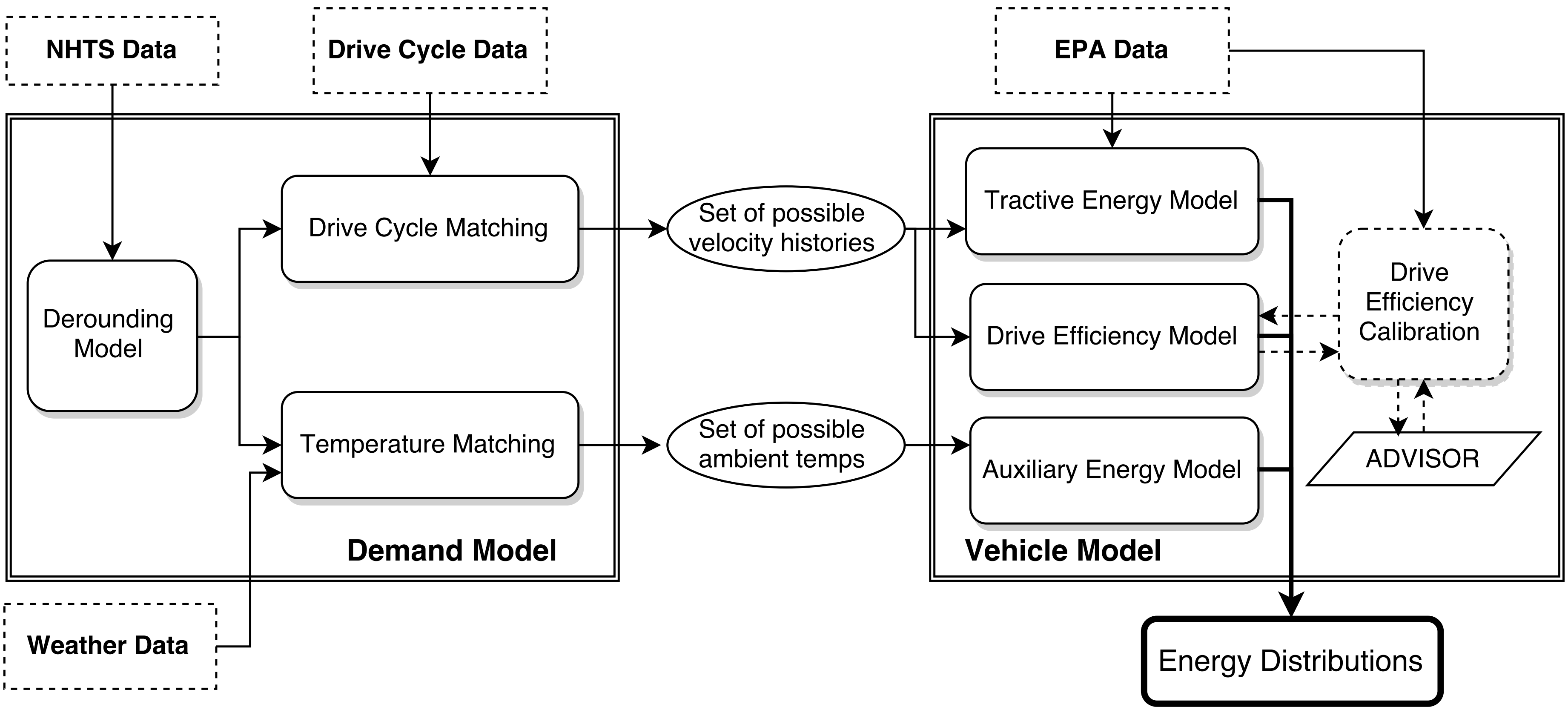
Miotti, Supran, Kim, Trancik, *Environmental Science & Technology* 2016; carboncounter.com


Electric


CARPOOL IS 3 OR MORE PERSONS PER VEHICLE


Demand model
Vehicle model
Household Travel Needs
Electric Vehicle Characteristics
How do mobile batteries measure up to energy demand?
Vehicle Range Requirements
Realized Range
Demographics/ Built Environment
Temperature
Drive cycles

