

Optimal Investment in Wind and Solar Power in California

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(based on Ph.D. research completed at
U.C. Berkeley Energy and Resources Group)

Research Question

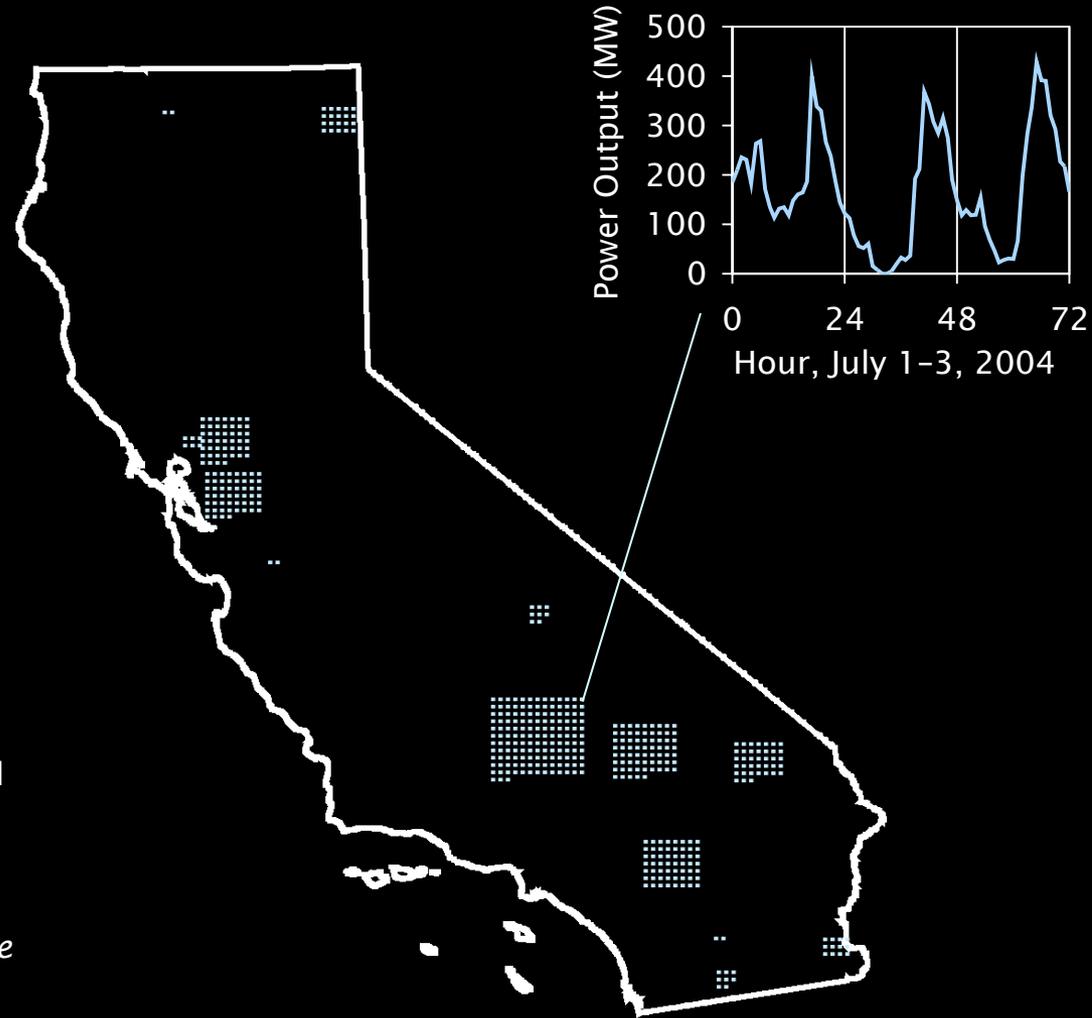
How much wind and solar power should California use by 2025?

METHODS

Research Approach

- Assign a cost to greenhouse gas emissions
- Build an optimization model to...
 - Choose
 - generator investments every 4 years
 - transmission investments every 4 years
 - hourly generator dispatch
 - hourly transmission dispatch
 - To satisfy hourly electricity loads, with a 15% reserve margin
 - At the lowest total cost (including carbon cost)

Wind Power Production

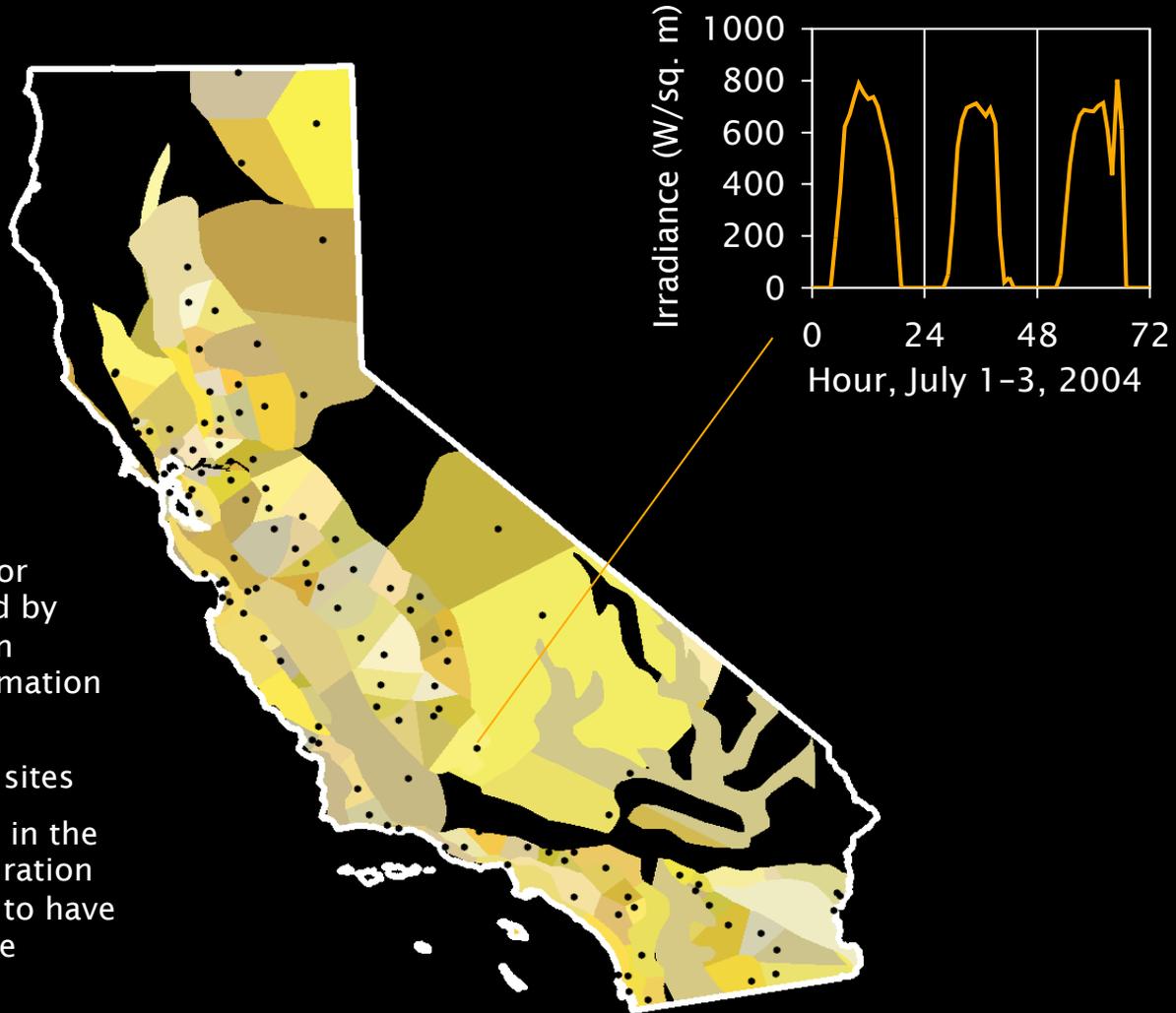


hourly data for 2002-04
from numerical weather
model run by AWS
Truewind

233 sites (23 GW),
augmented with an equal
number of fictitious
lower-wind sites

*site locations in this
diagram are approximate*

Solar Irradiance



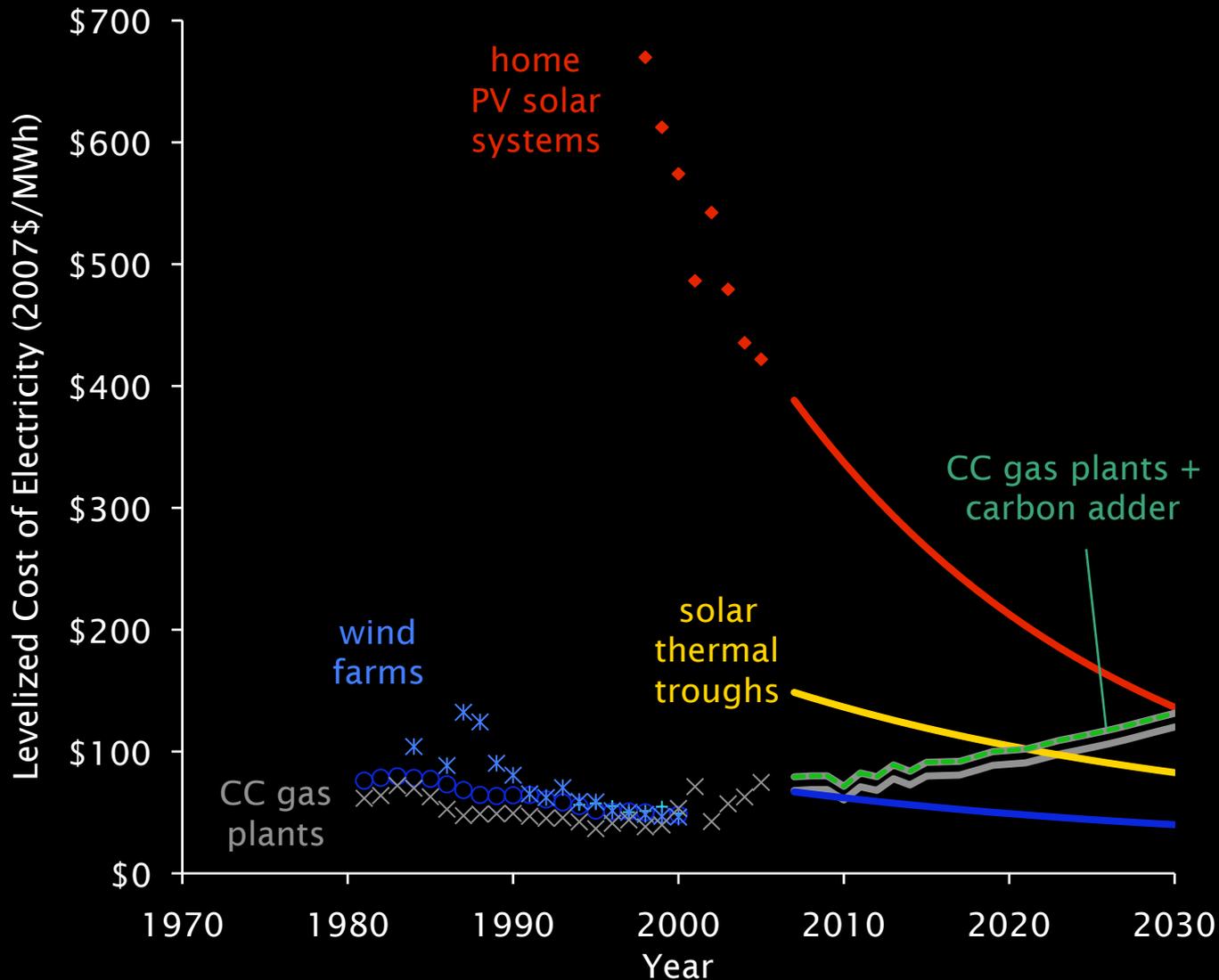
hourly irradiance for
2002-04 measured by
California Irrigation
Management Information
System

117 measurement sites
nearby PV systems in the
same evapotranspiration
zone are assumed to have
the same irradiance

Interzonal Transfer Capability



Projected Electricity Costs



Finance Assumptions

	Real Rate (net of inflation)	Nominal Rate
Finance Rate (to amortize capital costs)	6%	~9%
Finance Rate — distributed PV (home equity loan)	3%	~6%
Discount Rate (to convert to present-value)	3%	~6%

Projected Fuel Costs (2007\$/MBtu)

Year	Natural Gas	Nuclear	Coal
2010	\$5.34	\$0.99	\$1.61
2014	\$6.56	\$1.83	\$1.71
2018	\$7.56	\$2.20	\$1.83
2022	\$8.12	\$2.20	\$1.94

