Experience Curves for Environmental Impact Assessment of PV systems

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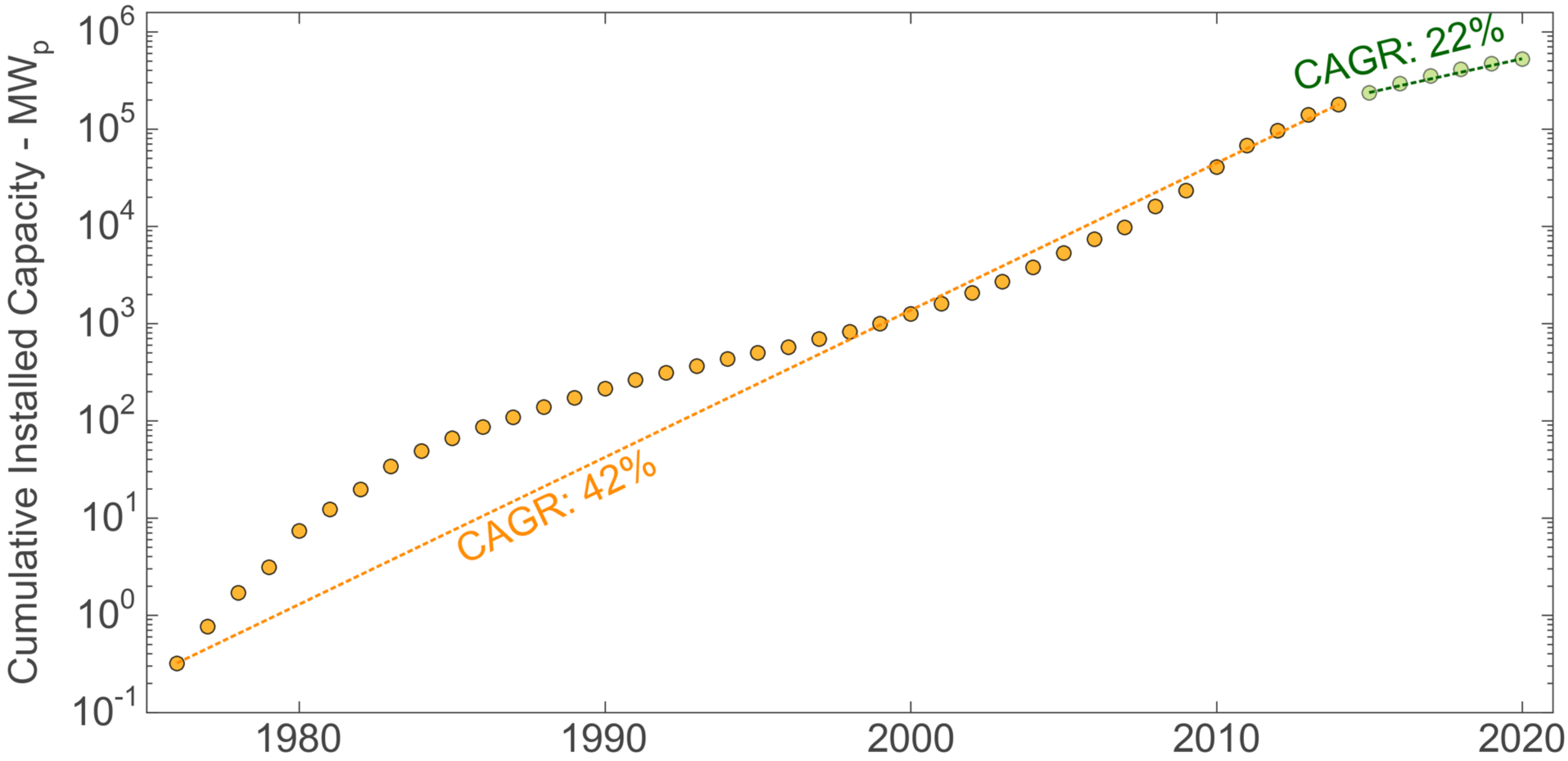
Context: strong growth of PV



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Context: concerns from fast growth

- As of 2013: for every W_p of PV
  - 8-32 MJ of energy used*
  - 0.6-3 $kgCO_2$-eq released*
  - In the past this was (much) higher

