REFLEX Analysis of the European Energy System

Technological Learning in Energy Modelling
Implementation of Experience Curves

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Technological Learning

- Technological learning: technical and economic performance (cost) of technology increase as producers gain experience

- Technological learning is the combined effect of several learning mechanisms that occur in
  well-functioning industries:
  - Learning by doing
  - Learning by researching (R&D)
  - Scale
    - Of the individual product
    - Of the manufacturing plants

Technological Learning: Experience Curves and Learning Curves

- When examining production, and empirical relationship can be found between:
  - Cost
  - Cumulative production (experience)

- First described by e.g. Wright (1936):
  - Labor costs of producing airplanes dropped significantly as workers produced more of them
  - Percentage of reduction observed was constant for every doubling of cumulative airplanes produced

Learning curve vs Experience Curve

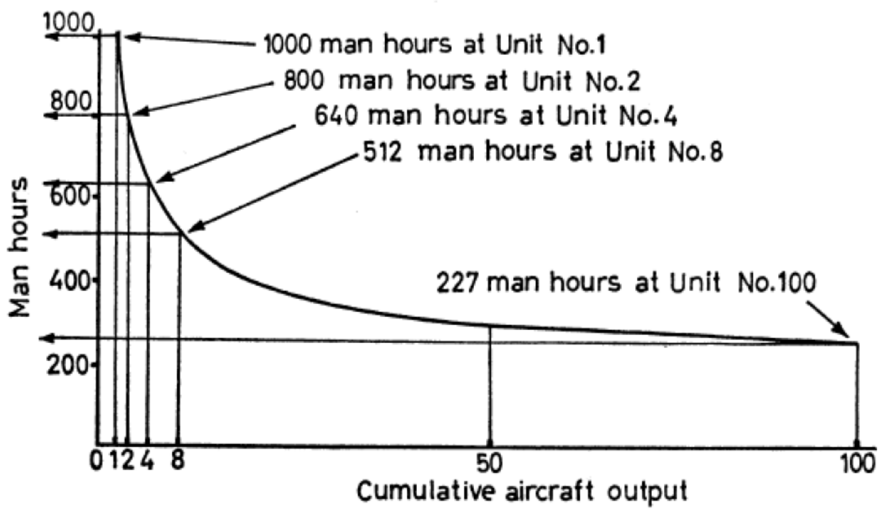
- In 1960's-1970's concept was expanded by Boston Consulting group
  - To include more parameters and describe total cost of a product
  - To look at whole industries, rather that learning in a single company

- **Learning curve**: Wright example → unit labor costs within company

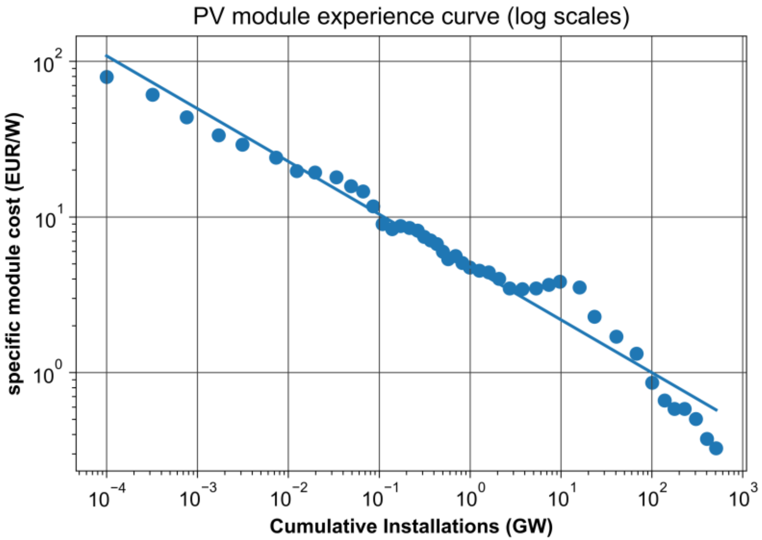
- **Experience curve**: BCG example → total costs of product in whole (global) industry