TripEnergy Model



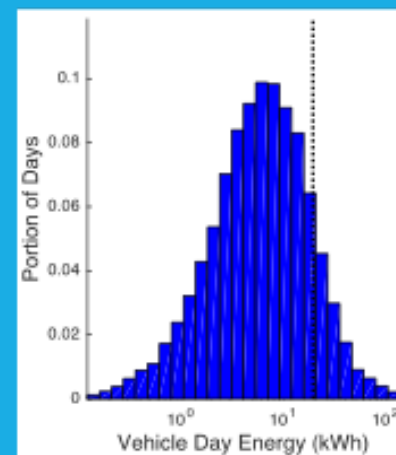
Demand Model

NHTS:

Limited information on a specific trip

TripEnergy Matching

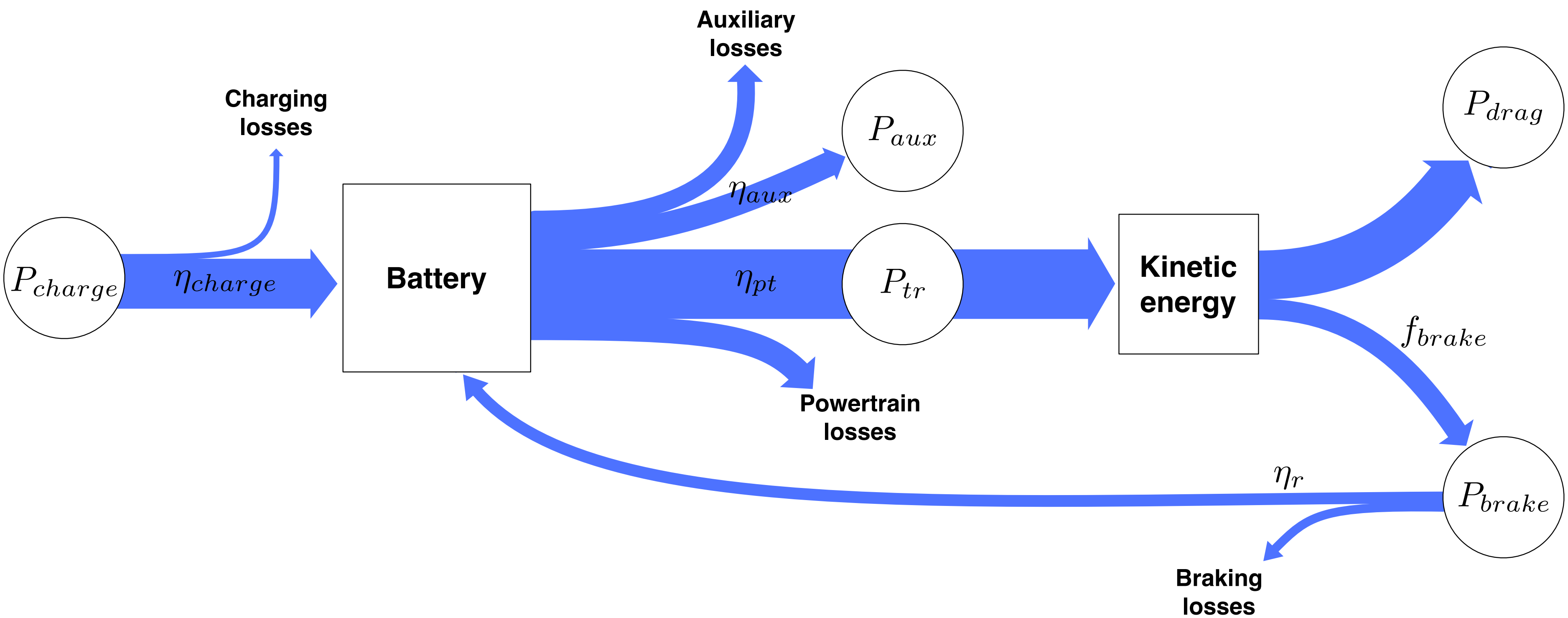
Trips with known energy requirements



Energy Distribution

GPS surveys + vehicle model

Vehicle Model



Tractive Energy Calculation

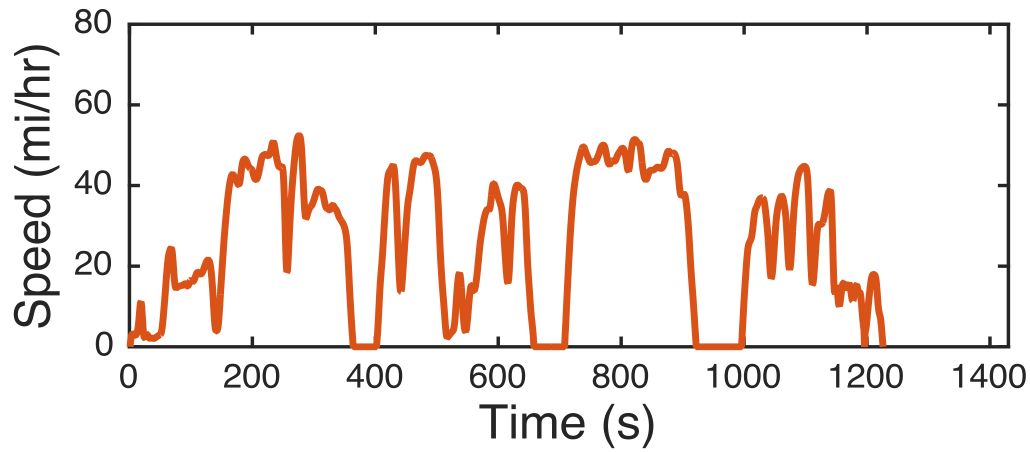
Drag Coefficients

$$F_{tr}(v) = a + bv + cv^2 + (1+q)m\frac{dv}{dt}$$

Rotational Inertia

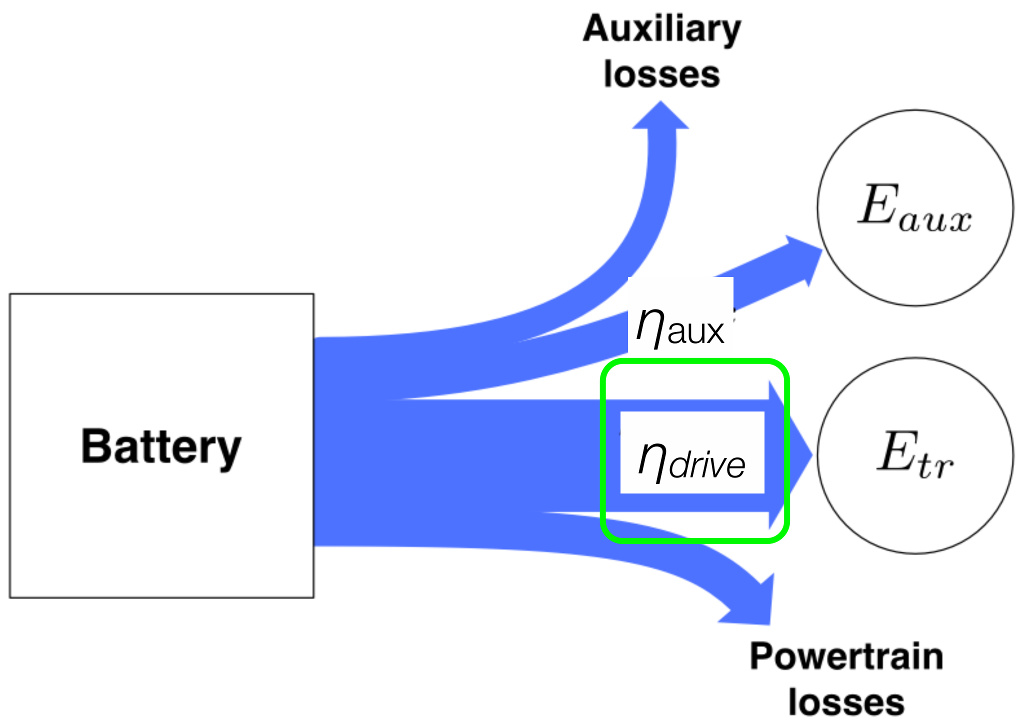
Mass

$$E_{tr} = \int_{F_{tr}(t)>0} F_{tr}(t)v(t)\,dt$$



Vehicle Model

$$\Delta E_B = \frac{E_{tr}}{\eta_{drive}} + \frac{E_{aux}}{\eta_{aux}}$$



Drive Efficiency Calculation

$$\eta_{drive} \approx f(\text{drive cycle})$$

Test Result:

$$\Delta E_B = \frac{E_{tr}}{\eta_{drive}} + \frac{E_{aux}}{\eta_{aux}}$$

Expression for Efficiency:

$$\eta_{drive} = \frac{E_{tr}}{\Delta E_B - E_{aux}/\eta_{aux}}$$

$$\eta_{drive}(\mathbf{f_{brake}}) = \frac{\eta_{pt}^*}{1 - \eta_{pt}^* \mathbf{f_{brake}} \eta_r^*}$$

