Experience Curves for Energy Technologies

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Glossary

diffusion Increase in market share of a new technology after a successful innovation.
economies of scale Decrease in unit cost of production through increase in scale of production.
experience curves The relationship between unit cost and cumulative deployment as represented by an exponential decay function.
innovation First commercial application of a newly developed technology.
interindustry spillover Transfer of knowledge, technologies, materials, and the like from one industrial application to another (e.g., the concept of jet engines from aeronautics to gas turbines).
intraindustry spillover Transfer of formerly exclusive knowledge and experience from one competitor to another (e.g., by labor mobility).
learning by doing Increase in skill level of labor through increasing experience.
learning curves The relationship between falling unit cost of production and increasing skill level of labor caused by an increase in experience, represented by an exponential decay function.

Experience curves are used to assess the future cost of a technology as a function of cumulative installations. The underlying rationale is that it is very costly to invent, develop, and prototype a new technology, process, or product. After an innovation—the first commercial application—a successful technology or product will spread from niche applications to larger markets. In this process of diffusion, unit costs will constantly decrease. This reduction of unit costs over time is described by experience curves.

1. DEFINITION OF EXPERIENCE CURVES FOR ENERGY TECHNOLOGIES

The concept of experience curves was derived from empirically observed learning curves in manufacturing. Learning curves describe the cost reduction effects by learning by doing. Through individual, organizational, and inter- and intraindustrial learning, the input of labor necessary to produce a certain product decreases as experience is gained. On the other hand, experience curves describe the cost reduction of a product or technology in general, disregarding the reasons for total cost reduction. Possible reasons for the reduction of unit costs during technology diffusion are economies of scale in all input factors (e.g., intermediates, transaction costs, other overhead), higher rates of production, changes in the production processes, and (particularly in the case of energy technologies) efficiency gains and changes in the product itself.

In the last years, experience curves have drawn considerable attention in the energy field due to a variety of technological challenges. Energy systems in many developing countries are in a phase of expansion and growth. Energy systems in most developed countries go through some restructuring, inducing a change in investor behavior. Both phenomena increase interest in present and future investment costs. Legislators, electricity generators,

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and other energy producers are also confronted with environmental demands (e.g., climate change, pollution, nuclear disposal and safety) that require the increased use of new cleanup technologies and new clean energy conversion technologies. Most of these new technologies are in early stages of their diffusion and considerable future cost reduction is expected.

Experience curves also play an important role in energy policy analysis. They are used to assess the "buy-down" cost of a new technology (Fig. 1). To optimize the size of a support program for a specific new technology, experience curves are used to determine how much additional investment is necessary to bring the cost of the technology down to levels at which it is economically competitive with other technologies. To that end, the incremental cost of the new technology and the speed of the cost reduction are determined from empirical data. The integral under the experience curve is equal to the investment required to buy down the cost of the technology between two arbitrary points on the curve.

Experience curves are also widely used in energy scenarios calculations. Investment costs and conversion efficiencies of energy technologies are important driving factors for future energy demand and supply. The most important energy system models, such as those of the U.S. Energy Information Administration and those used in the Intergovernmental Panel on Climate Change's (IPCC) Special Report on Emission Scenarios, use experience curves for the extrapolation of future energy costs because future investment costs for energy conversion and use are needed as inputs to these models. Because of their low data requirement and relatively robust nature, experience curves are very well suited to generate these inputs. The more sophisticated energy system models can include dynamic specifications into the model code such that the prices used for optimization of the model are generated during the model runs and depend, in a dynamic way, on the respective deployment figures of the current simulation.

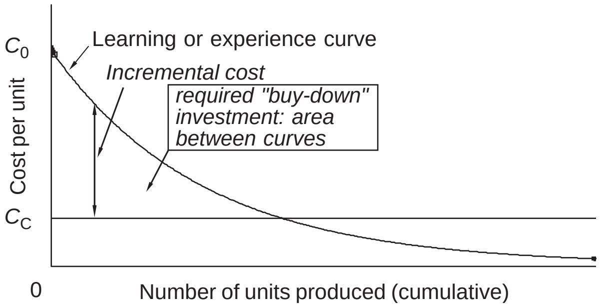

FIGURE 1 Experience curve for an equipment unit of a new energy technology. The unit cost for a piece of equipment falls with increasing cumulative deployment of the technology. C_0 is the cost of a technology at innovation. C_c is the cost of a conventional backstop technology. The integral over the incremental cost up to the point of intersection ("buy-down") indicates how much additional investment is necessary to make the new technology economically competitive with the established technology.