Example of learning and experience curves

Learning Curve



Experience Curve

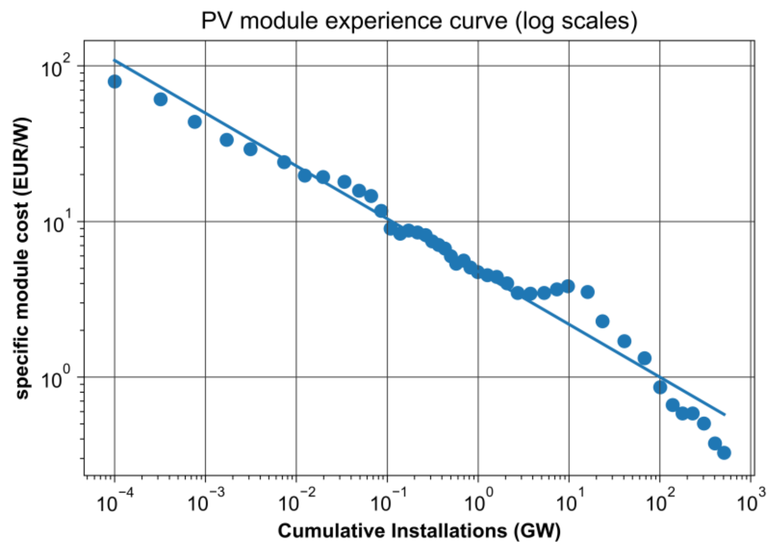


The Experience Curve

- General experience curve equation: $C(n) = A \cdot x^b$
- Or, more commonly: $C(n) = C_1 \cdot n^{\log_2(1-LR)}$
- Gives cost $\boldsymbol{C}$ as a function of cumulative production $\boldsymbol{n}$
- $\boldsymbol{C_0}$ is the cost of the first unit of production
- $\boldsymbol{LR}$ is the ***learning rate***, $(1 - LR)$ is the progress ratio $\boldsymbol{PR}$
- For every doubling of cumulative production, costs decline with $\boldsymbol{LR}$
- Typically, learning rates are between 10-30%

How to derive the experience curve

- To determine an experience curve, we gather empirical data:
  - Cost developments of a technology
  - Developments of cumulative production
- E.g. for PV we gather data on
  - Costs (in EUR/W) of either PV systems, modules, or other components (dependent variable - y-axis)
  - Cumulative installations of PV systems (independent variable - x-axis)
- By performing a regression we determine the values of the curve parameters



The value of experience curves

- Costs are key driver of technology uptake, but estimating ***future costs*** is of course ***difficult***

- Although based on ***historical*** data, experience curves are one of few methods that
  - Allow for evidence-based cost projections,
  - By giving ***empirical relation*** between production experience and cost developments

- Experience curves offer a mathematical function that allow for extrapolation / estimation of
  future technology cost