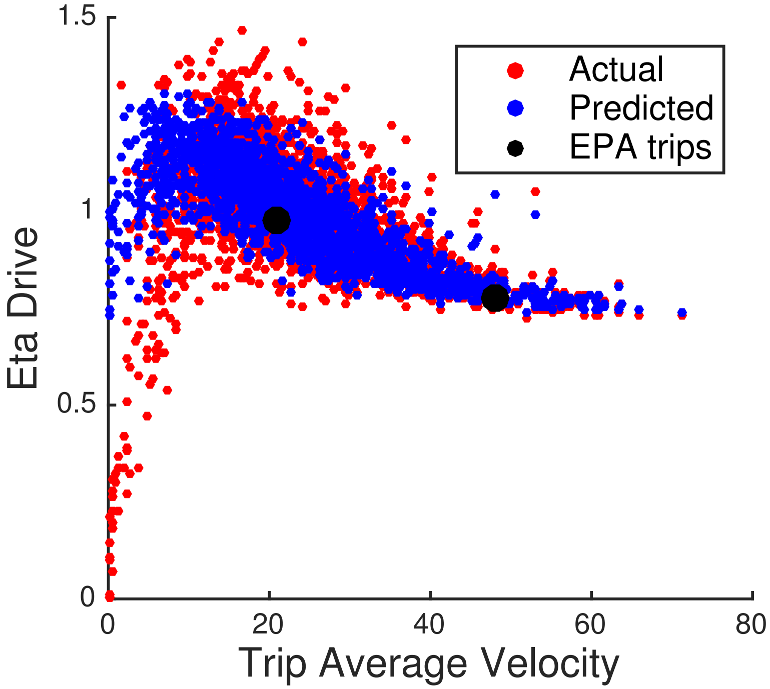
↓

Solve system of equations with EPA results

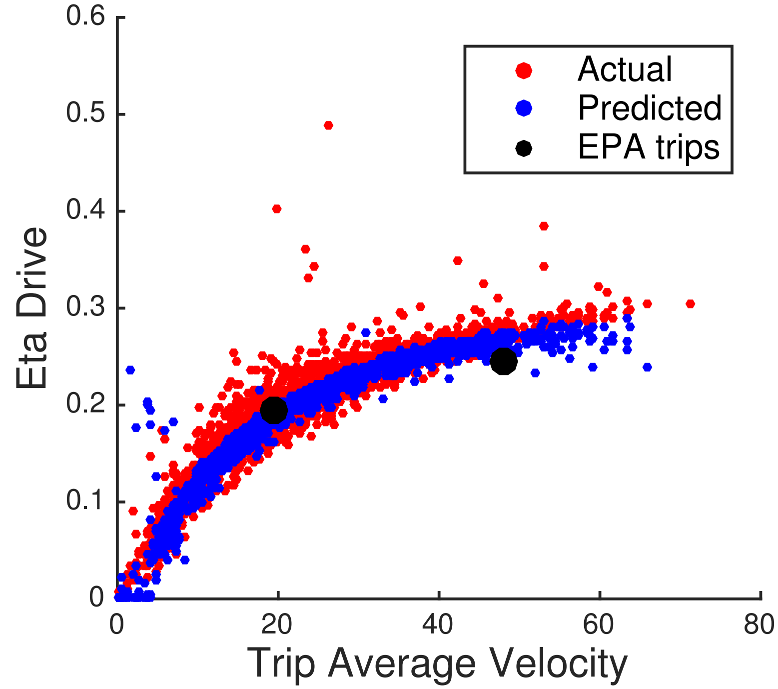
↓

$$\eta_{pt} = 0.908 \qquad \eta_r = 0.849$$

Drive Efficiency Validation

