Technological learning and experience curves for renewable energy technologies

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http://www.theenergycollective.com/dan-liggett/2247234/technological-advancements-support-sustainability

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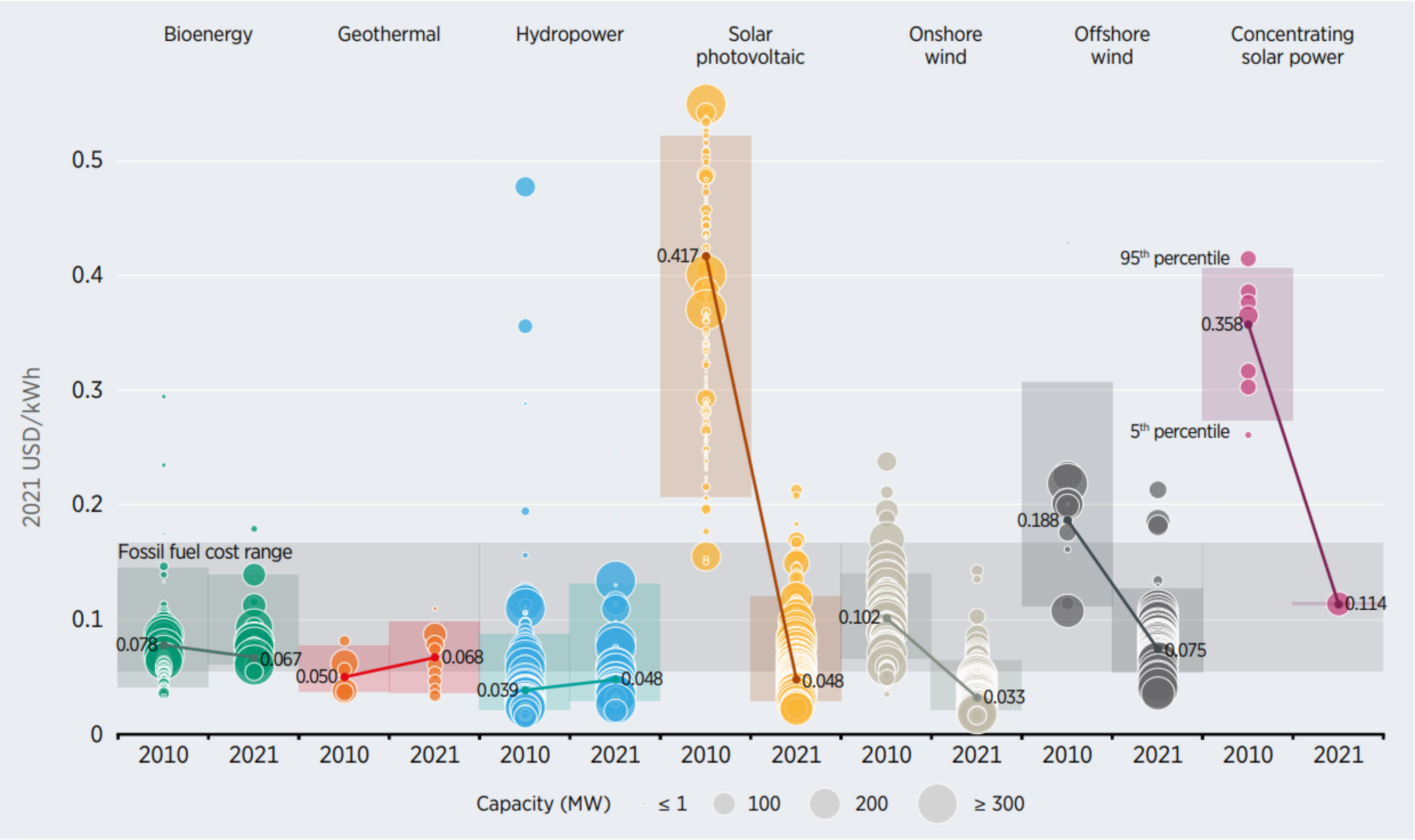
Learning objectives

- Understand drivers of technological learning
- Understanding and being able to apply experience curves, conceptually and mathematically
- Understanding limitations and pitfalls of experience curves, and how these may impact cost projections

Costs of electricity generation

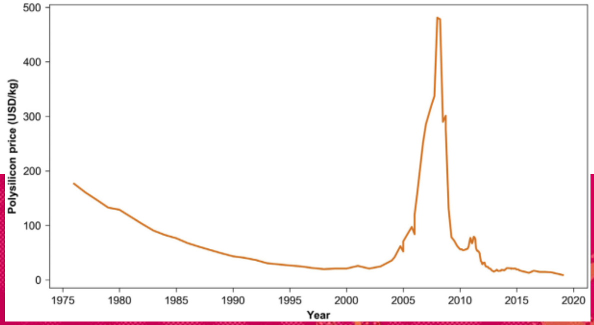
Figure 1.2 Global weighted average LCOEs from newly commissioned, utility-scale renewable power generation technologies, 2010-2021



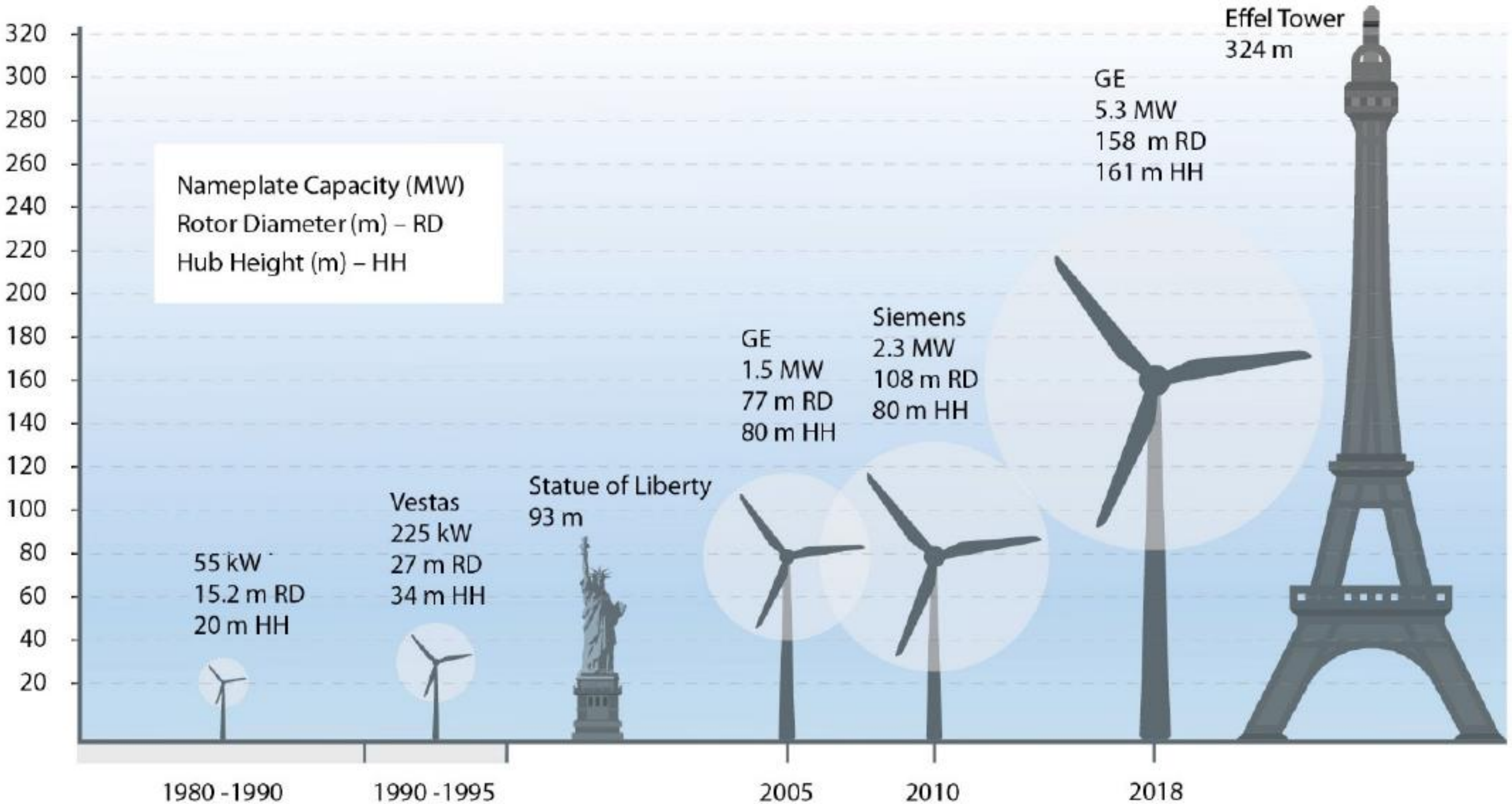
Source: IRENA (International Renewable Energy Agency), 2022: Renewable Power Generation costs in 2021

Factors influencing technological learning/ unit costs

- Learning by doing (Improved siting of wind farms)
- R&D (Development of specific components (gear boxes, generators) and regulating mechanisms (stall/pitch regulation))
- Economies-of-scale (Mass production of wind turbines)
- Upscaling of an individual device (Upscaling of wind turbines)
- Time (not too much or too little)



Upscaling: Windmill size as factor influencing unit costs (1/2)



Original source: NREL
Quoted in IEA Wind,
https://www.nrel.gov/docs/fy19osti/72437.pdf

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Upscaling: Windmill size as factor influencing unit costs (2/2)

The massive 75m wind turbine blades (each the size of an Airbus A380) coming to the Essex coast in 2014

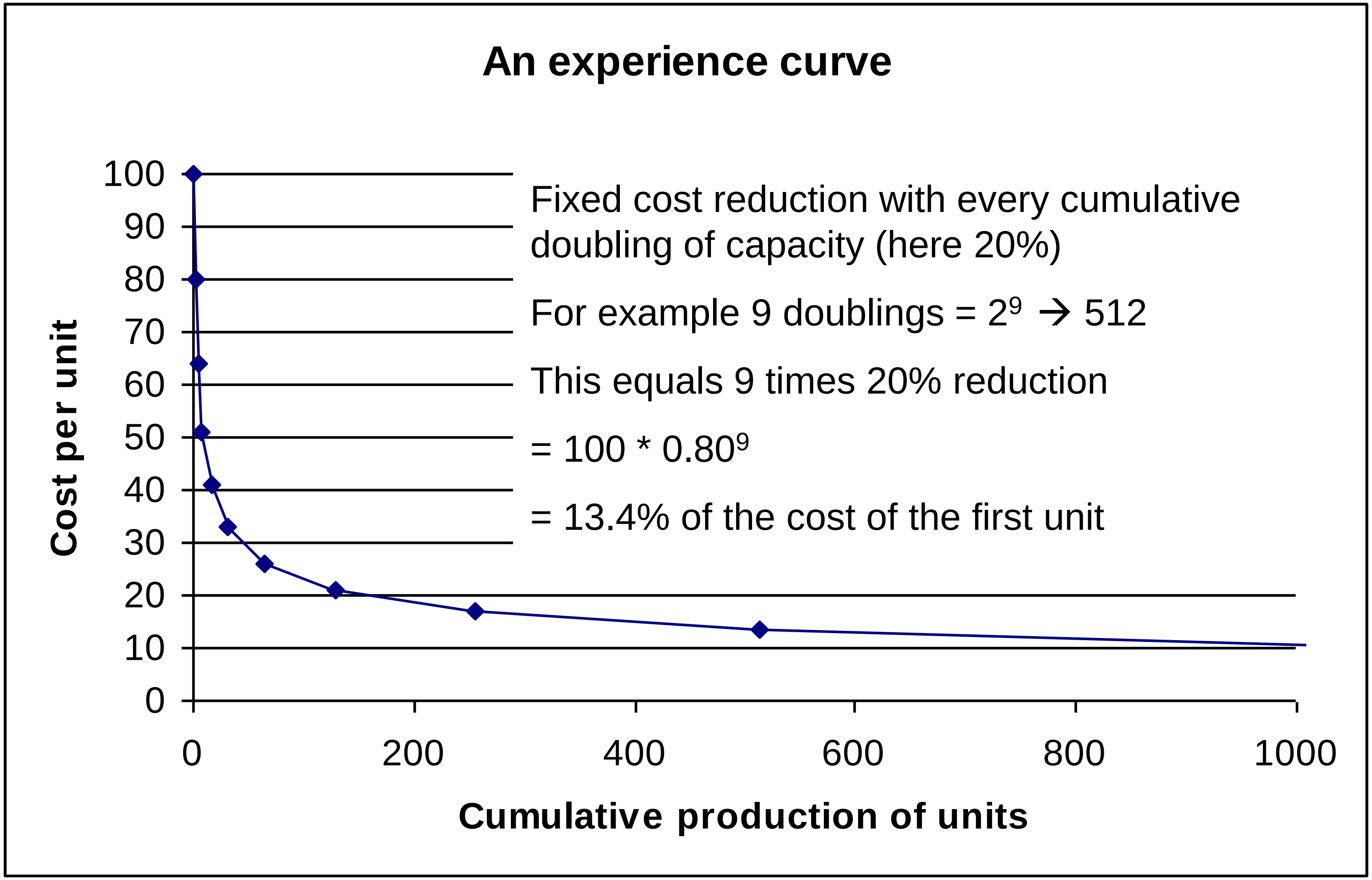
By EDDIE WRENN FOR MAILONLINE

PUBLISHED: 09:28 GMT, 1 August 2012 | **UPDATED:** 09:45 GMT, 1 August 2012

Giant turbine: The Siemans blade is the world's largest fiberglass component cast in one piece

Source: http://www.dailymail.co.uk/sciencetech/article-2181963/Wind-power-gets-massive-Worlds-biggest-air-turbines--twice-width-Airbus--erected-Essex-coast-2014-Siemens-Dong.html

Empirically observed cost development



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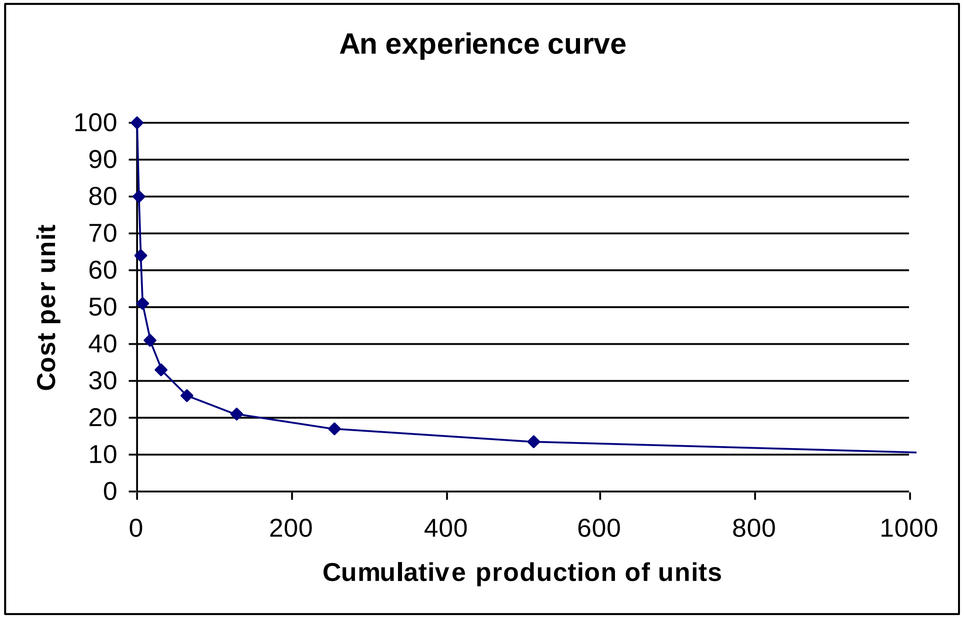
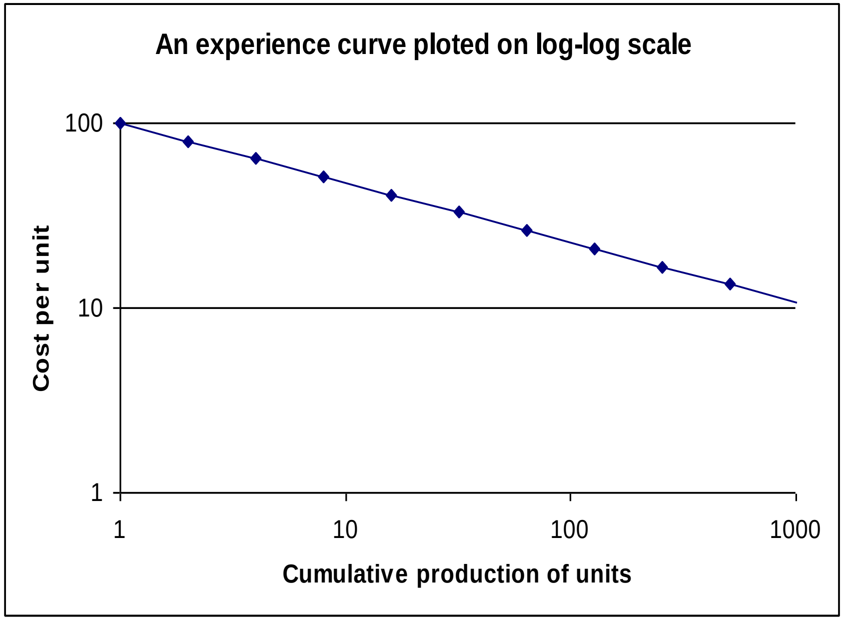
Empirically observed cost development





Methodology: What is an experience curve?

