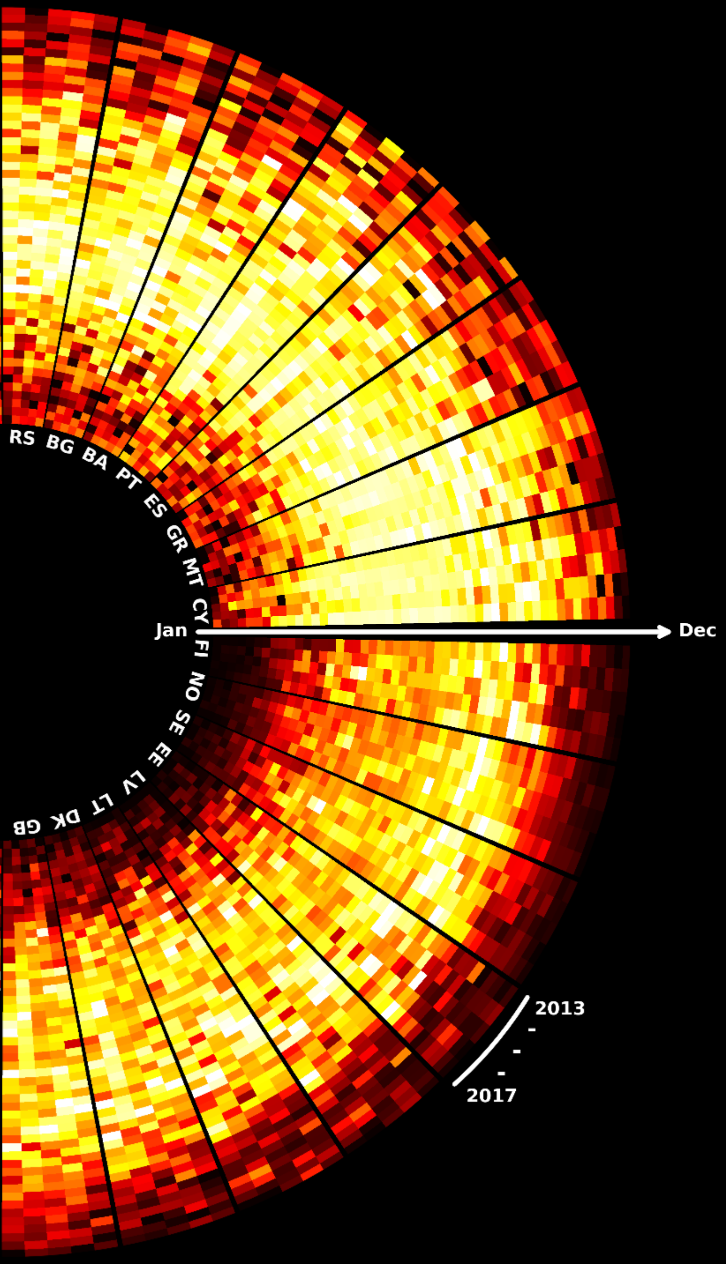


How does technology learn ?