Management consulting firms (e.g., Boston Consulting Group) use experience curves for consulting clients on strategic price-setting behavior. Experience curves describe cost reduction as a "black box." The actual reasons for the cost reduction are completely ignored in the model. This makes experience curves seemingly simple to use but also imposes some caveats on the use of the concept. The data requirements for an estimation by linear regression are seemingly very low, and extrapolation into the future seems almost trivial. This article first gives more detail on the concept and then discusses the reasons why cost reduction for the whole product or technology might occur. It explains how these reasons should be incorporated into the model and what kind of data problems result. Several examples for cost reduction in various energy technologies and some extensions to the model are discussed.

2. EXPERIENCE CURVES

2.1 The Concept

Experience curves assume a logarithmic relationship between the experience from cumulative installation and cost. Typically, this is represented by the following functional form:

$$C_{\mathrm{cum}} = C_0 * CUM^b, \tag{1}$$

where CUM is the cumulative output of the industry, C_{cum} is the cost of a unit product after output of CUM, b is the "learning index," and C_0 is the cost at the starting point of the data.

This functional form has some very convenient mathematical properties. For example, the parameter estimates are independent of the starting point of the data used for the estimation. The functional form is completely independent of the stage of development or diffusion of the technology. It implies that the cost reduction per additional unit of output decreases, so decreasing marginal reduction in costs is factored in. However, the functional form also prescribes that there is no limit to cost reduction. Some authors embrace this because they think that human ingenuity and competition will supply the opportunity for continually decreasing cost.

Other authors suggest including a minimum level of cost in the functional form by adding a simple linear term.

The functional form of the experience curve is estimated with linear regression after logarithmic transformation:

$$\log C_{\mathrm{cum}} = \log C_0 + b \log CUM. \qquad (2)$$

Empirical studies usually estimate the coefficients of this equation using ordinary least squares and usually report highly significant correlations for the logarithmic form. However, highly significant correlations are to be expected in a logarithmically transformed linear regression of integrated variables and should not lead the investigator to conclusions that are not actually supported by the data. In fact, econometrically tested and statistically significant estimations of the experience curves are hard to find in the literature.

The data requirement for the estimation of Eq. (2) is very small. The data necessary for production cost forecasts (i.e., cumulative installations) are easily available from energy scenario calculations. The high level of aggregation of the data does not require any explicit knowledge about future changes in technological details that are particularly hard to predict. However, some researchers prefer to modify the parameters for time periods in the far future or distant past rather than assuming homogenous cost reduction over several decades.

2.2 The Progress Ratio

The "progress ratio" (*PR*) describes the relative cost after a doubling of cumulative installation. It is a very explicit and obvious benchmark for cost reduction effects. It is calculated from the learning index b estimated with the experience curve:

$$PR = 2^{b}. \qquad (3)$$

A progress ratio of 85% means that costs are reduced by 15% with each doubling of installed capacity. This ratio is constant. It is also independent of the rate at which the experience is accumulated, of the developmental stage of the technology, and of possible qualitative changes in the product or technology.

The progress ratio has been calculated for other, non-energy-related industries (e.g., products of the chemical industry or airplane manufacturing). Typically, progress ratios lie between 75 and 85%.

2.3 Scope

Experience curves have been estimated for single firms but are more common for a whole sector or whole industry (e.g., the wind turbine industry, all makers of combined cycle gas turbines) or for cumulative experience in all varieties of one technology (e.g., solar photovoltaics). In a globalized world, and specifically in energy technology markets, it is reasonable to assume that learning processes draw from a worldwide base of experience. Therefore, experience curves for energy technologies should reflect global experience, and global data should be used for their estimation.