Emperically observed many times:

With every doubling of *cumulative* production, reduction costs tend to fall with a fixed %-age.

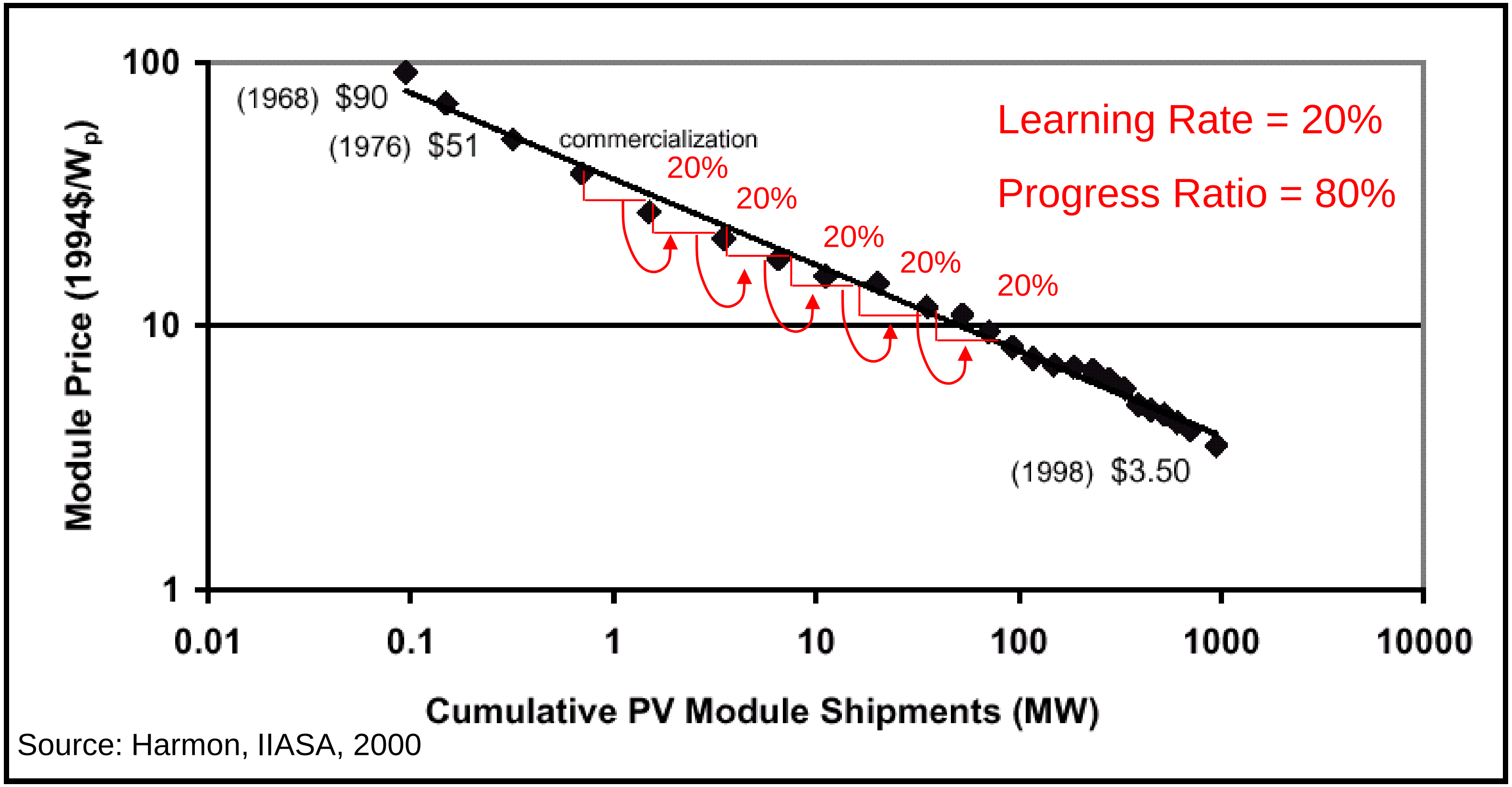


Figure 6-1: The experience curve of PV modules [1968-1998] (Maycock and Wakefileld, 1975; Ayres, 1998; NREL 1999;Thomas, 1999; Watanabe, 1999)

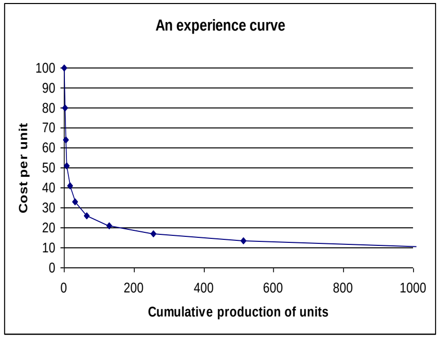
Definition experience curve

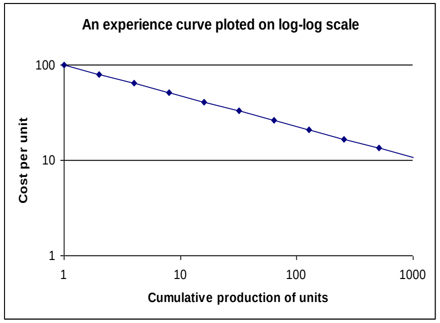
The experience curve describes how unit costs decline with cumulative production.

$$Cost(P_{cum}) = Cost_0 \cdot P_{cum}{}^{b} \quad (1)$$

$$log(Cost(P_{cum})) = log\,(Cost_0) + b \cdot log(P_{cum}) \quad (2)$$

$$\frac{Cost\,(P_{cum_2})}{Cost\,(P_{cum_1})} = \left(\frac{P_{cum_2}}{P_{cum_1}}\right)^{b} \quad (3)$$





$Cost_0$	=	Cost of the first unit produced ($P_{cum,\,0} = 1$)
P_{cum}	=	Cumulative production
b	=	Learning index (b < 0 if PR < 1)
$Cost(P_{cum})$	=	Cost at cumulative production P_{cum}

Progress Ratio = 2^b (4) — The progress ratio expresses the cost ratio for every cumulative doubling of unit production.

Learning rate = $1 - 2^b$ (5) — The learning rate expresses the decline in unit cost with every cumulative doubling of unit production.

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Difference between learning and experience curve

Learning curve

- Used to measure the learning speed in a single company

Experience curve

- Describes the learning speed within an entire industry sector
- Various factors may cause drop in unit cost

Application of learning/experience curves

Air plane industry (Wright, 1936)

FEBRUARY, 1936 JOURNAL OF THE AERONAUTICAL SCIENCES VOLUME 3

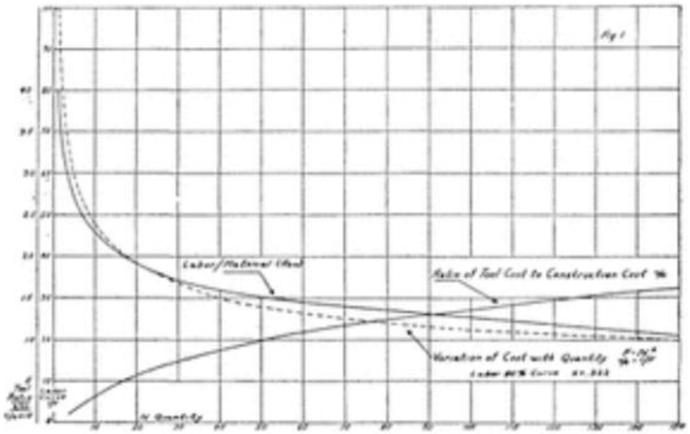
Factors Affecting the Cost of Airplanes

Presented at the Aircraft Operations Session, Fourth Annual Meeting, I. Ae. S.

T. P. Wright, *Curtiss-Wright Corporation*

Introduction

THIS subject is one which can always be relied upon to start a discussion whenever it is raised in aircraft circles. Great differences of opinion will be voiced as to the relative importance of various factors, depending somewhat on whether the discussion is between persons in the industry who are engaged in sales, engineering, design or factory work. The attitude of those outside the industry is usually quite supercilious with the intimation present that everyone engaged in the design, development, or construction of airplanes is a sort of prima donna. Therefore, because of the rather hazy information which seems to surround the



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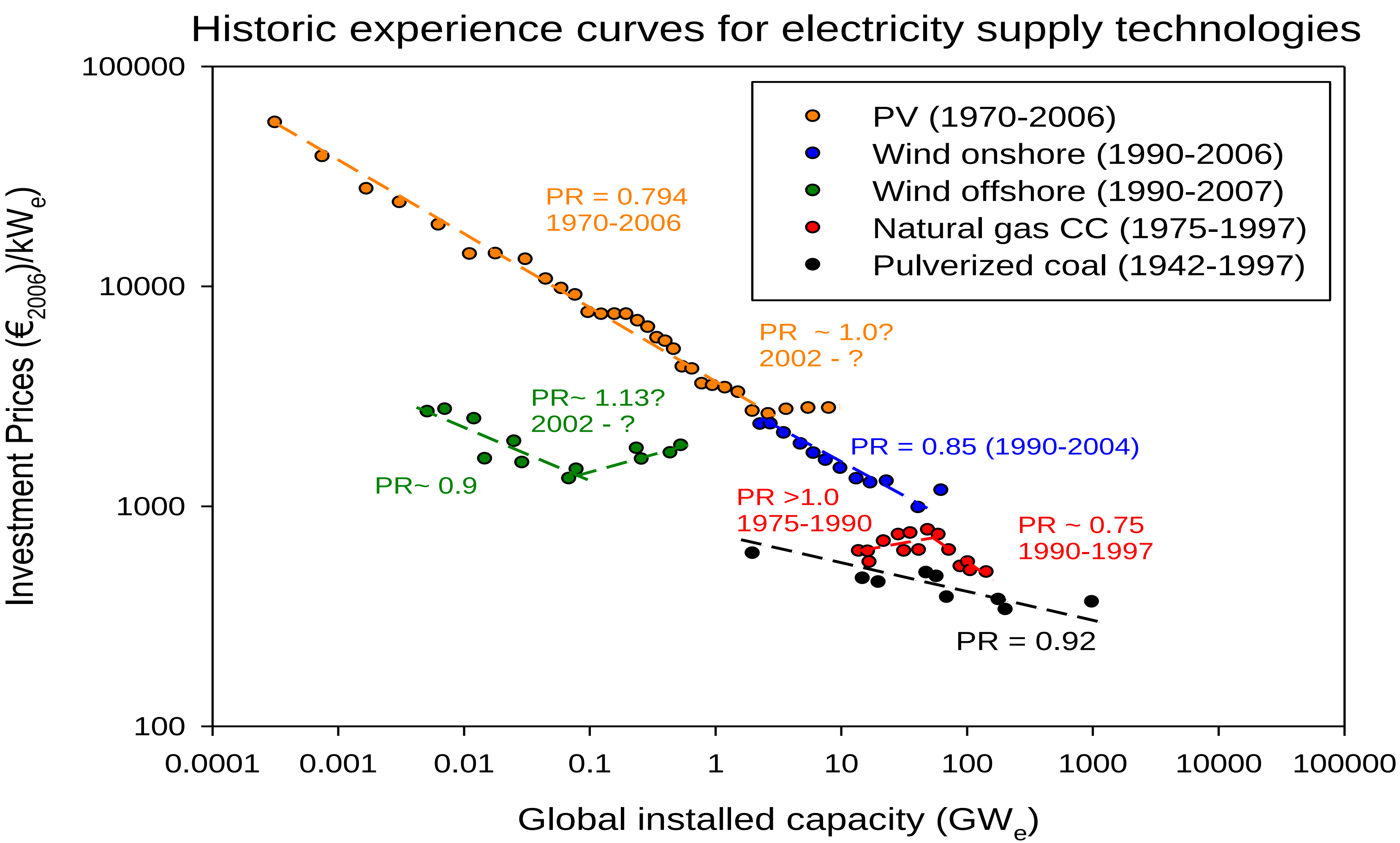
Energy supply technologies - overview



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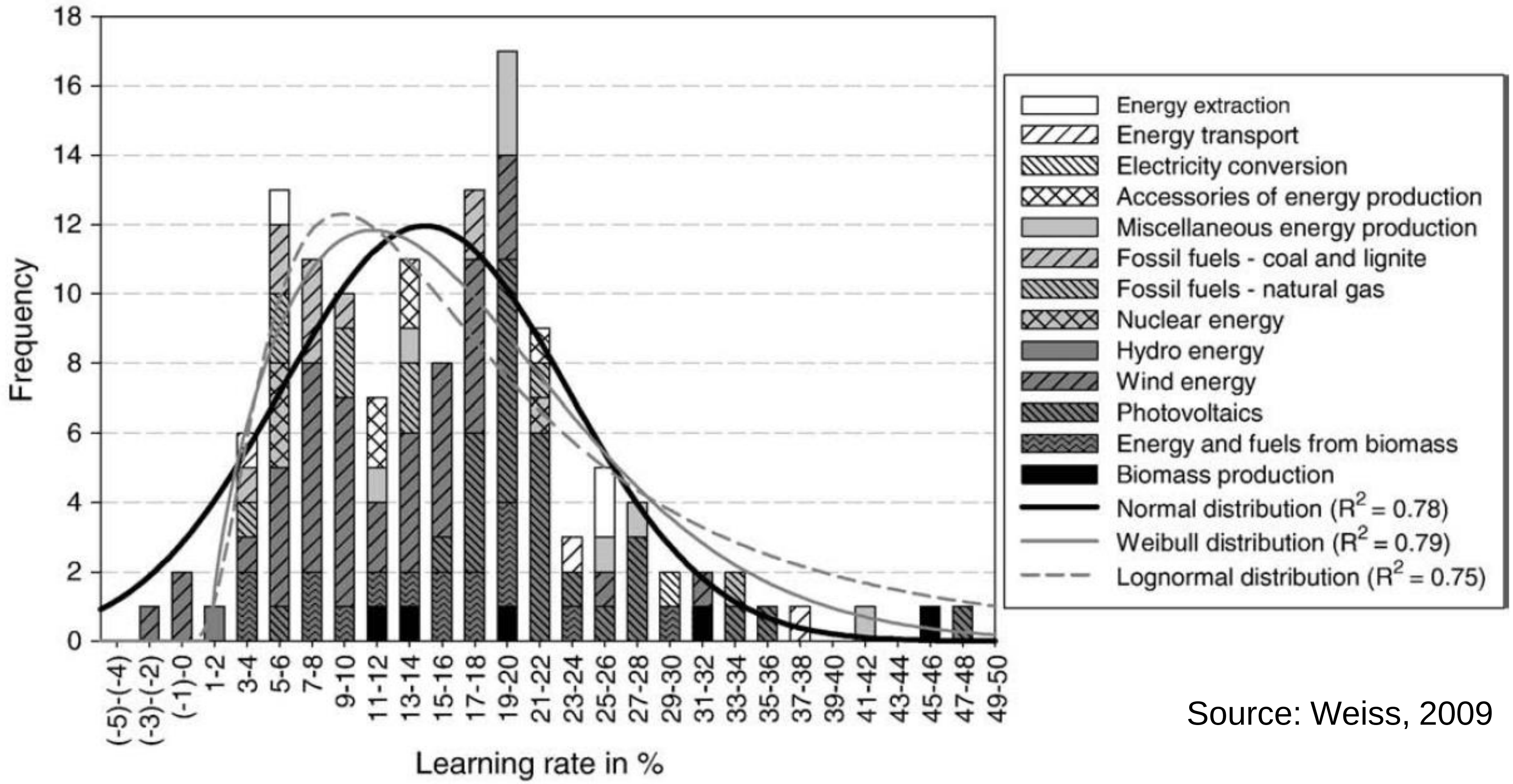
PR distribution of energy supply technologies