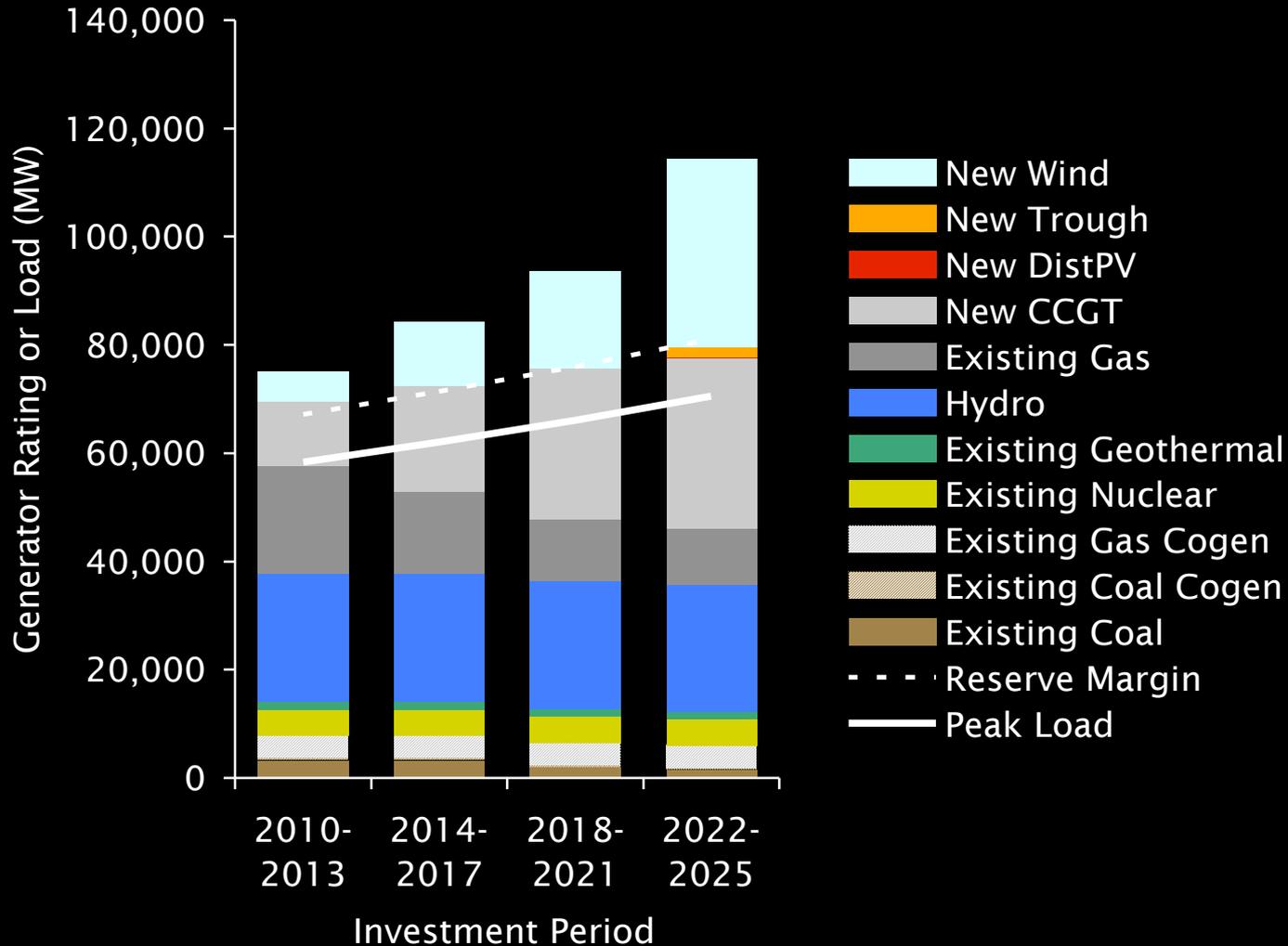
Projected Capital Costs (2007\$/kW)

	CCGT	DistPV	Trough	Wind
2010	\$694	\$7,549	\$3,368	\$1,648
2014	\$650	\$6,200	\$2,909	\$1,429
2018	\$610	\$5,093	\$2,512	\$1,239
2022	\$572	\$4,183	\$2,169	\$1,074
Inter- connect	+\$64	+\$0	+~\$250	+~\$330

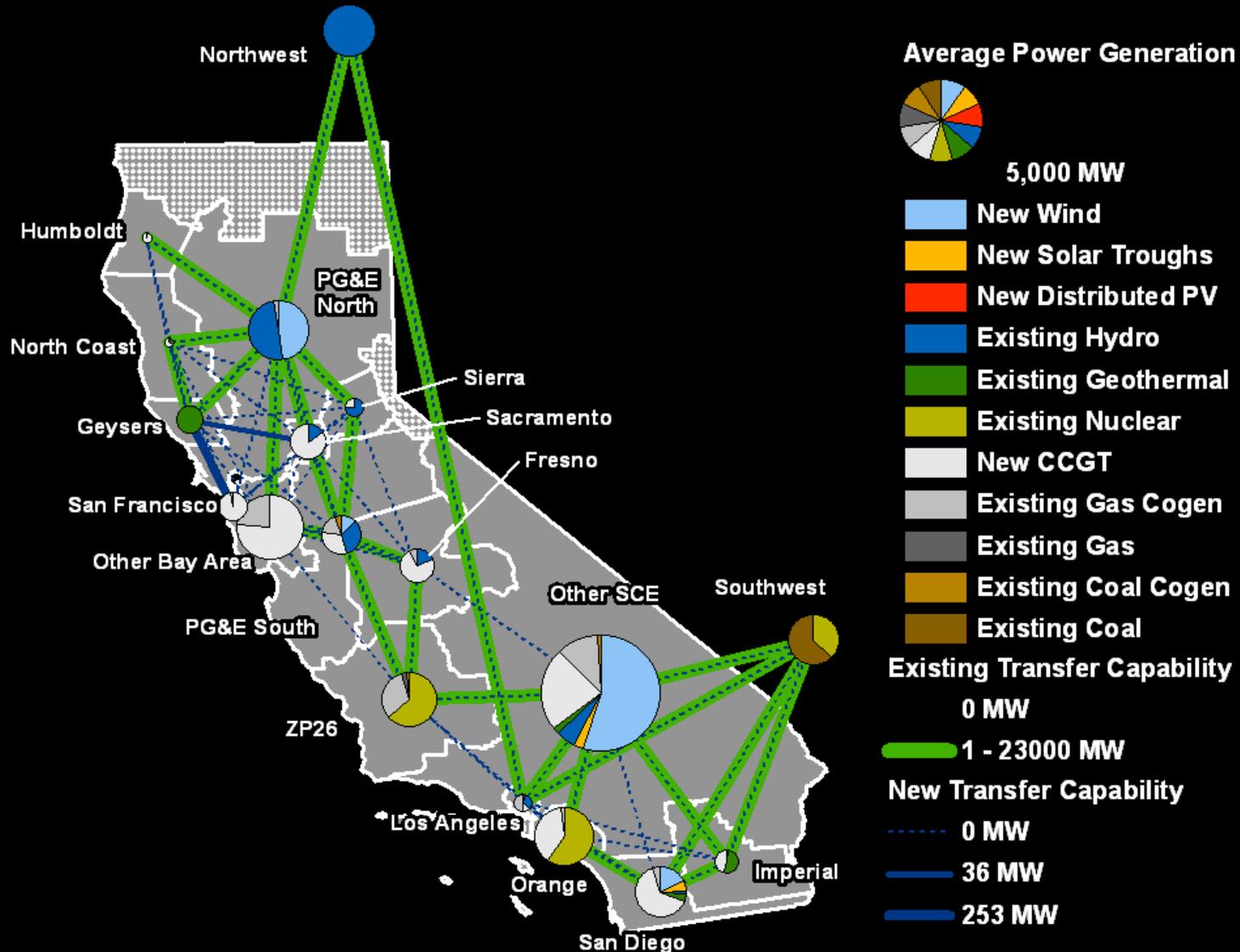
RESULTS

Optimal Generator Portfolio

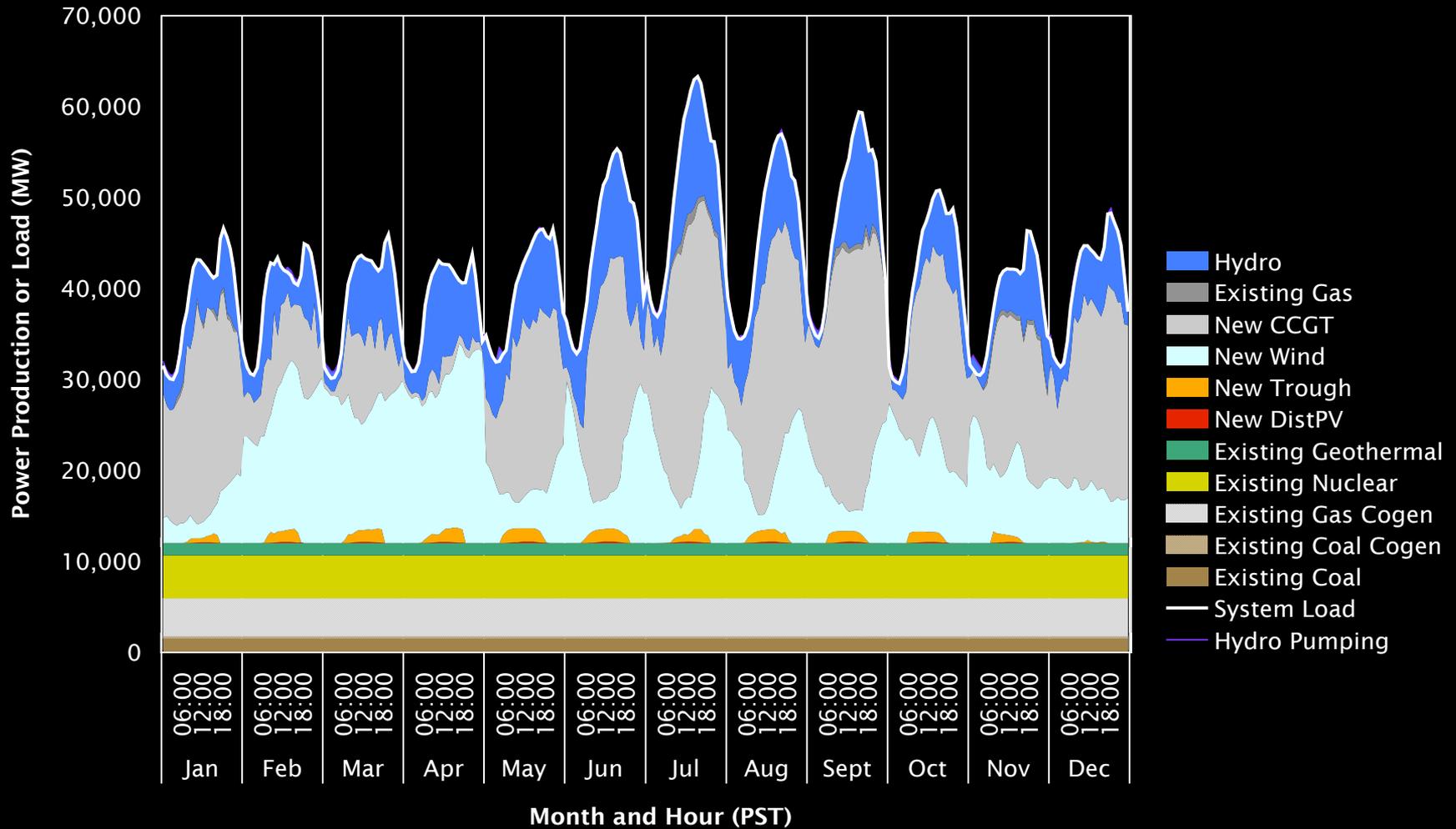
(\$30/tCO₂ Carbon Cost)