- These external costs are **paid back** by producing electricity

- When ***growth > 1/PBT*** PV industry is net
  - Energy user
  - GHG emitter

*M.J. de Wild-Scholten - doi:10.1016/j.solmat.2013.08.037

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Aim

- Show historical development of environmental impact of PV production
- Analyse **learning rates**
- Determine **net contribution of PV** in terms of
  - Energy
  - GHG emission reduction

E.g. when will all installed PV capacity have

- Produced more energy than was consumed
- Avoided more GHG emissions than were released

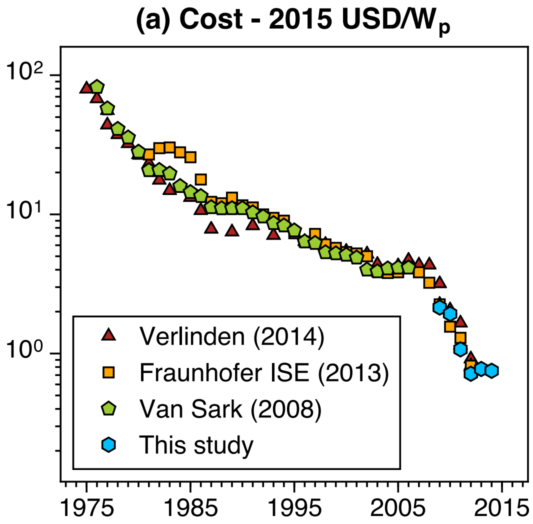
from all cumulated production?

Approach

- Combine historical development of PV for
  - Installed capacity (e.g. IEA PVPS, EPIA)
  - Energy demand and GHG from production (LCA studies)

- Establish experience curve
  - $C_{cap} = C_0 \times cap^{\log_2(1-l)}$
  - Every doubling of cap, cost C drops with l
  - Normally applied for cost but here for energy and GHG
  - Least-squares fit to data