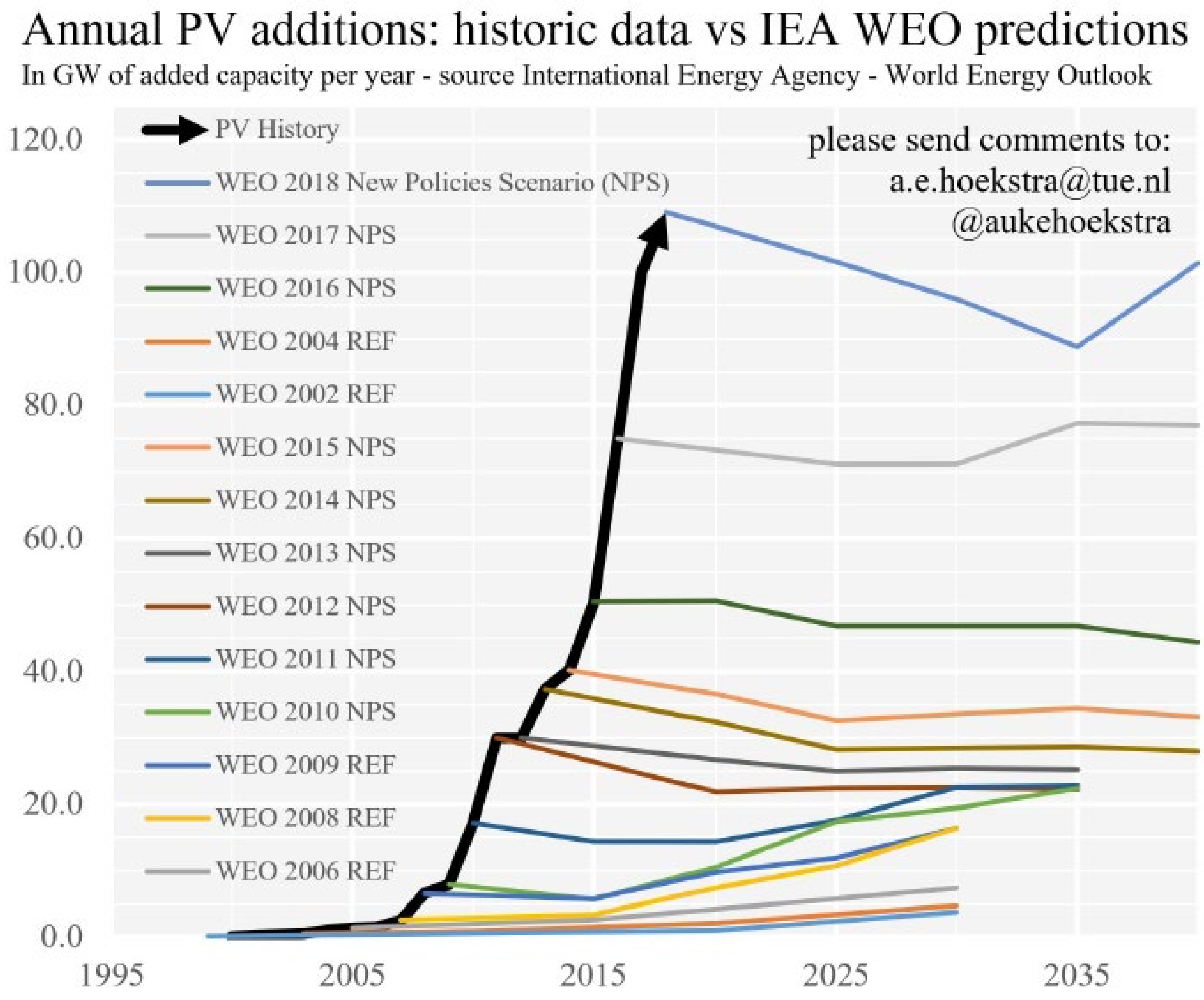
Marta Victoria

CORC
Novo Nordisk Foundation
CO_2 Research Center
AARHUS UNIVERSITY

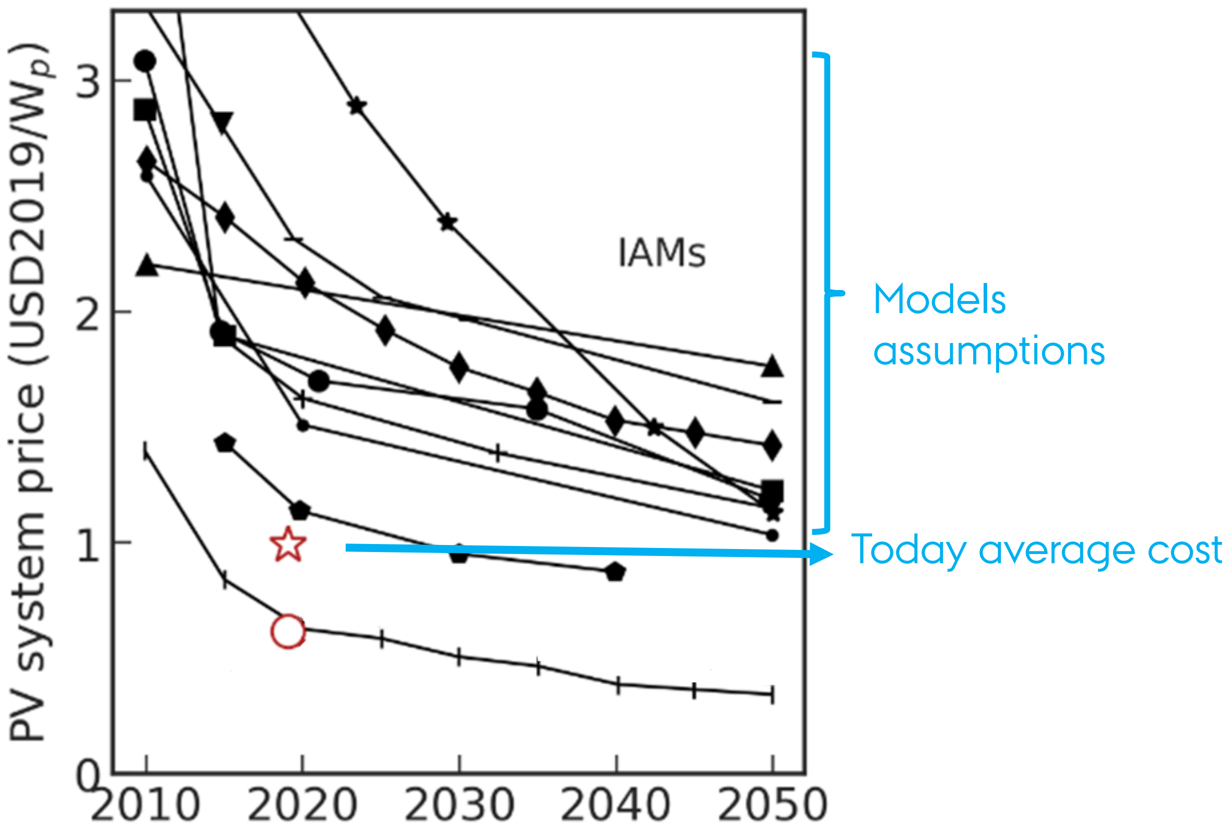
Outline

- Technology learning: the example of solar photovoltaics
- How do we include learning in systems modelling?
- How could learning impact CO2 capture and conversion?