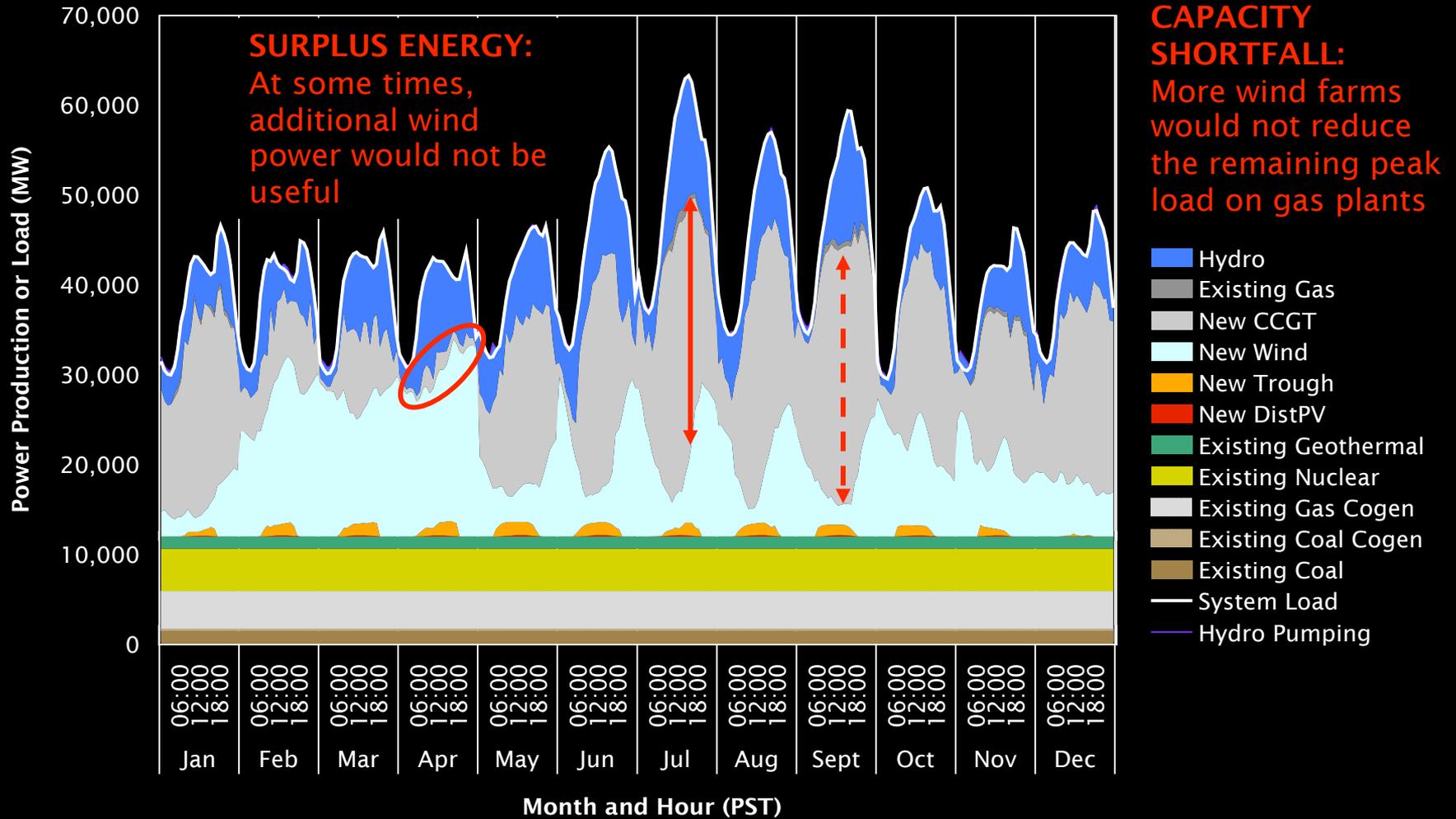
Geographic Distribution of Investments



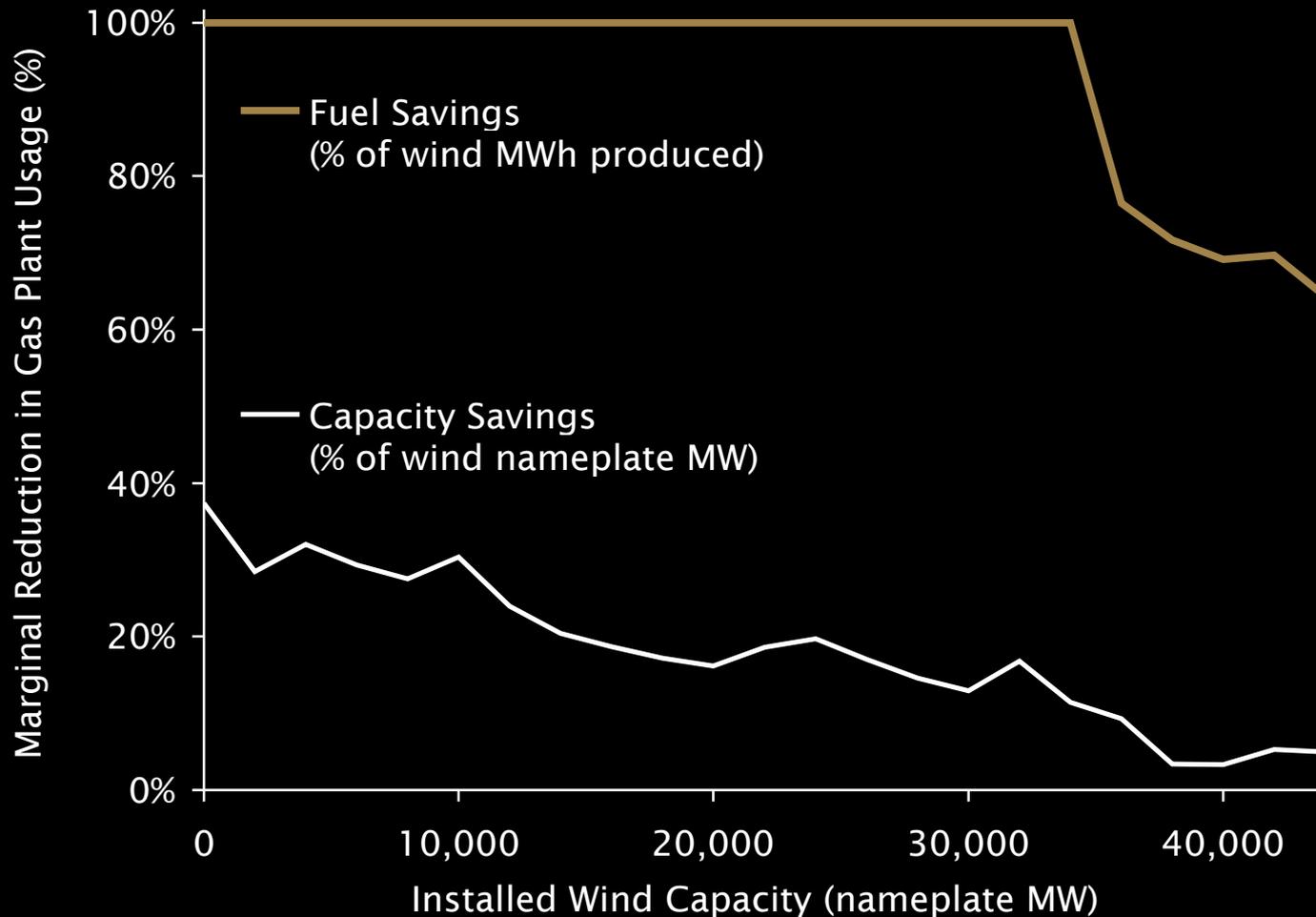
Hourly Generator Operation



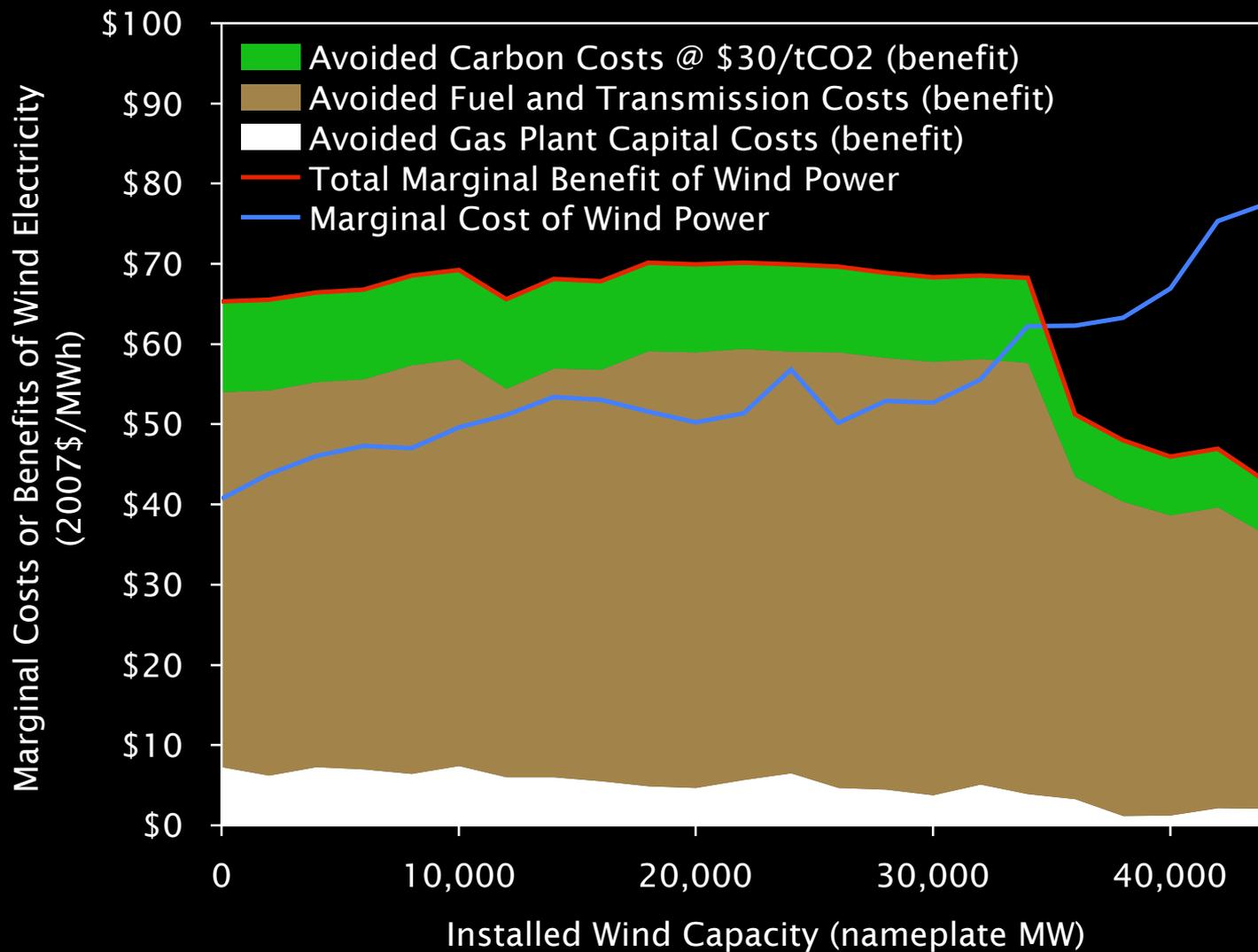
Hourly Generator Operation



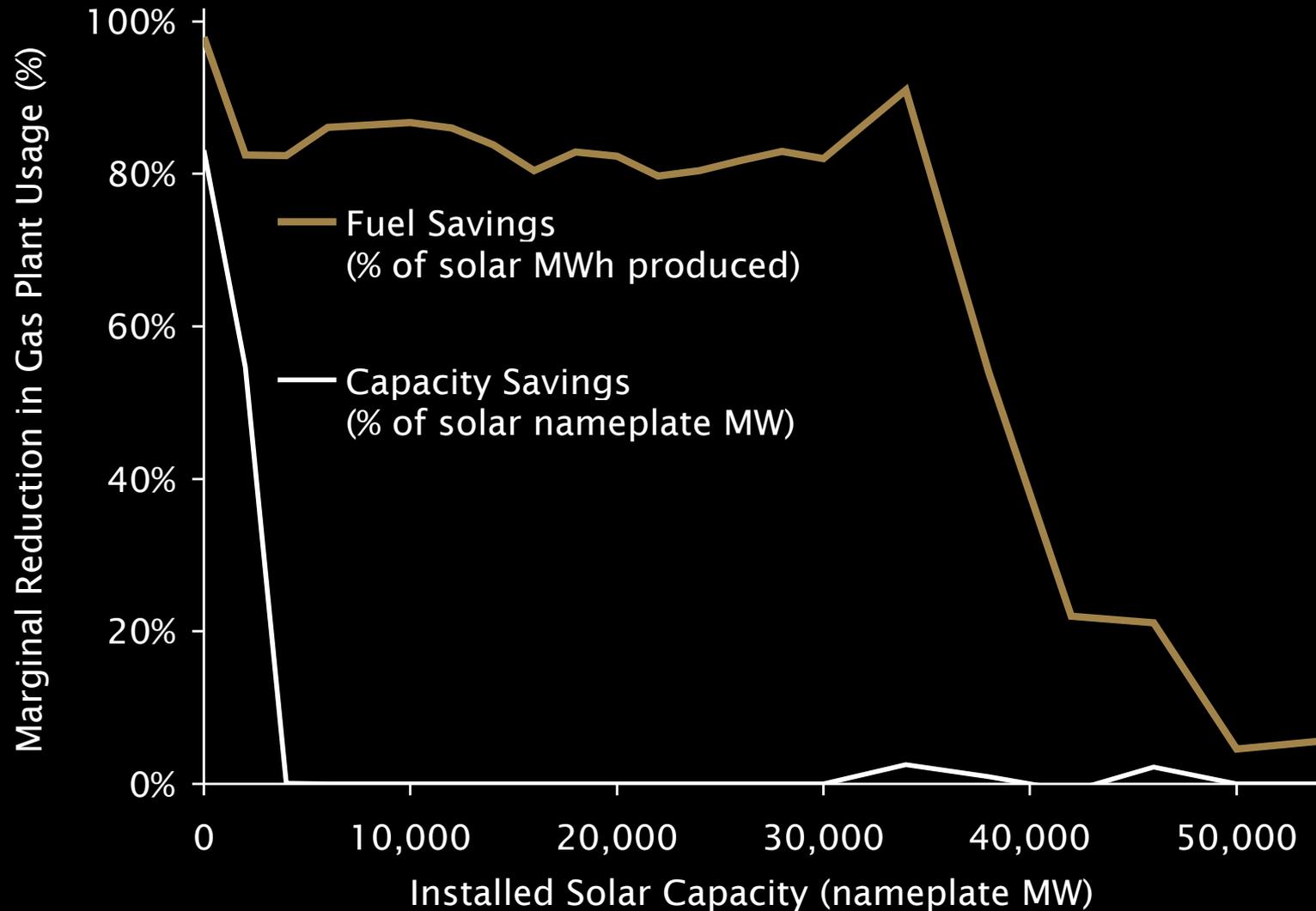
Effect of Additional Wind Power on Gas Plant Construction and Operation



