An "ideal gas law" for international diffusion of solar power?

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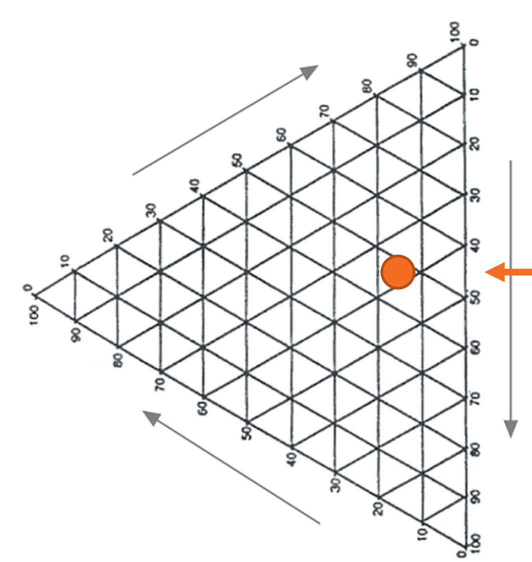
Perspectives on model validation & uncertainty

1.Don’t care

2.Accept inevitability



Empirical: explain most data with fewest free parameters

Self-identify: emphasis on reducibility, very little on completeness

Theoretical: Combination of

1. **Reducibility,**
2. **Completeness,**
3. **Social validation**

1. **Reducibility**: extent to which model can be reduced/derived from smaller set of principles or assumptions.
2. **Completeness**: # of influence factors accounted for.
3. **Social validation**: what your research community thinks is best practice.

Information Technology and Modeling

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- IT enables dramatic progress on completeness of models
- Have to explore power of IT, but also… history of progress has been from dramatic simplifications of complex systems, not completeness
- Important to continue search for minimalistic, empirically robust models

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PV Diffusion Modeling

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- Long history of prior work
- Approaches: Bass model, Agent based, Fuzzy logic, Multi-variable regression
- Increasingly temporally and spatially resolved datasets for variables (prices, home suitability, demographics, …)

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Approach: Start simple, check empirics

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- To predict: annual residential PV adoption per million detached houses (normalizing makes intrinsic variable)
- Start with ***one dependent variable***: Net Present Value as experienced by homeowners in region in that year.
- Collect data for multiple states/countries.
- Empirical check: is there a pattern?

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Data collection

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Find all data needed to calculation adoption and NPV in five regions: Japan, California, China, Germany and Hawaii, 2007-2014

Region	PV cost	Electricity price	Subsidies		Residential adoption	Detached Households
California	2007-2014 (IEA-PVPS 2014)	2007-2014 (EIA-CEP 2014)	2007-2014 (CSS 2017)		2007-2014 (CSS 2017)	2007-2014 (USCB 2000)
China	2011-2014 (IEA-PVPS-AR 2014)	2011 (CCTV-2011) 2012 (EPC-2012-2015)	2011 (IEA-PM, China) 2012 (IEA-PVPS-China 2012-2015)		2011-2014 (IEA-PVPS-China 2014)	2011-2014 (CICC 2015)
Germany	2007-2014 (IEA-PVPS Germany 2014)	2007-2014 (BDEW 2017)	2007-2014 (IEA-PVPS-AR 2014)		2007-2014 (Fraunhofer 2016)	2007-2014 (DSB 2017)
Hawaii	2008-2014 (IEA-PVPS 2014)	2008-2014 (EIA-HEP 2014)	2008-2014 (NC CETC 2015)		2008-2013 (IREC 2009-2014) 2014 (SEIA 2014)	2008-2014 (USCB 2000
Japan	2007-2008 (METI 2013) 2009-2014 (JPEA -1 2014)	2007-2014 (METI-SEP)	FIT: 2010-2012 (Muhammad-Sukki et al 2014) 2013-2014 (IEA-PM, Japan)	Subsidy/tax credit: 2007-2008 (NEDO 2009-2014	2007-2014 (JPEA-2 2014)	2007-2014 (MIAC-2013)