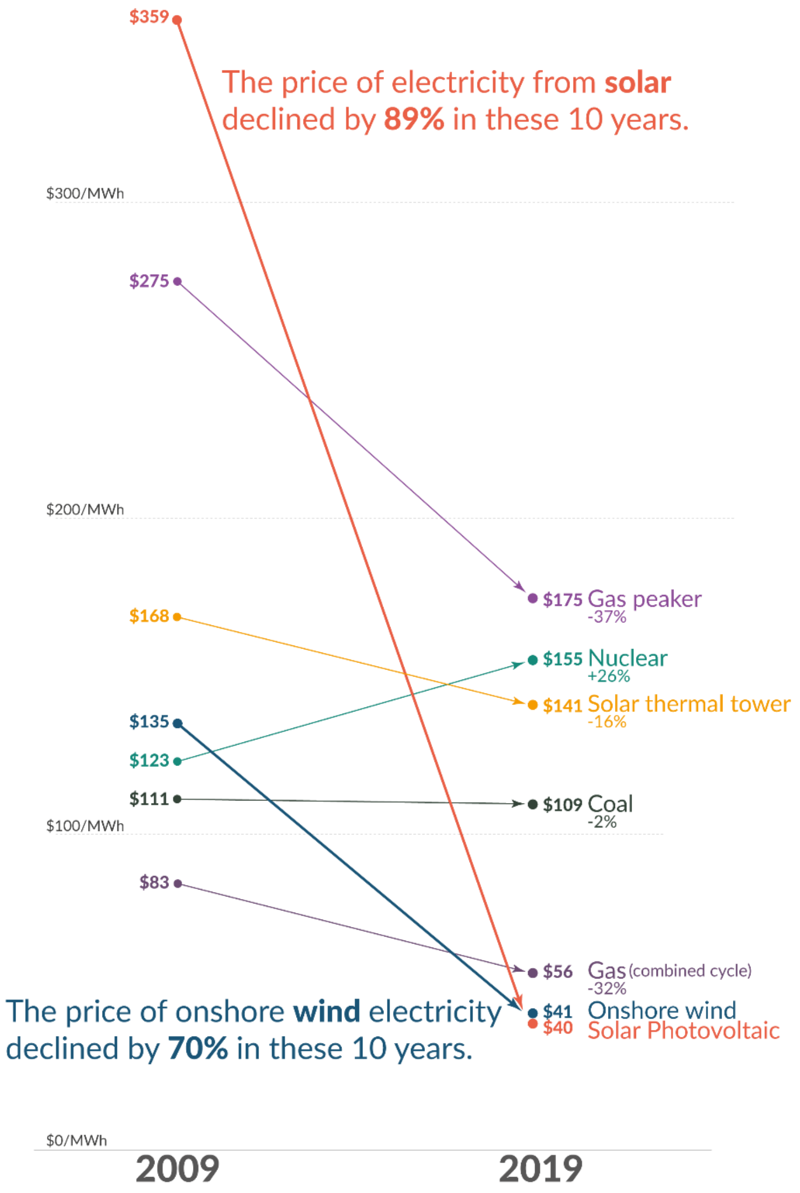
Almost everybody underestimated the potential of solar photovoltaics (PV)



Many models assumed too high future cost for solar PV

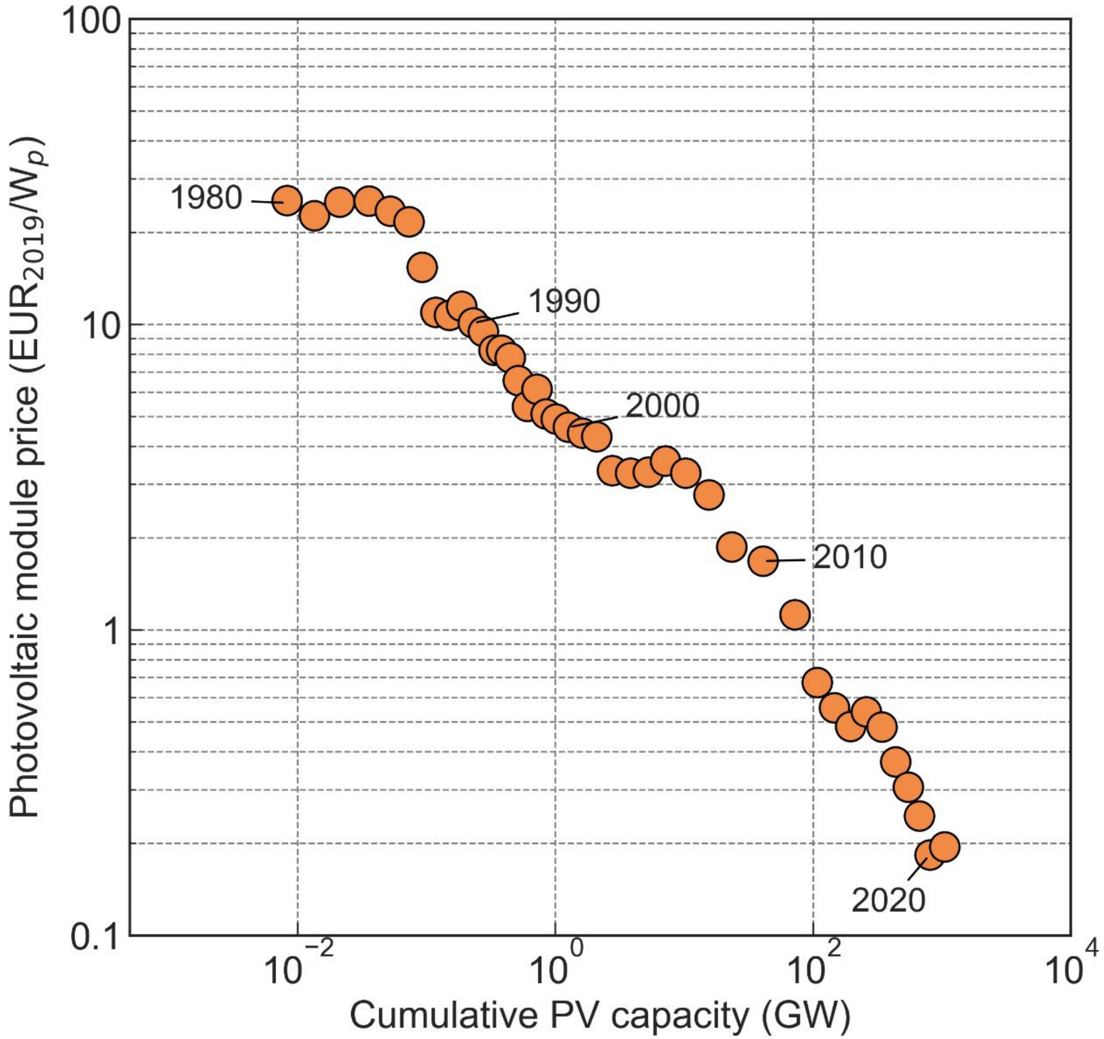


Victoria et al., Joule (2021)



Our World in Data

How did solar become so cheap so fast?



Learning by doing cost decreases as experience of production increases.