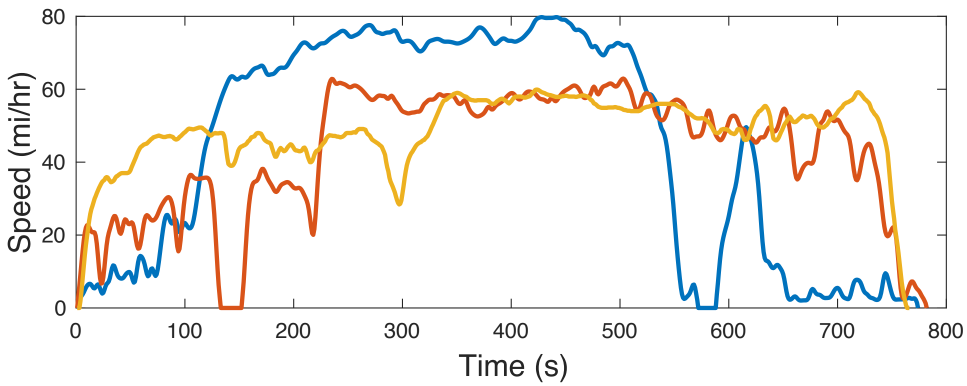


BEV

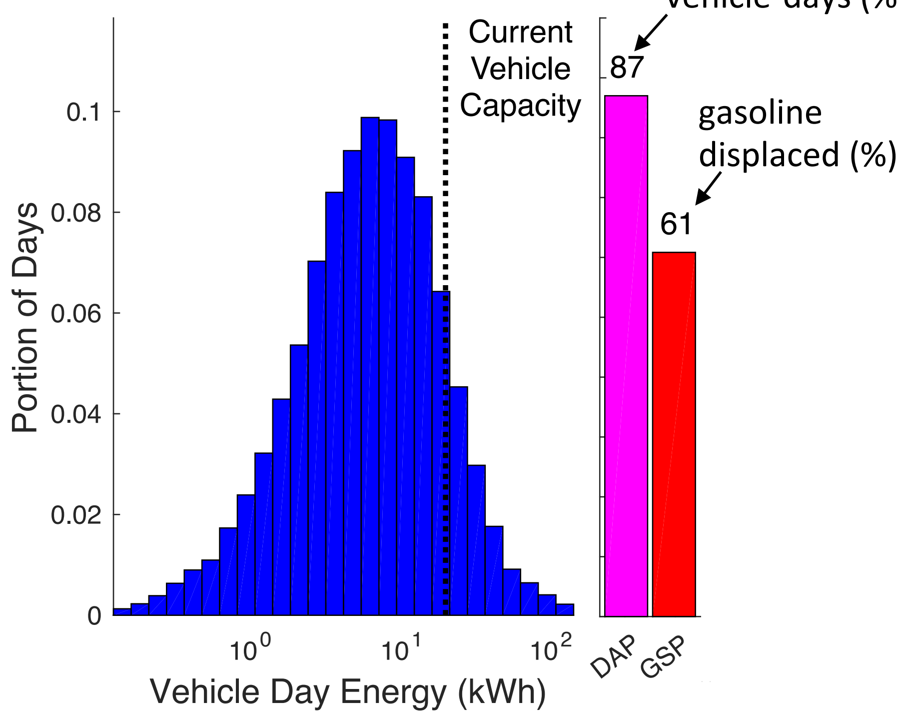


ICEV

Batteries evaluated against U.S. driving patterns



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