- As opposed to exogenous (e.g. time based) estimations of these developments

Experience Curves in Energy Modelling

- Modelling of low-cost, low-CO_2 pathways to future energy systems

- Models have a large portfolio of available technologies

- And need to make good investment decisions between these technologies

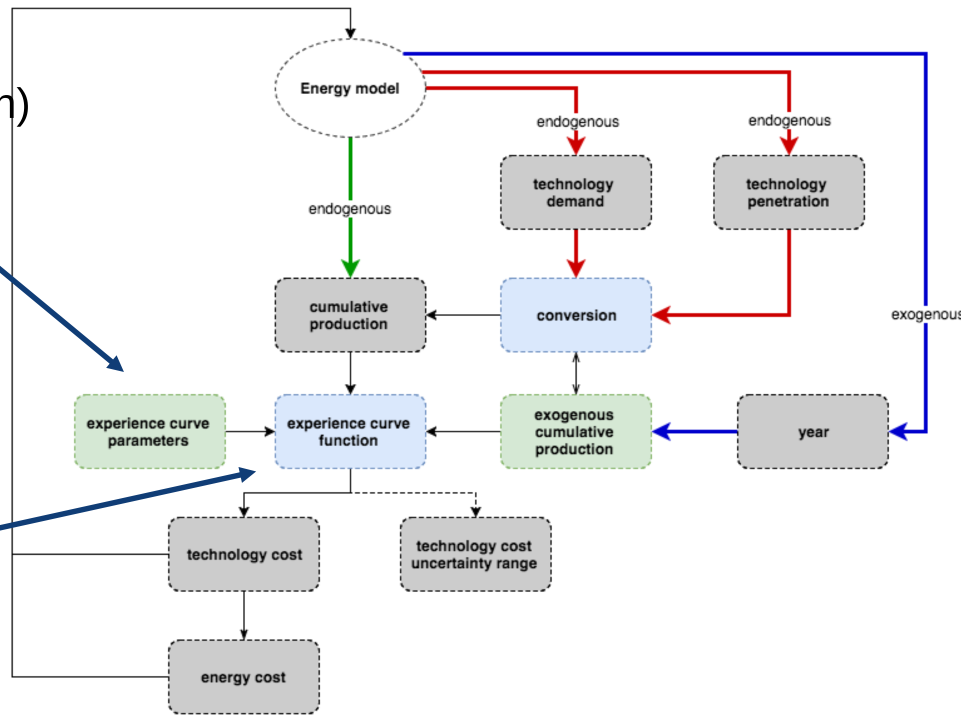
- With experience curves, models can derive future cost trajectories
  - Endogenously: feedback between model and technology costs ***within model***
  - Exogenously: technology cost determined ***outside of the model***

- This gives one of few methods to consider relation between cumulative capacities and cost reductions

Experience Curve Model Implementation - Overview

Empircal data on n (cumulative production) and C (cost)