Energy supply technologies: LR = 16 ± 9%



Source: Weiss, 2009

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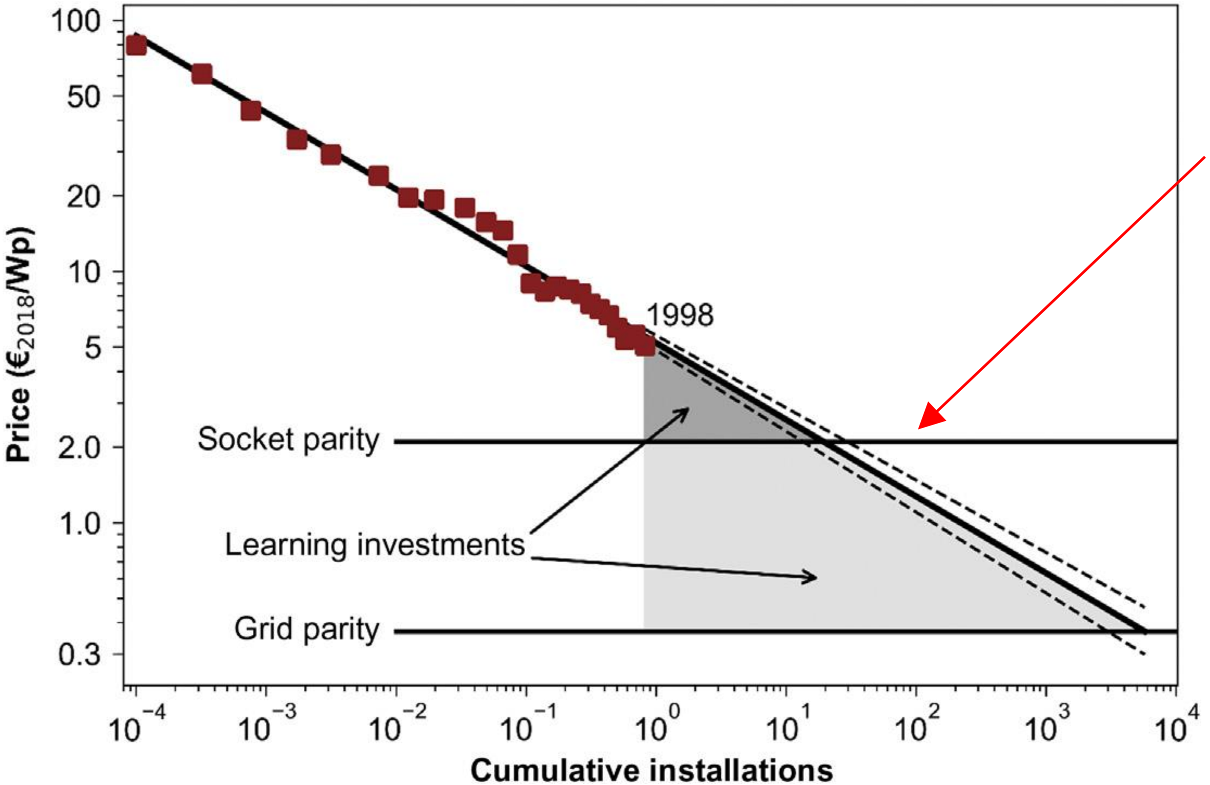
Why is this relevant for policy makers?

'Learning investments' – the cost of learning



Break-even with electricity tax

→ Used as
- estimation method for surplus costs
- Monitoring tool

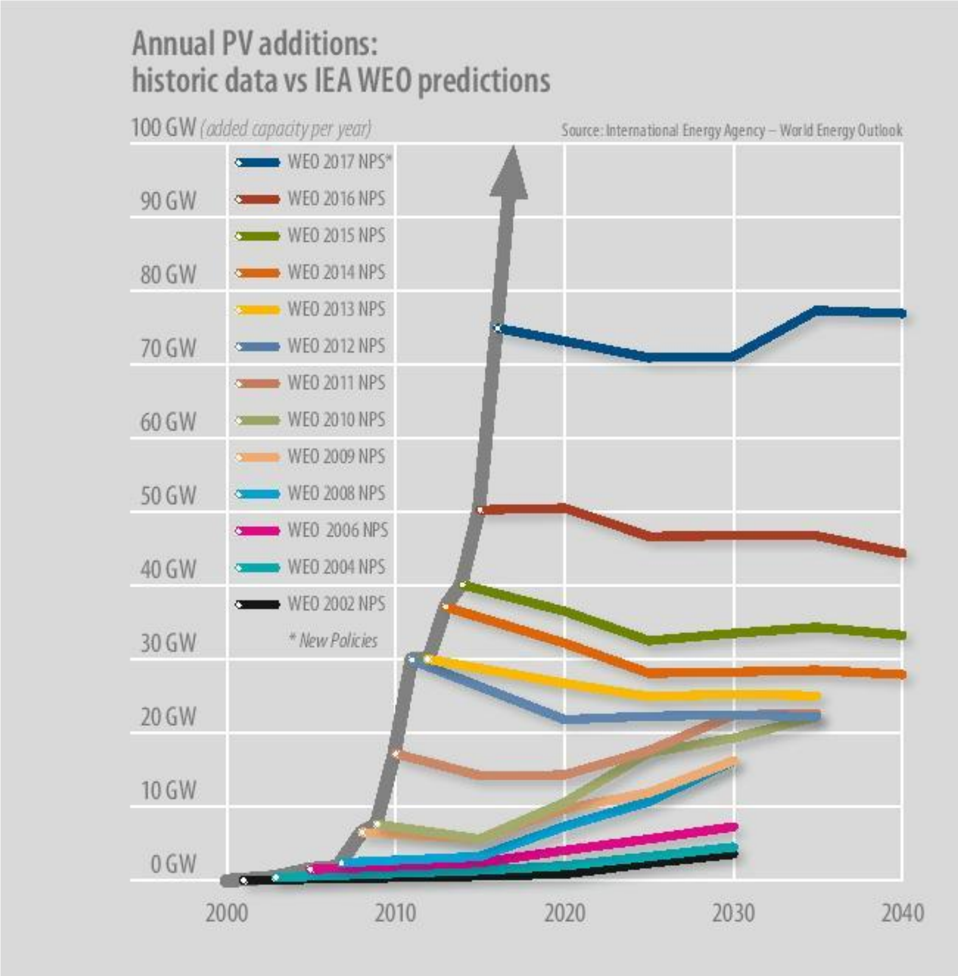
Source: Junginger & Louwen (Eds.) (2020) Technological Learning in the Transition to a Low-Carbon Energy System

The dependence of ‘learning investments’ on the progress ratio the case of PV

PR	Cumulative production until breakeven [GW_p]	Cumulative production [% of 3300 GW_p = current world capacity]	Surplus costs of reaching break-even [USD billion]
70%	23	0.7%	15
75%	48	1.5%	27
80%	148	4.5%	64
85%	957	29%	288
90%	39700	1200%	7110