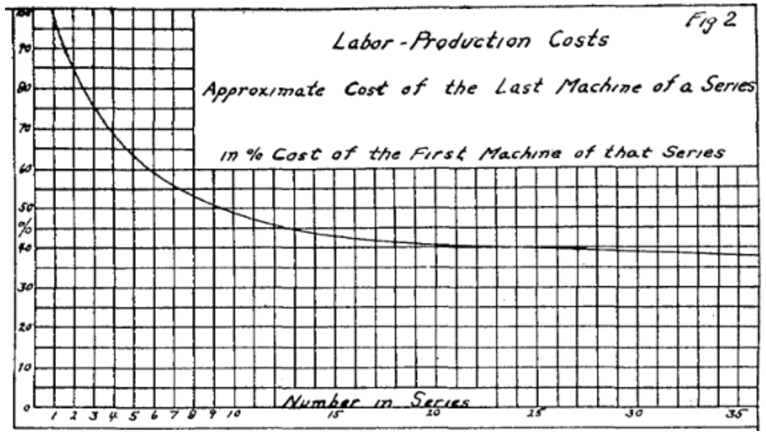
$$\frac{Cost_y}{Cost_{y_0}} = \left(\frac{Cumulative\ capacity_y}{Cumulative\ capacity_{y_0}}\right)^{-b}$$

Learning rate = relative price reduction every time cumulative capacity doubles

$$LR = 1 - 2^{-b}$$

PV module show LR=23% since1980

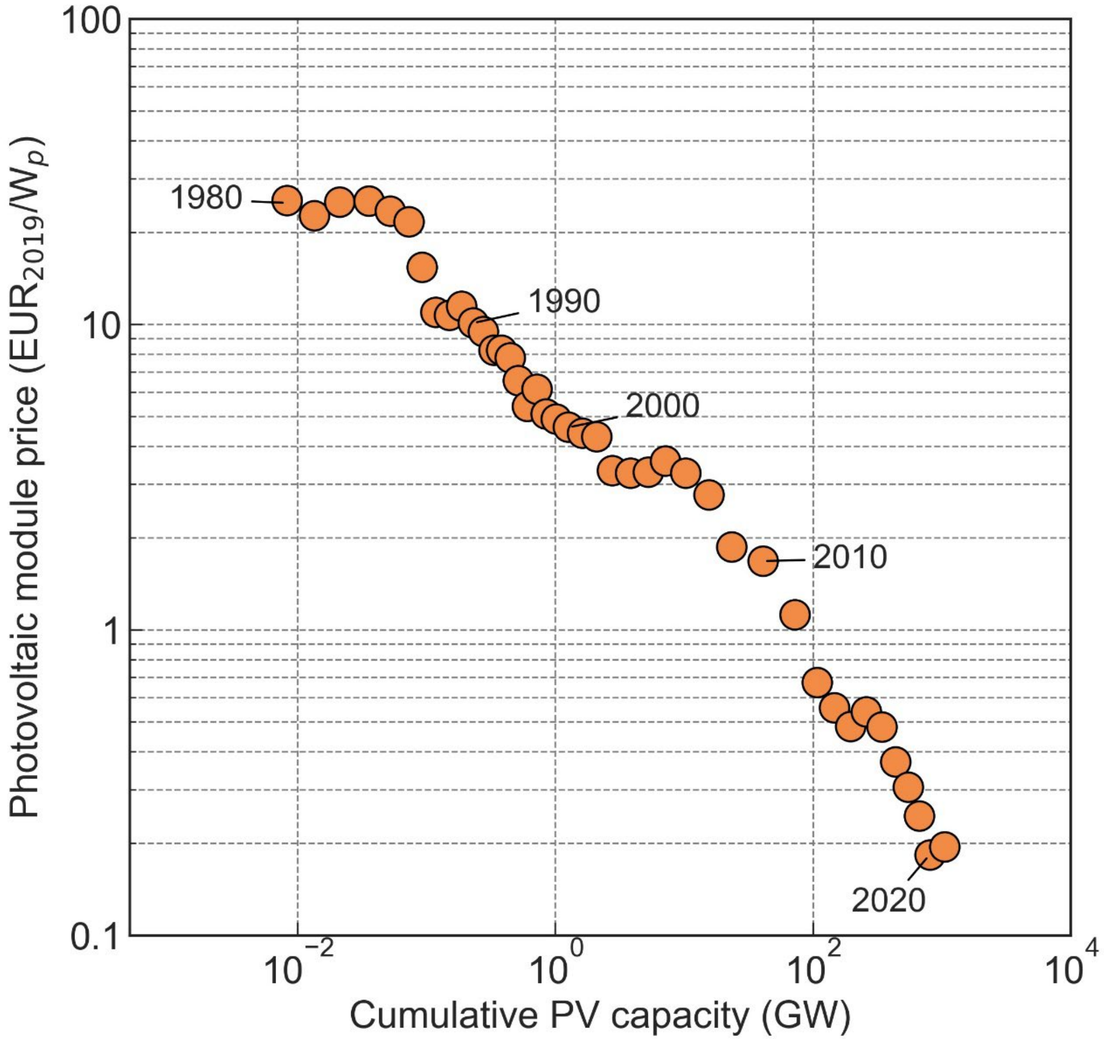
First-time observed in airplanes



Wright , 1934

Learning by research

How did solar become so cheap so fast?