Trends: cost and environmental impact



+ cost

+ cost

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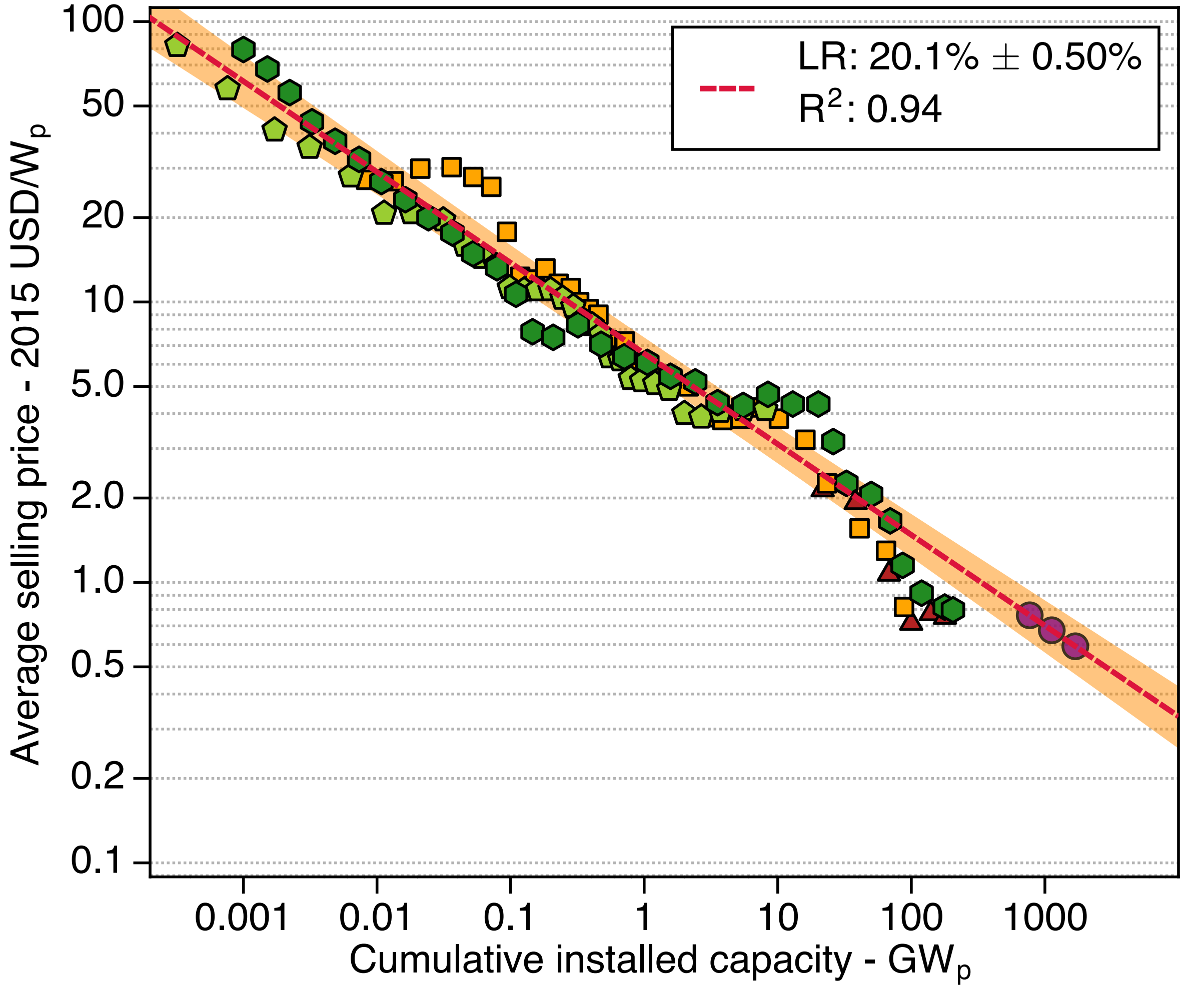
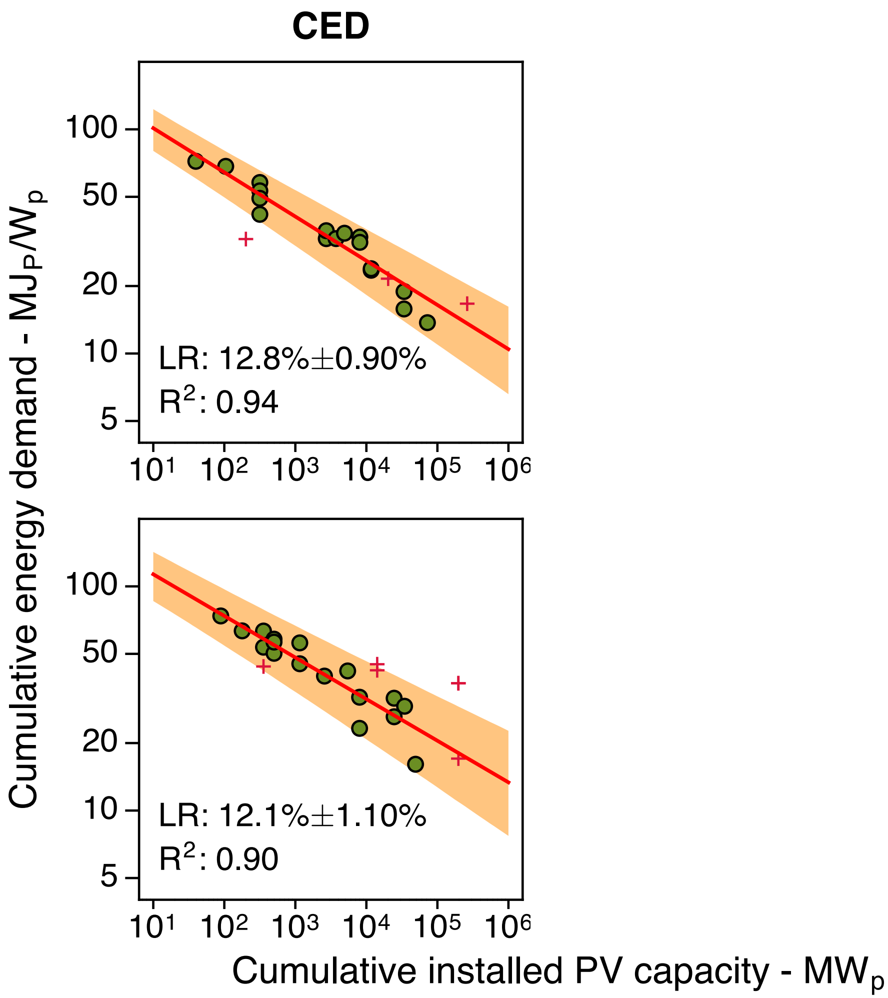
Experience curve - cost



