Riding down the experience curves: How technological learning may shape the energy transition

Prof. Dr. Martin Junginger, Utrecht University
With inputs from Atse Louwen, Subramani Krishnan, Gert Jan Kramer and many others

EMP-E conference 2018 'Modelling Clean Energy Pathways'
September 25 – 26th, 2018, Brussels, Belgium
REFLEX Project Scope and Applied Approaches

REFLEX
Analysis of the European Energy System under the Aspects of Flexibility and Technological Progress

Heat Sector  Electricity Sector  Mobility Sector

Technological Progress
(Investigated with the help of Experience Curves)

Model-based Analysis with focus on
Flexibility Options

Low-Carbon Energy System

Environment & Society
(Analysis based on Life Cycle Assessment)

Electricity Sector
Heat Sector
Mobility Sector

Power Plants
Storage
Demand Response
Transmission

REFLEX
Analysis of the European Energy System under the Aspects of Flexibility and Technological Progress
Partners of the REFLEX-Project

- Karlsruhe Institute of Technology
- Fraunhofer Institute for Systems and Innovation Research
- ESA² GmbH
- TEP Energy GmbH
- Utrecht University
- Royal Institute of Technology, Stockholm
- Technische Universität Dresden
- AGH University of Science and Technology, Krakow
- Trasporti e Territorio, Milano
Experience curves in Reflex

Develop and implement experience curve models into the sectoral models of project partners

Identify most relevant energy technologies in the electricity, heat and transport sector (supply, demand, storage)

• Collect empirical data on installed capacity and cost development of these technologies
• Devise/update experience curves for these technologies
• Incorporate experience curves into the various energy models to enable endogenous modeling of technological developments and cost reductions
• Take into account (statistical) uncertainty of devised learning rates
• Decompose experience curves to account for e.g. input material prices or available geographical potential (multi-level experience curves)
Experience Curve Model Implementation in Reflex
But first I want to take you 20 years back…

Figure 4-1: Cumulative worldwide PV module shipments [1976-1998] (Ayres, 1998, NREL, 1999)

But first I want to take you 20 years back…

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

20 years back...

A number of key technologies require maturation.

The cost of access to space must be substantially lowered.

Safety and environmental concerns must be resolved.

Optimal designs for space-based solar systems need to be established.

Orbital slots for collecting platforms and frequencies for power transmission need to be obtained.

Conclusion

Since 1983 the average growth rate of photovoltaic module shipments has been 15 percent a year. In 1998 the production was 150 megawatts, and in 1999, about 200 megawatts. In 1998 the cumulative production was around 800 megawatts, with the operating capacity probably about 500 megawatts, perhaps 600 megawatts. The growth of operating photovoltaic capacity in the last five years can be estimated at roughly 30 percent a year.

Since 1975 the learning rate (cost reduction as function of cumulative production) has been roughly 20 percent. In 1998 turnkey costs of grid-connected photovoltaic systems were $5–10 a watt. In the future these costs may come down to about $1 a watt.

Today photovoltaics generally cannot compete with conventional power plants in grid-connected applications. Photovoltaic electricity production costs are about $0.3–1.5 a kilowatt-hour, depending on solar insolation, turnkey costs, depreciation periods, and interest rates. Under favourable conditions and at favourable sites, the lowest cost figure may come down to $0.05-0.06 a kilowatt-hour.

It remains uncertain whether and when photovoltaics will compete with fossil fuels on a large scale. This mainly depends on the development of photovoltaics, on the price development of coal and natural gas, and on possibilities for (or policies on) carbon dioxide removal at low cost.
Back to the future: current Solar PV Global Capacity

- 98 GW of solar PV capacity added in 2017

- Global total increased 33% to 402 GW (equivalent of 40,000 PV panels every hour)

- More solar PV was installed than the net capacity additions of fossil fuels and nuclear power combined

For comparison: back in 2000, the WEA assumed 100 GW installed by 2020 to be the most optimistic scenario
Photovoltaics

Modules / systems < 10 KW

Modules, systems and BOS 10-100 kW

US systems
Results: Photovoltaics

- Contribution of BOS has increased to around 50% of system costs now (from ~20%)
- BOS Learning rate around 12-13%
- 2006-2016 learning rate for modules almost 30% (but likely a shake-out effect) -> Time horizon has significant effect on estimated learning rate
- Overall, PV modules have reduced in cost by over a factor of 100 between 1968 and 2018
- No signs of this trend slowing down, but overall system costs will decline at a lower rate than the modules
Wind onshore, farms and turbines

WTMR system costs 1982-2016

Specific Installed Cost (EUR2014/MW)

Cumulative Installed Capacity (MW)

LR: 6.0 ± 1.3%

Post-2008 Data (BNEF + WTMR)

BNEF turbine price (LR: 26.0 ± 3.1%)

WTMR system data (LR: 25.0 ± 2.1%)
Onshore Wind – development of capacity prices

WTMR system costs 1982-2016

Specific Installed Cost (EUR2014/MW)

Cumulative Installed

10^3 10^4 10^5

LR: 6.0±1.3%

Fig. 1. Development of costs and prices of emerging technologies (Boston Consulting Group, 1968).
Onshore Wind capacity vs. LCOE

A. Power Capacity

Cost ($/kW)

Capacity Factor

CF = 0.0013(CAP) + 0.21
R² = 0.7388

B. Energy

Cost ($/kWh)

Installed capacity (GW)

Cost ($/kWh)

Cumulative Production (TWh)

Cumulative Production (TWh)

Onshore Wind, discussion

- Costs shown for capacity typically refer to turnkey system costs (or turbine prices) but do not account for:
  - Changes in capacity factors (increase over time)
  - Changes in site quality (decreasing quality of sites)
  - Changes in O&M costs (decrease over time ?)
  - Experience curves for LCOE provide better learning rates (about 10%) than capacity based experience curves
  - Onshore wind to outcompete all fossil electricity by 2025