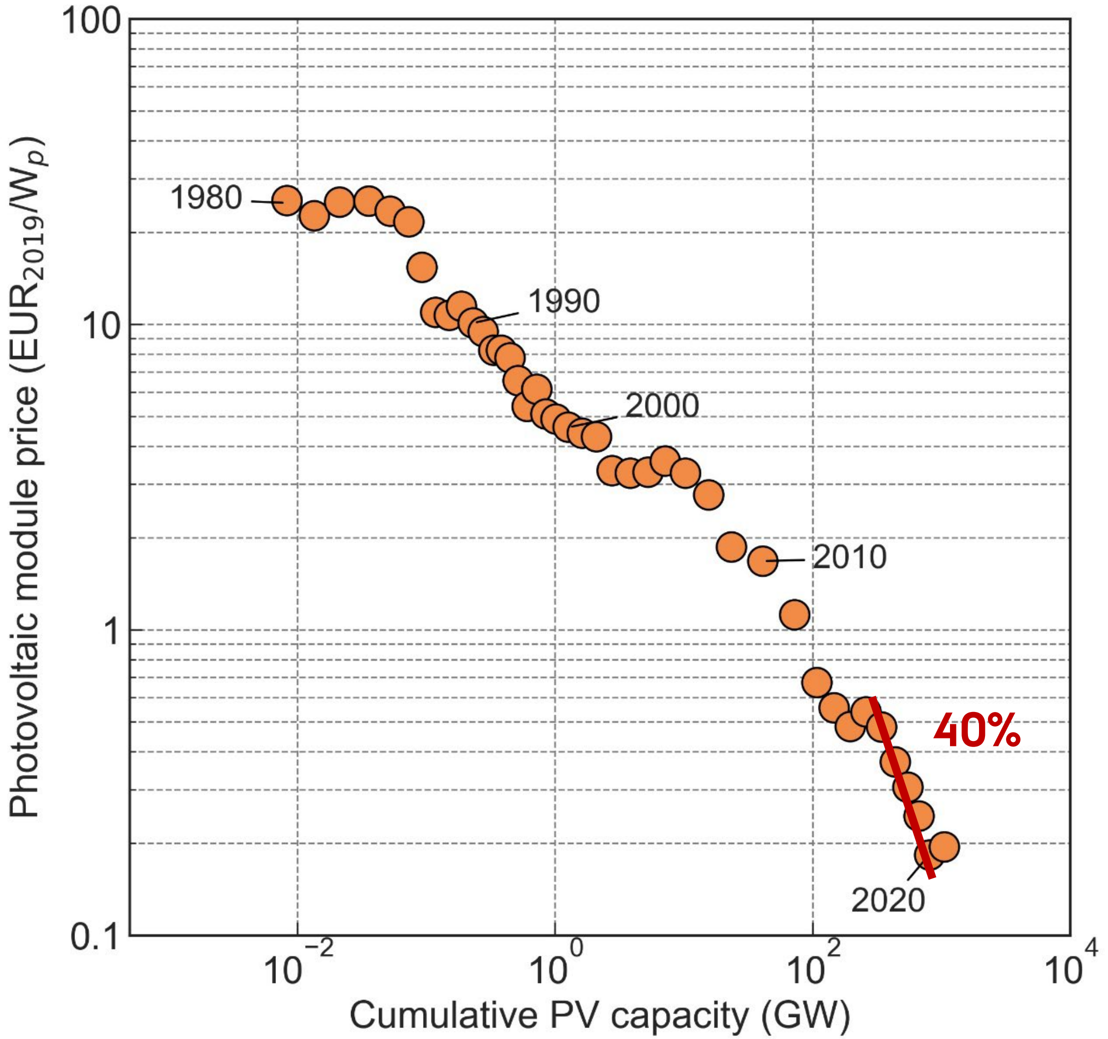
Solar PV is a modular technology

Drivers:

- efficiency increase
- massive scaling and automation of manufacturing
- harsh competition reduces economic margins
- cost reduction in other system components
- reliability improvements.

Victoria et al., Joule (2021)

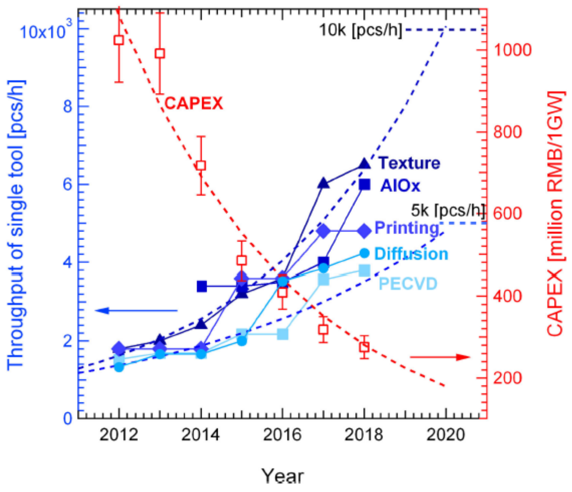
How did solar become so cheap so fast?



Solar PV is a modular technology

Drivers (after 2007):

- Supply chain and cell design standardized
- Manufacturing tools standardized (higher throughput)
- Historical lab-research available transferred to industry



Chen et al., From laboratory to production, IEEE-PV Journal 2018

- Learning on soft costs (labour, regulation, permitting…)
- Local or global learning
- Spill-overs from other industries
- Policies that stimulated market-growth

Large-scale systems modelling

We look for cost-optimal system designs and define constraints to represent physical or societal limitations.

Detailed accounting of carbon capture, use and storage.

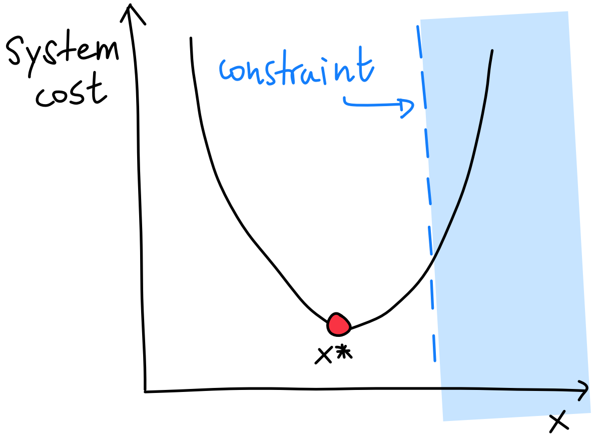
$$\min \left(\sum_{n,s} \textit{generation costs} + \textit{storage costs} + \textit{transmission costs} + \sum_{n,s,t} \textit{variable costs} \right)$$