Experience curves – Environmental Impact



Application of this "Environmental Experience Curve"

- Normally, experience curve can be applied to describe costs developments over time, and project these in to the future
- Another application is to establish e.g. the total required subsidies for a technology to reach a competitive level
  - Integral of the curves gives these total (cumulated) costs

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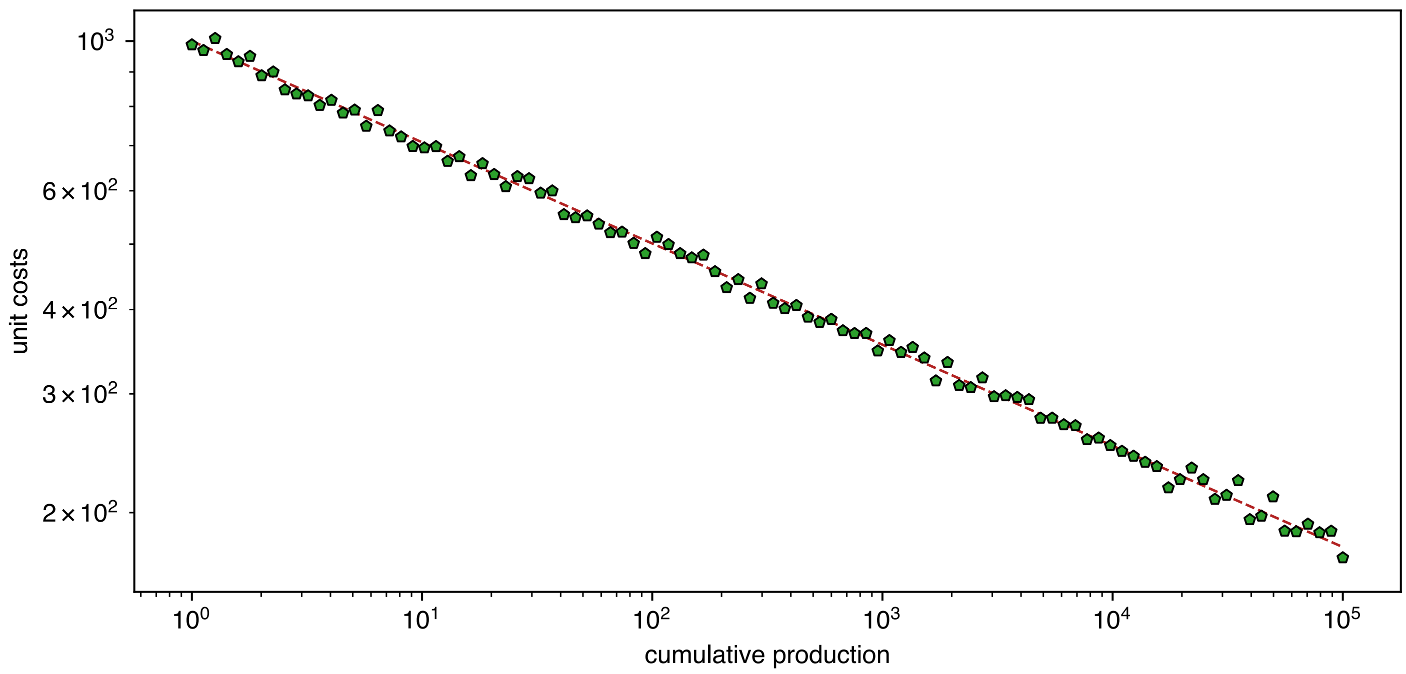
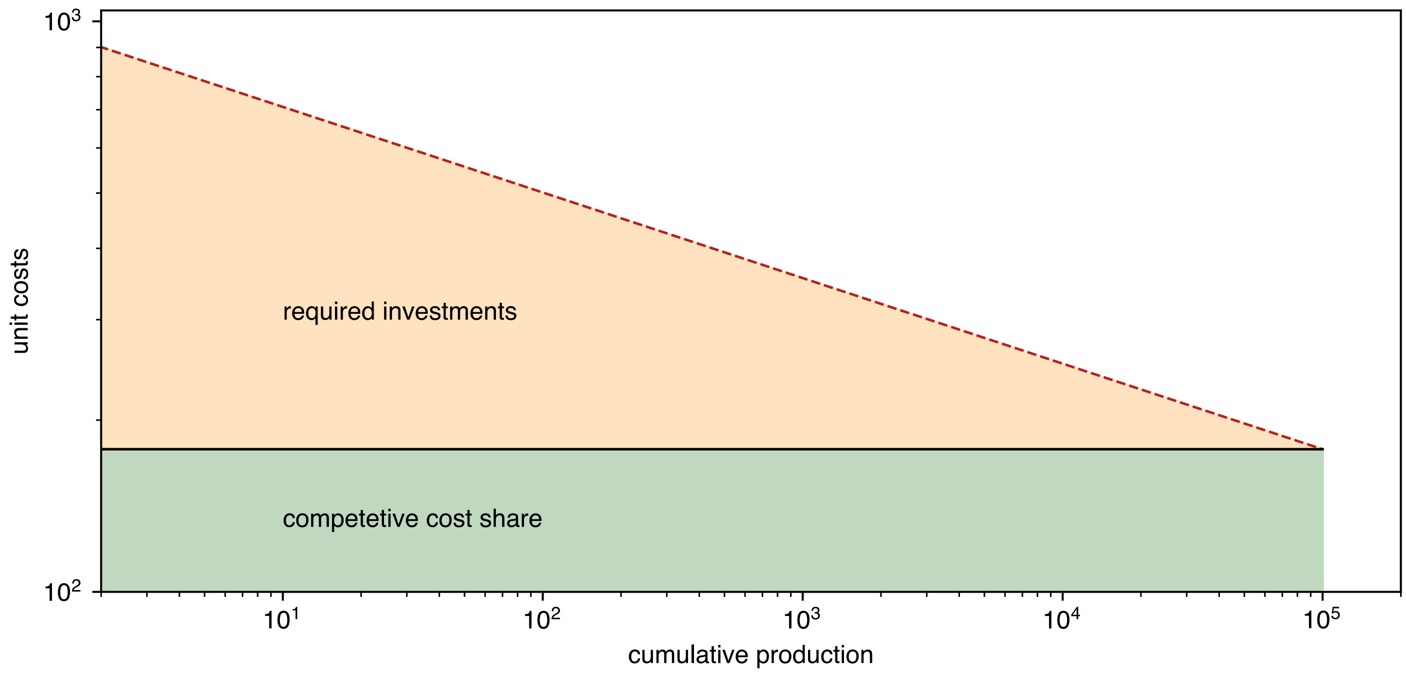
Integral of experience curves gives the cumulated costs