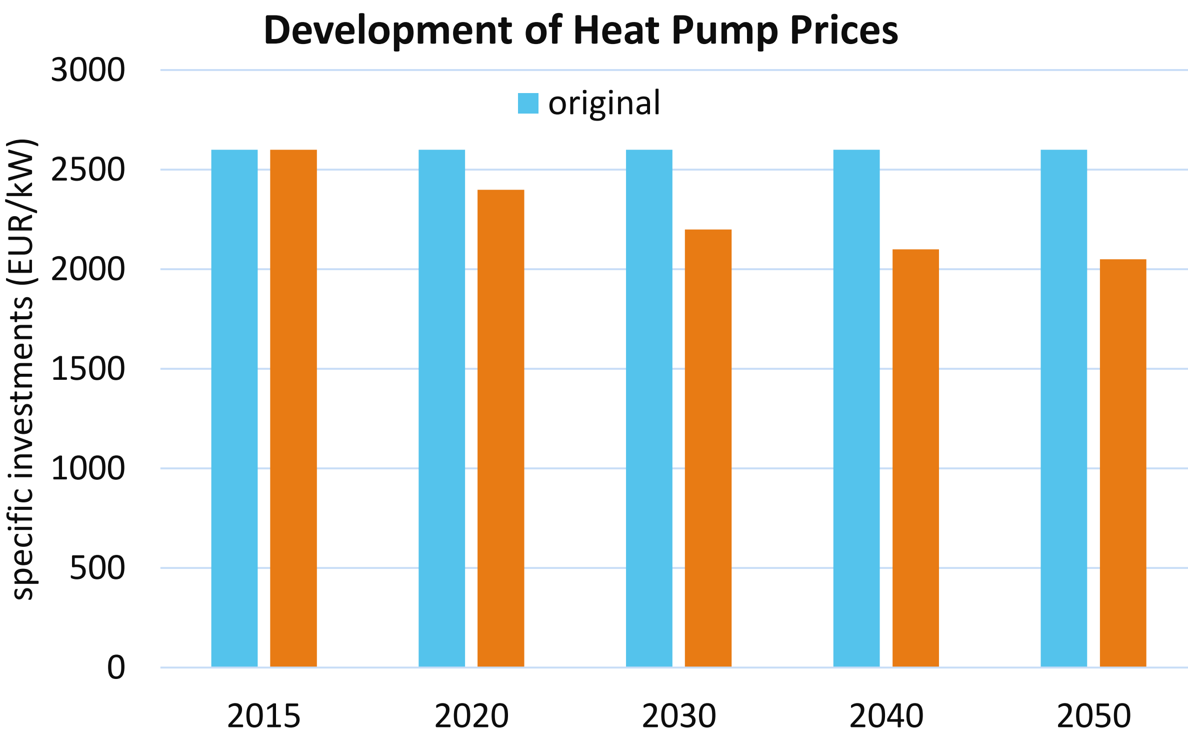
$$C(n) = A \cdot n^b$$



Key technologies investigated within REFLEX models

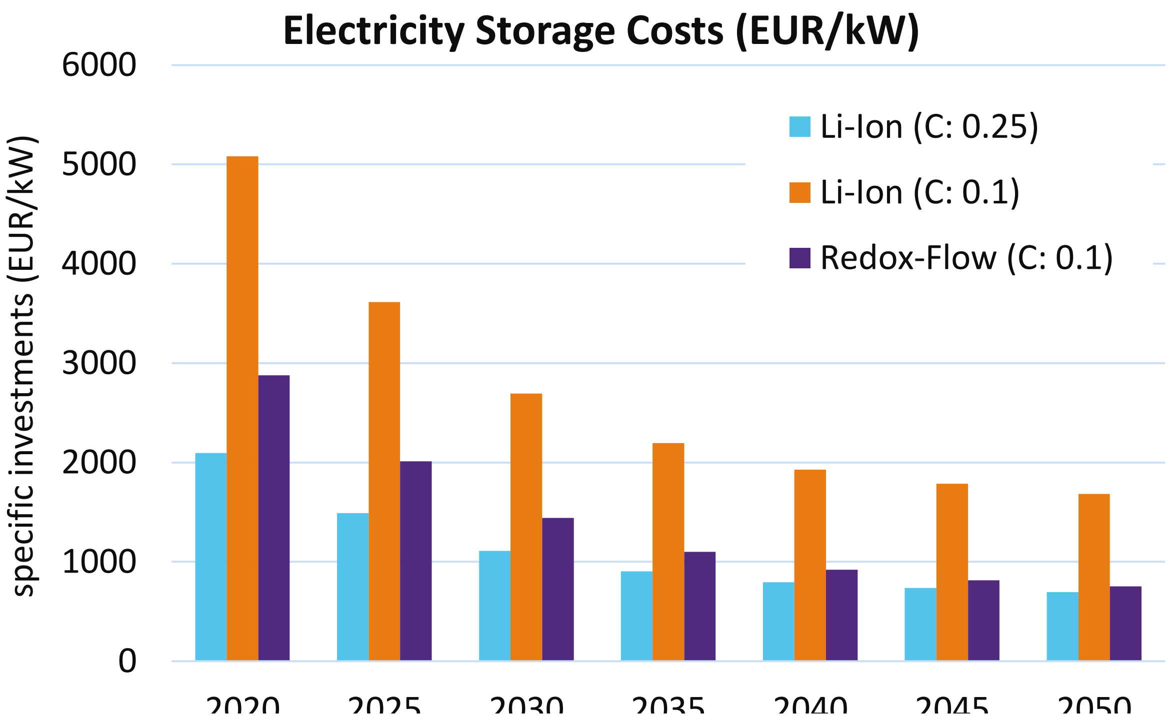
- CCS post-combustion for electricity generation
- Energy storage:
  - Residential Li-Ion batteries
  - Utility scale Li-Ion batteries
  - Utility scale Redox-Flow batteries
- Electric vehicles
  - Li-ion battery packs
  - FCEV fuel cell stacks
- Electricity demand technologies
  - Heat pumps
  - Alkaline electrolysis / Power-to-H2

Key results from the REFLEX project



Steffi Schreiber, Christoph Zöphel, Christoph Fraunholz, Dr. Andrea Herbst, Dr. Tobias Fleiter, Dr. Ulrich Reiter (2019). Experience Curves in Energy Models – Lessons Learned from the Reflex project.