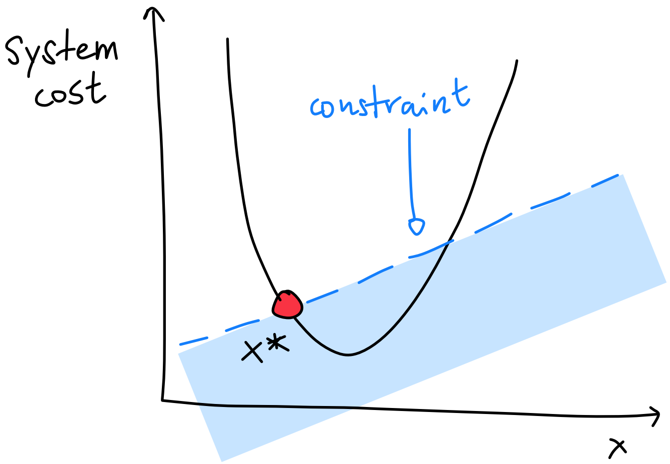
$\textit{subject to}:$

$$\sum_{s} \textit{generation}_{s,t,n} + \textit{balance}_{t,n} = \textit{demand}_{t,n} \leftrightarrow \lambda_{t,n} \quad \forall t,n$$

$$\sum_{s,t} CO_2 \textit{ emissions} \leq CO_2 \textit{ limit} \leftrightarrow \mu_{CO2}$$

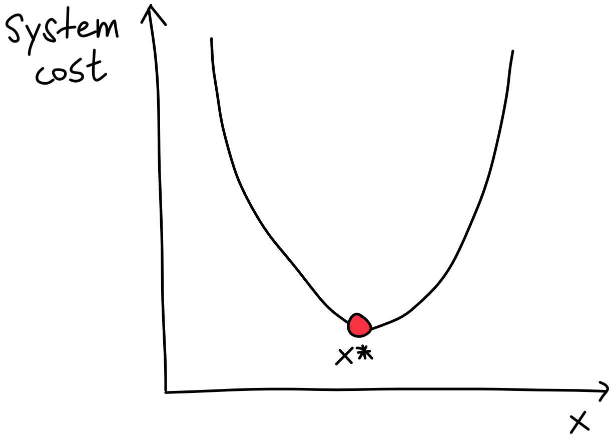
Cost and efficiency assumptions for the DEA Technology Data catalogue

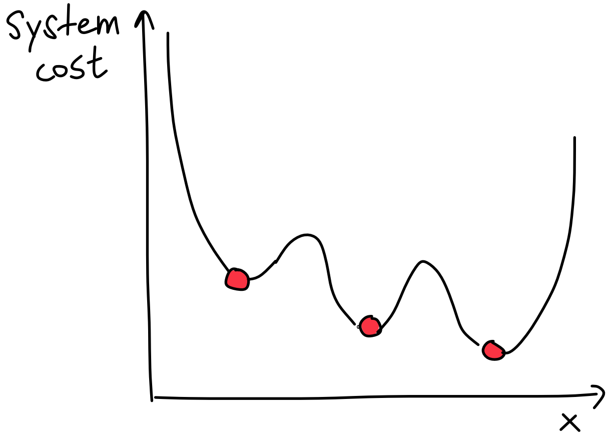




We keep to problem linear to ensure a unique solution.

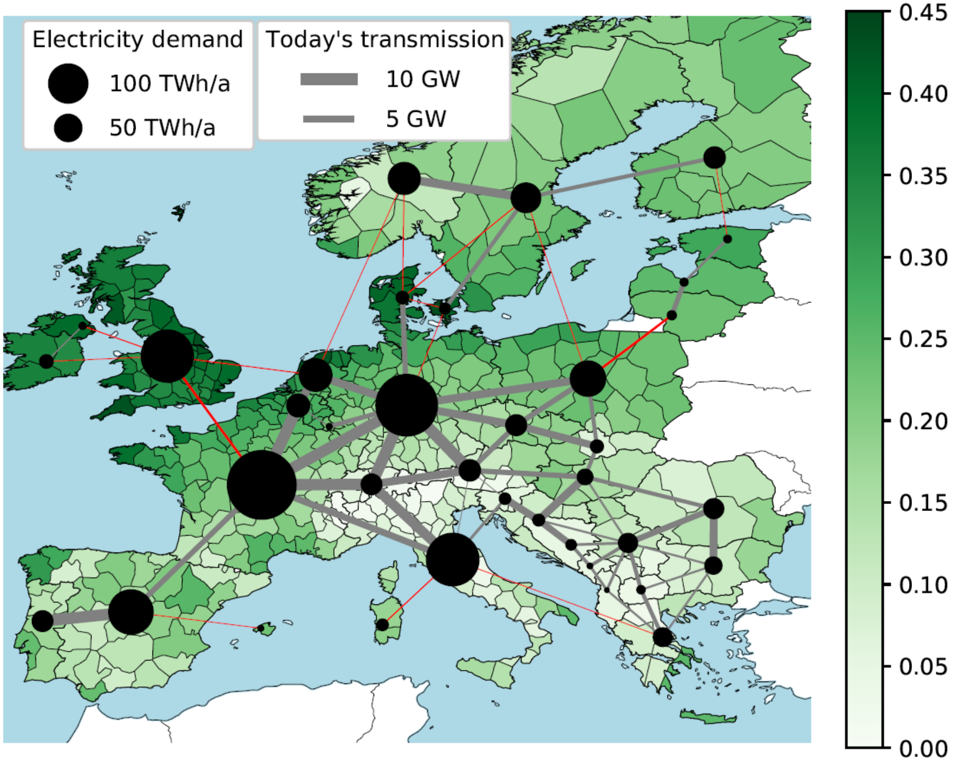
Learning is not linear, including it in the model makes it non-linear, non-convex and multiple solution exist