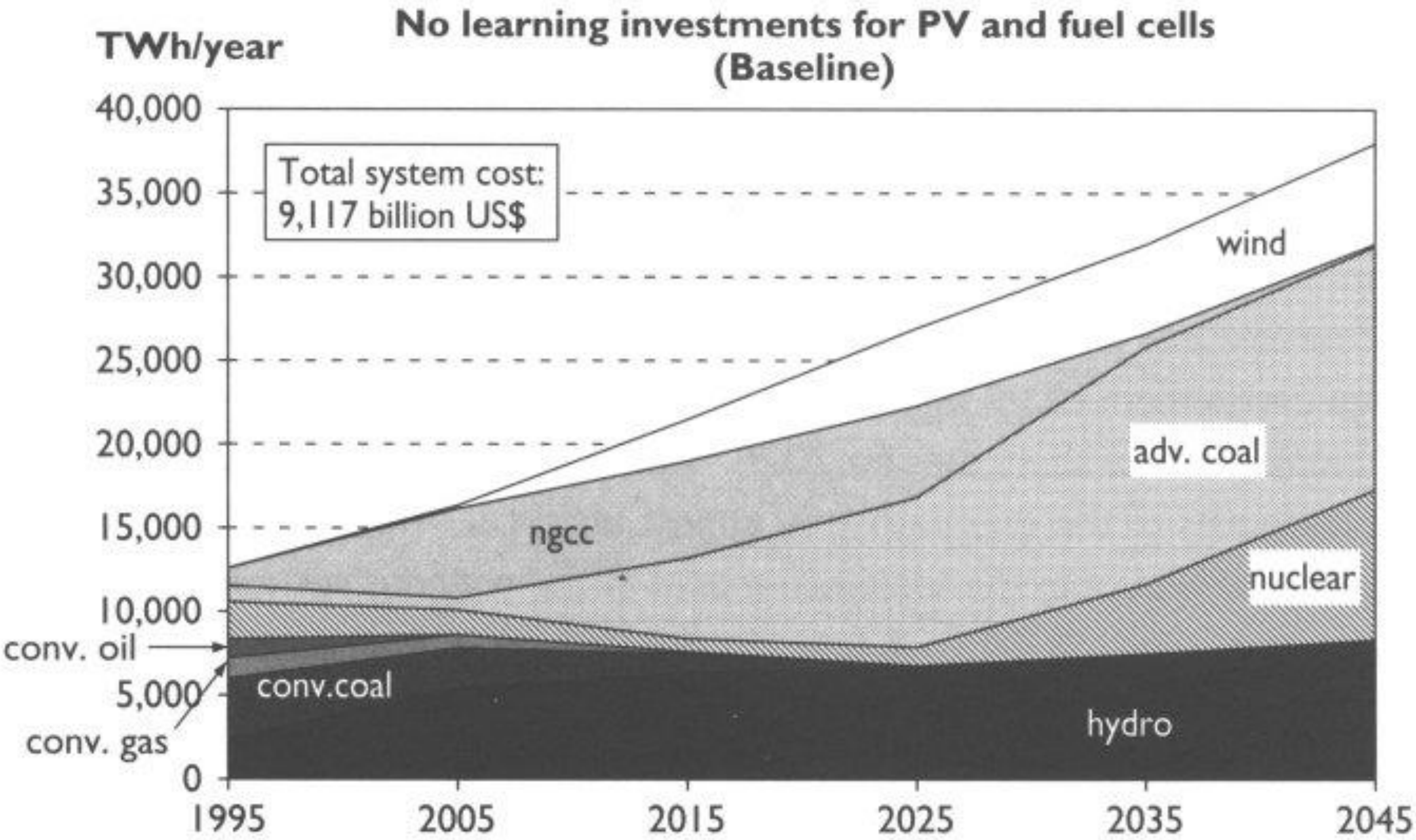
Source: Van der Zwaan and Rabl, 2002

Learning investments in energy models



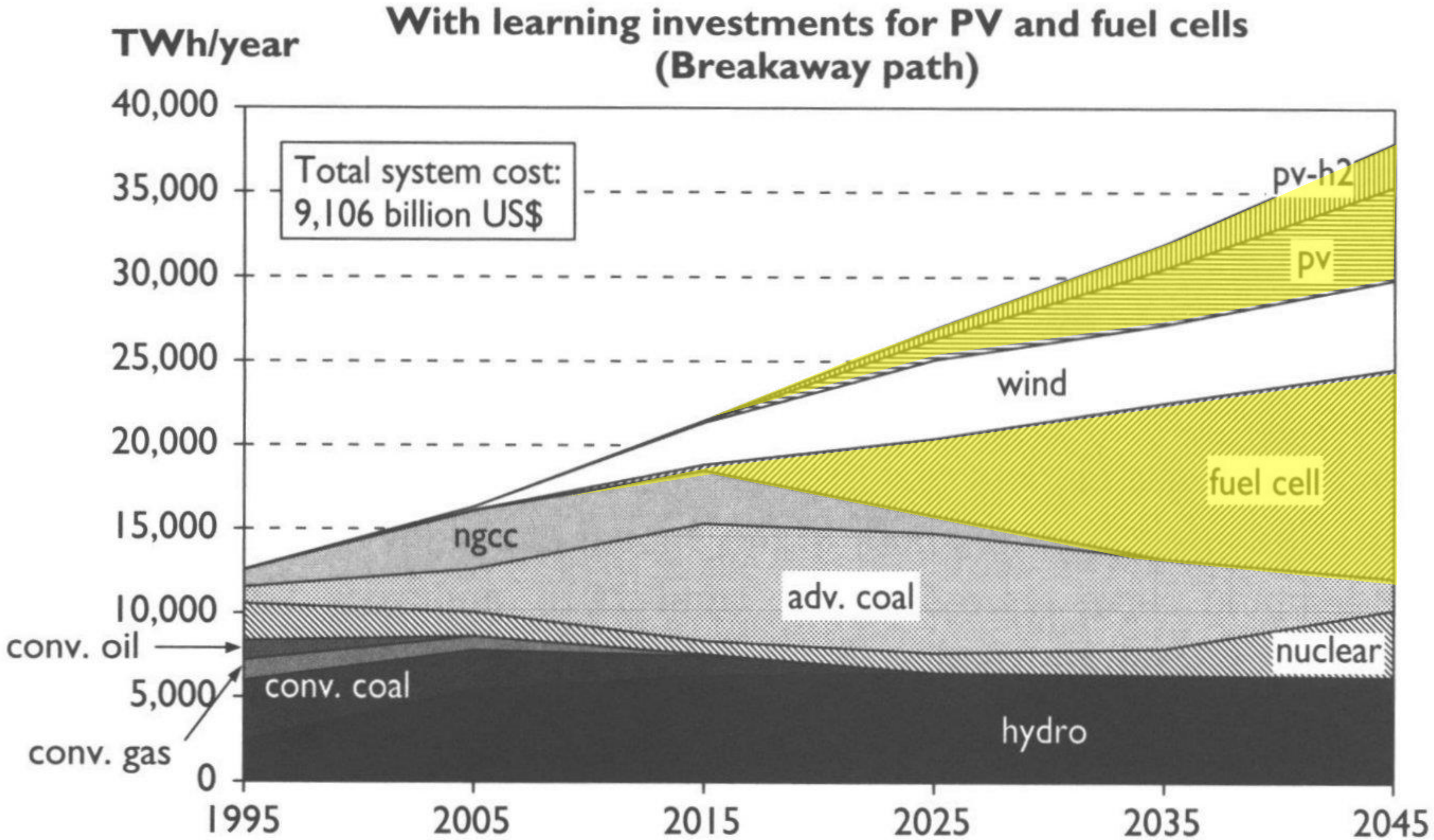
Source: PV-magazine.com

Learning investments in energy models



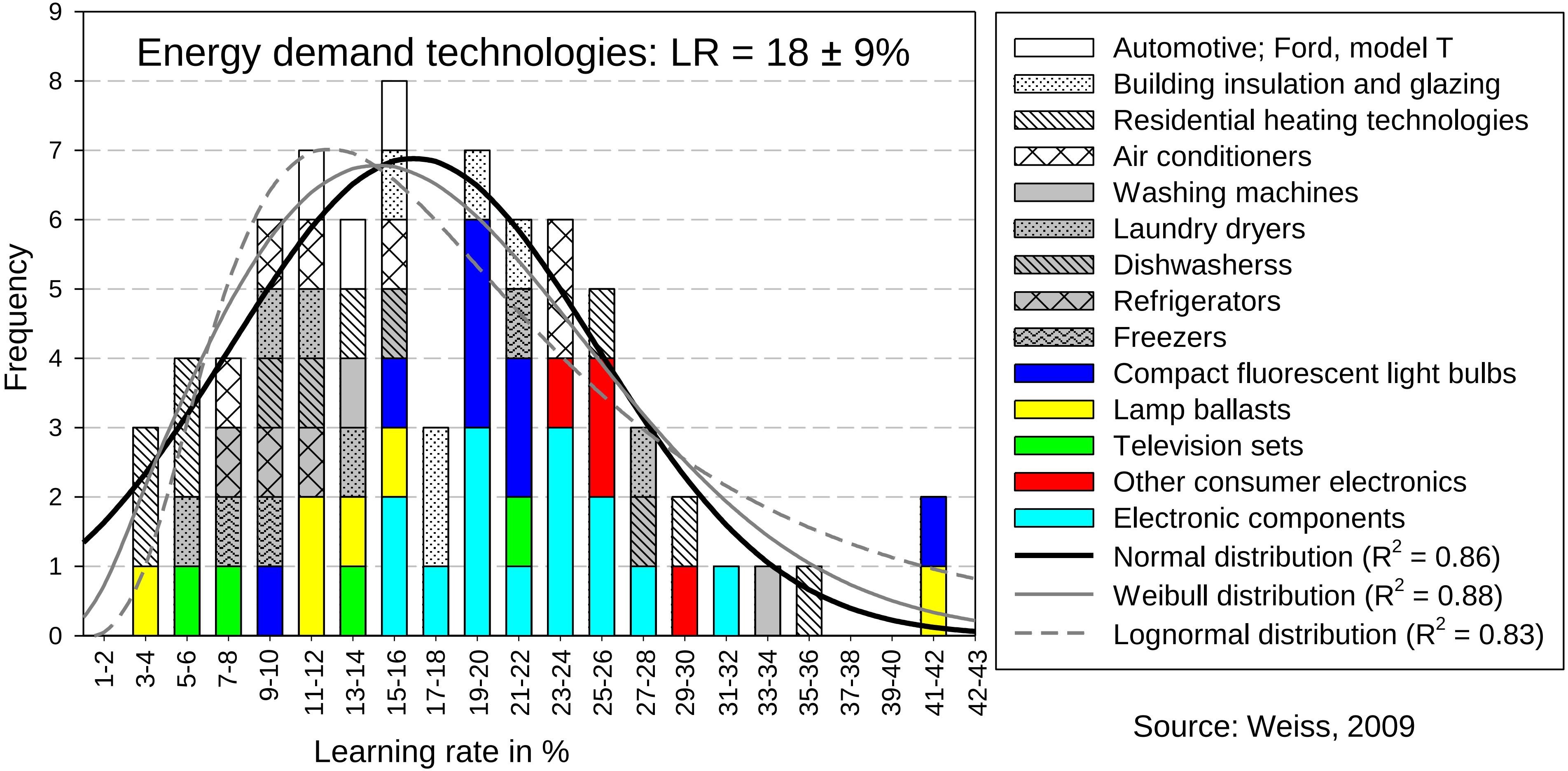
Source: : Mattson, 1997; Reproduced in Junginger, van Sark, Faaij (2010), Technological Learning in the Energy Sector

Learning investments in energy models



Source: : Mattson, 1997; Reproduced in Junginger, van Sark, Faaij (2010), Technological Learning in the Energy Sector

Review of experience curve analyses for energy demand technologies



Source: Weiss, 2009

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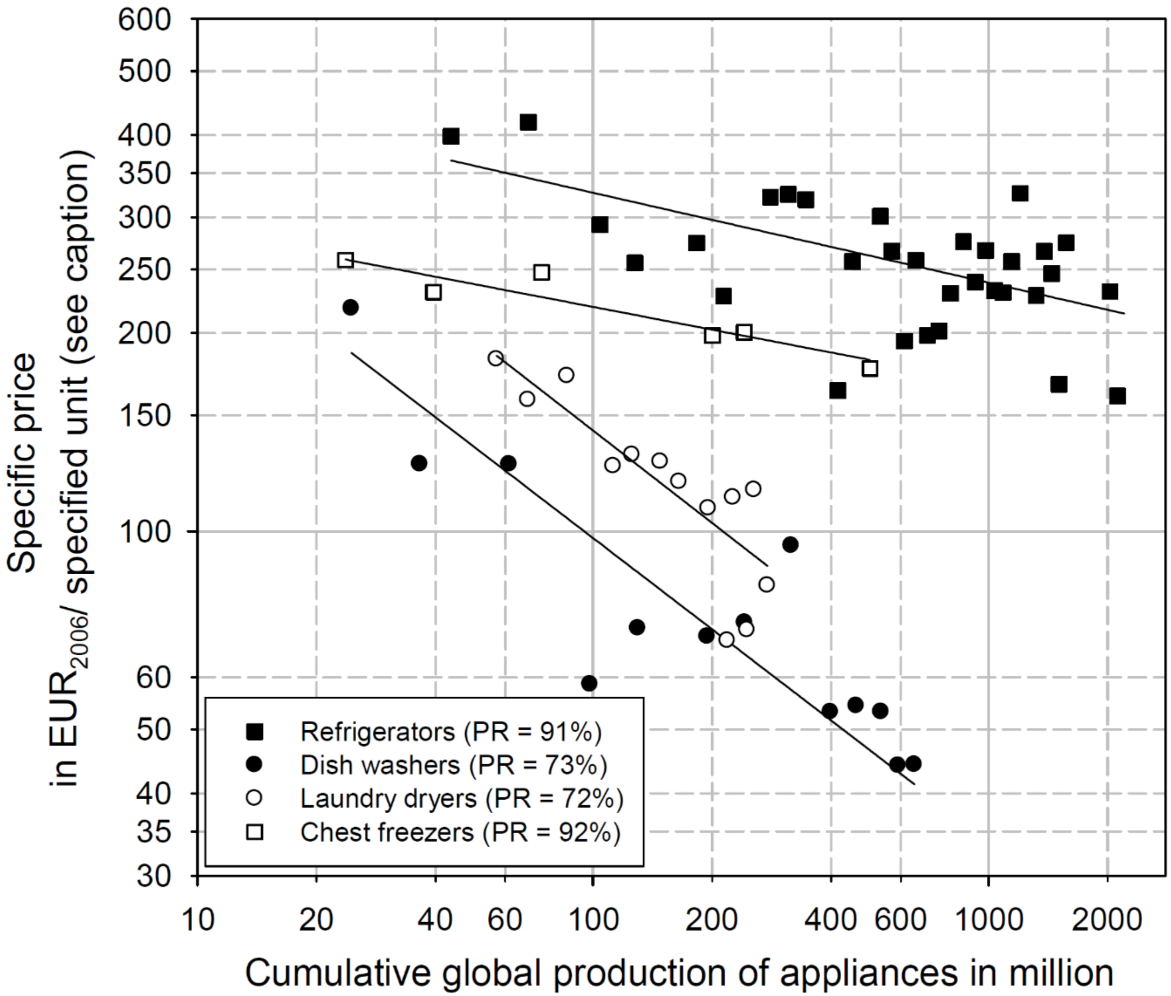
Energy demand side technologies

Establishing experience curves provides several additional challenges:

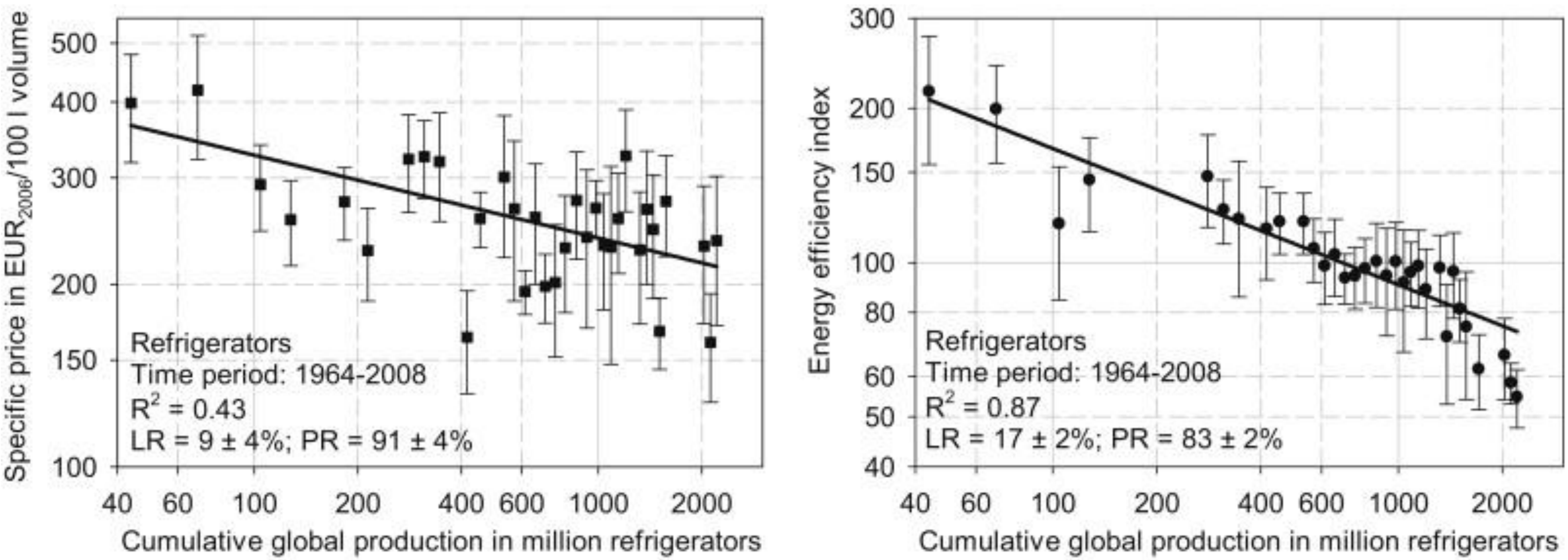
- Supply-side technologies typically only optimize one goal: lowest cost of energy delivered.
- Demand-side technologies also have to meet consumer demands, (more) safety aspects and often a multitude of functions
- In some cases trade-off between low costs and high energy efficiency