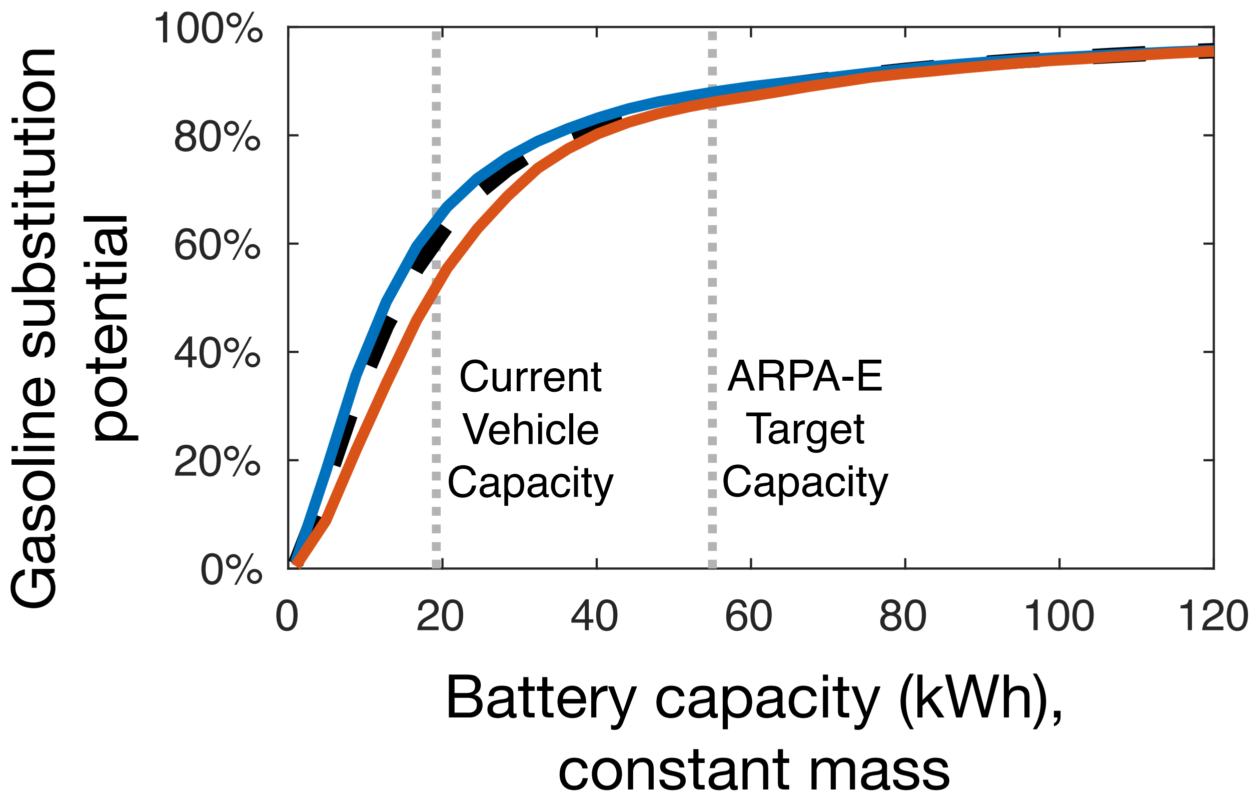


87% of vehicles can be replaced by a low-cost electric vehicle on an average day, even if only nighttime charging is available.