3. REASONS FOR COST REDUCTION AND CONSEQUENCES FOR THE FORMULATION OF EXPERIENCE CURVES

Experience curves, as a typical black box model, do not make any assumptions about the reasons for cost reduction. However, for the applications of experience curves, these may not be ignored. This section explains the reasons for cost reduction and implications for the interpretation of progress ratios and cost reduction effects. In energy technologies, there are five reasons for cost reduction and improvements in the competitiveness of a technology: learning by doing, economies of scale in production of the equipment, improvements in the efficiency and quality of the equipment, standardization, and market conditions.

3.1 Learning by Doing

Learning by doing results in cost reductions whenever a firm or any other type of organization improves its productivity of labor through day-to-day operations. Wright studied the development in labor productivity in the U.S. airframe industry and showed that the number of hours required to produce an aircraft declines with the cumulative number of aircrafts produced. Arrow introduced the learning by doing hypothesis into economic mainstream and built a theory of macroeconomic growth on it.

Cost reduction through cumulative experience can be achieved within the firm, but firms can also profit from intra- and interindustry spillover effects. Mobility of "human capital" and copycat behavior are possible causes of intraindustry spillover and can be treated jointly with learning by doing even when looking at a single firm. Argote and Epple showed that "organizational forgetting," which would reverse the cost reduction through learning by doing, occurs as well.

Cost reduction through learning by doing has been estimated in the past using the same functional form that later served as the blueprint for the experience curve. Learning by doing reduces the overall cost of a project to the degree that labor is used as a factor of input to production. The share of the total cost for this input factor is not likely to remain constant over time. Thus, if learning by doing is not the only factor contributing to cost reduction, theory does not fully support the use of the same functional form for both curves even if this is common practice.

3.2 Economies of Scale in Production and in Input Factors

The classic reason for cost reduction is economies of scale in the production process and in the procurement of input factors. When the output of an industry grows from a few hand-manufactured units per year to mass production, unit costs can go down by several orders of magnitude. Input materials for large-scale production can be purchased at better prices, and overhead can be reduced. Administrative effort and transaction cost per unit are reduced.

Upscaling a given production facility happens in an incremental way. Thus, even the cost of the aggregate production of a whole industry, particularly a small industry such as any national wind turbine industry, might not follow a smooth decay but rather have kinks. Just like in the case of learning by doing, there are natural limits to the size of factories, after which economies of scale might actually disappear and turn into diseconomies of scale in the form of increases in unit costs. The experience curve is a simplifying and generalizing representation of this growth process.

Economies of scale refer to the scale of current production, that is, to the current output per time. Because the classic experience curve concept does not control for time or the rate of production, estimating the equation can result in the same progress ratios for a given cumulative output at low and high rates of production. The experience curve concept assumes that the experience contribution of the *x*th unit depends only on how many units of experience have been gained before and not, for example on the cumulative sales in monetary terms. This points to the problem of defining the exact metrics to be used in the curve (e.g., whether the cumulative output should really be expressed in units produced or in a different metric), discussed in Section 4.

3.3 Improvements in Efficiency and Usefulness of the Product

Energy equipment can also exhibit qualitative changes over time that lead to higher efficiency of conversion without increasing unit cost in proportion. For example, bigger wind energy converters do not usually cost more in proportion as they grow larger, but their specific (marginal) cost per megawatt of capacity decreases. In addition, the efficiency of fuel use typically increases with changes in quality and size of the generator, so that the specific cost of the energy service goes down even more.

Efficiency changes can be taken into account in experience curves, but only if the delivered energy service (e.g., the kilowatt-hours of electricity) are the measure of experience as well as the unit for which costs are considered. Just like in the case of diseconomies of scale, equipment might evolve into an application suited for specific niche markets and, as a result of these qualitative changes, specific costs might be higher in later stages of technology diffusion.

3.4 Diffusion and Standardization

A fourth reason for the reduction of cost with increasing maturity of a technology is the standardization that a successful technology will undergo during its diffusion from niche markets into general markets. Standardization drives down overhead and compatibility costs. A logistic rather than exponential curve seems to be the appropriate representation of this phenomenon.

3.5 Market Conditions

All phenomena discussed so far might not have any effect on unit cost of production or on prices of the technology if the market structure is not sufficiently competitive. Not only might monopolists and oligopolists be able to charge prices that are far higher than the costs of developing, producing, and distributing a product or technology, but a noncompetitive market structure also relieves market participants from the pressure to improve products and production processes. Thus, learning and efficiency gains might be realized more slowly than in competitive situations. Other market conditions, such as the maturity of the market on the demand side and the opportunity of spillover effects, might affect the speed of learning and improvements of the industry standard in economic or technological terms and, thereby, have indirect effects on the cost reduction over time.