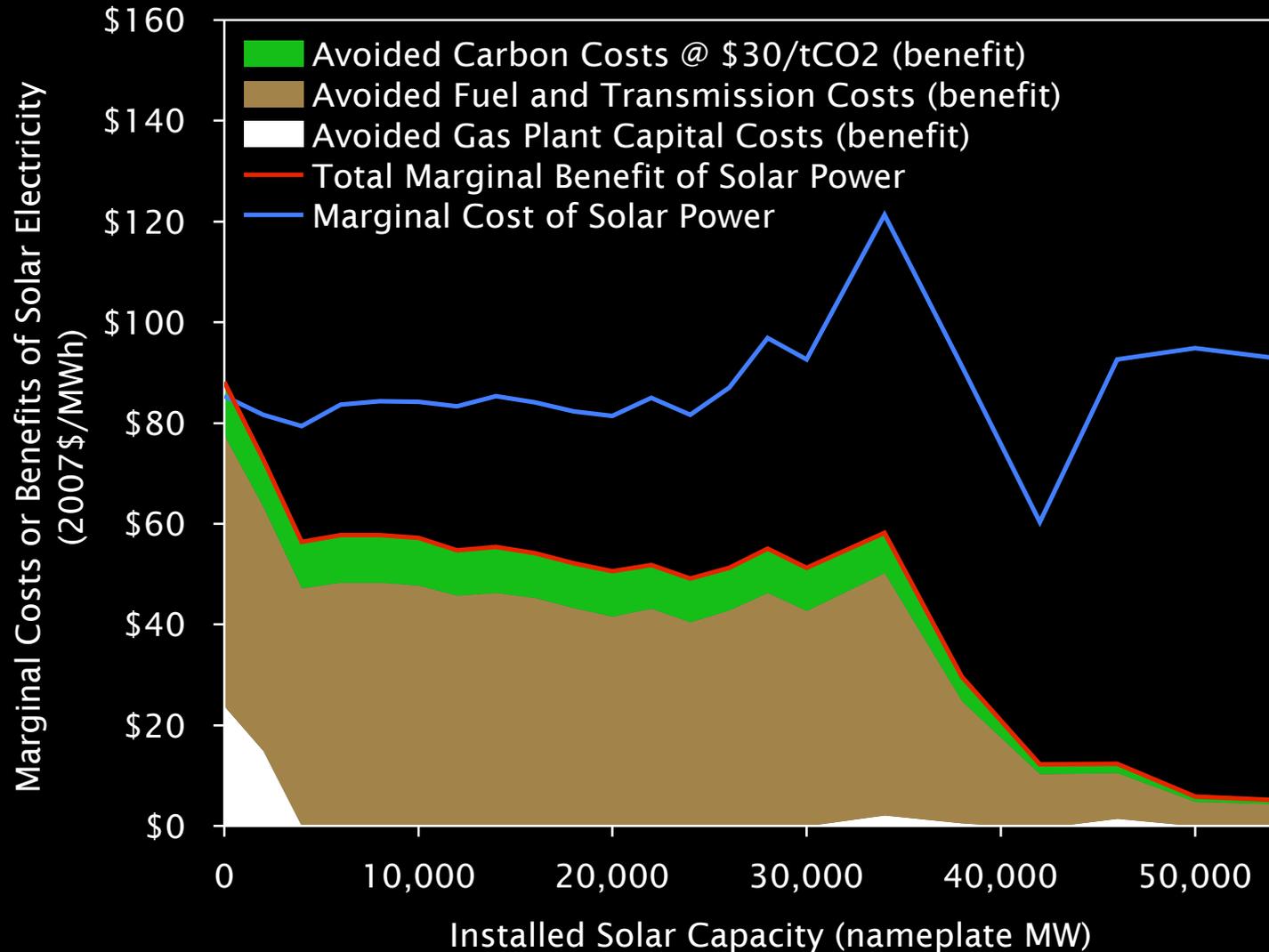
Marginal Cost and Benefits of Wind Power



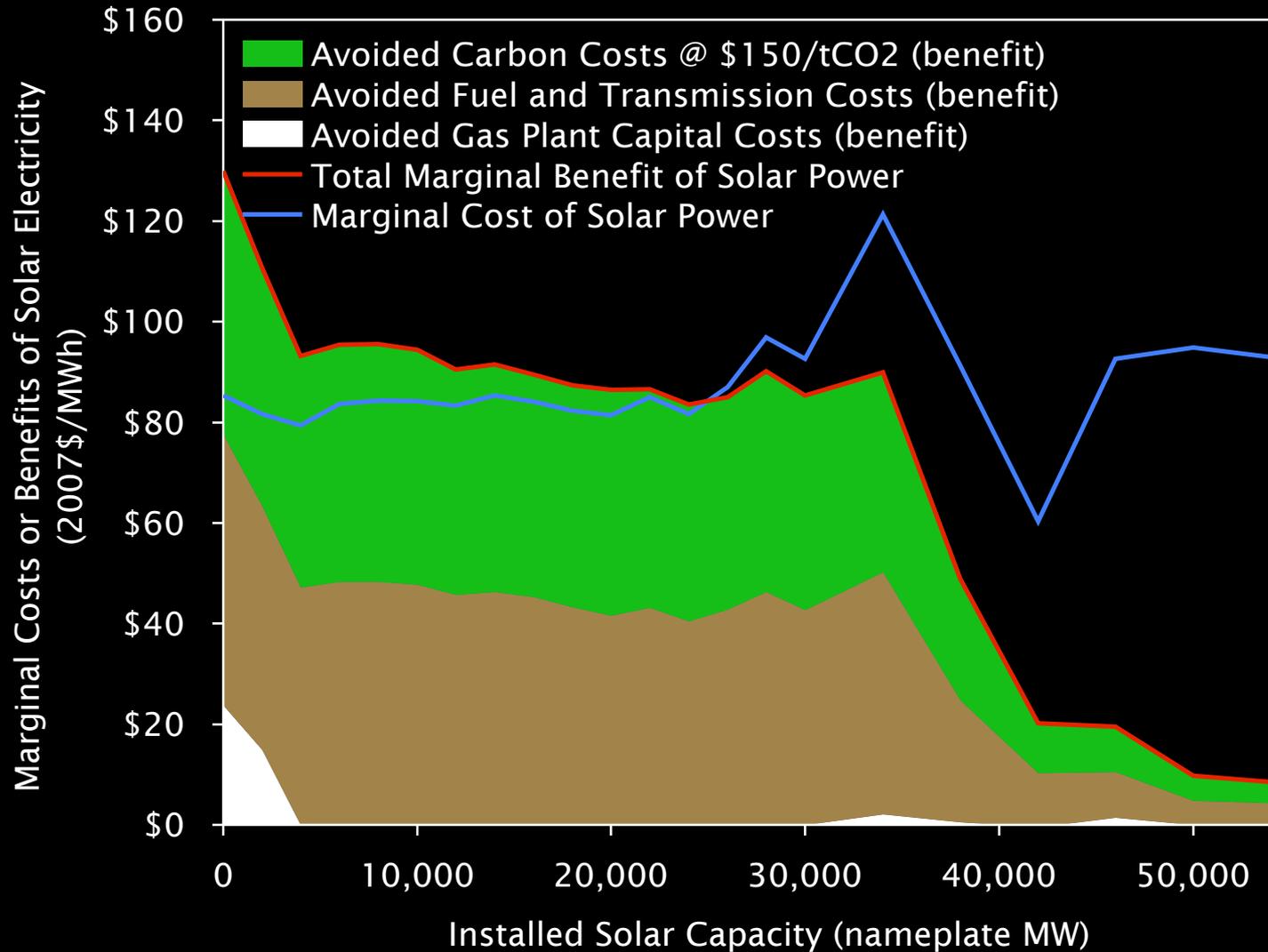
Effect of Solar Power on Gas Plant Usage



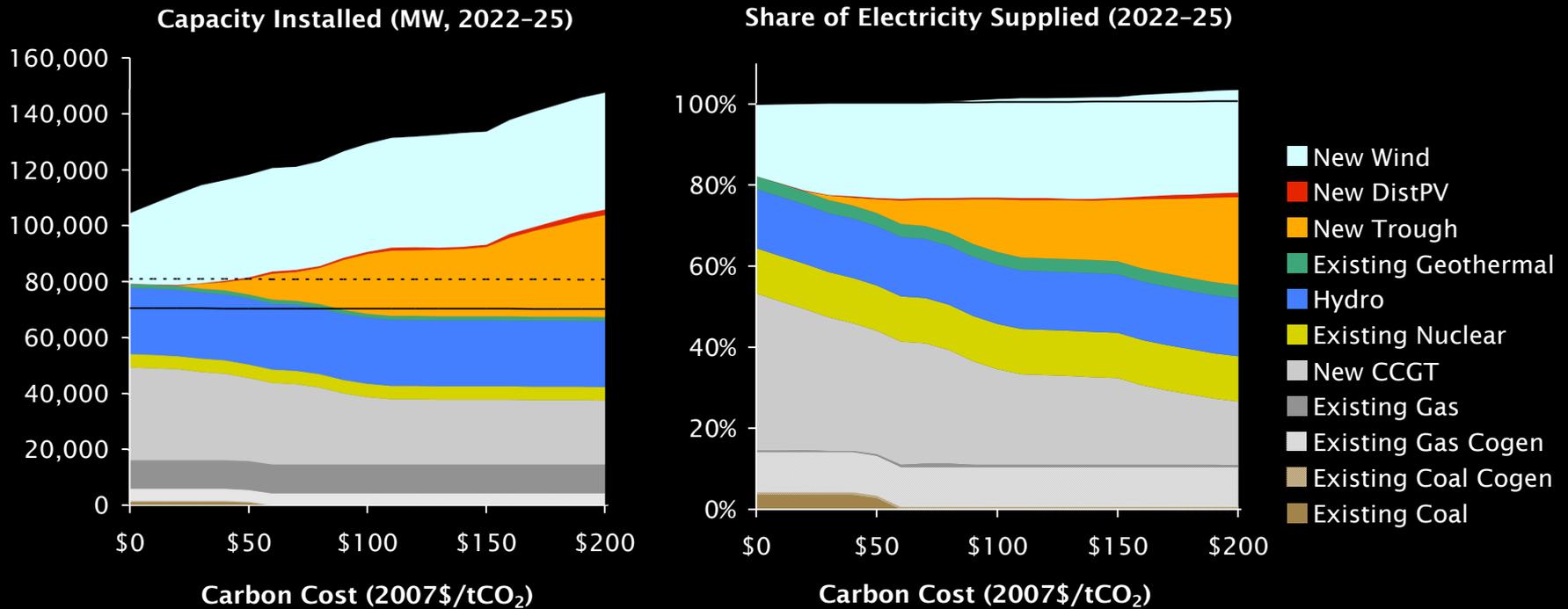
Marginal Cost and Benefits of Solar Power