Integral of experience curves gives the cumulated costs

- E.g. compared to an incumbent technology



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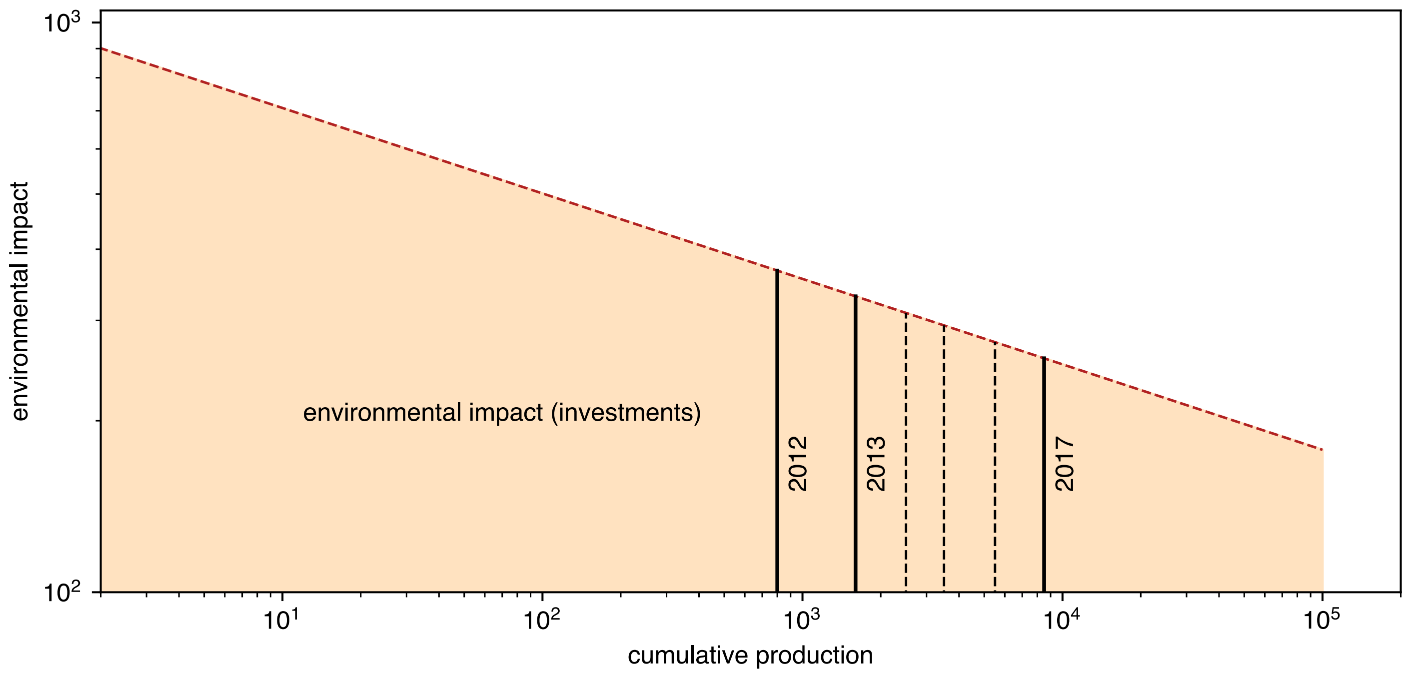
Here, we use the integral to calculate cumulative and net Energy + GHG emissions



Here, we use the integral to calculate cumulative and net Energy + GHG emissions

- Cumulated environmental impact calculated from integral of experience curve
- Environmental Benefits of PV electricity calculated from
  - Cumulative installations, per country
  - Country level solar irradiance
  - Global average PV system yield

- As we are interested in the time-dependent net impact, we calculate results annually

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Net contributions - Energy

$$E_{\text{net}} = \sum_{y=1975}^{n} \left[E_{\text{produced}}(y) - E_{\text{consumed}}(y)\right]$$

$$E_{\text{produced}}(y) = \sum_{l} cap(y,l) \times PR(y) \times \text{insolation}(l)$$

$$E_{\text{consumed}}(y) = \left(\frac{CED}{\text{cap}}\right)(y) \times f_{CED}(l) \times \text{capgrowth}(y,l)$$

from experience curve

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Net contributions - GHG emissions

$$GHG_{\mathrm{net}} = \sum_{y=1975}^{n} [GHG_{\mathrm{avoided}}(y) - GHG_{\mathrm{emitted}}(y)]$$

$$GHG_{\mathrm{avoided}}(y) = \sum_{l} cap(y, l) \times PR(y) \times \mathrm{insolation}(y, l) \times GHG_{\mathrm{grid}}(y)$$

$$GHG_{\mathrm{emitted}}(y) = \sum_{l} \left(\frac{GHG}{cap}\right)(y) \times f_{GHGgrid}(l) \times \mathrm{capgrowth}(y)$$

from experience curve

Locations and Performance

- Analysed multiple scenarios for production in
  - 100% Europe
  - Global (based on actual production shares over time)
  - 100% China

- Analysed two scenarios for performance
  - Constant low performance: worst case (PR = 0.5)
  - Increasing performance: from 0.5 in 1970 to 0.8 in 2015 onward (still conservative)

When does break-even occur?