Offshore wind farm CAPEX, corrected for water depth and distance to shore (blue diamond)
Offshore LCOE trends varying strongly per country

Offshore wind

- Data is very much scattered (very different farms from 1990-now)
- Only for >300 MW farms of last years a learning rate of 10% is observed for EUR/kW
- Pre-2016 trends of LCOE show increase, even when correcting for distance-to-shore and commodity prices
- 2016/2017 show drastic decrease of LCOE
- Also for offshore wind, geographical potential gives constraints
- So what now?
  - Experience curve method does not seem suitable at the moment
  - Use exogenous estimates
Electricity storage - batteries

BEV/HEV battery packs, FC stacks

Alkaline Electrolysis

- Presented here are stack costs (EUR/kW),
- Depending on the model we might need, e.g.: EUR / kg H₂
  - Electricity price 75% of total cost
- Ambition to also assess the development of specific electricity consumption (kWh/ kg H₂)
P2H - discussion

- Alkaline vs PEM
- SEC (kWh/kg H₂)
- E.g. (Alkaline electrolysis):
  - 2011: 50 kWh/kg
  - 2015: 46 kWh/kg
  - 2020 (expected): 44.7 kWh/kg


But there are also problems and failures – adv. biofuels

Abengoa shuts down Hugoton, Colwich, St Louis HQ

In Kansas, Abengoa has decided to suspend production at its new cellulosic e as well as its corn-based ethanol plant in Colwich as part of the recent financial woes that may eventually lead to bankruptcy. The company also plans to shutter its Bioenergy headquarters in the US, based in St. Louis, Mo. The US t about 10% of its global staff with 462 people.

World's 'first' commercial second-generation bioethanol facility 'shuts down'

Local media are reporting that the Beta Renewables cellulosic ethanol plant in Crescentino, Italy has been shut down.

The €250 million ethanol refinery has the capacity to produce 40,000 tonnes of bioethanol per year, from around 270,000 tonnes of biomass. Established in 2011, it was the world's first commercial scale bioethanol refinery.

Financial restructuring at US headquartered Group Mossi & Ghisolfi (M&G), who built and operated the facility, is behind the shutting down of the bioethanol plant.

DuPont to sell cellulosic ethanol plant in blow to biofuel

CHICAGO/NEW YORK (Reuters) - DuPont Industrial Biosciences, a unit of DowDuPont Inc, on Thursday said it halted operations at a two-year-old ethanol plant and will sell it, dealing another blow to efforts to create biofuels without using food crops.
But there are also problems and failures – (BE)CCS

**INVESTIGATION**

After spending €587 million, EU has zero CO2 storage plants

Uniper and Engie recently announced their intention to cancel ROAD, the demonstration project focusing on the capture of CO2 at one of the coal-fired plants in Rotterdam and its storage in an empty gas field in the North Sea seabed.

The Port of Rotterdam Authority is very disappointed with Uniper and Engie’s announcement of their plans to terminate the ROAD project. Carbon capture and storage (CCS) is one of the key means through which coal-fired plants can reduce their CO2 emissions. The companies have failed to meet the expectations they had created with regard to a large-scale CCS pilot project.

In the view of the Port Authority, there’s no reason why the coal-fired plants should not remain open for a long time, provided they limit the negative environmental impact of their CO2 emissions by redirecting their residual heat (mainly for re-use in industry), by implementing CCS and/or by co-firing with biomass or lignin (a residual product from bio-based industry). After all, the Paris Agreement on climate change requires signatories to structurally reduce their CO2 emissions. Companies cannot afford to ignore this requirement.

**UK government spent £100m on cancelled carbon capture project**

*20 January 2017*

The Janschwaalde coal-fired plant is now being developed to capture CO2.

Peterhead power station was a bidder in the competition.
"No Quick Switch to Low-Carbon Energy"
The transition cannot be completed by 2030*

*Implicitly a response to Al Gore and a number of high-profile, heroic proposals current at that time

Three Phases of the Energy Transition

1970s to 2000 – Creating the Technologies

Ca. 2000 to 2030 – Technologies to scale

Post 2025 – Making the system work

Figure: G.J. Kramer and M. Haigh, Nature, 462, 568 (2009)
Good but Uneven Progress to Low-Carbon Energy
A status update

*Coal and natural gas used in power generation with carbon capture and storage
Good but Uneven Progress to Low-Carbon Energy
A status update

Good but Uneven Progress to Low-Carbon Energy
A status update

Good but Uneven Progress to Low-Carbon Energy
A status update

Good but Uneven Progress to Low-Carbon Energy
A status update

Conclusions

○ Technological progress of many (and especially modular) renewable electricity generation and storage technologies and associated cost reductions have been rapid in the past decades, and these trends are expected to continue for the coming decades as well…

○ But this is also needed to sustain (near-)exponential growth and to (out-)compete (with) fossil fuels

○ But many large-scale plants (2nd gen. biorefineries, CCS pilots) are barely deployed and struggle with technical difficulties – and thus do not learn…

○ Experience curves are a suitable tool to model past and project future cost trends, but apply with care…
Interested for more? Join the workshop tomorrow!

- Implementation of experience curves in energy and integrated assessment models and associated methodological challenges
- Further assessments of cost trajectories of low carbon technologies
- Application of the experience curve concept for projecting environmental impacts of energy technologies

And last but not least:
We are working on a dedicated book on experience curves to be published end of 2019 with >10 technology chapters, Reflex model results, methodological innovations etc. Interested? Contact h.m.junginger@uu.nl
Thank you!

Questions? h.m.junginger@uu.nl