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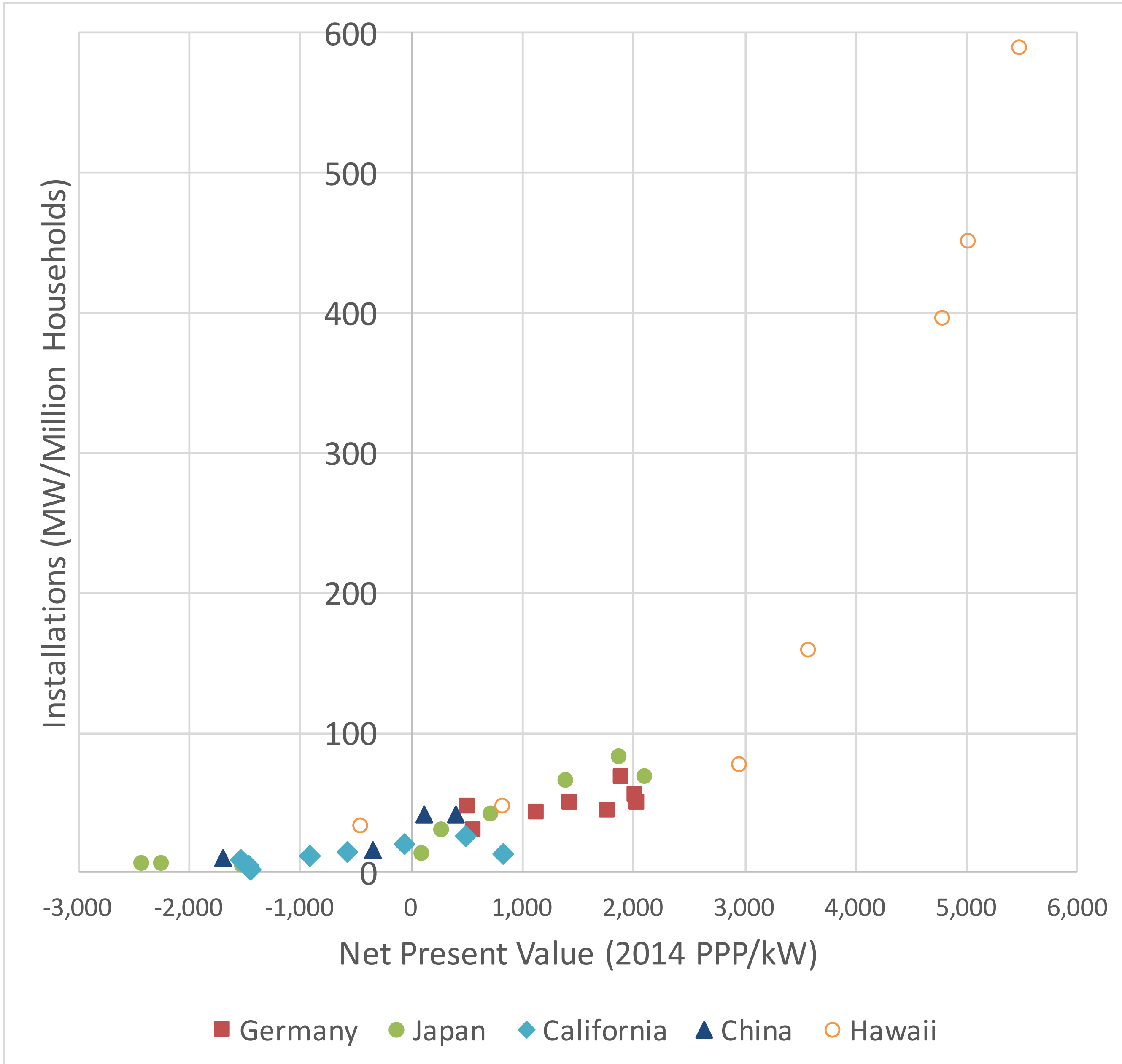
Result: Annual Installation vs. NPV

- Converted all currencies to 2014 Purchase Power Parity $
- Surprisingly tight correlation



Adoption rate example: Japan in 2010

- 862 MW of residential PV installed in 2010 (JPEA).
- Assume potential adopters = number of detached homes = 29 million
- Adoption rate = 30 MW/million households in 2010.