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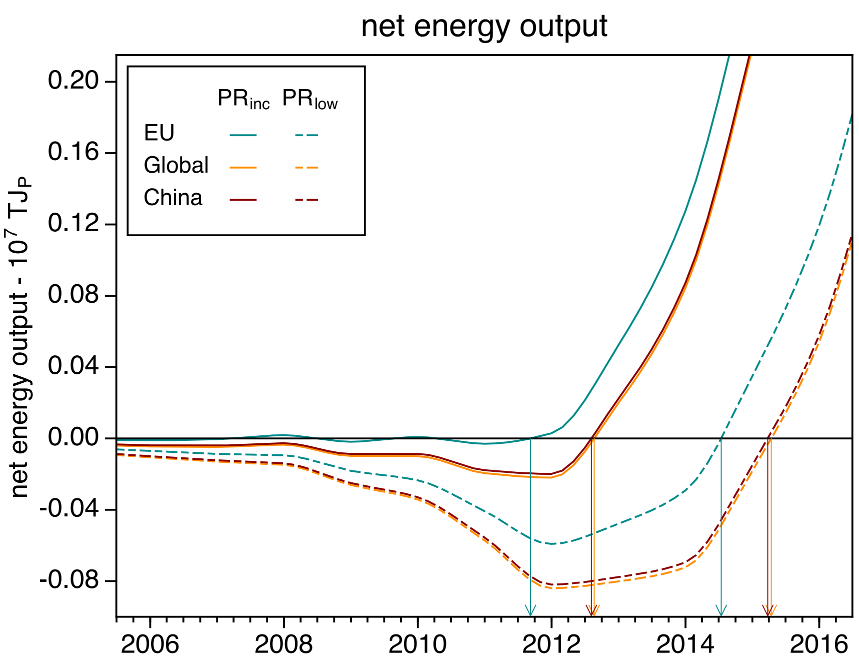
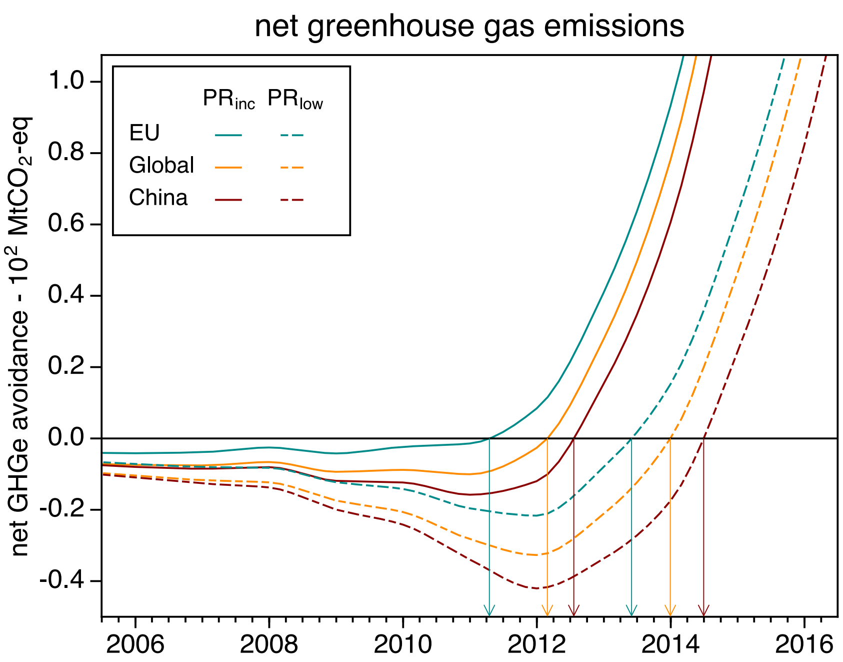
Results – multiple scenarios