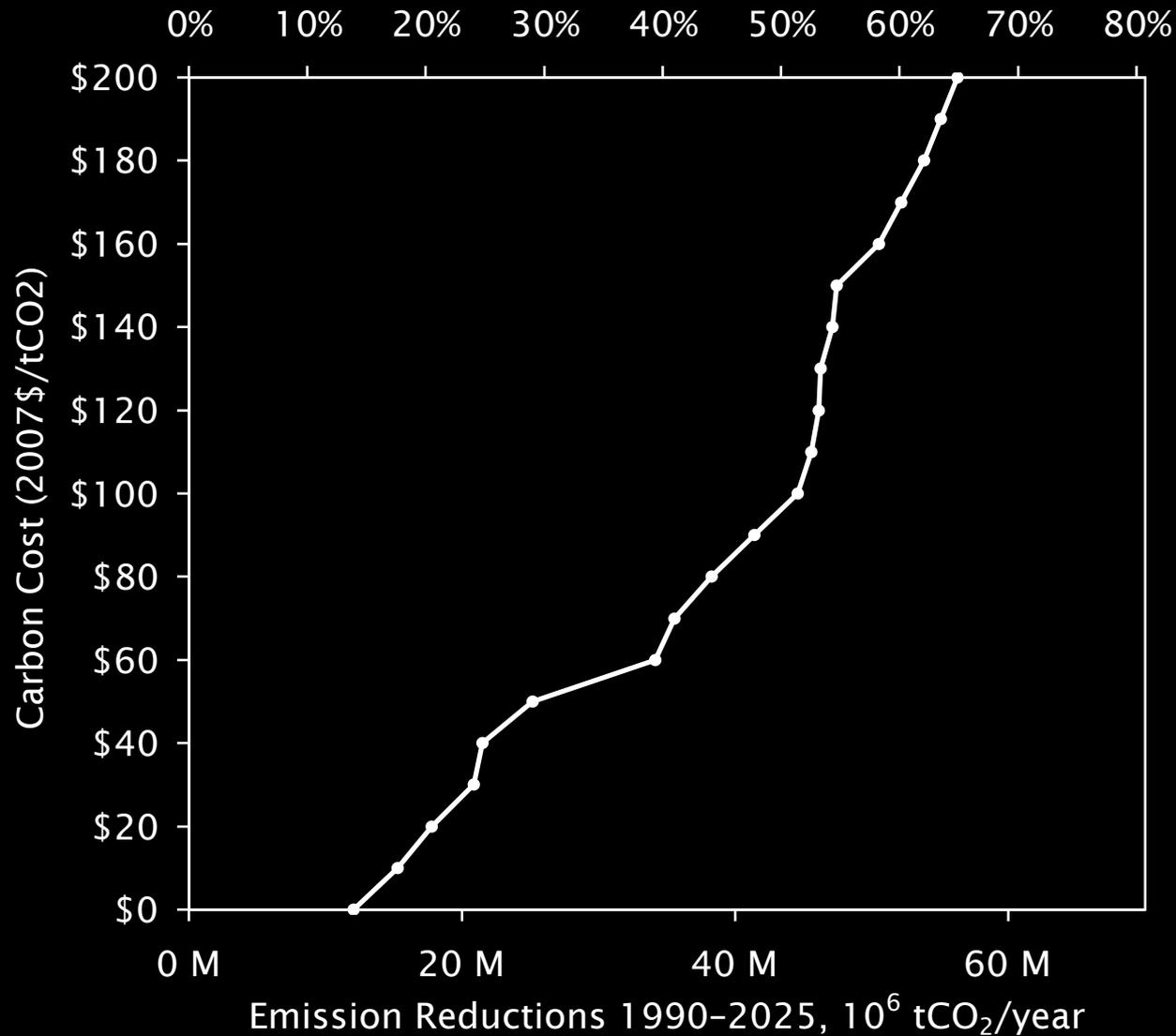
Marginal Cost and Benefits of Solar Power



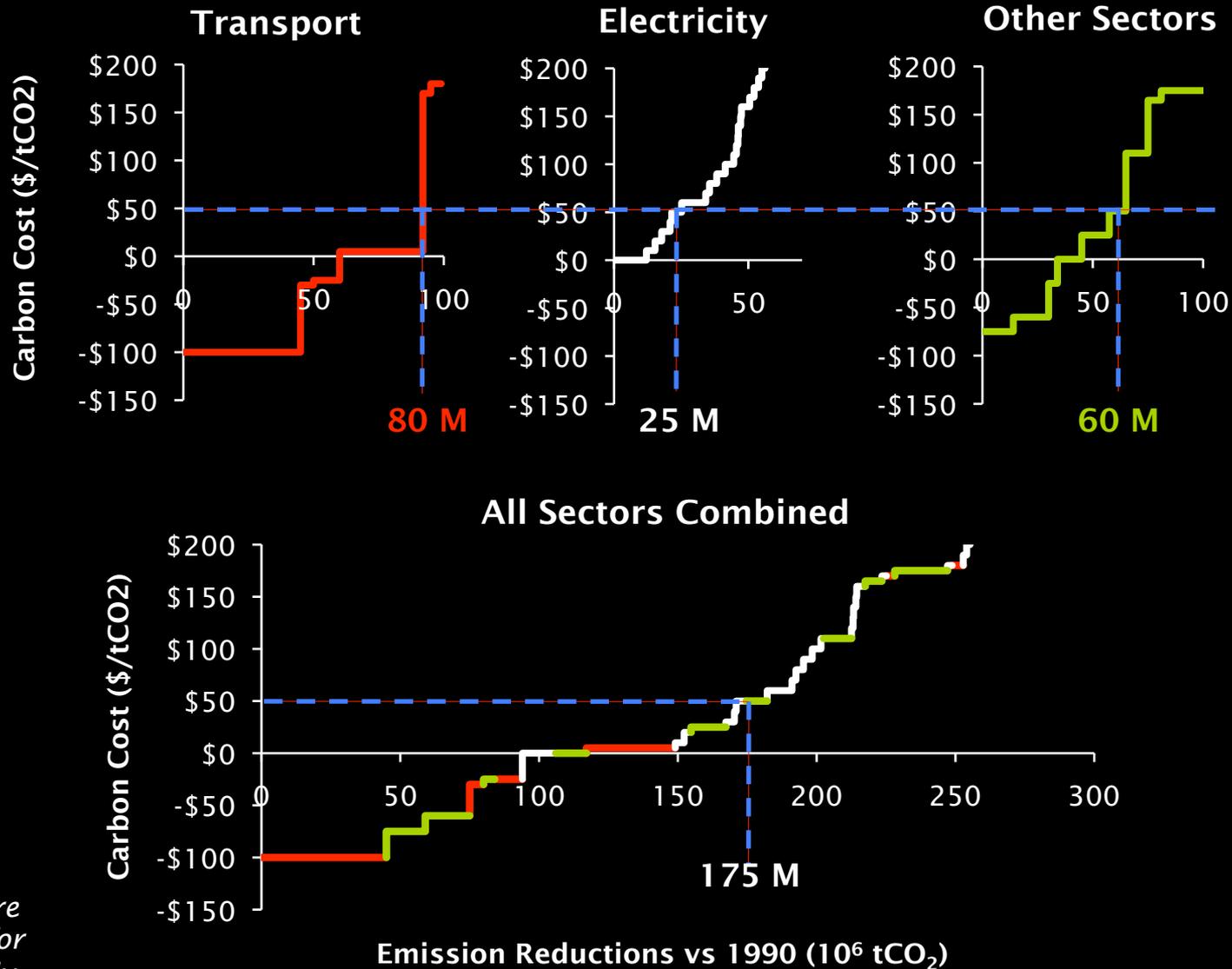
Effect of Carbon Cost on Portfolio Design