Net Present Value (NPV)

$$NPV^{j}(\frac{\$}{kW}) = (-C_{total}{}^{j} + S^{j}) + \sum_{i=1}^{N} \frac{E^{j} * P_i^j}{(1+int)^{i}}$$

- j is a year in a given region.
- $C_{total}{}^{j}$ is investment cost of the PV system in year j
- S^j is investment subsidy in year j
- E^j is annual electricity production of the PV system in region (based on one central location)
- N is the lifetime of the system =20 years.
- P_i^j is displaced electricity price, FIT price or retail price in net metering region
- int, is the 10-year moving average of long-term interest rate less inflation

Net Present Value Example: Japan in 2010

- PV installed price = 584 yen/Watt
- Electricity price = 20 yen/kWh
- Feed-in-tariff (1st 10 yrs)= 48 yen/kWh
- Annual generation of 3.9 kW system in Tokyo = 4,500 kWh
- Self consumption = 45%
- *Assume* retail price net metering for years 11-20
- NPV_{2010} = 28,000 yen/KW = 280 \$2014 PPP

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Zooming in on 0-100 MW/million household

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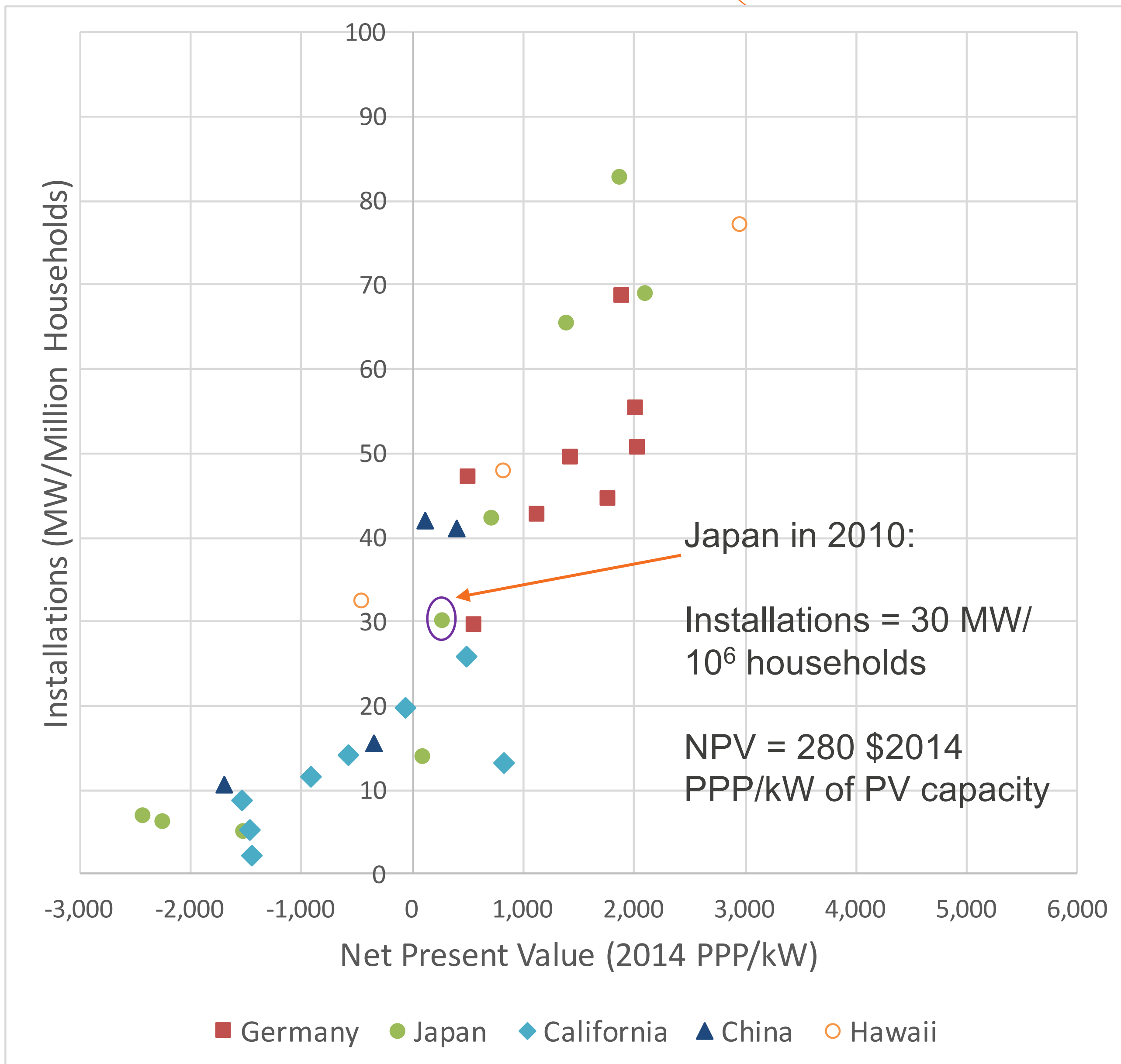
Magnification reveals spread, but still good correlation