Key results from the REFLEX project



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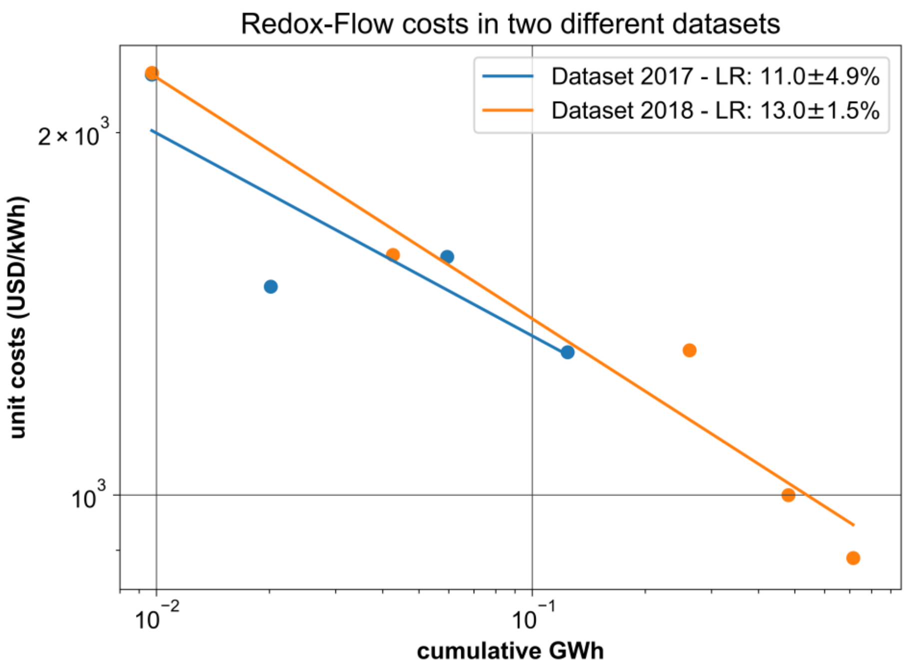
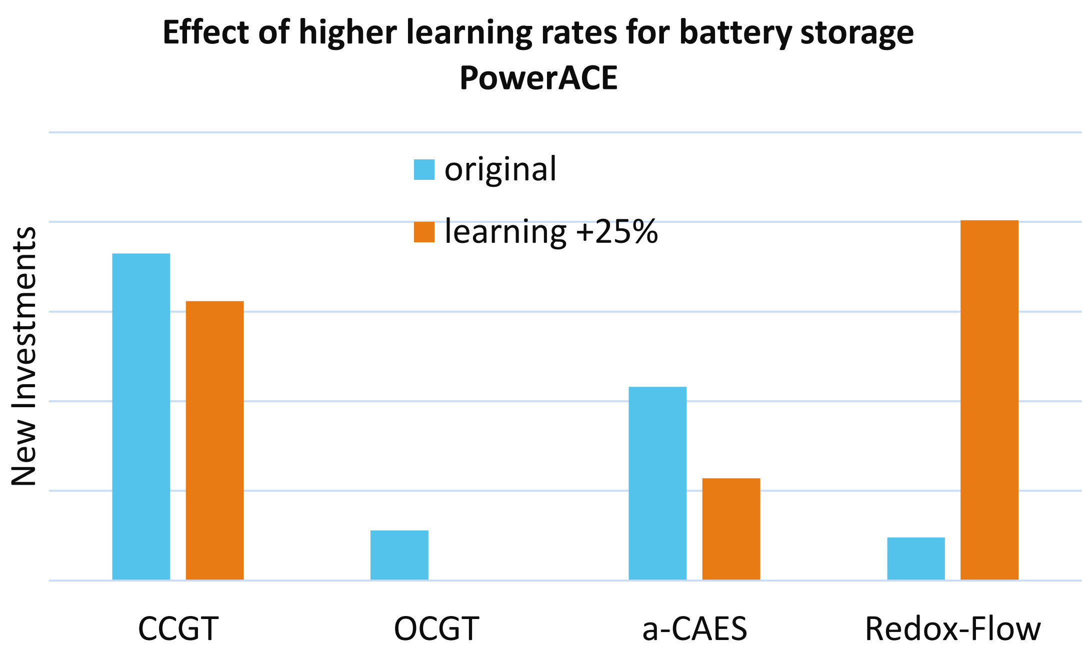
Uncertainty in Experience Curves