Large household appliances



Source: Junginger et al., 2010

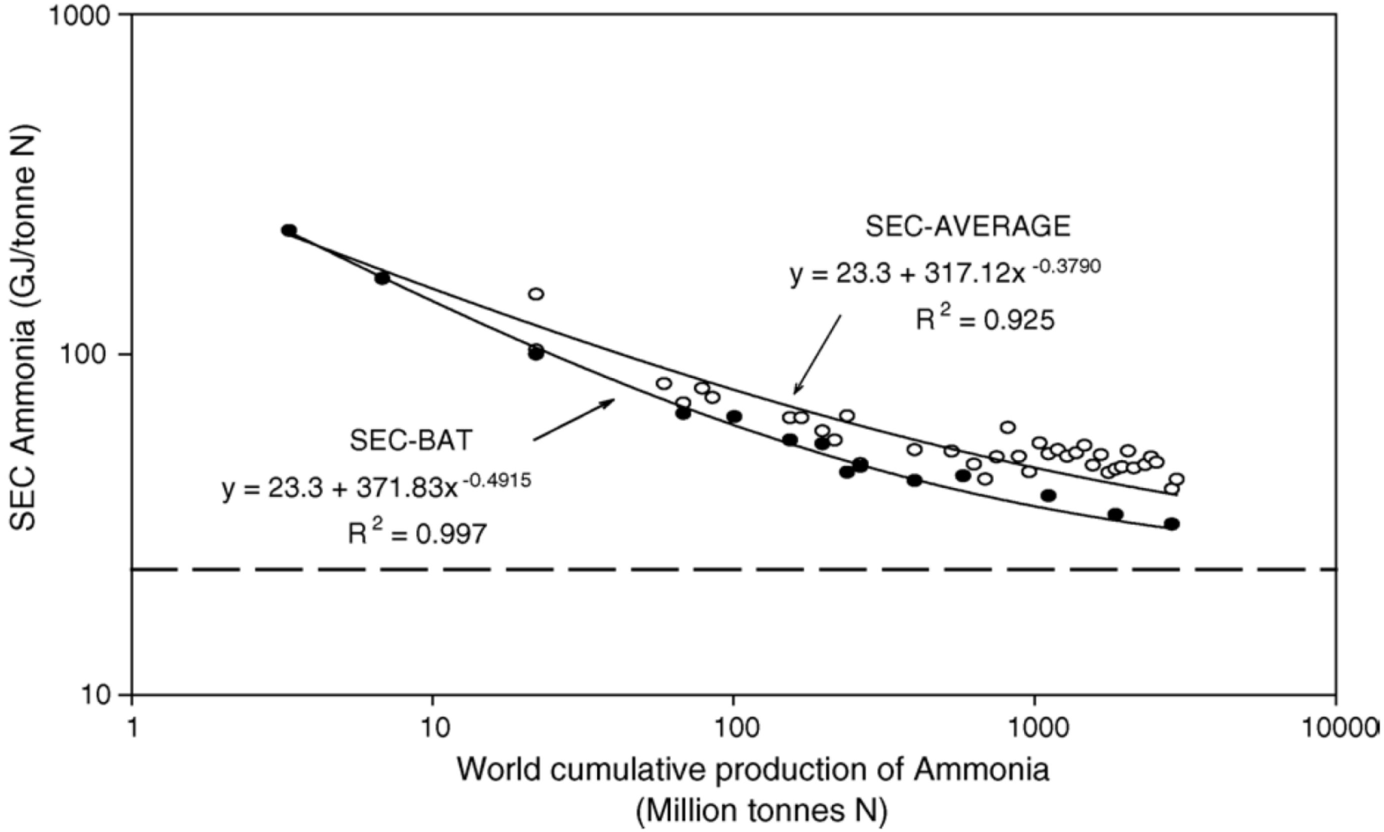
Energy efficiency learning



Similar findings for wet appliances

Source: Weiss et al., 2010

Production of Ammonia

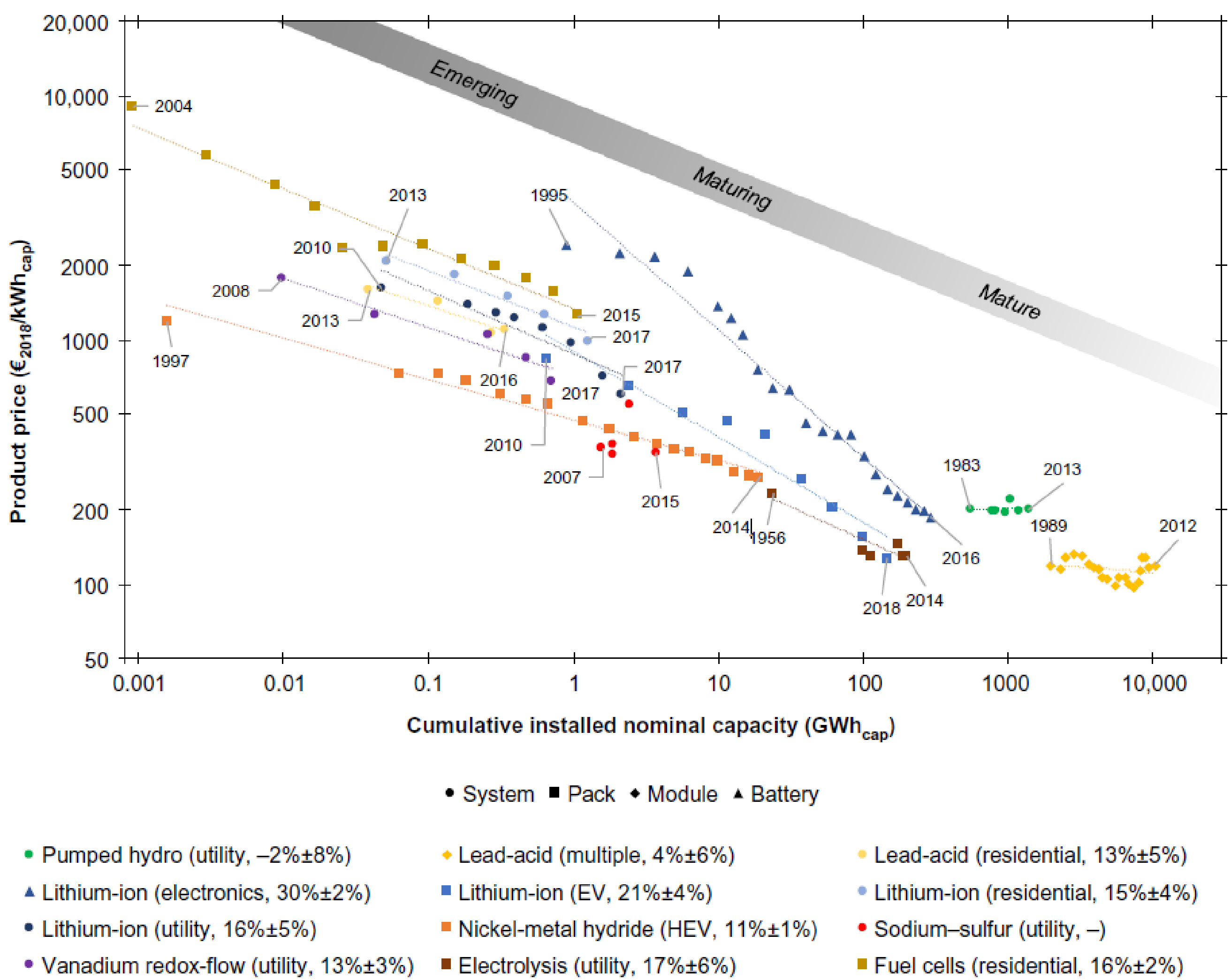


Experience curve for specific energy consumption

Energy constitutes major cost factor in ammonia production

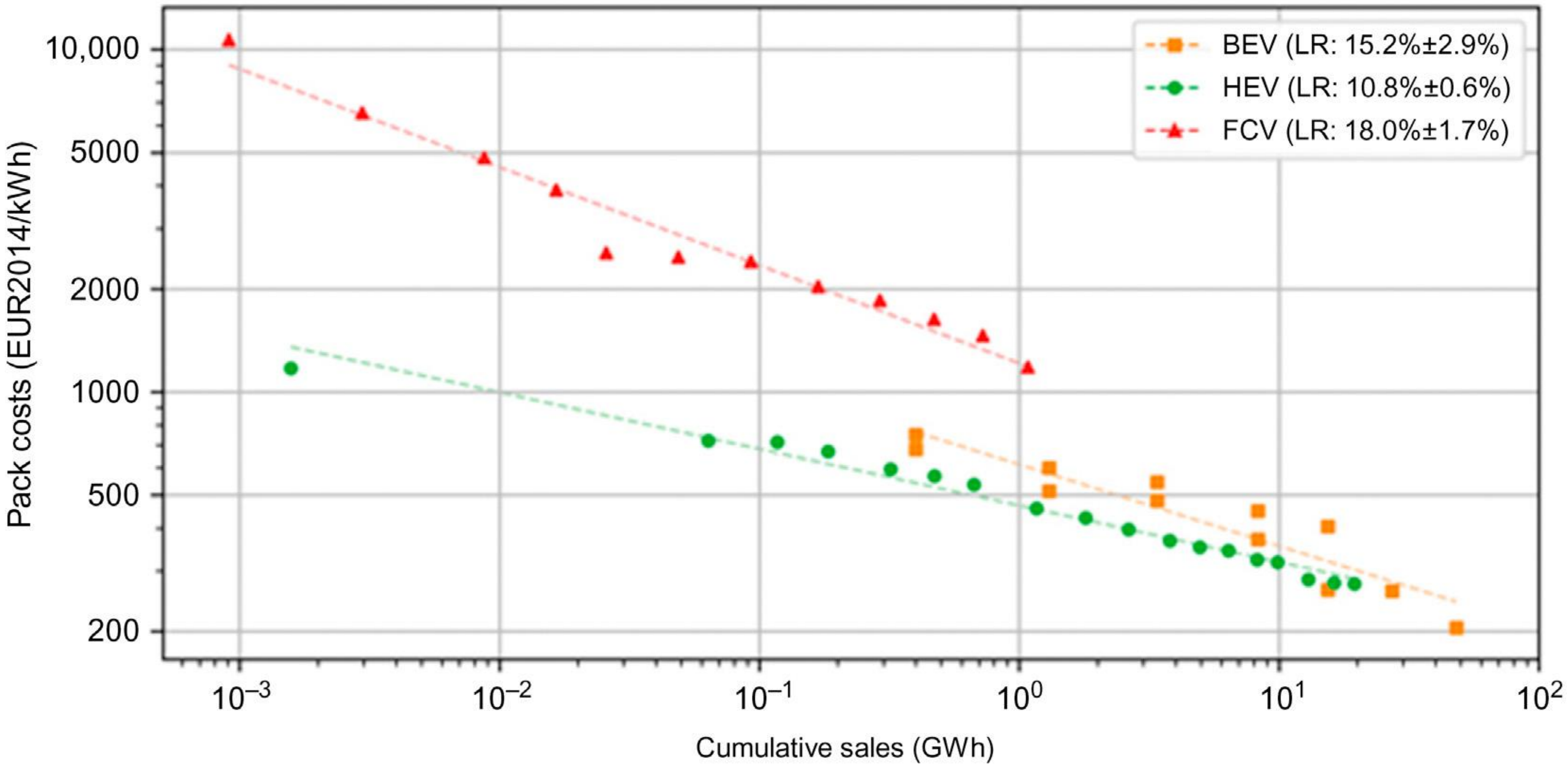
Source: Ramirez, 2006

Grid-scale electricity storage



Source: Junginger & Louwen (2020)

Electric vehicle battery packs and fuel cell stacks



Source: Junginger & Louwen (2020)

Limitations and pitfalls of using experience curves

Illustrated using the case of wind energy (and a few other examples)

1. Different types of experience curves
2. (Data) Uncertainty of historic experience curves
3. System boundaries
4. Market based differences
5. Impact of raw material costs and production scale
6. Negative learning? The case of nuclear energy

1. Types of experience curves

How would you set up an experience curve in the case of wind energy?

- What unit would you chose for the cumulative capacity axis?
- What unit would you chose for the costs?

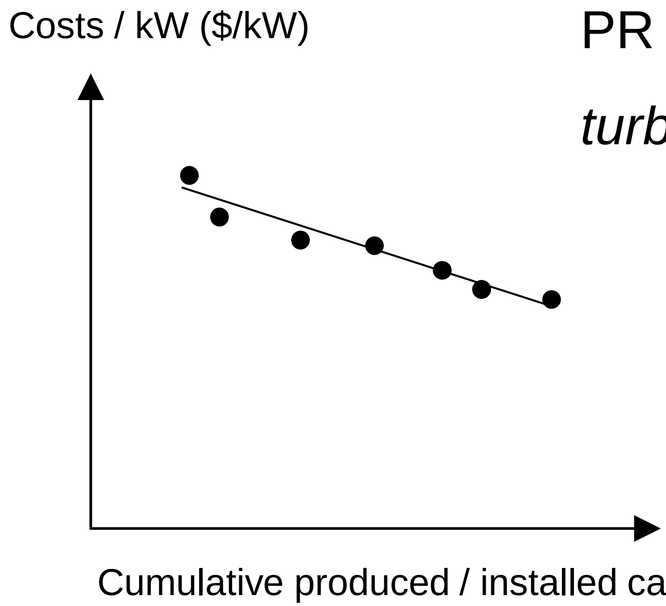
Turbines have different sizes with different capacities

⇒ Cumulative production in kW, not in number of turbines

⇒ Measurement in costs/kW, not per turbine

1. Types of experience curves

Type I The costs of wind turbines (per kW) vs. the cumulative number of kW installed

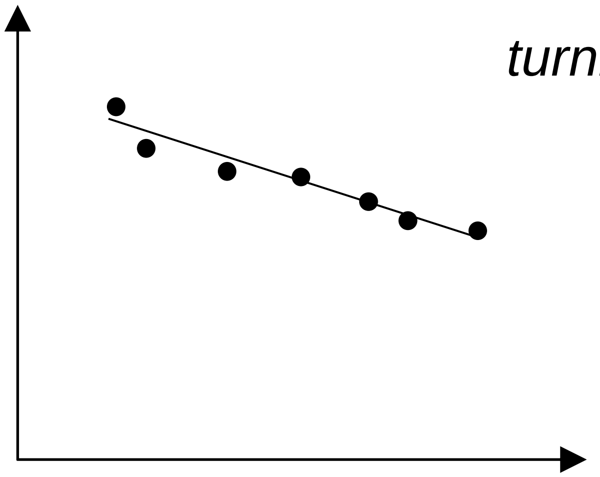


PR depends on *turbine investment* costs:

- Rotor blades
- Gearbox
- Generator
- Transformer
- Nacelle
- Tower

1. Types of experience curves

Type II The costs of wind farms (per kW) vs. the cumulative number of kW installed



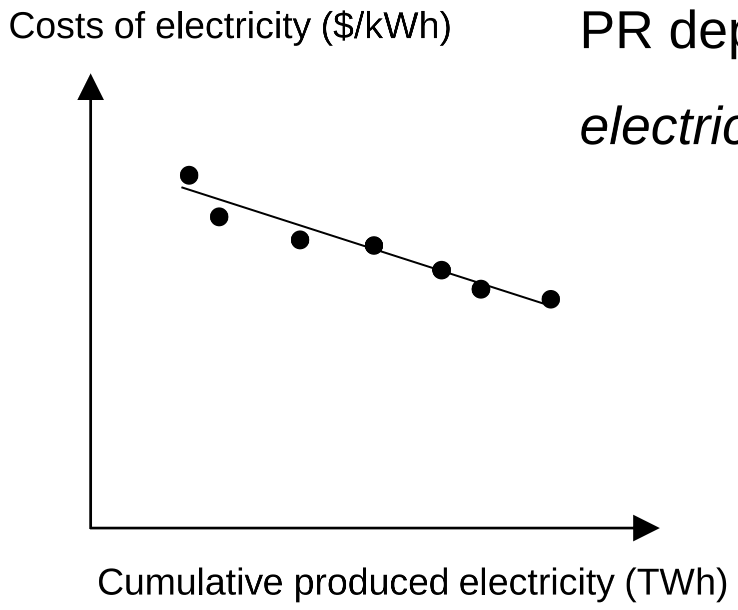
PR depends on

turnkey investment costs

- Turbine costs (and thus all factors mentioned for type I)
- Foundation costs
- Grid connection costs
- Overhead costs

1. Types of experience curves

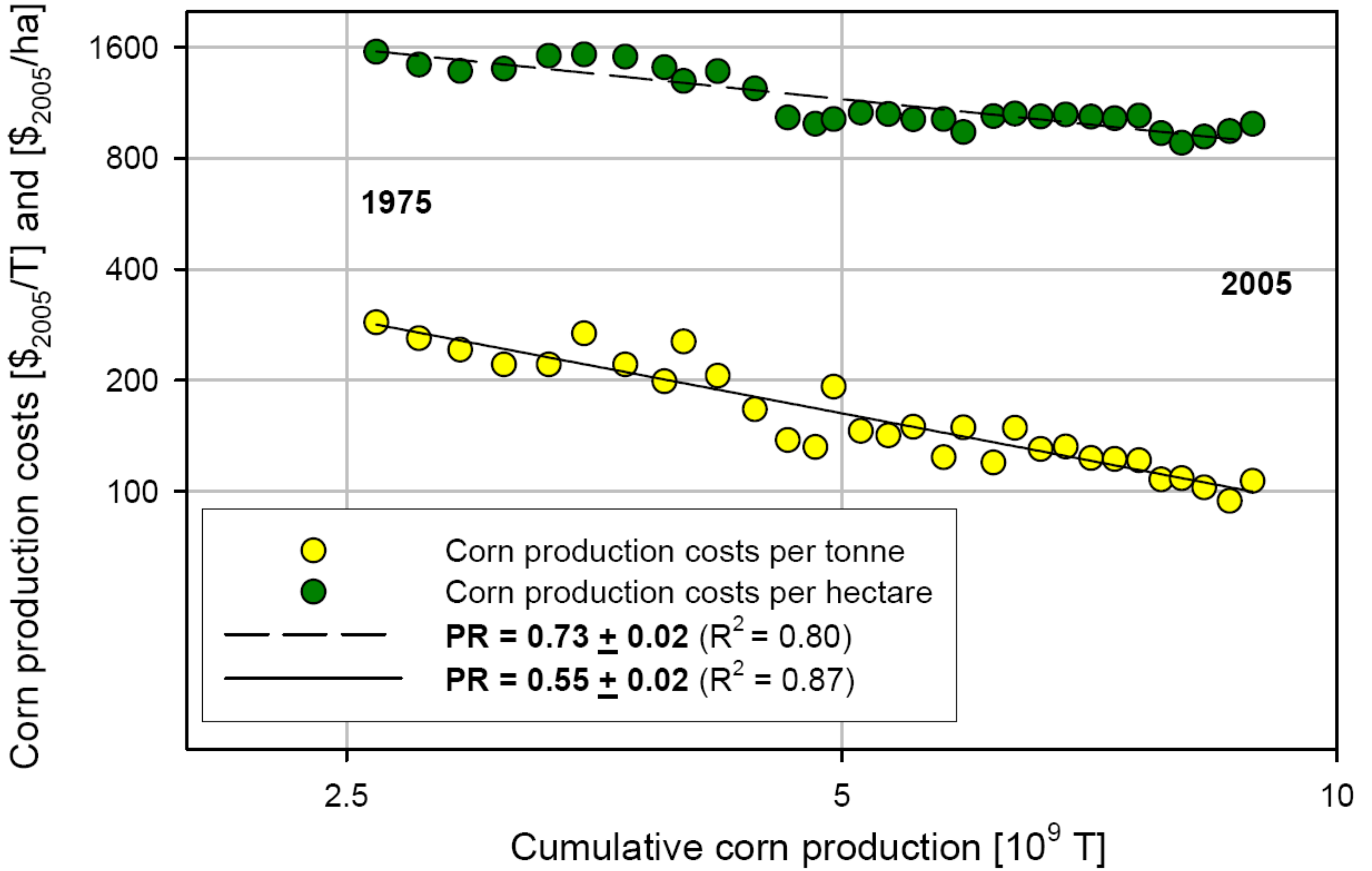
Type III The costs per kWh vs. the cumulative number of kWh produced



PR depends on *electricity production costs*

- Investment costs (and thus all factors mentioned for types I and II)
- Interest rate and economic lifetime
- O&M costs
- Siting / average wind speed
- Availability / load factor

Experience curves for corn production in the US per tonne and per hectare



Source: Hettinga , 2007, UU

1. Types of experience curves

Conclusions

- Progress ratios of experience curves measuring different performances cannot simply be compared with each other.