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

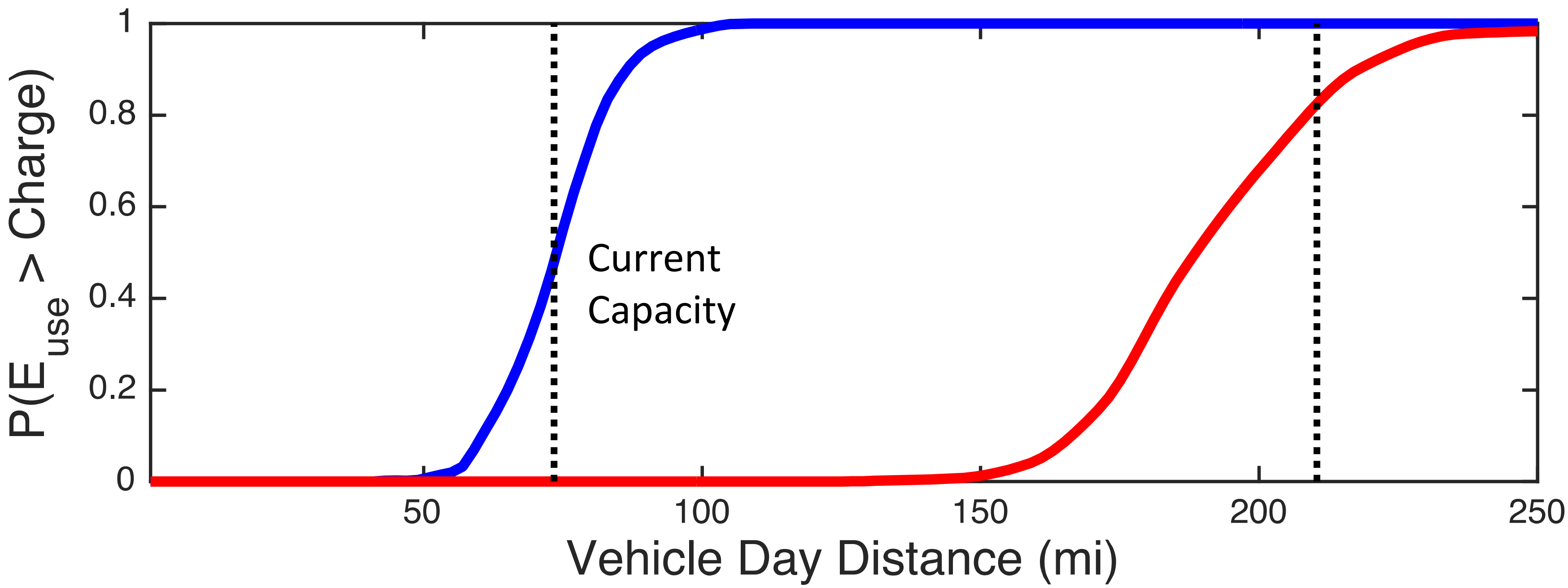
Needell, McNerney, Chang, Trancik, *Nature Energy* 2016

Diminishing returns to battery improvement



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

Predicting electric vehicle range



- Range is not constant—73 miles on average but with a distance of 58 miles, a 5% chance of running out of charge
- Range does not increase linearly with battery capacity

How much improvement needed in energy storage technologies and materials?

- *Example 1:* Evaluate stationary storage cost structures against electricity demand, prices and resource availability
- *Example 2:* Evaluate mobile battery specific energy against personal vehicle travel patterns

Conclusions and discussion

- Energy storage development next ~15 years critical for renewables growth and climate change mitigation
- Some storage technologies becoming profitable for renewables in several locations, but further development needed
- 87% of US personal vehicle-day energy needs met with today's batteries w/out recharging, but other powertrains needed to enable widespread electric vehicle adoption
- Energy storage materials and device development targets can be quantified by examining patterns of energy demand