Explaining correlation with model

- Assume new PV customers added with increased NPV follows normal distribution.
- Adoption at given NPV:

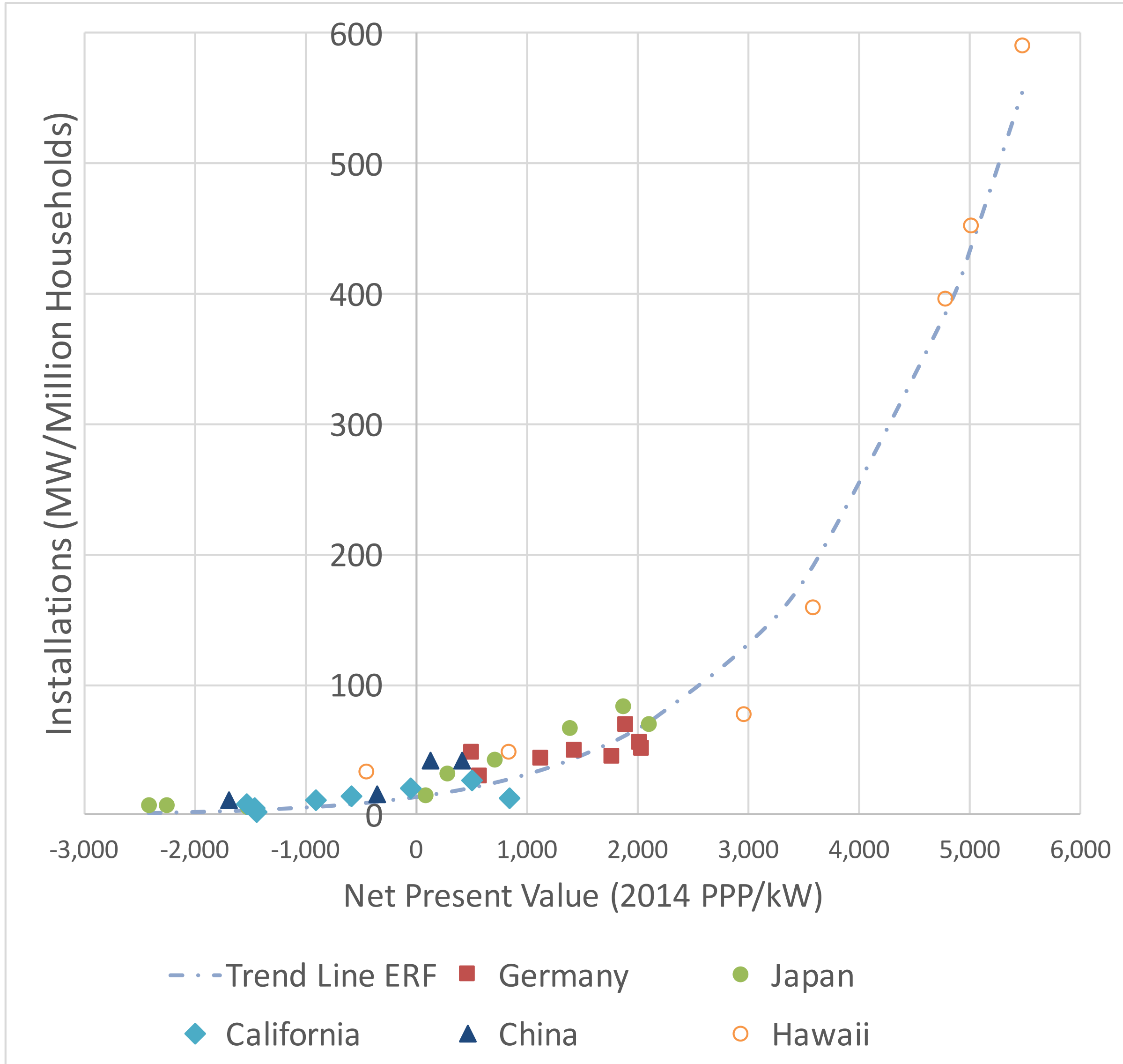
$$Annual\ adoption\left(\frac{MW}{million\ hh}\right)(NPV) = \ \alpha \int_{-\infty}^{NPV} dx\ e^{-(\frac{x-\mu}{\sigma})^2}$$