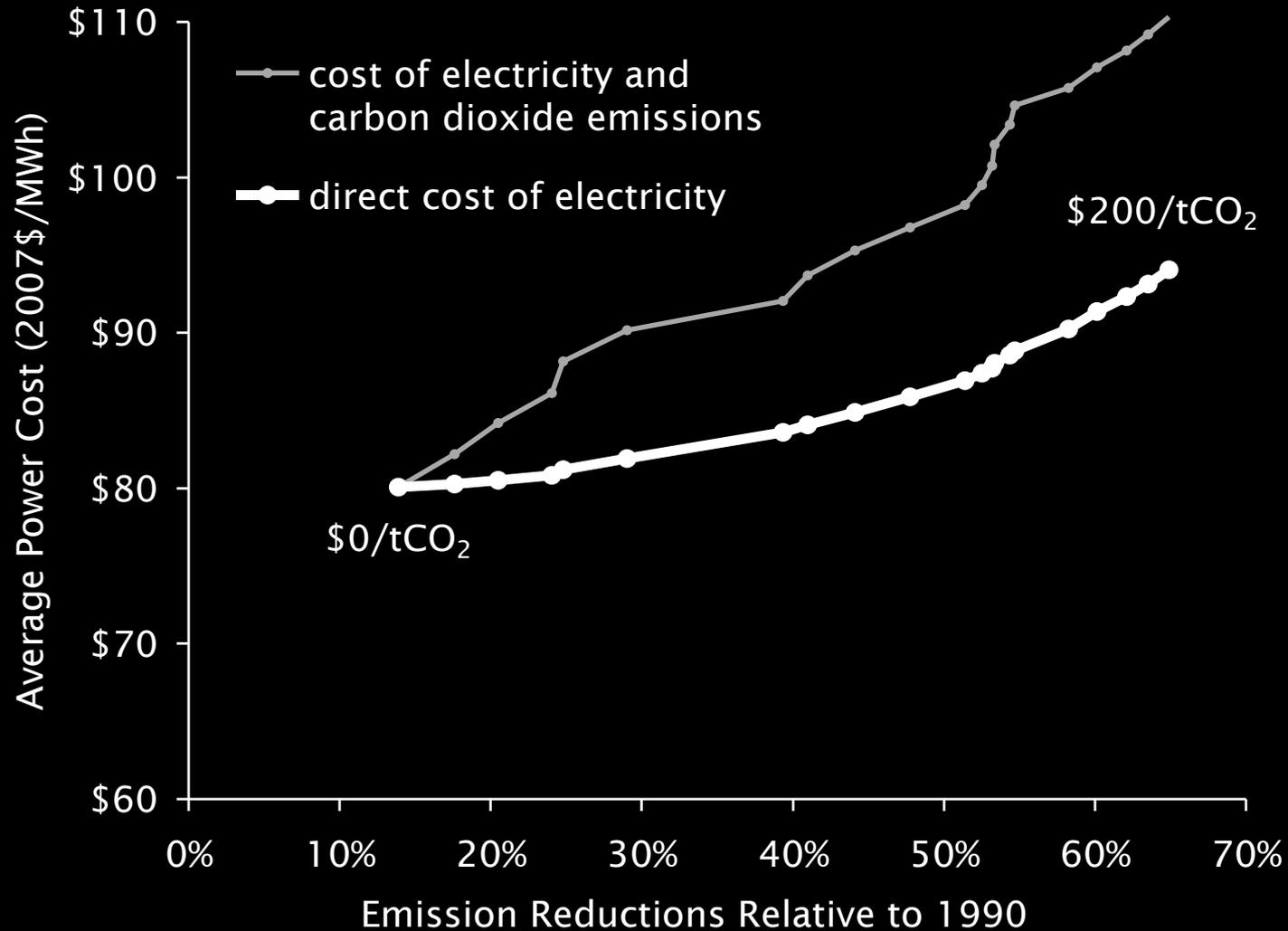
“Supply Curve” for Emission Reductions



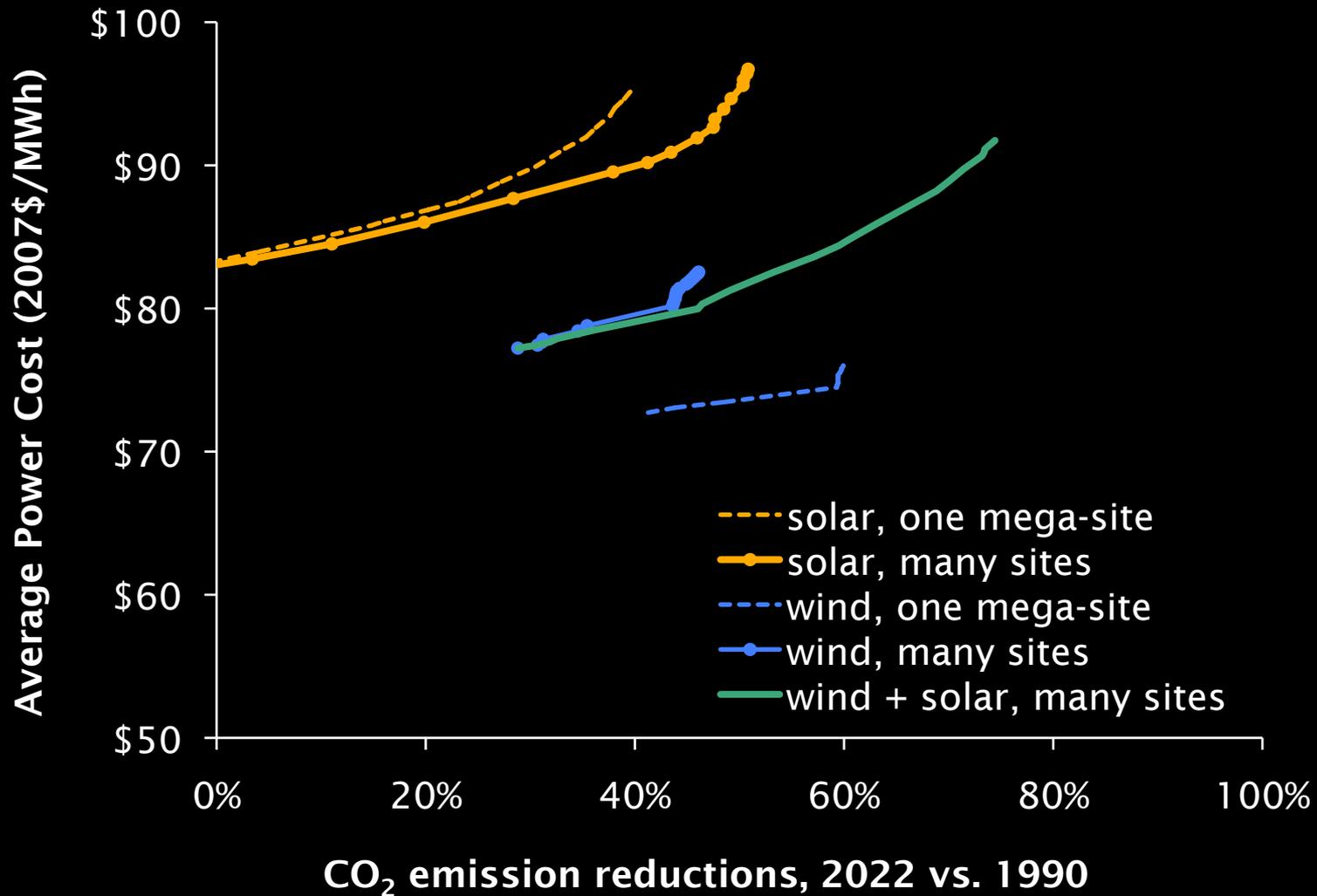
Harmonizing Targets Across Sectors



Effect of Emission Reductions on Power Bills

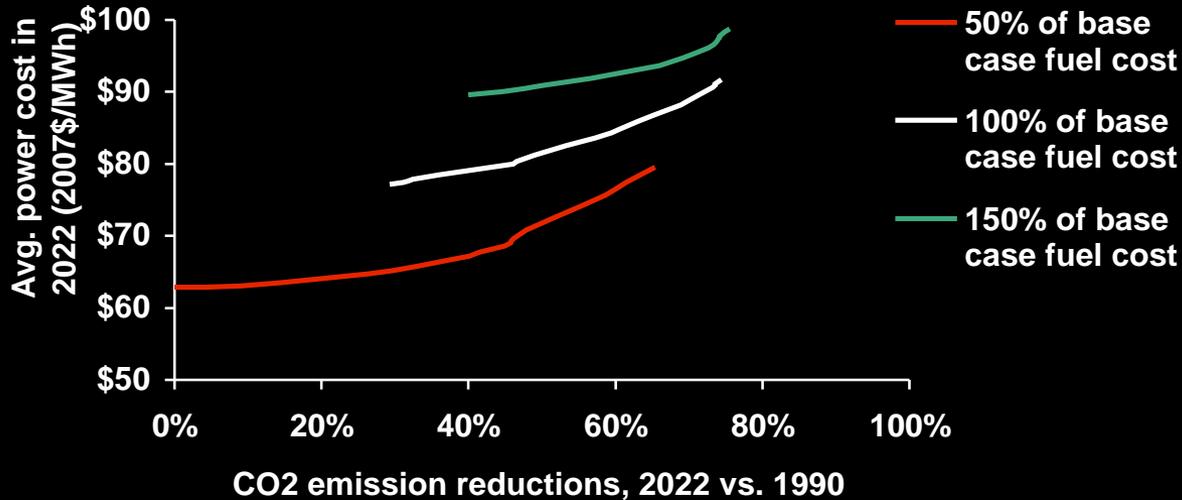
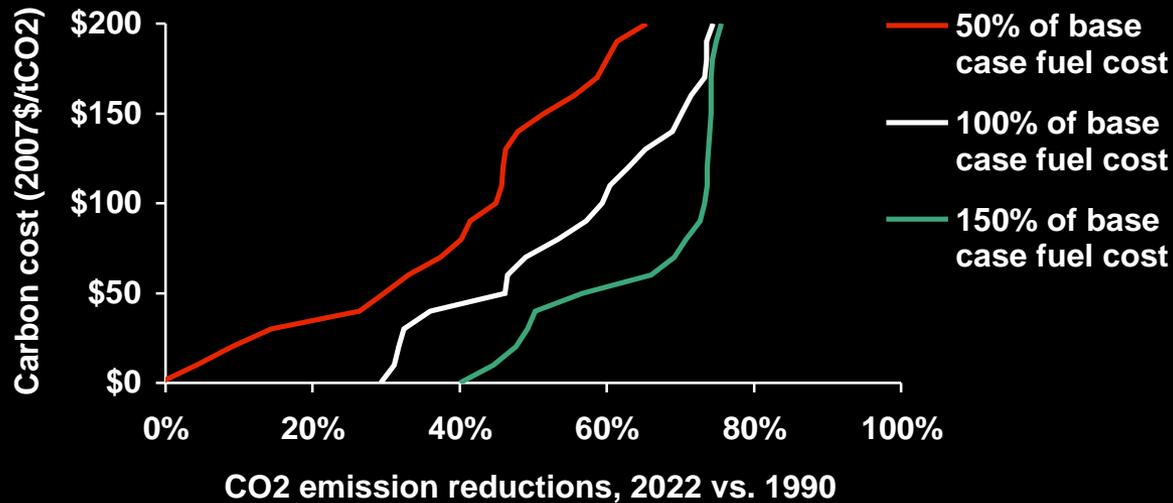


Combining Wind and Solar Reduces Emissions and Costs

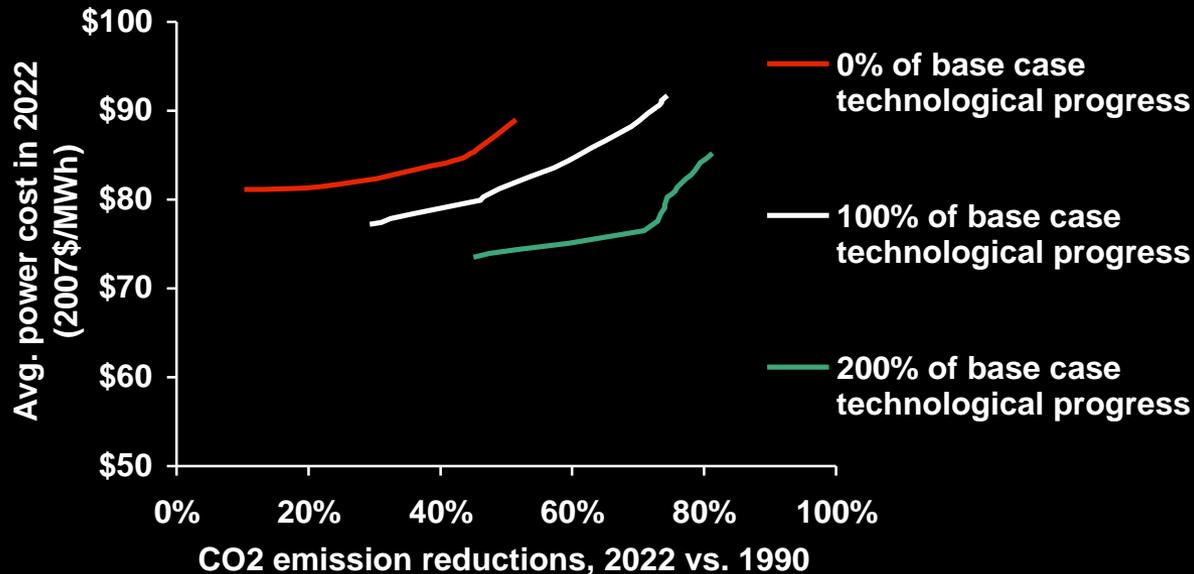
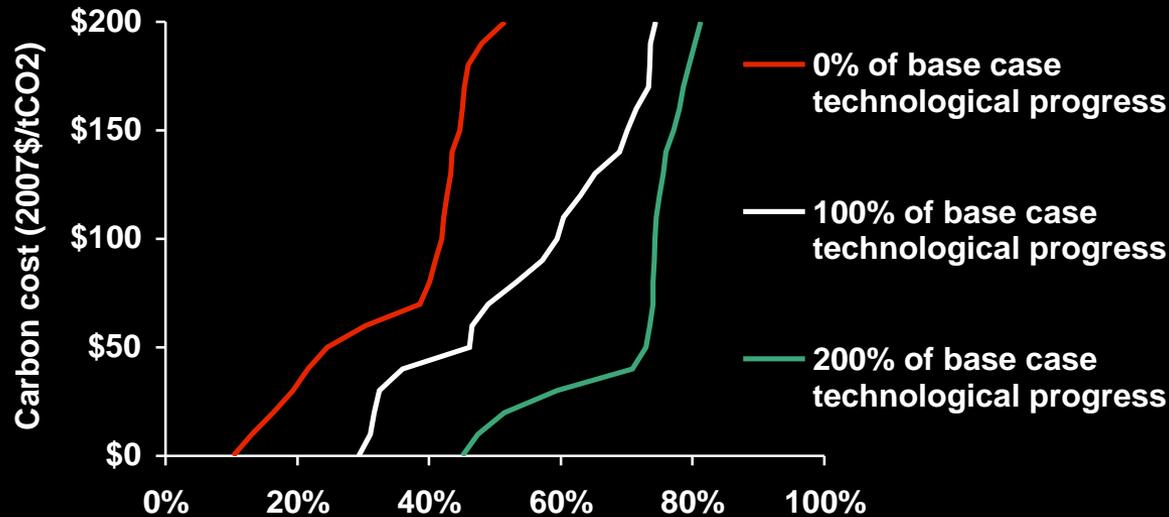


SENSITIVITIES

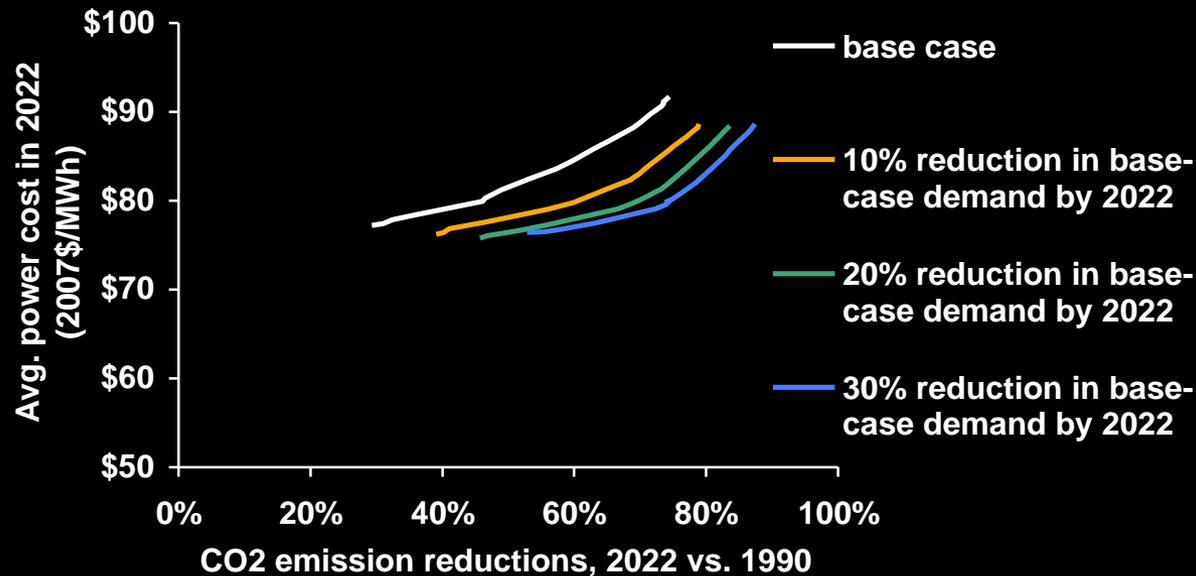
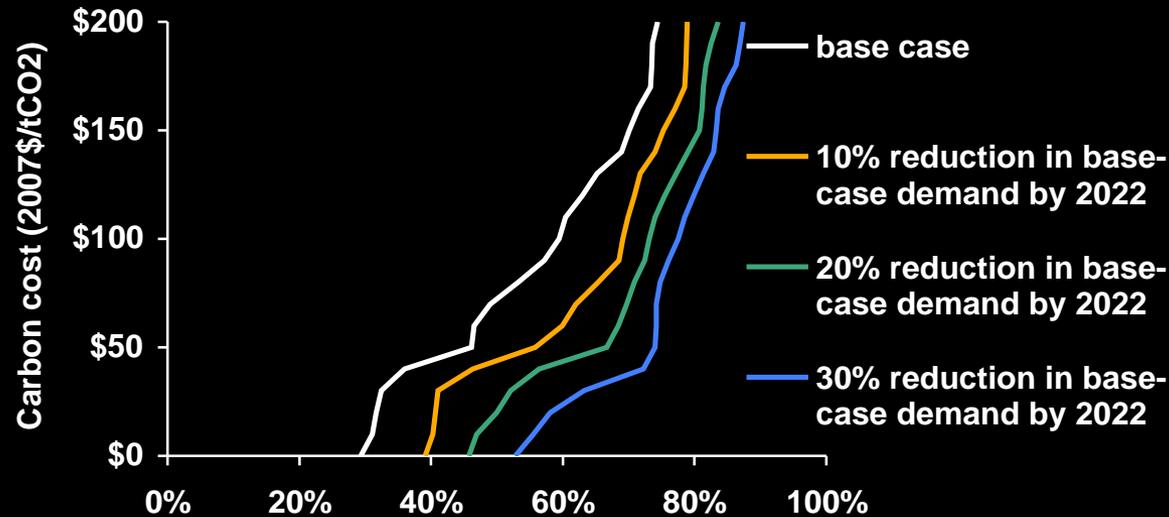
Effect of Fuel Costs