In addition, the market situation in input factor markets (e.g., labor, materials) can play an important role in both improving and reducing cost reduction and experience effects. However, in an abstract and very general model of cost reduction with increased experience, it is very hard to account for these effects.

4. PROBLEMS OF DATA IDENTIFICATION AND STATISTICAL INFERENCE

Considering the reasons for a possible decrease in unit cost of energy technologies, it becomes clear that the variables representing experience as well as cost need to be chosen with care. Some of the changes (e.g., improved efficiency of conversion, improved reliability) only reduce the cost of the delivered output of the technology, whereas others (e.g., economies of scale in production, learning by doing) reduce the cost of equipment manufacturing and will have effects on both possible metrics: the cost of capacity and the cost of the energy service. Other identification problems and problems of statistical inference are discussed in this section.

4.1 The Dependent Variable

4.1.1 Cost per Capacity or per Energy Service

Most of the newer studies of energy technologies, particularly those in the field of renewable and intermittent energy sources, concentrate their analyses on the cost per unit capacity of the technology. These data are readily available for some technologies. Data on the cost of the energy itself (e.g., the power output for some technologies) are harder to obtain for several reasons. The actual energy output depends on local load factors and the supply with fuel inputs. Fluctuations in fuel prices and operation and maintenance (O&M) costs introduce additional uncertainties. Long-term trends in fuel prices or O&M costs might even offset any cost reductions through cumulative experience if measured in prices per energy service. Still, when experience curves are used for a comparison between different energy technologies, the assessment should always refer to the cost per unit of energy (e.g., kilowatt-hour) because this metric accounts for internal changes in the energy technology as well as in the other conditions that influence the relative costs of different technologies. Only this metric, if any, allows for the assessment of buy-down costs (as defined earlier as the amount of investment needed until the costs reach the level of any backstop technology). To do so, it is recommended to define standard (e.g., average) conditions for load factors and fuel input prices and quantities. To extrapolate cost reduction into the future, the standard situations (e.g., load factors, efficiency, fuel prices) need to be extrapolated into the future as well. This apparent abstraction is a reminder of the character of experience curves as a highly abstract tool for long-term technology assessment rather than as a planning tool for the design of an energy system on short and intermediate time horizons.

Related to this problem is the question of how to include O&M costs. These might be subject to a long-term cost reduction of their own as experiences with use of the new technology are collected and as the design of new equipment is improved for ease of use and reliability.

4.2.2 Costs or Prices

Another problematic aspect of the dependent variable is the question of whether cost or price data are used. Experience curve theory relates to the production cost for equipment or the energy product. Most empirical applications of experience curves to energy technologies use prices because they are easier to obtain than are cost data. When using price data as a proxy for costs, researchers implicitly make very restrictive assumptions on the market structure. Because experience curves include observations from many years, structural changes in the markets for energy technologies should be excluded if price data are used. Another major reason for various trends in prices and costs is changing market transformation policies and subsidy schemes for new energy technologies.

4.2 The Independent Variable: The Measure of Experience

4.2.1 Cumulatively Installed Capacity versus Cumulative Production of Energy Service

The measure of the accumulation of experience should be chosen in close analogy to the measure of cost for which the experience curve is estimated. For the reasons mentioned previously—economies of scale, market fluctuations, and qualitative changes in the technology—cumulative energy services delivered would be the relevant measure for experience when thinking about the competitiveness of an energy technology, but data access and international aggregation are easier for cumulative capacity in megawatts. Current research investigates the usability of other measures of experience (e.g., cumulative investments, cumulative units of installation).

4.2.2 The Specification of the Technology

Whenever spillover effects from other industries are present, the estimation of cost reduction is possibly flawed. This is often problematic when technological concepts originate in other industries (e.g., gas turbine having its roots in jet engines). Also, the design of a technology might change in the course of product diversification and the establishment of a technology in new (e.g., distributed) applications.