$$= \quad \bar{\alpha}\ (1 + \mathrm{erf}\left(\frac{NPV - \mu}{\sigma}\right))$$

  - erf (x) is the error function,
  - $\bar{\alpha}$ is a constant that can be fixed at 4,000 MW/million households (hh)
  - μ is the peak customer acquisition value
  - σ is the spread (variability in preferences)

Nonlinear regression results

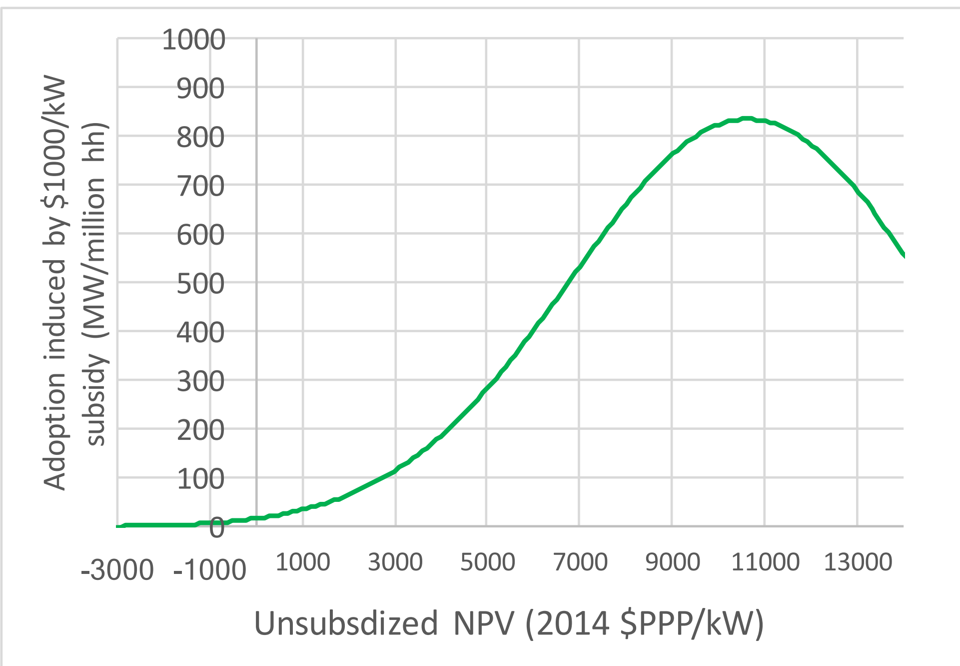
- μ = $11,110 $/kW
- σ = $5,400 $/kW
- total square error (TSE) = 9,574.
- "Ideal Gas Law" for PV diffusion?



Application: Subsidy effectiveness

- Due to spread in consumer preferences, there are some consumers at (almost) any price
- How much adoption can be attributed to a subsidy?