- For the example of wind energy, experience curves for electricity depend on more variables/factors than experience curves for capacity.

Limitations and pitfalls of using experience curves

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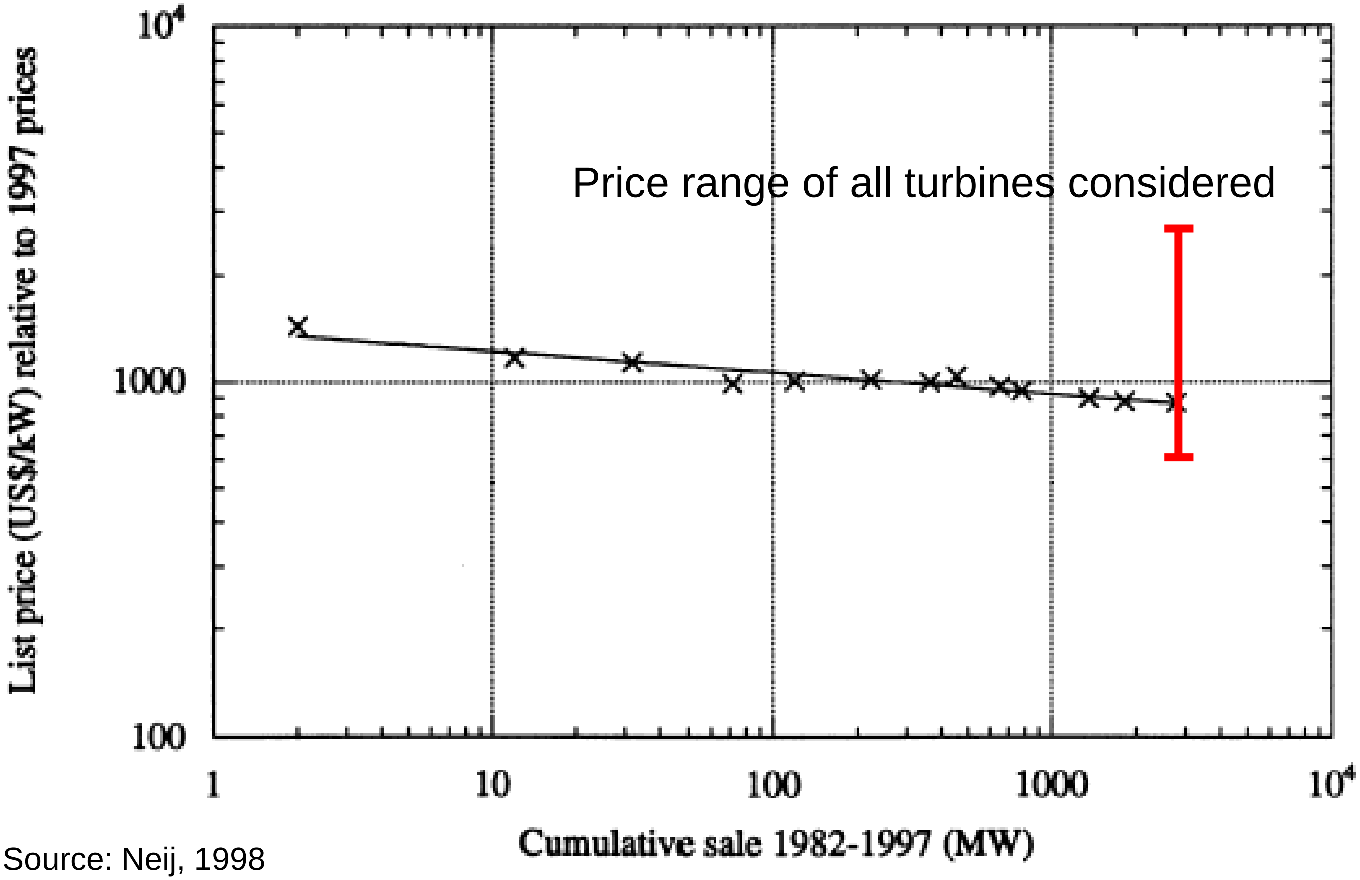
5. Impact of raw material costs and production scale (wind/PV)
6. Negative learning? The case of nuclear energy

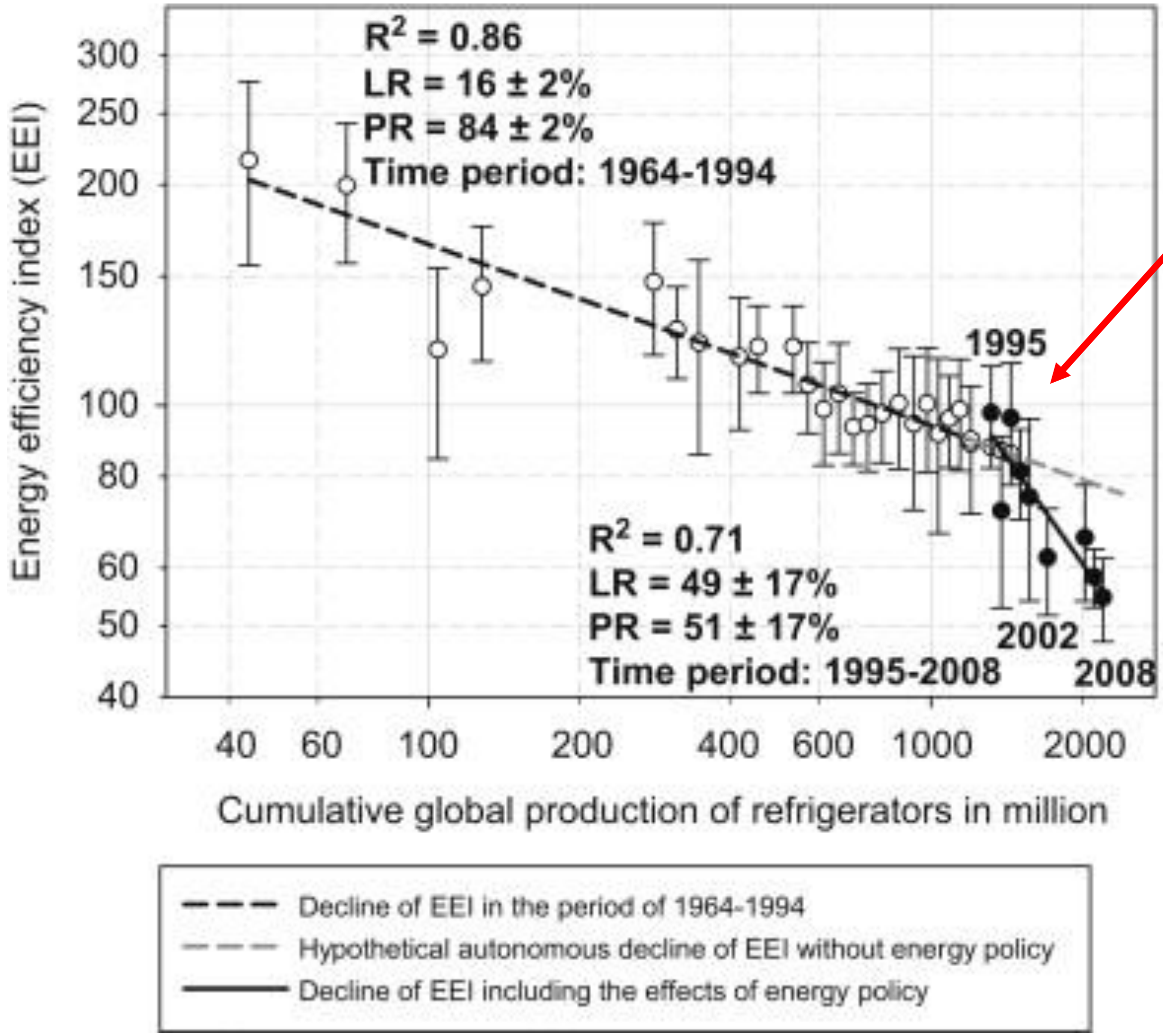
2. Data uncertainty

Experience curve for Danish produced wind turbines of 4 major manufacturers



Source: Neij, 1998

2. Data uncertainty



1996: EU Directive 96/57/CE on energy efficiency requirements for cold appliances

Always check effect on R^2

Source: Weiss, 2009

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2. Data uncertainty

Conclusions

- Average cost data is required to devise experience curves, cost ranges are often significant
- PR may have changed because of new context (e.g. new policy)
- Only assume a change in the PR when there are arguments to support this change and the fit of the new curve is significantly better than the old one

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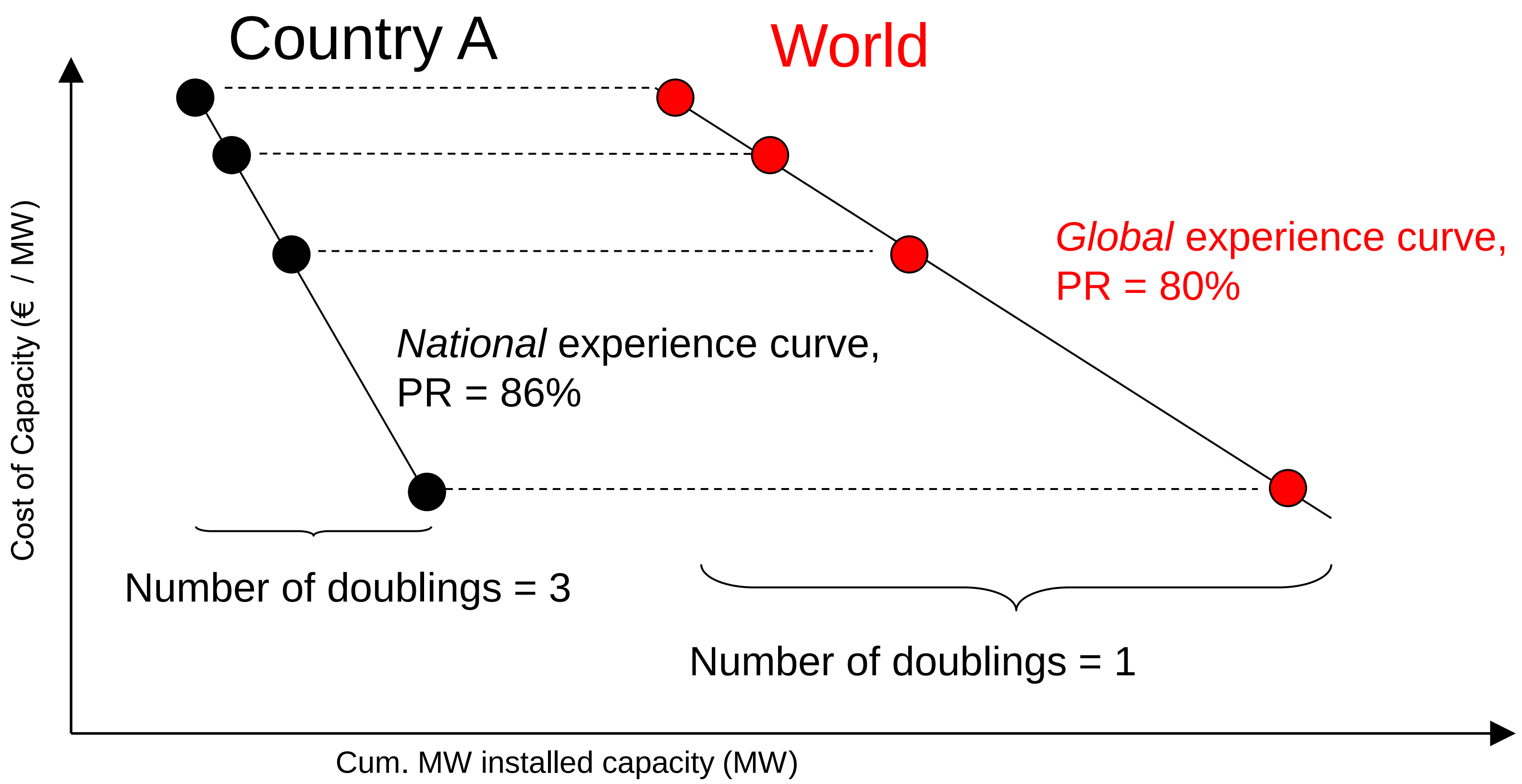
3. System boundaries

Choosing different system boundaries may result in different PRs:



3. System boundaries

Conclusions

- When looking at a ‘partial’ market, the PR is not only determined by the global drop of cost, but also by the cumulative production / installation speed in the selected market relative to the global speed.

- Choosing system boundaries should take into account how the global market is built up.

Limitations and pitfalls of using experience curves

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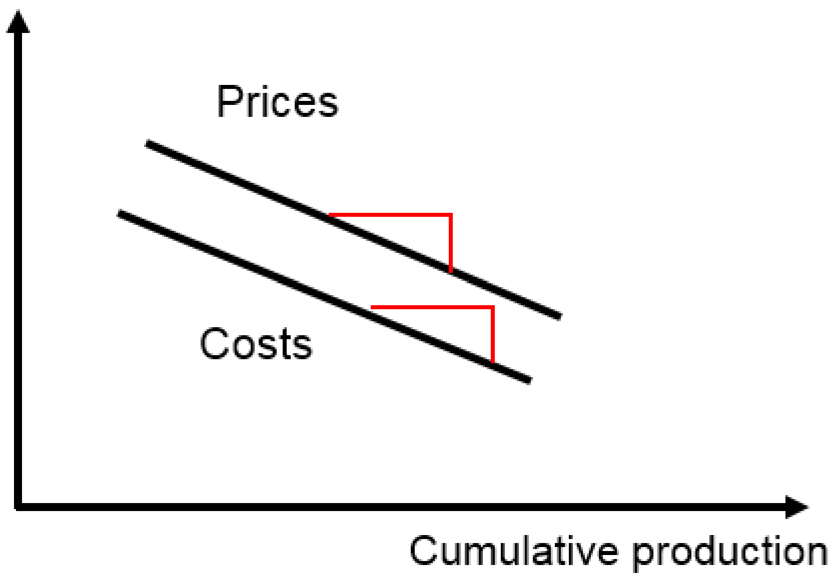
4. Market based differences

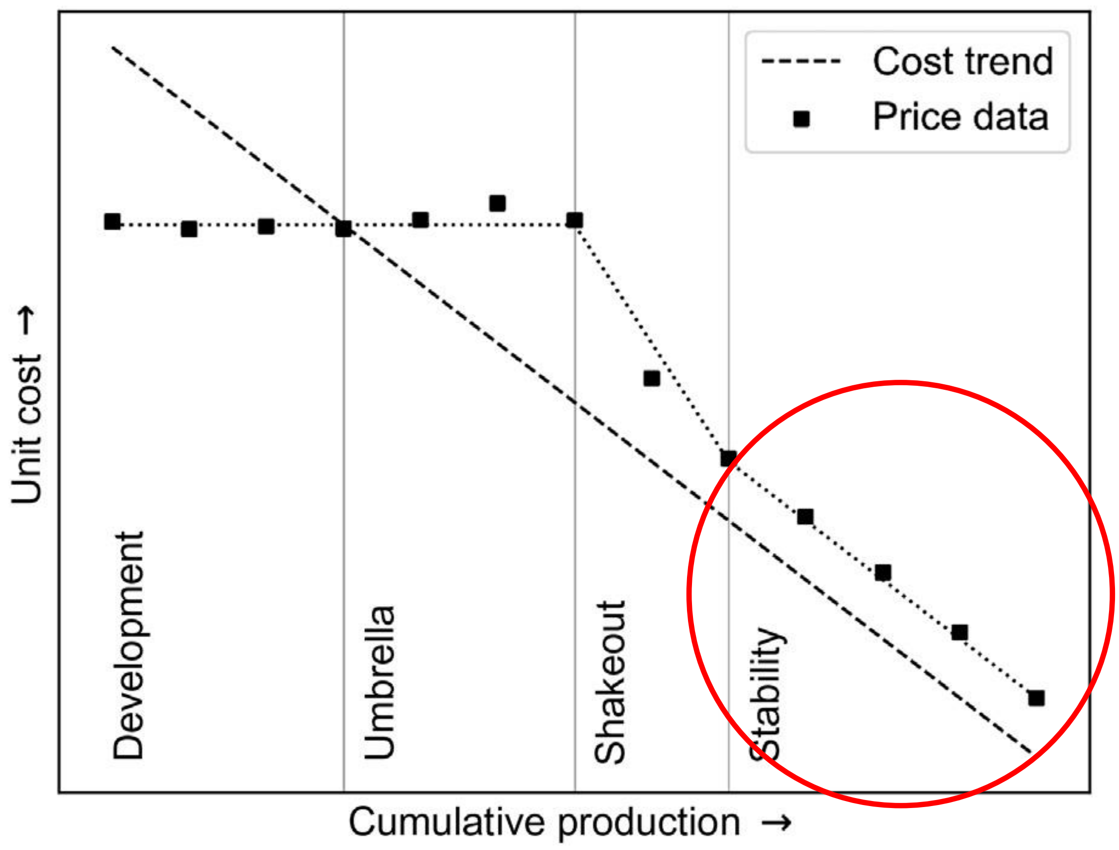
Experience curves should ideally be based on COSTS

However, due to data availability, they are often based on PRICES

Ideally, in a competitive market progress ratios are the same.