The attribution of learning and accumulating experience also depends on which technology one actually examines. For example, the outcome when the experience collected with solar photovoltaic power generation is aggregated over all semiconductor materials that have been used for the purpose is drastically different from that when just the currently prevalent material is included in the experience measure. This phenomenon is highly technology specific, and no general recommendation can be given.

4.2.3 Global or National Scale

Typically, in a globalized world, the cumulative experience worldwide should be used as the driver for cost reduction through increased experience. With the exception of nuclear power, the markets for energy technologies are typically global markets. However, if there are specific local dynamics in a technology, the time series could become inconsistent. Furthermore, global data can sometimes be very hard to access, particularly for new technologies that are developed in several countries in parallel.

4.3 The Functional Form: Expression of the Speed of Cost Reduction

The assumption of exponential decay of costs reflects the fact that marginal improvements in the production processes diminish with increased experience. For experience curves, this form has been inferred from the idea of the learning curve. Fast learning with the first batches of production leads to rapid cost reduction initially, which can slow down during later stages of higher industry or business maturity. The traditional logarithmic shape of assumed cost reduction has very pleasant mathematical properties that technically allow for the estimation by simple linear regression and ordinary least squares methods. However, there is no reason to assume that the reduction in production cost for any piece of energy technology can be indefinitely continued, as implied by this functional form. Common sense suggests that the material cost is a natural lower limit for the cost. This means that the function should at least contain a constant price floor. The smooth logarithmic function also does not account for radical changes, implying that the curve should not be used for monopolies or monopsonies.

Furthermore, as discussed previously, learning and the other cost-reducing phenomena strongly depend on the rates of production. Thus, not all influences are captured by the classic functional form, and a multivariate approach might be much more appropriate even at the expense of the simplicity of the approach. In addition, market conditions and the circumstances of development and production of the equipment are likely to change during the time in which experience is accumulated, so that even at constant rates of deployment or constant rates of growth of production, the velocity of learning and improvements in the technology will not remain constant. Although the simple functional form has its own merits, it might not be able to account for the full story. This once again underlines the black box character of the approach. Experience curves are a tool for generating smooth curves for future projections on a large scale and for the long term, and they are not necessarily suitable for the assessment of historic trends or detailed short-term predictions. Because of this limited ability to reflect the actual processes, experience curves might be suitable only for very coarse assessments.

4.4 Spurious Regression

The experience curve concept implies a statistical relationship between a cumulative variable (e.g., cumulative deployment) and a noncumulative variable (e.g., unit cost). A statistical analysis of such a pair of variables needs to account for the autocorrelation and integration characteristics of the data. Typically, the cost at time t_{x+1} after the deployment of CUM_{x+1} will not be independent of the cost in time t_x after the deployment of CUM_x but can be represented by $C_{x+1} = C_x - \Delta C + \varepsilon$ (i.e., it should resemble a random walk with a downward drift term). Cumulative deployment CUM_{x+1} can be represented by $CUM_{x+1} = CUM_x + \Delta CUM$, where

ΔCUM equals the amount deployed during the period of observation. If the period of observation is a regular interval and the technology exhibits a typical growth pattern of a diffusion phase, the amount deployed during each period ΔCUM itself can be represented by $\Delta CUM_{x+1} = \Delta CUM_x + \Delta(\Delta CUM_x) + \varepsilon$ (i.e., it a random walk process with a upward drift). Thus, CUM_{x+1} does not fulfill the requirements for a stochastic variable. Rather, the classic concept requires an ill-defined regression of a random walk with drift with the integration of a random walk with drift. This vulnerates the standard assumptions of ordinary least squares regression, and in most cases a logarithmic transformation does not change the inherent characteristics of the data, so that the regressions based on the classic concept are most likely to be spurious. Extensive testing of the data and the error term should be conducted to prevent conclusions that are not supported by the data. However, proper statistical treatment and testing is the exception rather than the rule.