Effect of Equipment Costs

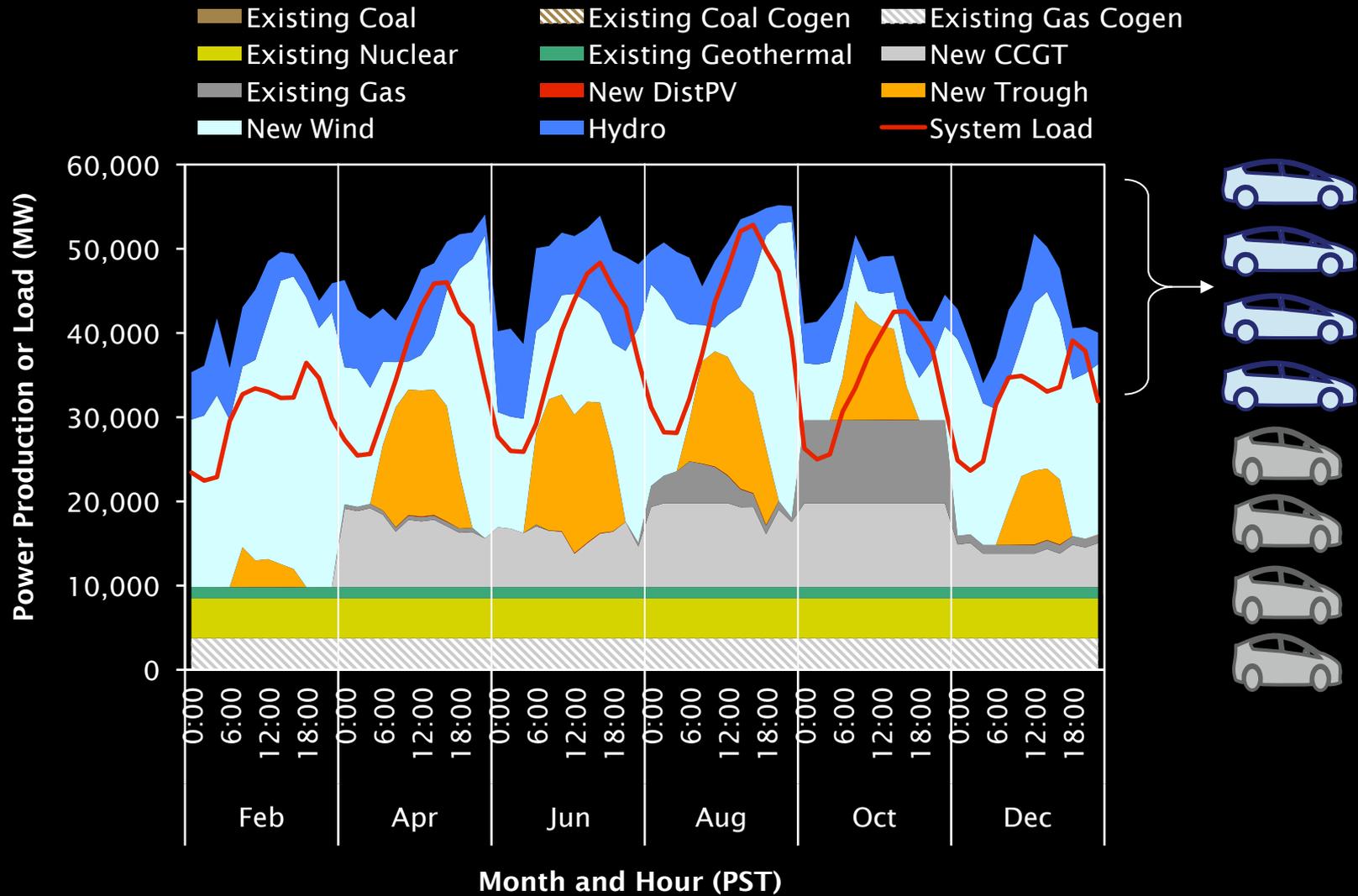


Effect of Conservation and Efficiency

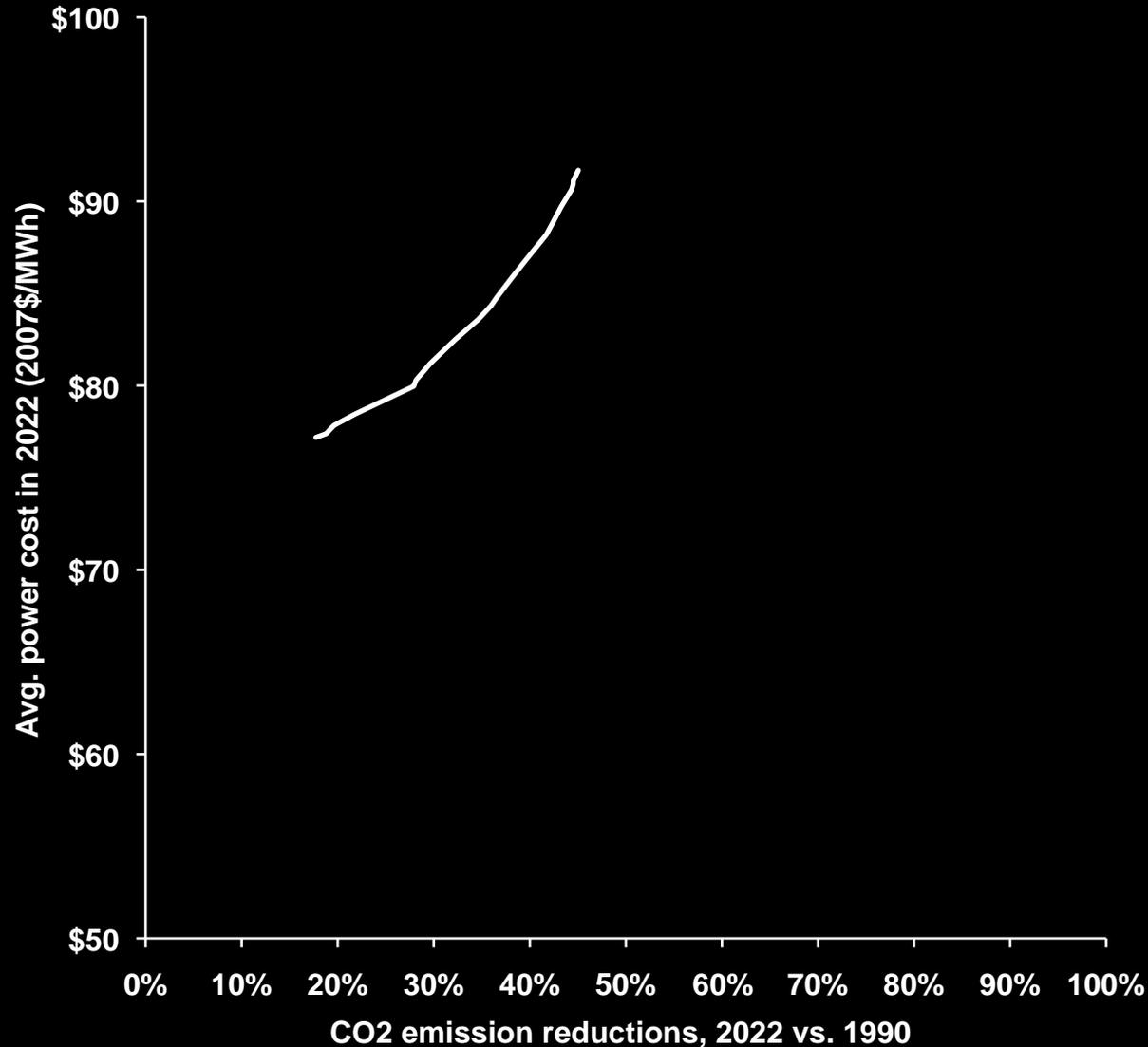


HIGH RENEWABLE RESOURCE SCENARIO

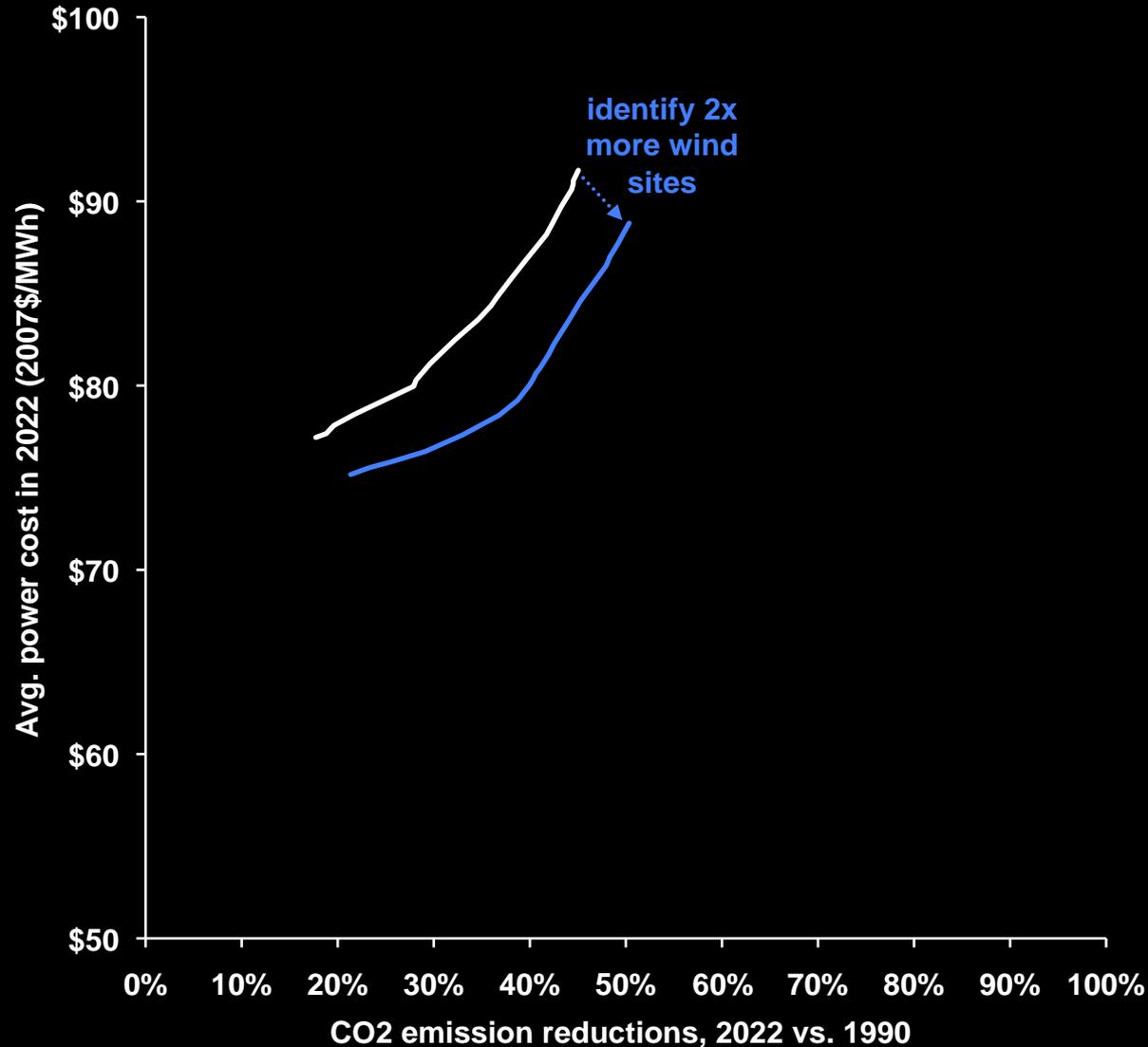
Using Surplus Renewable Power for Vehicles