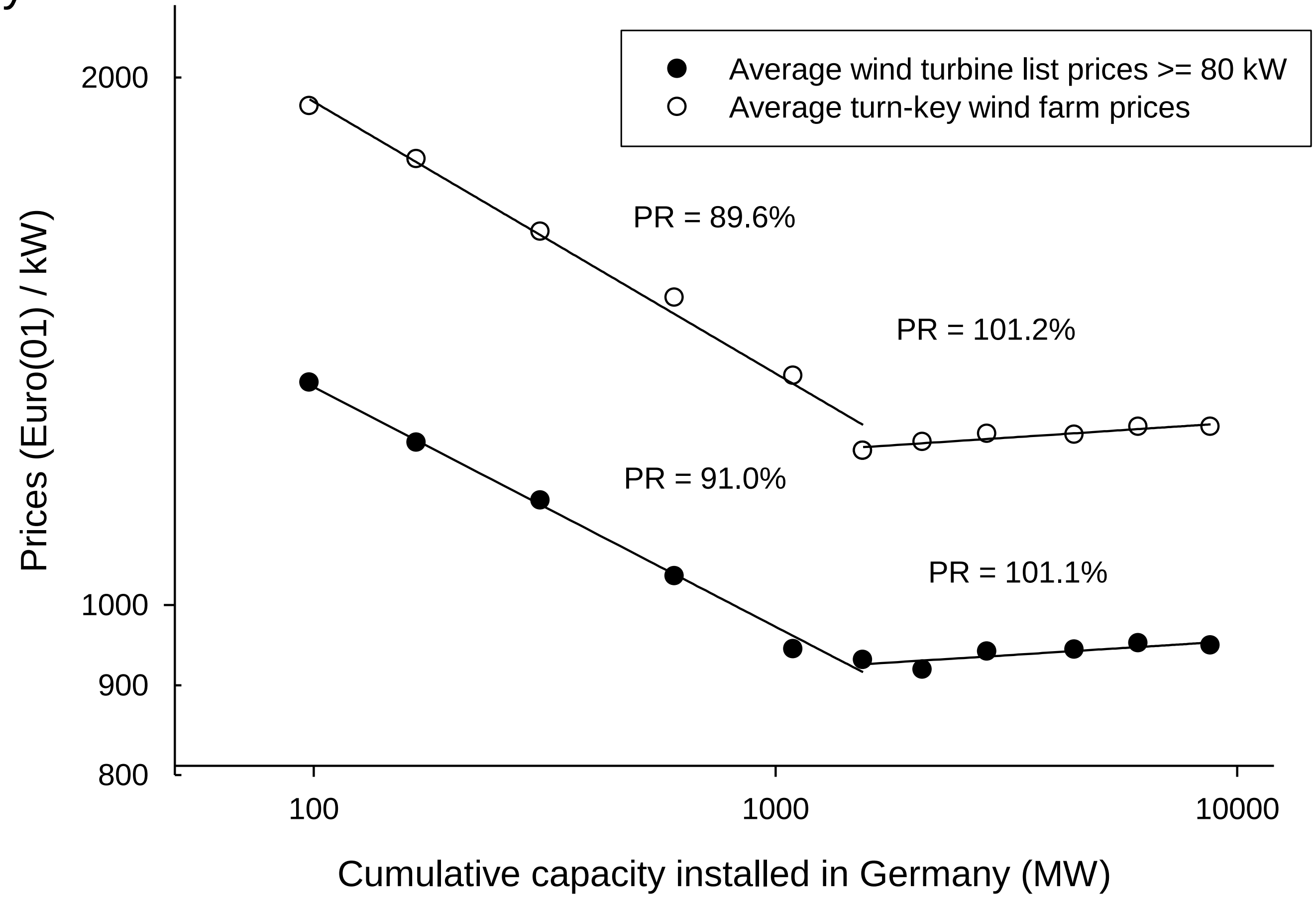
4. Market based differences



Source: Junginger & Louwen, 2020

4. Market based differences

Experience curves of wind farms and wind turbines 1991-2001 - The case of Germany



4. Market based differences

Conclusions

- The use of prices for the construction of learning curves may not represent the ‘real’ learning rate.
- Price may remain constant or even increase if demand increases strongly (e.g. caused by policy support measures) → data not suitable to measure technological learning.
- National experience curves may not be representative for the global market.

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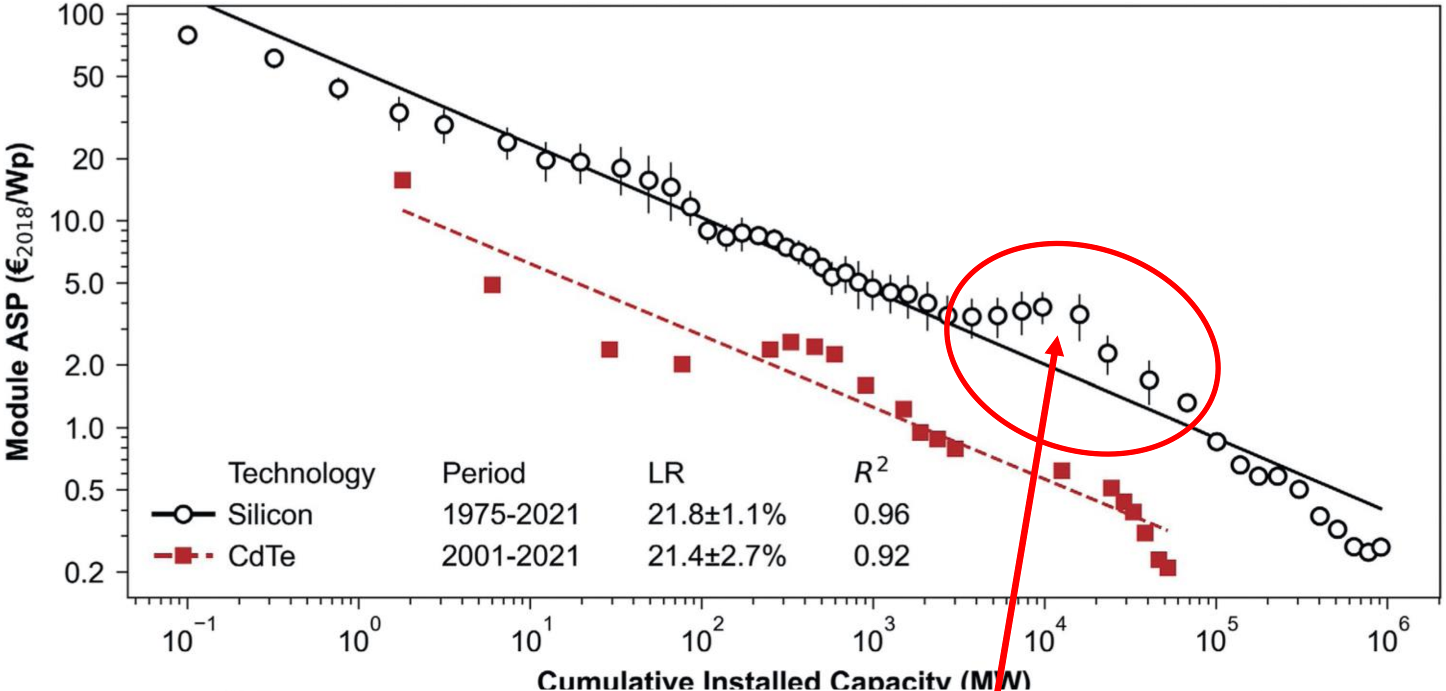
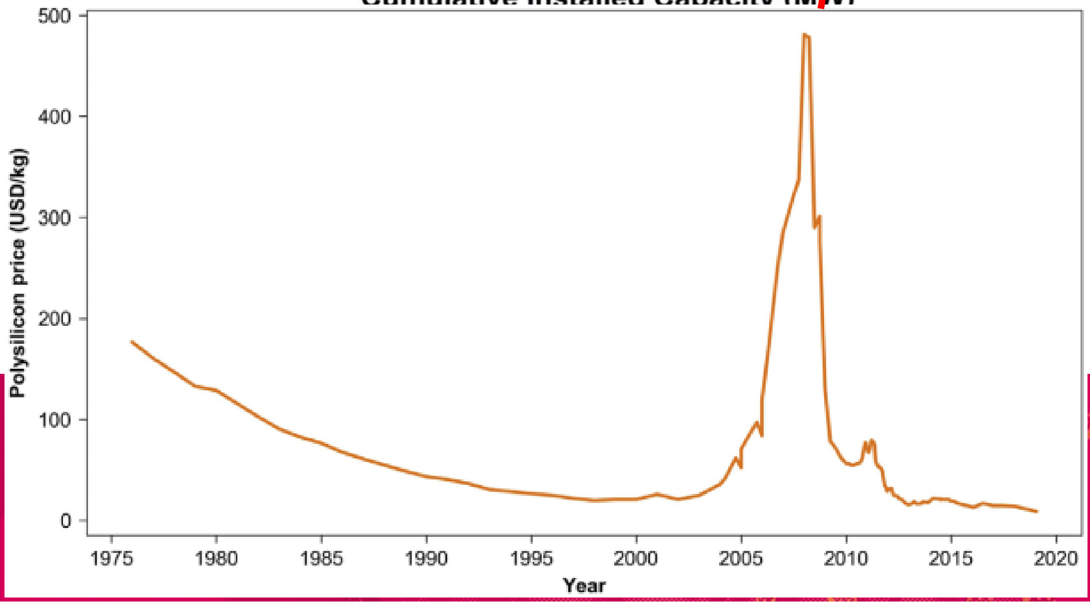
5. Impact of raw material costs & production scale



Experience curves for ASP of silicon and CdTe-based PV modules

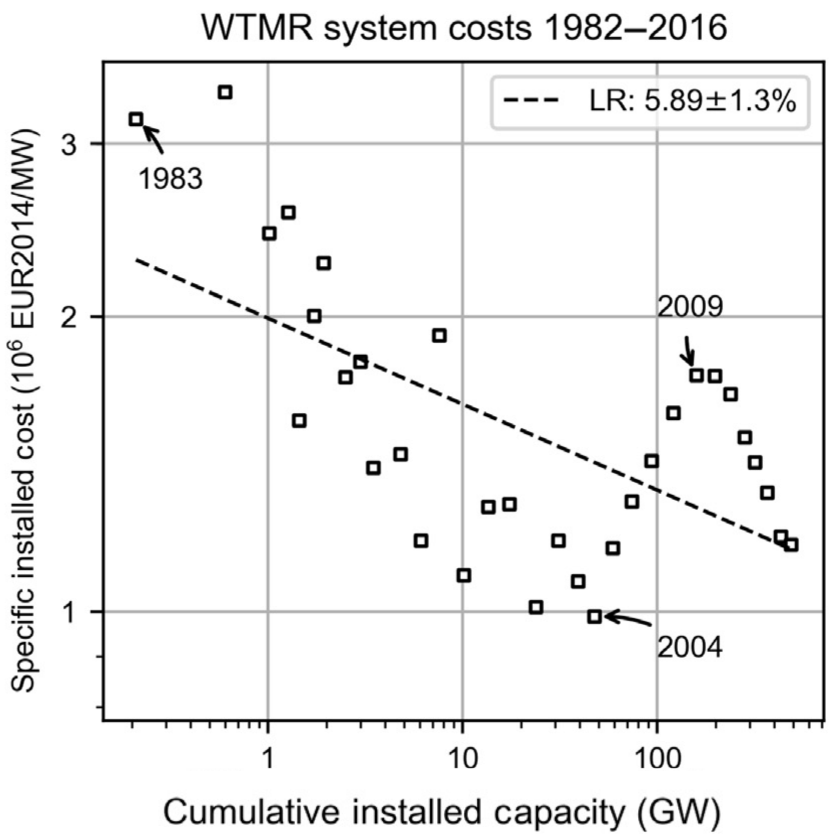
Source: Louwen et al, (2021)



Source: Junginger & Louwen (2020)