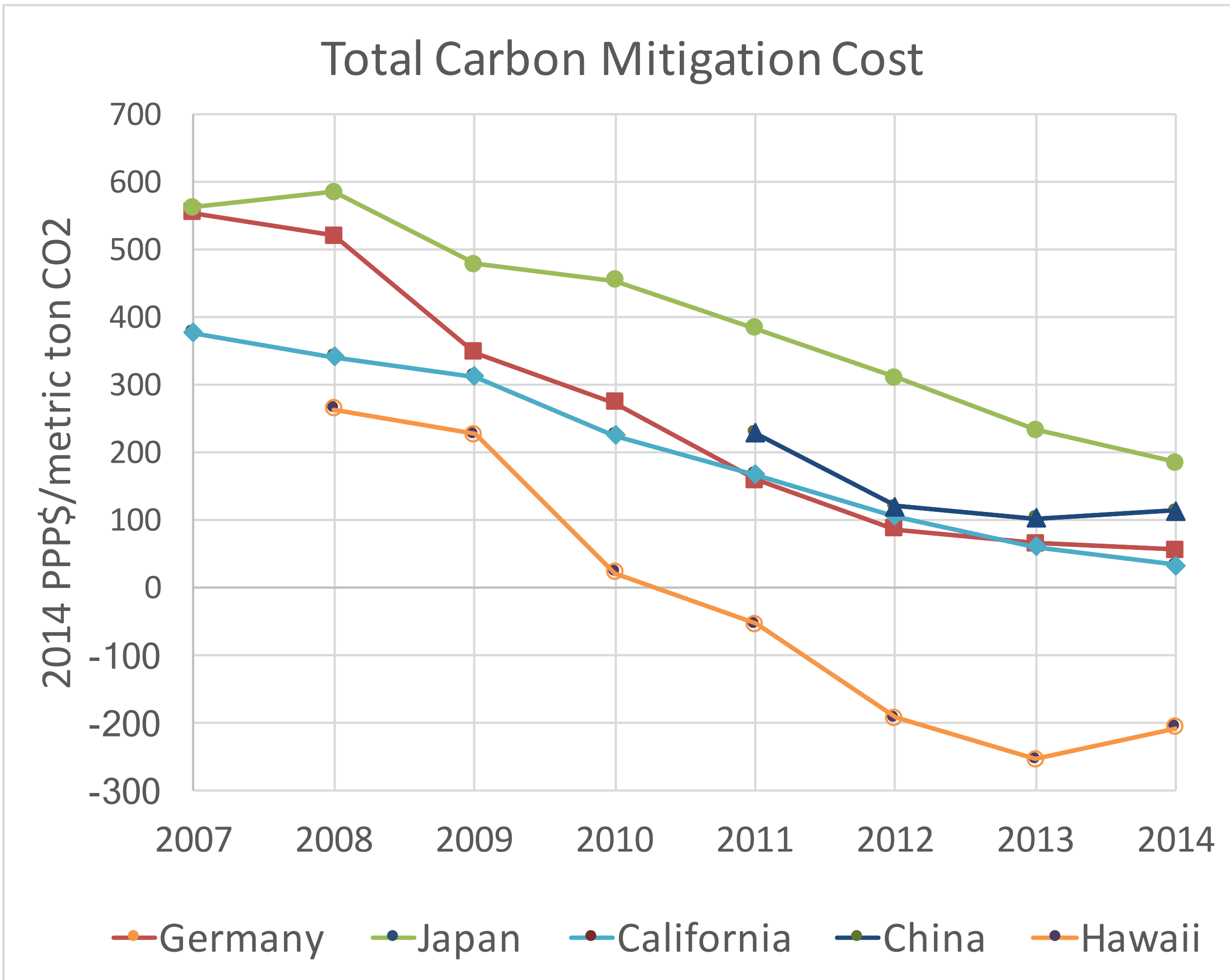
$$Subsidy\ induced\ adoption\ \left(\frac{MW}{million\ hh}\right) = Adoption\ (NPV\ with\ subsidies) - Adoption\ (NPV\ no\ subsidies)$$



Subsidy is more effective for higher NPV (up to a point)

Application: total vs. public carbon mitigation costs

$$Total\ Mitigation\ cost\left(\frac{\$}{ton\ CO_2}\right) = \frac{Total\ expenditures\ (\$)}{Total\ PV\ generation\ (MWh) \times CO_2 reduction\left(\frac{tons\ CO_2}{MWh}\right)}$$