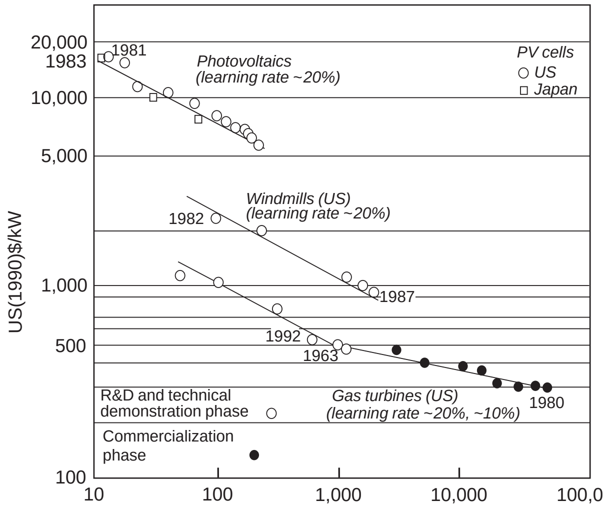

FIGURE 2 Experience curves for energy technologies in a variety of International Institute for Applied Systems Analysis estimates. Figure courtesy of Nakicenovic, N., Gruebler, A., and MacDonald, A. (Eds.) (1998). "Global Energy Perspectives." Cambridge University Press, Cambridge, UK.

5. SOME CASE STUDIES

Recently, the classic experience curve concept has been applied to the area of new energy technologies, mostly renewable energy technologies but also combined cycle gas turbines. In this section, several technology-specific applications are discussed. These case studies demonstrate possible problems with the concept and new energy technologies and offer interesting ideas for improvement. Several large-scale research efforts on experience curves were aggregated in the International Energy Agency (IEA)-led International Collaboration on Experience Curves for Energy Technology Policy (EXCETP). All case studies have in common that where more than one estimate has been made, the estimated progress ratios span wide ranges where, as described previously, the estimate should be robust with regard to the selection of data. This fact is a clear warning to pay close attention to selecting the metrics and the database for the estimation and to testing the estimates for statistical validity, as explained previously. Figure 2 contains a classic display of several examples of estimates of experience curves that have been partly included in the following literature survey.

5.1 Wind Energy Converters

Several studies have applied the concept to various data sets with varying success. Junginger reviewed 16 studies on cost reduction in wind turbine production and found that they used different cost units and different proxies for the cumulative experience—and got very different results. Most of these studies interpreted the results of the classic function with a very specific set of reasons. These studies hardly ever accounted for the data, identification, or statistical problems mentioned previously. Most studies indicated that progress ratios for wind energy converters have been much higher (the cost reduction has been slower) than the classic rule-of-thumb progress ratios of 75 to 85%. The range of results was 62 to 96%.

5.2 Solar Photovoltaics, Niche Markets, and the Influence of Market Transformation Programs and Policies

Solar photovoltaics has been studied extensively with experience curves. Progress ratios between 68 and 82% have been estimated. The technology was characterized by high initial investment cost and comparatively high maintenance cost due to changing micro-design. The countries with the highest installed capacity of solar panels are Japan and Germany, where the installation was subsidized. Other market transformation initiatives have been launched for developing countries. Using these examples, the effect of market introduction subsidies on the cost of the equipment has been estimated. The induced cost reduction effects have then been factored into the benefit/cost ratio of the policies to justify the intervention. The experience curves were the basis for the assessment of the necessary amount of subsidy.

Even if the fuel is free and even in good locations, electricity from photovoltaics currently is more expensive than standard grid power. However, in certain niche markets, either sunny rural locations remote from the grid or sunny urban locations where no backup power supply is available, photovoltaics can be a cost-effective solution. From this starting point, the current costs of photovoltaic systems, the market size of the niche markets, and the progress ratio can be used to calculate the point in time at which solar photovoltaics will break even with grid-connected power technologies.

5.3 Gas Turbines and the Influence of the Diffusion Stage of the Technology

Nakicenovic and colleagues estimated a two-stage learning process for gas turbines. After a steep decay in cost with a progress ratio of approximately 80% in the airline industry, a lower rate of cost reduction follows with a progress ratio of approximately 90% (Fig. 2).