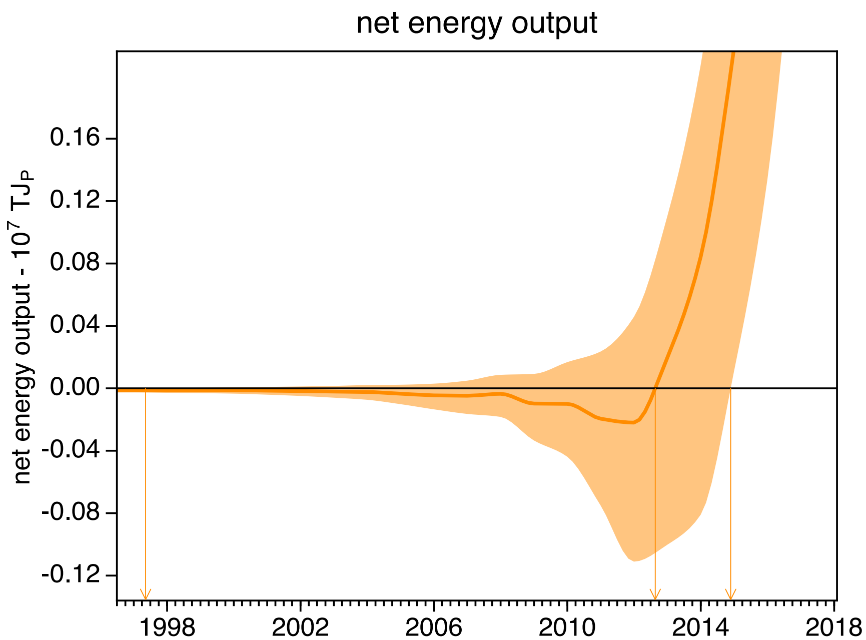


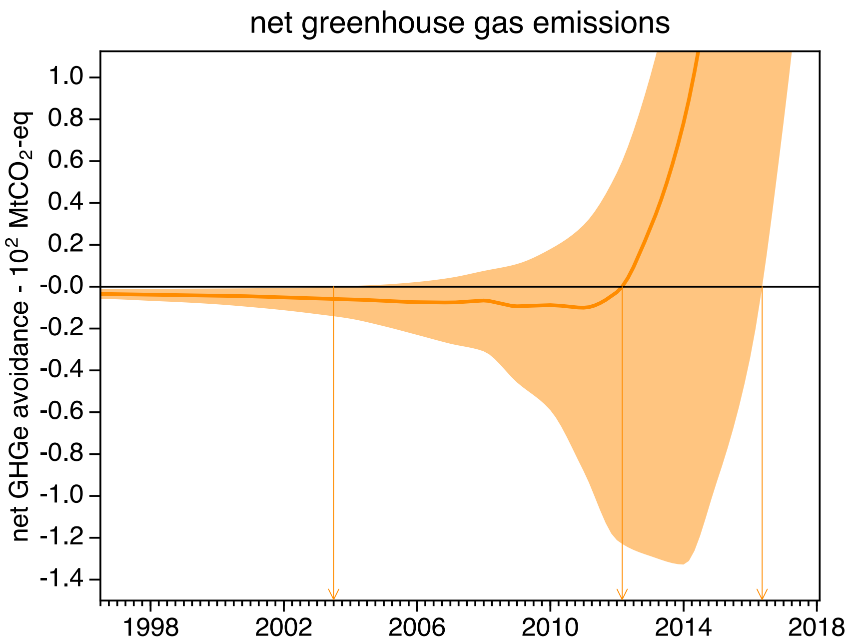


Uncertainty

- As the empirical data (LCA results) are scattered around the experience curve model, there is uncertainty in the parameters
- To analyse, we performed Monte Carlo analysis
  - Draw samples of EC parameters from normal distribution $\mu \pm 1.96\sigma$
  - Recalculate net contributions for each sample set

Uncertainty – one scenario





Summarising

- Experience curve theory applicable to other metrics than cost, here: CED and GHG emissions
- Clear decrease observed in environmental impact concurrent with increased cumulative capacity

- Break even for energy was here Q3 2012
  - 95% range from 1998-2015
- Break even for GHG was here Q1 2012
  - 95% range from 2003-2016

What does this mean?

- Environmental benefits of PV will be larger, but there is a tradeoff regarding the grid electricity mix GHG
  - Low GHG in mix means low benefits, but also
  - Low GHG in mix means less emission from manufacturing
- From now, at similar growth rate, net environmental benefits of PV quickly and constantly grow
  e.g. large constant growth of PV can be sustained without increasing worldwide emissions