5. Impact of raw material costs & production scale

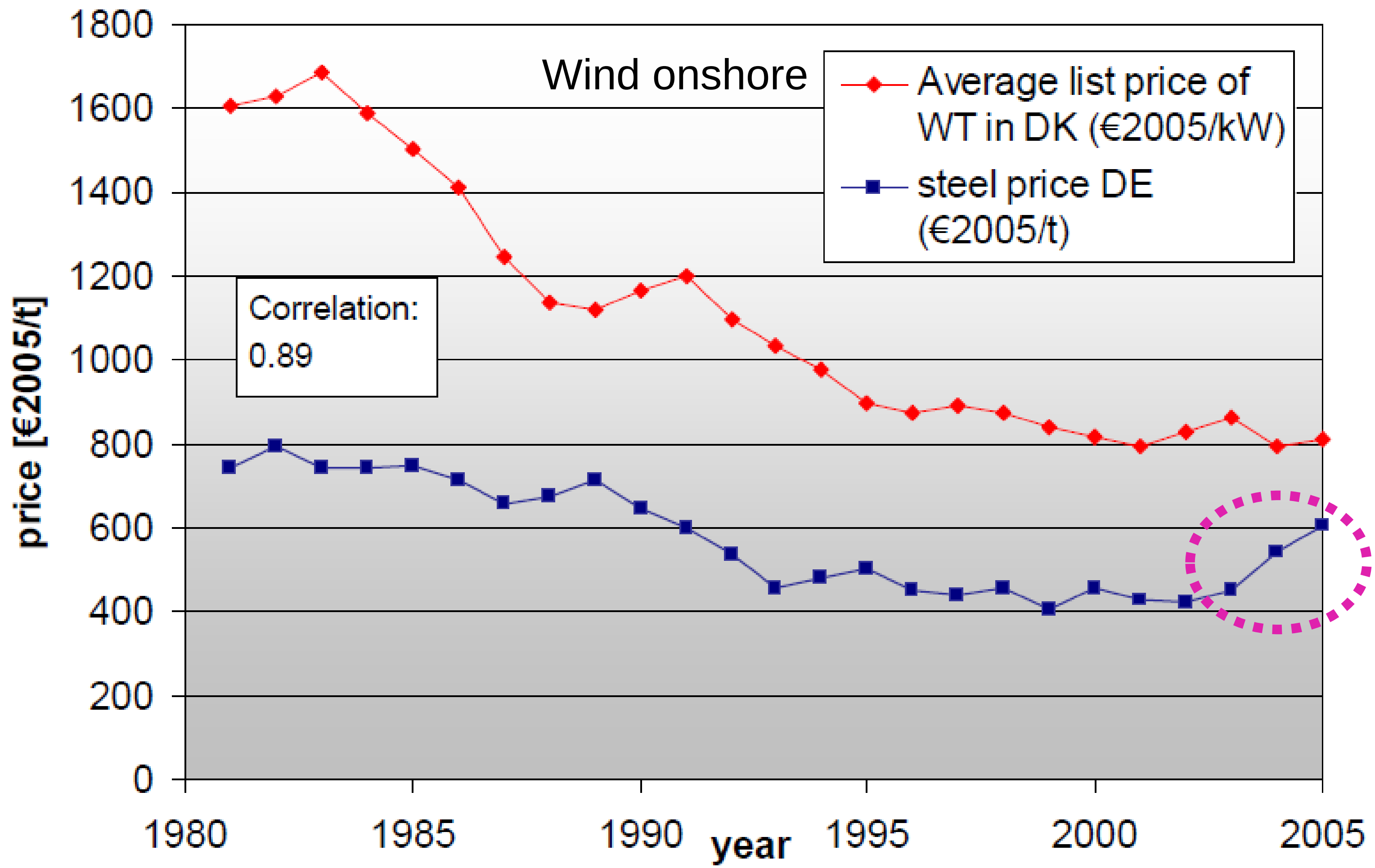
Onshore wind energy



Overview of onshore system and turbine price data and experience curves

Source: Wiser and Bolinger (2017)

5. Impact of raw material costs & production scale



Source: Folz, 2008

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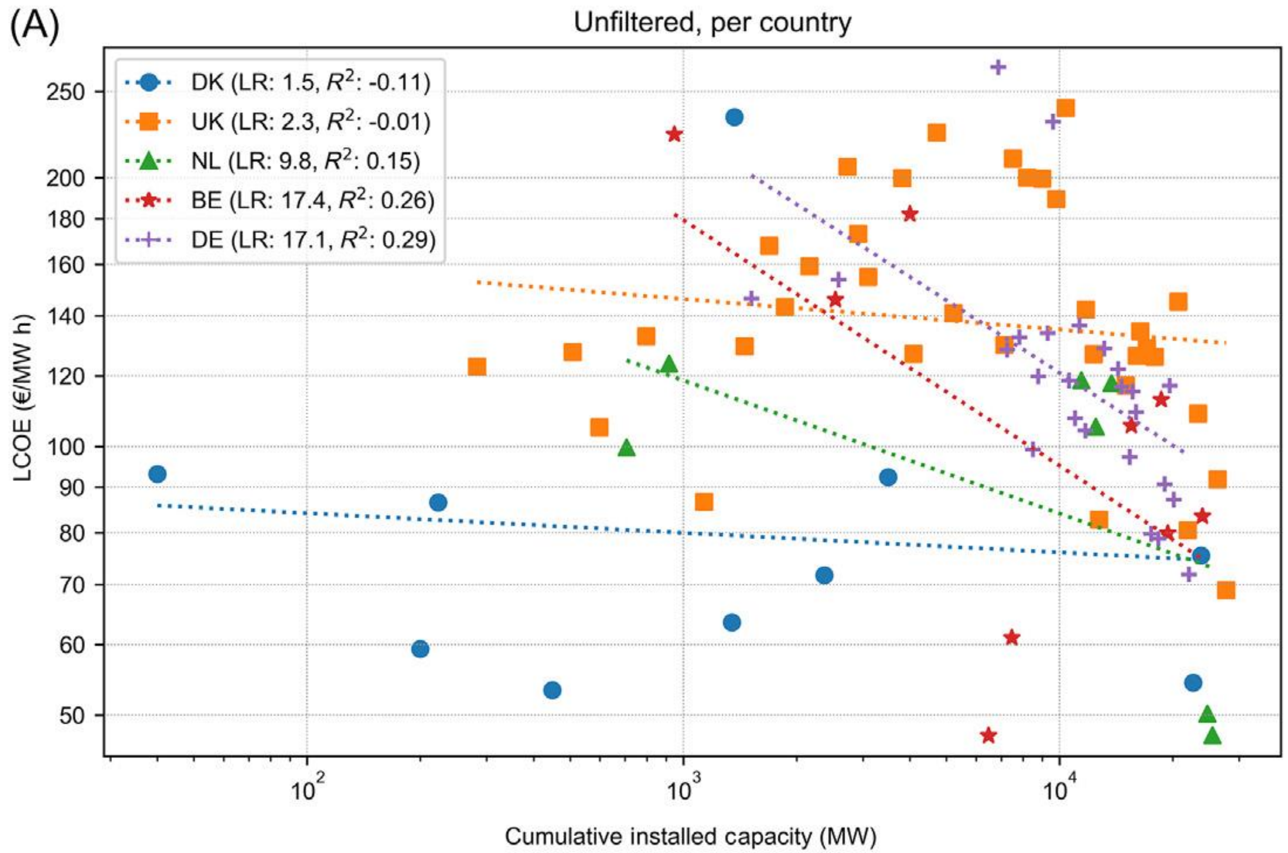
5. Impact of raw material costs & production scale

offshore wind energy



Levelized cost of electricity (LCOE) for individual offshore wind farm in Denmark, the United Kingdom, the Netherlands, Belgium, and Germany

Source: Junginger & Louwen (2020)

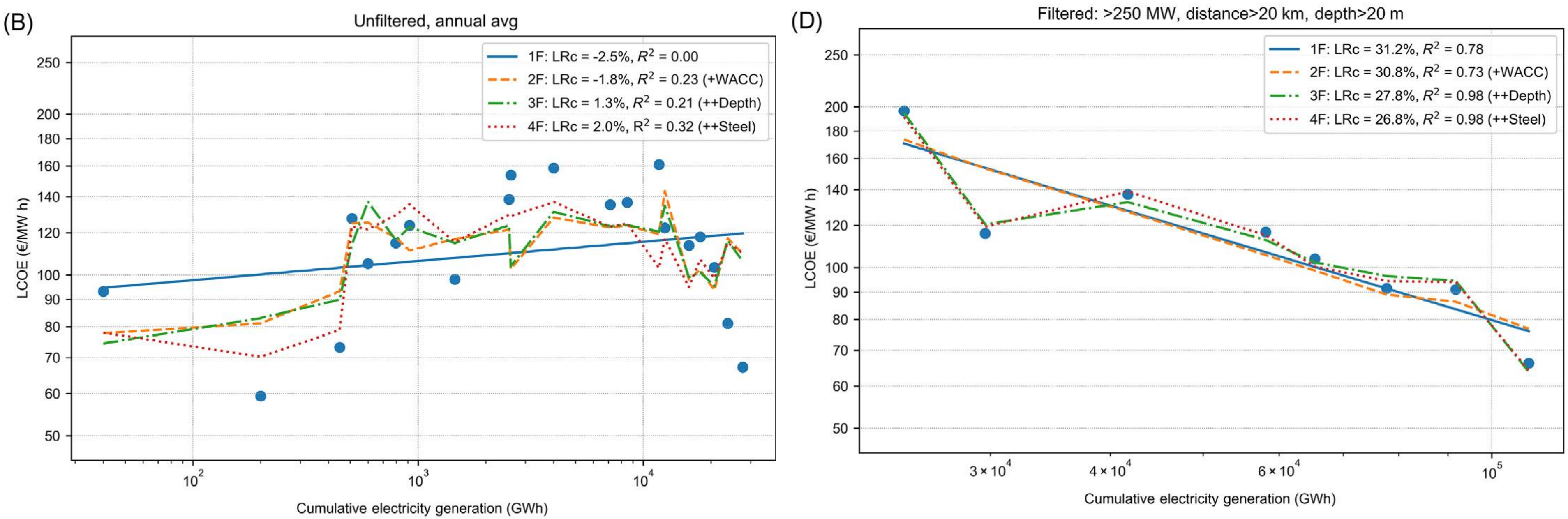
5. Impact of raw material costs & production scale

Average distance from port and water depth in commissioned offshore wind projects, 2001-18

Source: IRENA, 2019. Renewable Power Generation Costs in 2018.

5. Impact of raw material costs & production scale

offshore wind energy



Average annual levelized cost of electricity (LCOE) for individual offshore wind farm in Denmark, the United Kingdom, the Netherlands, Belgium, and Germany (B) unfiltered, and (D) filtered

Source: Junginger & Louwen (2020)

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5. Impact of raw material costs & production scale

Several factors caused increase of prices:

- Higher material costs (wind, PV)
- Strong increase market demand induced by support policies (wind, PV)
- Large differences in farm/system size (wind offshore, PV), water depth, distance to shore (wind offshore)

Source: Junginger & Louwen (2020)

Limitations and pitfalls of using experience curves

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4. Using prices and involved difficulties
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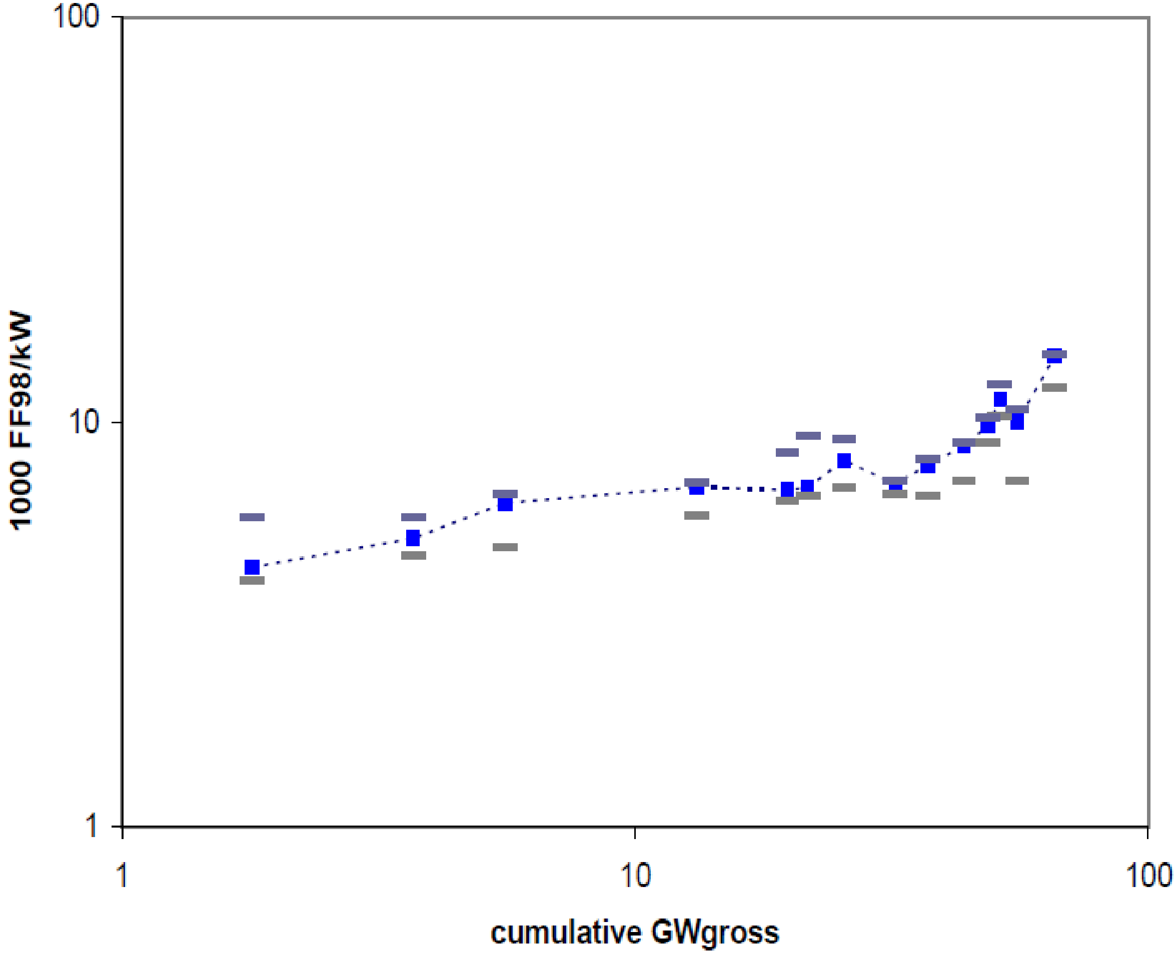
6. Negative learning? The case of nuclear energy

6. Negative learning? The case of nuclear power



Source: Grübler, 2009

6. Negative learning? The case of nuclear power

- Suggested factors driving up the investment costs for nuclear power plants
  - Increasing safety demands (also before Chernobyl) by regulators
  - Increasing interest rates (especially in the 1980's)
  - Increasing complexity of the design

Source: Grübler, 2009

- The case of nuclear power plants is the only energy technology (known to me) where the (one-factor) experience curve approach seems not to be applicable (and where total costs have not declined)

Summary of main findings

- The experience curve seems applicable for (almost) all energy technologies – also costs and efficiency of (several) energy demand technologies costs

- No structural trend was identified that PRs change over time or with increasing market diffusion

- Experience curve extrapolation has some advantages compared to bottom-up studies, but cost projections may be more uncertain due to strong sensitivity to PR.

Limitations of experience curves

- (One-factor) experience curve theory appears *not* to include the effects of increasing raw material costs, at least not on the short term
- Experience curve theory does also *not* account for limitations related to geographical constraints (relevant for e.g. wind, hydro, and biomass)
- Experience curves allow to project production costs; but they do *not* allow to forecast the development of market prices.

Final conclusions

- Experience curves are a useful tool to get indications on the possible cost reduction potential of a (renewable energy) technology

- However, estimation of progress ratios is not a trivial task, and great care must be applied before historical curves can be extrapolated into the future.

- Great care must also be applied when comparing progress ratios, be it between different regions, different types of experience curves or different technologies.

Tomorrow practical

- Requires (basic) knowledge of integrals
- For a refresher see: https://www.ombplus.de/ombplus/link/Integr/Overvi
  - need to set up an account, free for UNIGE students
- Or use other sources
  - high school math books, youtube videos, …

- Calculating with growth rates, see next slide:

Determining Growth Rates in time series

- $$y = y_o\,(1+i)^n$$

with

i = growth rate (e.g. interest rate)

n = number of years

$$\frac{y}{y_o} = (1+i)^n$$

$$i = \left(\frac{y}{y_o}\right)^{(1/n)} - 1$$

Logarithm Rules

$$\log_a xy = \log_a x + \log_a y$$

$$\log_a \frac{x}{y} = \log_a x - \log_a y$$

$$\log_a x^n = n \log_a x$$

$$\log_a b = \frac{\log_c b}{\log_c a}$$

$$\log_a b = \frac{1}{\log_b a}$$

The following can be derived from the above rules.

$$\log_a 1 = 0$$

$$\log_a a = 1$$

$$\log_a a^r = r$$

$$\log_a \frac{1}{b} = -\log_a b$$

$$\log_{\frac{1}{a}} b = -\log_a b$$

$$\log_a b \log_b c = \log_a c$$

$$\log_{a^m} a^n = \frac{n}{m}, m \neq 0$$

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