- Especially for newer technologies, datasets are often still quite limited
- With low amount of datapoints, uncertainty is generally high
- As datasets are updated/improved, parameter values can change and uncertainty generally decreases

Effect of uncertainty of experience curve parameters



- Due to higher learning rate for batteries new investments shift across the model
- Not only competing storages are affecting each other

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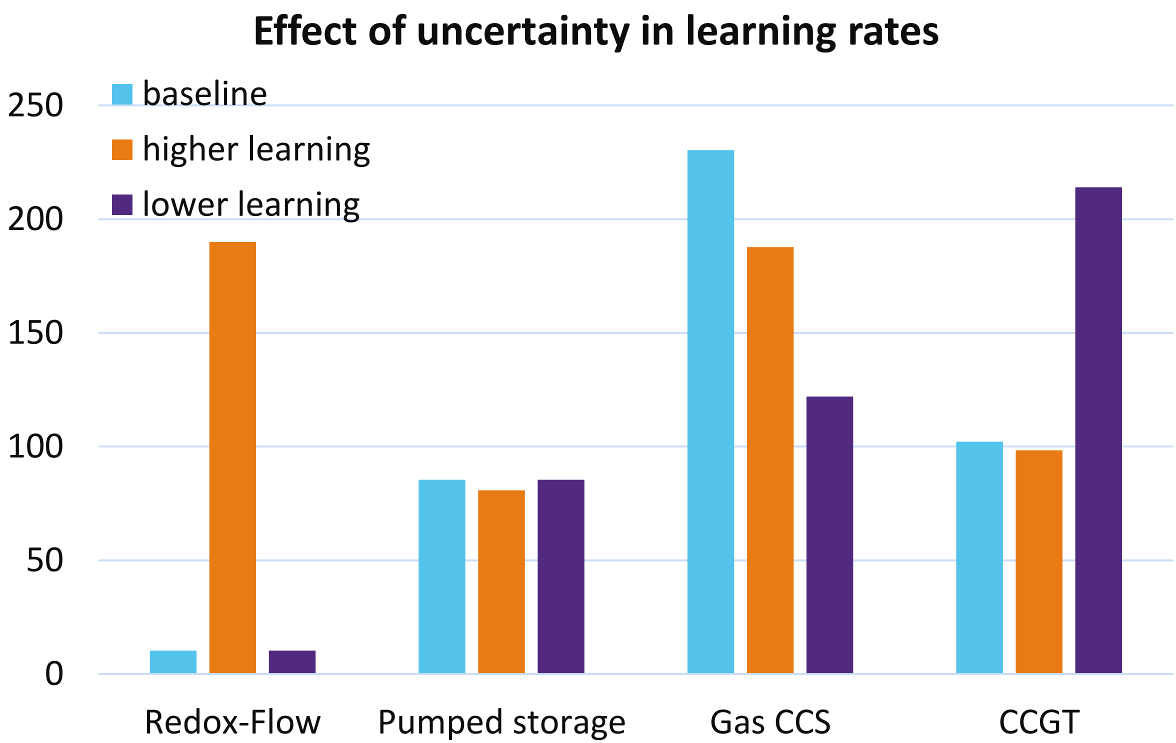