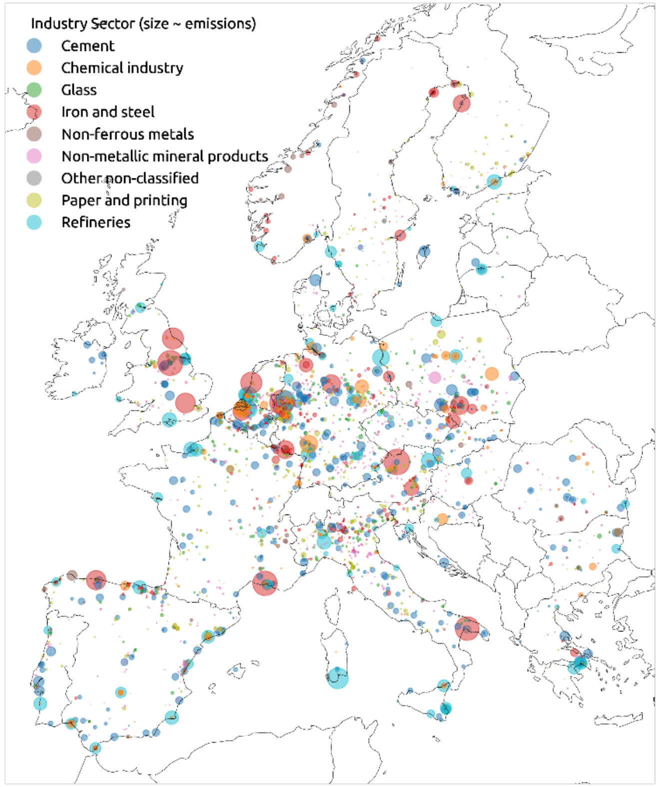


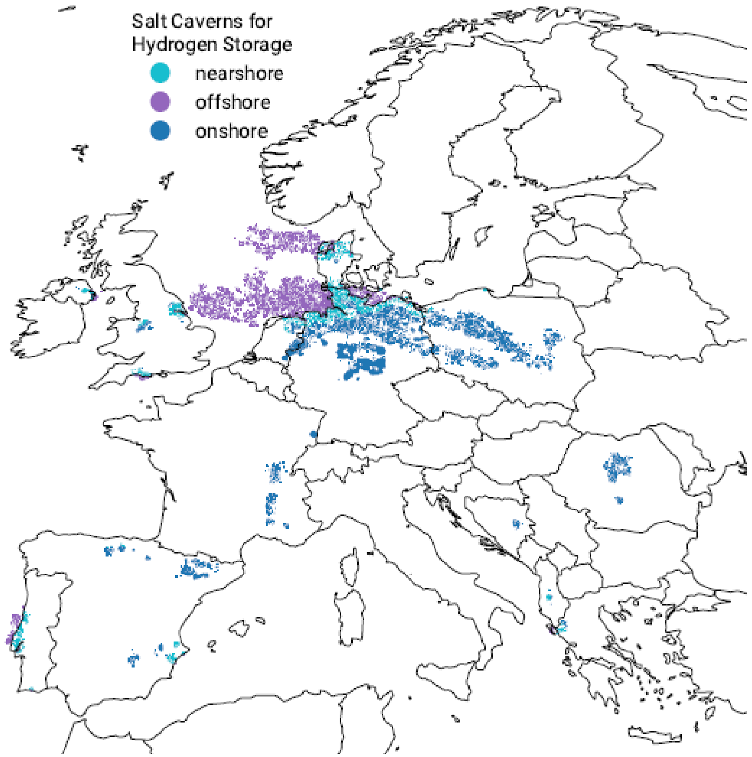


Large-scale systems modelling

Our open model included detailed representation of networked sector-coupled Europe: Electricity, Heating, Transport, Industry and feedstock, carbon cycle







Including learning in large-scale systems modelling

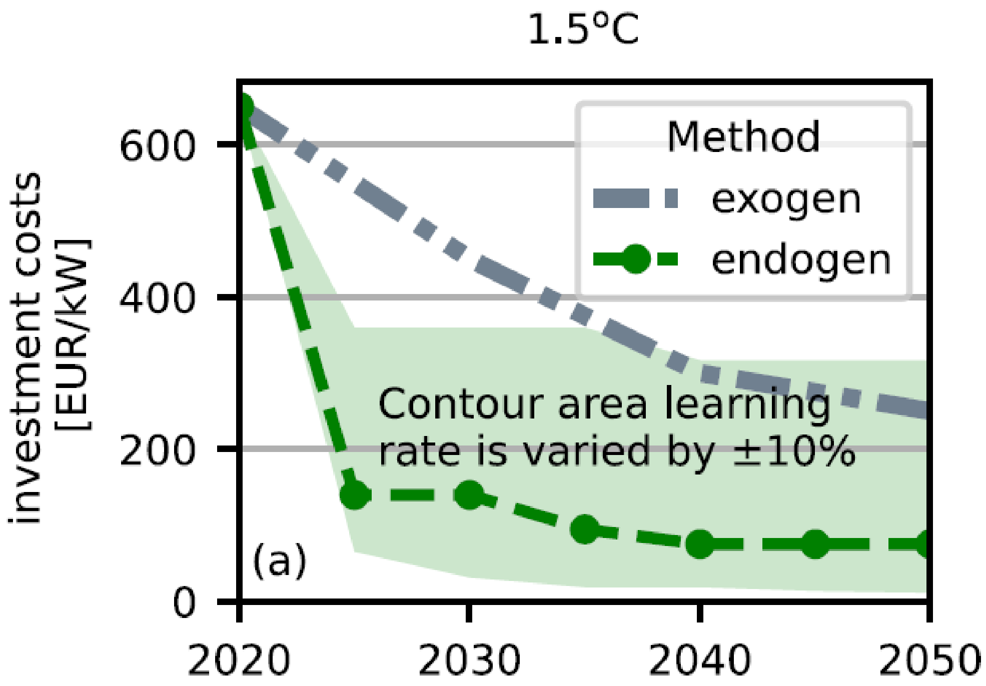
nature communications

Article https://doi.org/10.1038/s41467-023-39397-2

Endogenous learning for green hydrogen in a sector-coupled energy model for Europe

Technology	Global capacity [GW]	European share [%]	Learning rate [%]
Solar PV	707[58]	22[58]	24[31]
Onshore wind	699[58]	26[58]	10[31]
Offshore wind	34[58]	73[58]	10[31]
Electrolysis	1[159]	Local learning	16[9]