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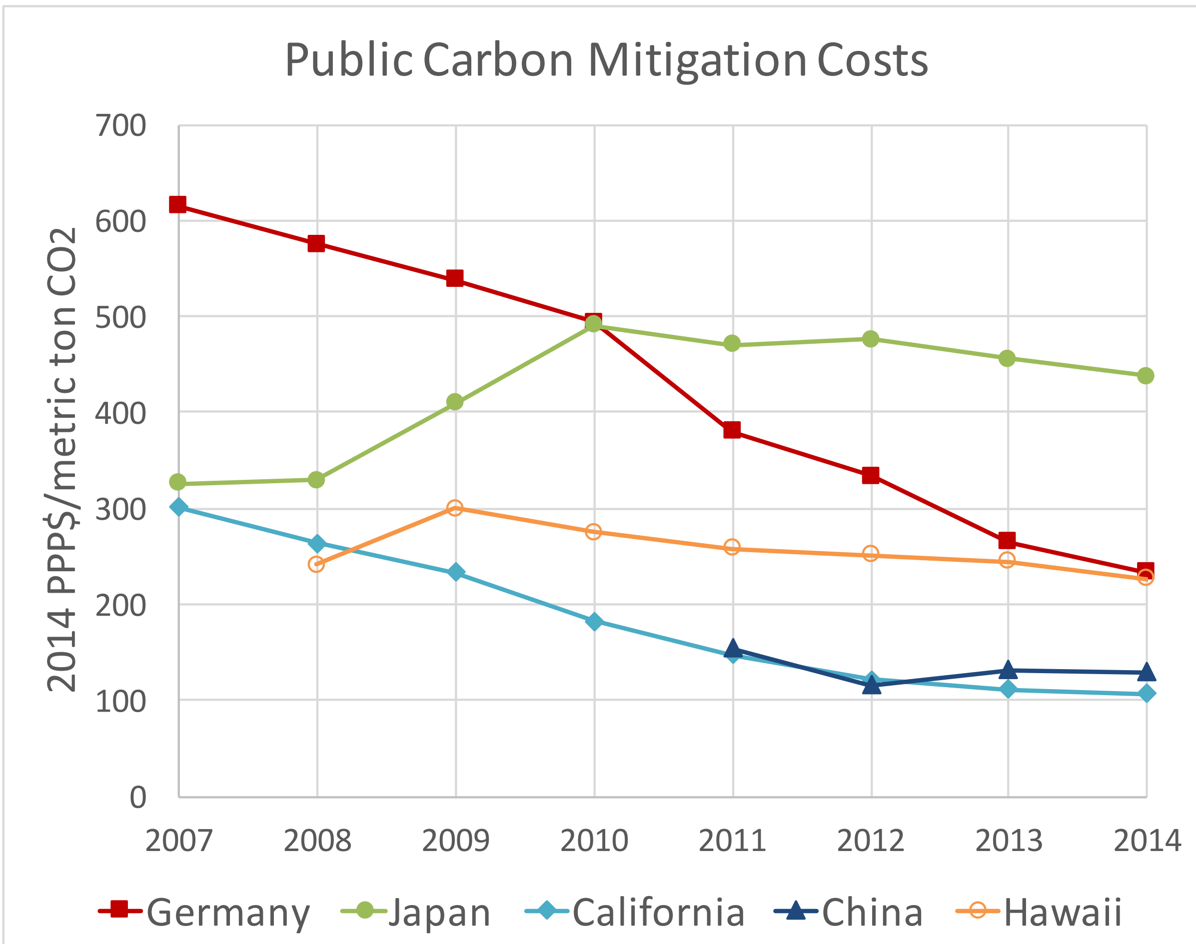

Improving the model

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- More regions, years (note Hawaii is only region with high adoption)
- Divide into sub-regions (variations in irradiance, subsidies, prices)
- More explanatory variables (e.g. resale value, FIT vs. investment credit, purchase vs. lease)

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Bigger picture: PV diffusion modeling and policy

- Subsidizing NPV **not** the only route to promote diffusion, also community solar, lease model, nudging, …
- Bigger models needed to assess, e.g. agent-based, multivariable regression.

Thank you for your attention!

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