- Higher learning rates shift investments to redox-flow
- Lower learning rates shift investments to CCGT
- Effects only apparent for years 2040-2050

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Some key issues with model implementation of experience curves

- Global vs local models

- Spillover effects

- Lack of data for key technologies
  CCS is especially a problem > no/little empirical data

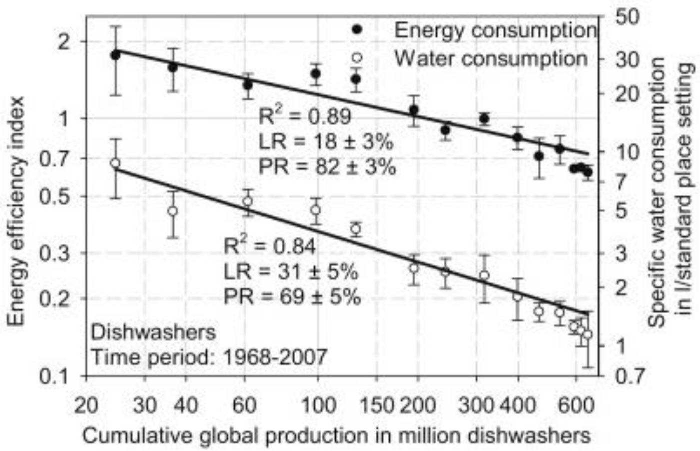
- Mathematics of models vs experience curves power law
  Implementation leads to issues with non-convexity: no optimal solution in optimization models (local maxima, multiple global equilibria)

- Deployment constrained by model targets (e.g. renewables penetration)

Further applications of experience curves in energy modelling

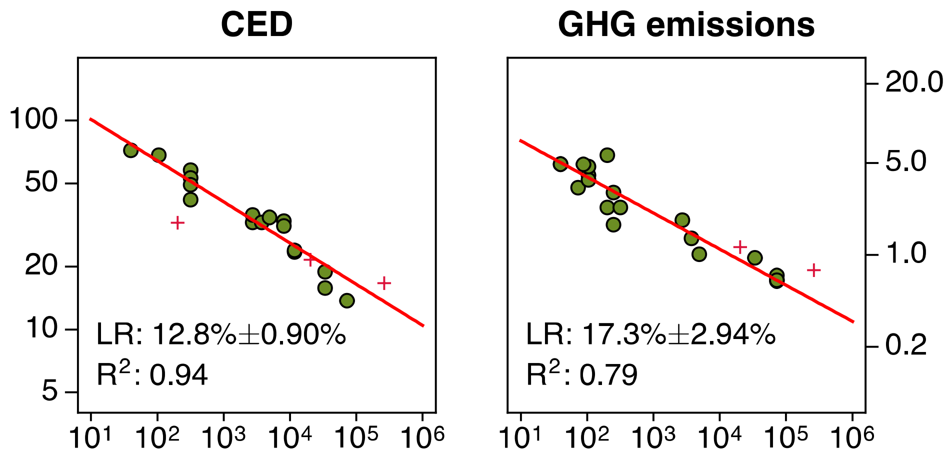
- Commonly, experience curve are applied for cost developments
- In more novel applications, experience curves can also be applied to environmental impact

Energy & Water Use of Dishwashers



Weiss et al, 2010 (10.1016/j.enpol.2009.10.022)

Energy Demand & GHG emission from PV production



Louwen et al, 2016 (10.1038/ncomms13728)

Summarizing

- Experience Curves were developed and implemented within REFLEX models
- Future costs developments are based on empirical data and relate technology cost to cumulative installations developments
- Uncertainty in experience curves that result e.g. from small datasets for new technologies can affect modelling results
- Future work on experience curves could include additional metrics in energy modelling

Thank you for you attention!

REflex
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European Energy System