

Learning Curves tracing the optimal path for Technology Learning Systems

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1. Overview

Within energy technology policy experience and learning curves² have since 1990's moved from obscurity to mainstream, but there are currently indications of fading expectations on the curves as efficient policy tools. In 1999, the International Energy Agency initiated an international collaboration on experience curves for energy technology policy (IEA 2000, Appendix C) and the initiative was followed up in the two first IEA Energy Technology Perspectives reports (IEA, 2006, 2008). The analyses in these reports contrast with the perfunctory treatment of the curves in the latest report from 2012. Kahouli-Brahmi (2008) found the curves to be standard features in most energy models but today there appear few papers developing the methodology.

The view of the learning curves as just expressing useful correlations between price and cumulative output is one obvious reason for the diminishing interest. The results from the last ten years of efforts only seem to verify concerns about uncertainty and instability of learning rates expressed in 2006 by both the Stern Report and the first IEA Energy Technology Perspectives report (Stern, 2006, p. 362, 412; IEA, 2006, p. 231). The lack of theoretical understanding leads to confusion about extrapolated learning rates and interpretation of the learning phenomenon itself (Nemet, 2009; Nordhaus, 2009; Yeh and Rubin, 2012). Uncertainty about the theoretical status of the learning curves hampers their use as reliable policy tools and undermines the legitimacy they can give to deployment programmes.

This paper addresses the theoretical status of learning curves and the stability of technology learning. The shape of the learning curve follows from two established bodies of scientific knowledge, namely, non-equilibrium thermodynamics and second order cybernetics. Earlier work based on cybernetic theory (Wene, 2007, 2010, 2011) has explained measured distributions of learning rates. Present and earlier results demonstrate that experience and learning curves describe fundamental and stable properties of human systems of interaction in a competitive environment.

2. Methods: The Learning System moves in Eigentime

Feroli and Zwaan (2009) insist on calendar time for explaining learning curves. However, the distinction Observer-Observed is important both in non-equilibrium thermodynamics and in second order cybernetics. This is expressed through the introduction of *eigentime*, i.e., internal time for the observed system different from the calendar time of an external observer. Fock (1937) introduced the concept of eigentime in physics. For thermodynamic systems Prigogine (1947) proposed thermodynamic time with respect to which entropy production remains constant. This time scale is called eigentime by Andresen and Gordon (2002) and used in their analysis of biological systems.

For the learning system the eigentime is the same between consecutive doublings of cumulative output, i.e., the rate of doubling is constant in eigentime. This paper applies results from non-equilibrium thermodynamics and cybernetics to a learning system moving in its natural eigentime.

- *Non-equilibrium thermodynamics*. Competitive markets act as boundary conditions keeping the learning system in a non-equilibrium steady state, but in the near-equilibrium region under normal market conditions. The growth of entropy is at minimum when the internal entropy

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² Distinction between learning and experience curves follows IEA (2000). A learning curve relates performance of the learning system to one of the inputs, e.g., labour, raw materials, energy, or to a set of inputs. An experience curve is a learning curve where the set of inputs is equal to total inputs expressed as total cost.

production is constant in eigentime (Andresen et al, 1994). Assuming that the learning system follows the path of minimum entropy provides the equation for the learning curve.

- *Second order cybernetics*. The cybernetic theory for technology learning considers the learning system to be operationally closed. According to the closure theorem such system develops eigenbehaviour, which in a mathematical formalism can be characterised by an eigenfunction and an eigenvalue. The eigenfunction for the eigentime operator is the equation for the learning curve and the eigenvalue provides learning rates.

3. Results

Results are relevant for energy policy design as well as theoretical understanding:

- *Stability of the learning curve and learning rates*. Thermodynamic theory and cybernetic theory lead to the same shape for the learning curve. Entropy production is a Lyapounov function, which means that if the system is perturbed it will strive to return to the state at which its entropy production is the lowest, i.e. to the original learning curve.
- *Equation of motion*. Together with the earlier results (Wene, 2007, 2011) the findings on eigenfunctions to the eigentime operator can be generalised to provide an equation of motion for the learning system.
- *Application to PV modules*. Observations on PV modules over four decades and five orders of magnitude of cumulative output can be compared to the theoretical predictions of shape and rate for the learning curve. One conclusion is that learning has continued at the learning rate predicted by the cybernetic theory during the silicon scarcity bubble 2005-2008. This result is also consistent with the prediction from stability theory. The bubble cost is USD100 billion.

4. Conclusion.

Analyses based on two well-established theories concur about the shape and stability of the learning curve. Development of the two approaches will provide insights about management of perturbations and about relation between operational closure and stability of dynamic systems. The results on PV modules emphasise the need for coordination among government deployment programmes in order to avoid costly bubbles on the global markets.

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