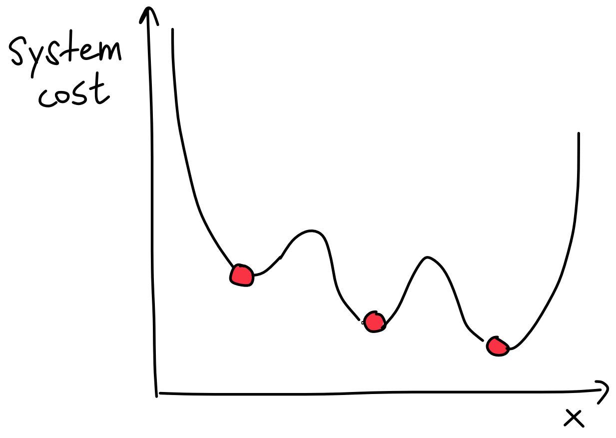
Zeyen, Victoria, and Brown, Nature Communications, 2023

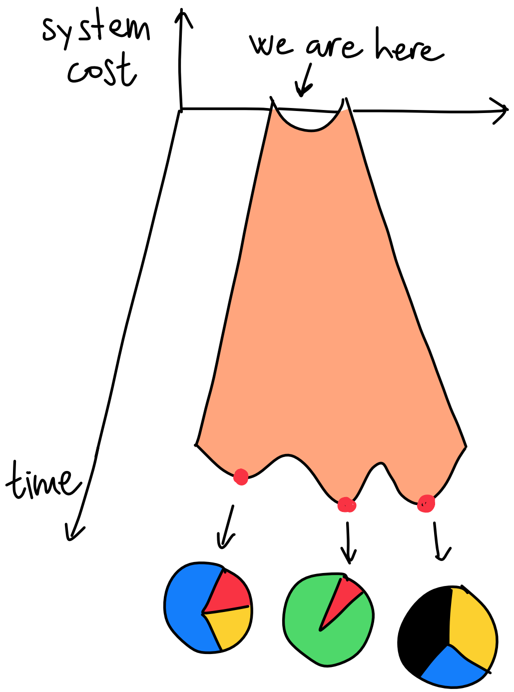


Electrolyzers deployment occurs earlier, and costs are reduced further if we consider endogenous learning

Including learning in large-scale systems modelling

We keep to problem linear to ensure a unique solution.
Learning is not linear, including it in the model makes it non-linear, non-convex and multiple solution exist





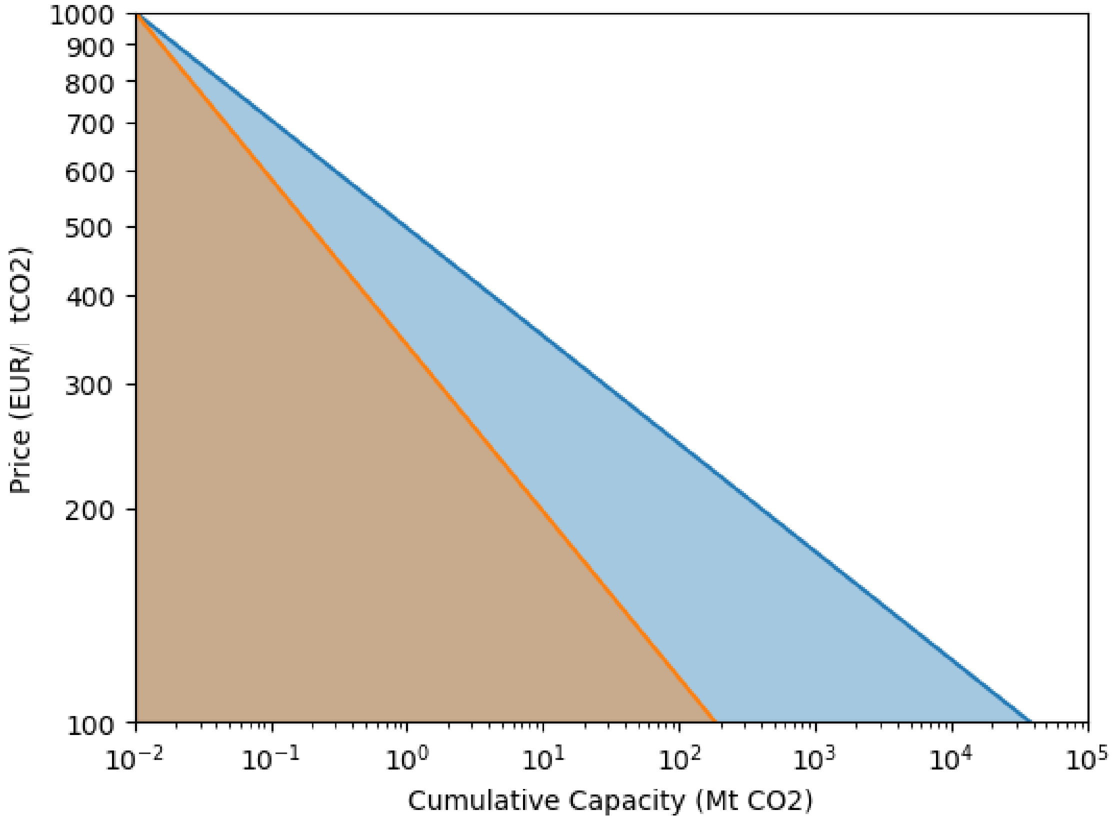
Grub, Planetary Economics, 2014

How could learning impact CO_2 capture and conversion?

A back of the envelope calculation.

Cumulative capacity for DAC today is 0.01 $MtCO_2$/year at 1000 EUR/tCO_2.
When do we achieve 100 EUR/tCO_2 ?

IEA
The state of Carbon Removal, 2023



Analysis by Sina Kalwait

- With 15% learning rate,
  when we reach 185 $MtCO_2$/year
  it costs us 24,000 million EUR
  it takes us 36 years

- With 10% learning rate,
  when we reach 37,000 $MtCO_2$/year
  it costs us million 4,500,000 million EUR
  it takes us 60 years

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