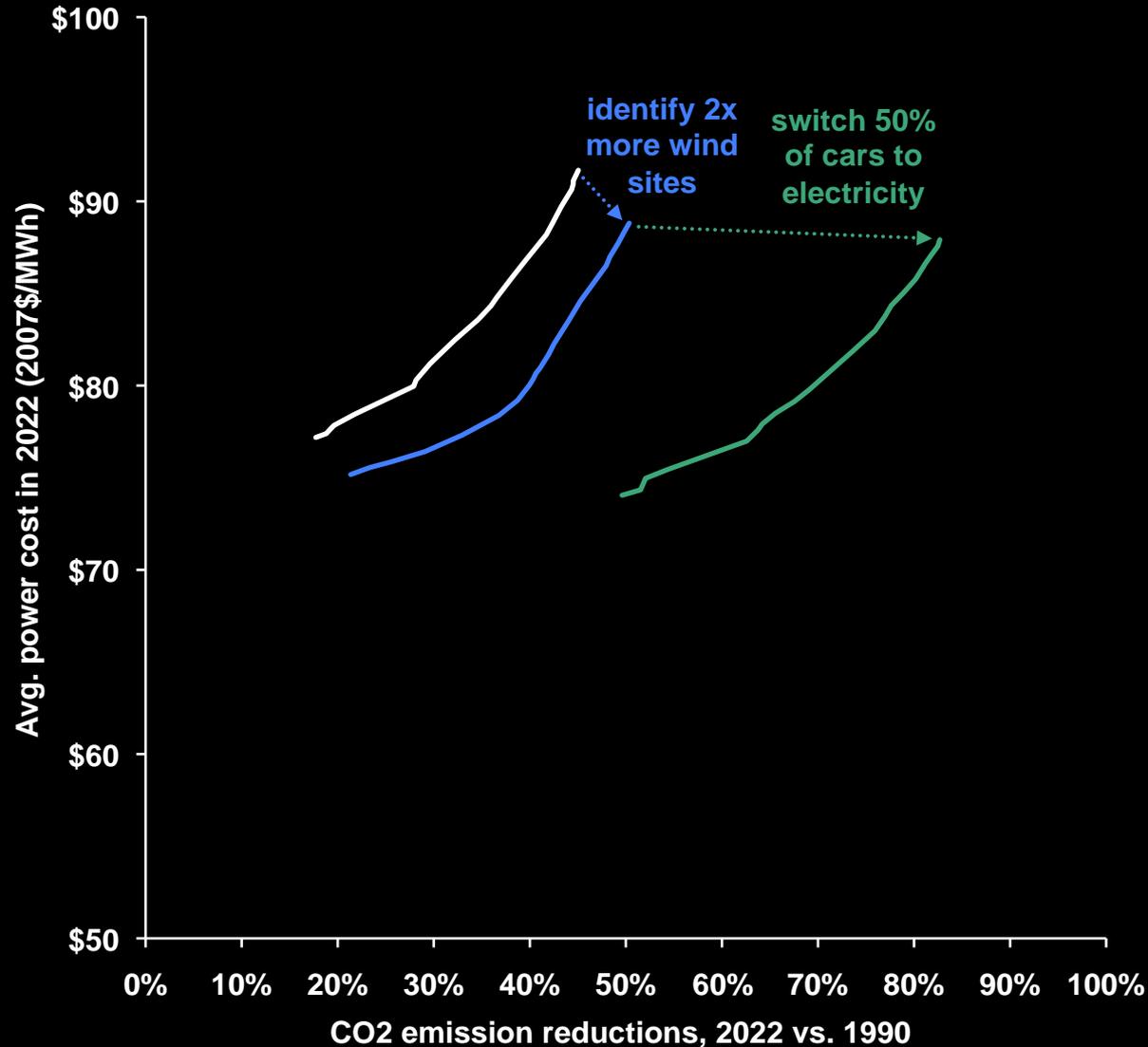
Improving the Cost-Emissions Tradeoff



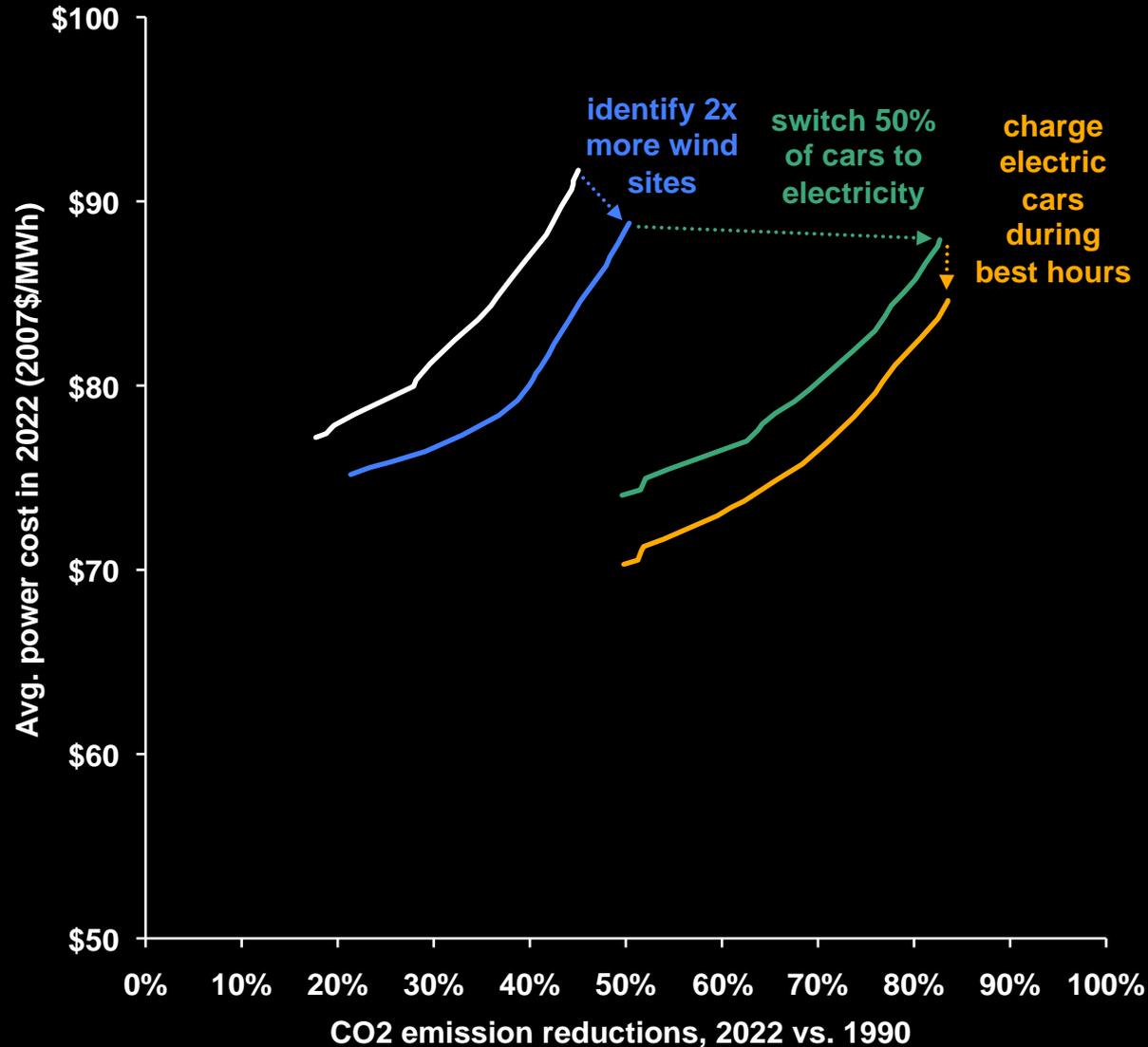
Improving the Cost-Emissions Tradeoff



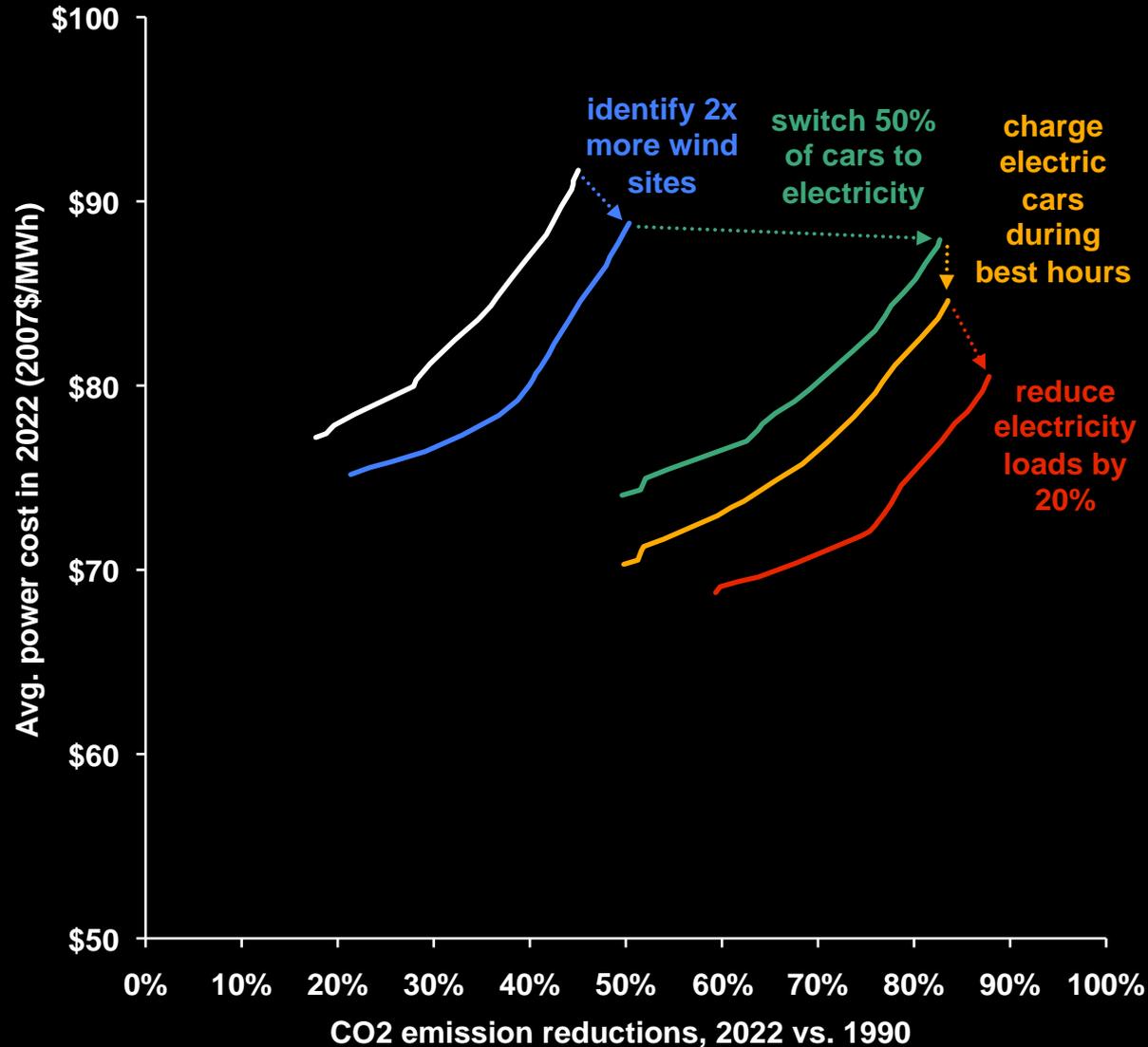
Improving the Cost-Emissions Tradeoff



Improving the Cost-Emissions Tradeoff



Improving the Cost-Emissions Tradeoff



CONCLUSIONS

Conclusions

- There appears to be no sharp limit to the use of wind and solar power
 - costs rise smoothly and slowly as the system uses more intermittent renewable power
- Renewable power is worth developing to save fuel, even if its contribution to peak demand is low
 - Renewable power can become uneconomical when *too much* is produced at some times
- More renewable power can be used if diverse sites and technologies are developed
- Demand-side flexibility may allow wind and solar power to play a larger role at a lower cost
 - *e.g.*, well-timed charging of PHEVs, automatic adjustment of air conditioner and refrigerator setpoints

Thanks!

- Thanks to my advisors, Daniel Kammen, Alex Farrell, Severin Borenstein and Shmuel Oren for their encouragement and ideas
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