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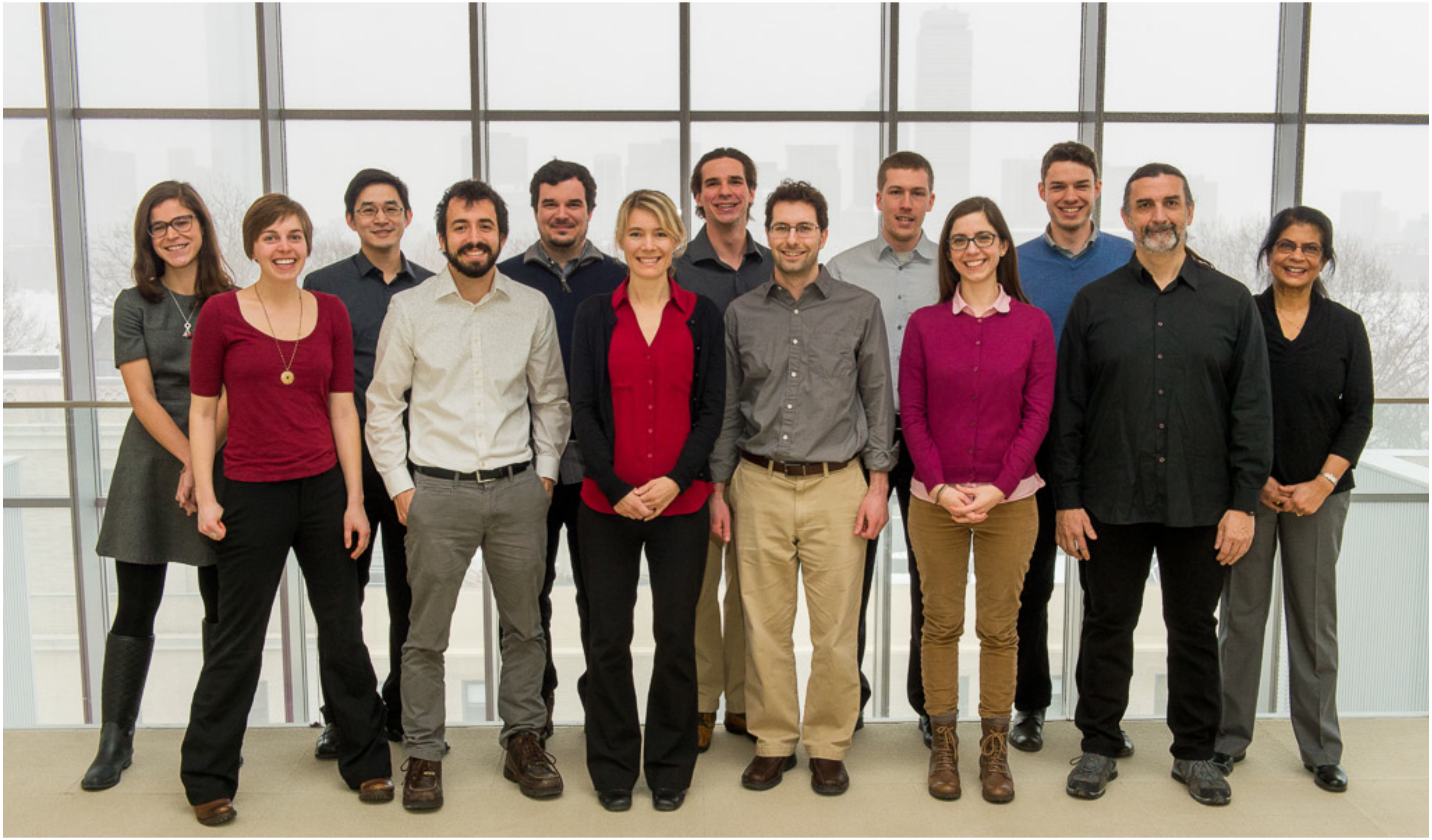
- **Energy storage materials and device development targets can be quantified by examining patterns of energy demand**



Magdalena Klemun, Michael Chang, Gonçalo Pereira, Joshua Mueller, Fabian Riether, Marco Miotti, Mandira Roy
Morgan Edwards, Zach Needell, Jessika Trancik, James McNerney, Göksin Kavlak, Victor Ocana