According to Colpier and Cornland, who analyzed the economics of the natural gas-fired combined cycle gas turbine (CCGT), the specific investment price for larger CCGTs has decreased by as much as 35% in real terms during the past decade. Compared with experiences in other industries, this is a very high decrease. CCGT is not a new technology in itself but rather a combination of the established technologies of gas and steam turbines that has been used since the 1970s. To find an explanation for the high rates of cost reduction, Colpier and Cornland expanded the classic theory by taking into account strategic pricing behavior. They hypothesized that a strategically pricing firm sells at prices lower than marginal cost during the development phase of a product. The firm develops into a market leader, reduces its own marginal cost with increased experience and can sell under a “price umbrella,” that is, at prices higher than marginal cost and constant until competitors have caught up. In the subsequent “shake-out phase,” prices will drop sharply and approach marginal cost. The authors claimed that this phenomenon has been observed for many different technologies. Their analysis indicated that the prices for CCGT technology have been dropping in a way that looks like a margin shake-out rather than the less drastic decrease of unit construction cost through experience and economies of scale. This could be supported by the fact that the CCGT market is dominated by only four manufacturers and their licensees. The authors concluded that the decline of the specific investment prices is likely to level off in the future.

More generally, pricing behavior is linked not only to the developmental stages of a technology but also to the rate of deployment and the rate of technological change, both of which affect the rate of learning and of cost reduction in different ways.

5.4 Gas Infrastructure

Zhao investigated historical cost development of gas pipelines. She ignored O&M costs and focused on the construction cost per cubic meter of pipeline capacity. In the United States, these costs increased and decreased twice between 1985 and 1998. Zhao observed no learning effects in onshore pipeline construction and found no significant cost reductions or progress ratios. For offshore pipeline installation, she measured cost in U.S. dollars per cubic meter of pipeline volume and days required to lay 1 km of pipeline. Her data, in fact, indicated that costs go down, although no statistical significance could be achieved. She concluded that because pipeline construction is not a replicative process, learning effects are probably small. Economies of scale can be achieved (e.g., through increased capacities, i.e., pipe diameter), although it is unclear how she derived these results. Experience curves seem to be an inappropriate tool for the analysis of the cost of gas infrastructure.

6. *CONCEPTUAL MODIFICATIONS*

Quantitative estimates for experience curves should be used with caution because the theoretical foundation, as well as the empirical support, is rather weak. Nevertheless, the occurrence of cost reduction with increasing diffusion and market penetration of a technology is undisputed. To get better estimates for the velocity of cost reduction, more research is under way.

One school of modifications amends the factors that are ignored by the traditional formulations by a simple addition of the logarithm of cumulative expenses for research and development (R&D) in Eq. (2). This formulation implies that cumulative R&D expenses are a perfect substitute for commercial investments in the technology after its innovation in their effect on cost reduction. Attempts to estimate this specification have not resulted in satisfactory results, due mainly to the statistical and conceptual problems discussed previously.

Other studies have tried to decompose the cost reduction effect into its components, as explained in section II. Here, too, the statistical problems of serially correlated and integrated regression residuals and unit roots have not been solved. However, future research into such multivariate approaches is necessary and promising.

In this respect, it is also useful to work on temporal analyses of economic cost functions. Isoard and Soriat took a first step in this direction when they combined cost functions and learning curves to capture the simultaneous econometric estimation of learning by doing and returns to scale, endogenizing technical progress. A test for Granger causality establishes the causal relationship between deployment and cost reduction.

Other extensions are possible and should be explored. In theory, experience curves can be conceived for aspects other than energy unit costs. Other parameters that improve with cumulative deployment through continuous changes in the average technological design could be the efficiency of energy conversion or the emissions of pollutants from a conversion process. For these, too, the average improvement over time could be modeled with exponential decay functions. Linking these results back to the unit cost can give additional insights into the nature of cost reduction processes.

For future research, it is important to strengthen the foundation of the concept. One such avenue is linking the concept to the life cycle analysis of technologies. The life cycle of a technology starts with the invention of a new technological concept. The concept is simulated and prototyped before the actual innovation. The innovation itself consists of the first commercial application of the technology. For energy technologies, this often happens in niche markets (e.g., aeronautics). The innovation is followed by a diffusion phase, when the market penetration of the technology increases, often along a similar (logistic) path as followed by the sinking cost of the technology. The forces effecting such a diffusion pattern can theoretically be subdivided into supply–push and demand–pull forces. Therefore, market forces and the economic environment should be included in deriving a better founded concept for the cost reduction of new energy technologies.

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Further Reading

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