Working Paper

Diffusion and Learning Curves of Renewable Energy Technologies

Lena Christiansson

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Abstract

In this analysis, experience (or learning) curves are used to study future potentials and obstacles for the diffusion of renewable energy technologies. Experience curves describe improvements in technology as a result of gaining experience in producing and using a technology (learning). These evolutionary technology improvements and cost reductions are (among other factors) important driving forces for the diffusion of new technologies. Experience curves have been used for several years within many industries and are applied here as a method for describing possible dynamics in the introduction of renewable energy technologies. In a comparison using the experience curves, wind technology seems to have comparatively less difficulties entering the energy market, while photovoltaic technology will require higher cost reductions (learning) than measured today and/or huge market volume growth. The analysis also shows that, given adequate support, renewable energy technologies could meet much of the growing future energy demand, contributing to a new energy era.

Table of Contents

1. Introduction

The demand for energy is likely to increase over time with population growth and as the global economy expands. However, present energy systems based on fossil fuels cause a range of environmental problems including the greenhouse effect, acidification, photochemical smog, etc. A sustainable, environmentally compatible development will therefore require a new energy system whose emphasis should be placed on efficient energy use and renewable energy sources.[1]

The objective of this paper is to highlight the importance of the diffusion of new technologies to achieve a sustainable energy future with a focus on new renewable energy technologies. Diffusion theory has been used before to study the origins, adoption, and effects of the spread of innovations; in this paper it will be applied to renewable energy technologies. One of the most important findings from diffusion research is that technologies change during the diffusion process.[2] In fact, the dynamic nature of technologies is one of the most important factors for sustaining the diffusion process. A closer examination of the dynamic transformation of technology shows that it includes improved performance, widening fields of applications, and cost reductions in technology production (learning by doing) and use (learning by using). The driving factors of technological change and diffusion can be presented as a dynamic interaction of both "demand pull" and "technology push" factors.[3]

In this paper two factors for the diffusion of renewable technologies are discussed: the market potential and the experience (or learning) curve. The *market potential* illustrates the potential of a demand pull-effect, and the *experience curve* illustrates learning effects in the supply of technology, i.e. reductions in the production costs of renewable technologies (as example of a technology push factor). To describe learning effects, learning curves have been used for several years within many industries; learning curves in a generalized form are called *experience curves*.[4,5,6] One reason why experience curves are a good tool for analyzing the possible diffusion of renewable energy technologies is that the dynamics of renewable energy technologies can be compared to the development of other new energy technologies, rather than to the development of conventional energy technologies. In contrast to large conventional energy facilities which require extensive construction in the field, most renewable energy technologies can be constructed in factories. Therefore, these technologies are more similar to mass-production technologies than to conventional power plants. This means modern manufacturing techniques that could lead to cost reduction because of assembly-line production, economies of scale, standardization, etc.

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[1]"UNCED Rio Declaration", *United Nations Conference on Environment and Development*, Rio de Janeiro, 1992.
[2]N. Nakicenovic and A. Grübler (eds), *Diffusion of Technologies and Social Behavior*, Springer Verlag, Berlin, 1991. D. Foray and A. Grübler, "Morphological Analysis, diffusion and lock-out of technologies: Ferrous casting in France and the FRG", *Research Policy* 19(6):535-550.
[3]C. Freeman, "The Economics of technological change", *Cambridge Journal of Economics*, 18: 463-514, 1994.
[4] F. Krawiec and J. Thornion, *Investigation of Learning and Experience Curves*, Solar Energy Research Institute, Golden CO, USA, April 1980.
[5]L. Argote and D. Epple, "Learning curves in manufacturing", *Science*, Vol. 247 No. 4945:920-924, 23 February, 1990.
[6]D. Sahal, *Patterns of Technological Innovation*, Addisson-Wesley, Reading, Mass., 1981.

2. Experience (Learning) Curves

Experience curves describe how unit costs decline with cumulative production. The latter is used as a proxy for the accumulated experience or learning in production. Experience curves have frequently been used for example in processing industries and in industries involved in mass production of consumer durables. The cost reduction described with the experience curve is related to many factors including economies of scale in production, process improvements, learning-by-doing, and reduction in raw material costs.[7] The experience curve can be described with the following function:

$$C(x)=a*x^{-b}$$

C= cost (or labor input) per unit of output
a= cost of first produced unit
x= cumulative production over time
b= learning index

The learning index, b, can be used to calculate the rate at which cost declines each time the cumulative production doubles, $1-2^{-b}$, where the value of 2^{-b} is called the progress ratio. A progress ratio of 80%, for example, means that the costs are reduced to 80% each time the cumulative production is doubled. In Table 1 progress ratios for a sample of technologies/products are presented, divided into three categories: big plants, modules, and continuous operation. The three categories represent three different economies of scale that yield cost reductions. The first category (*big plants*) represents economies of scale due to upscaling of units, e.g. larger boilers and generators per power plant. The second category (*modules*) represents economies of scale due to mass production of identical units such as automobiles and semiconductors. The third category (*continuous operation*) is a combination of the first two categories, representing continuous production of standardized commodities in large scale units, e.g. chemicals or plastics. In Figure 1 the distribution of the progress ratio is divided into these three categories and is compared to an earlier published distribution function of progress ratios in 108 industries.[8]

When costs (and prices) fall in accordance with the experience curve theory, the total market for the product expands and the rate of adoption accelerates. Moreover, when market pull and the adoption rates increase, production increases and prices decline, i.e. cost depends on the adoption rate of a new technology/product and vice versa (a positive feedback effect). Price reductions, however, are not the only factor stimulating product sales. In addition, design, performance, functions, user-friendliness, and durability are also important. Moreover, the process of adoption of new technology can cause a breakthrough for innovative firms, which leads to further accumulation of knowledge (innovative firms grow faster than non-innovative) and, often, expanded research programs which are oriented towards further technology and product improvements.

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[7]The experience curve must be recognized as an aggregate description of the evolution of an industrial activity rather than a description of every possible cause of learning. In a macroscopic viewpoint, the cause of the experience curve phenomenon can be related to the major events that have taken place during the evolution of an industry.
[8]L. Argote and D. Epple, "Learning curves in manufacturing", *Science*, Vol. 247 No. 4945:920-924, 23 February, 1990.

One important consideration, however, is that the rate of learning can change over time. For instance, experience curves can often be divided into two phases — a start-up (or R&D) phase and a steady state (or production) phase. The start-up phase can be connected to intensive RD&D programs resulting in steep experience curves and relatively high cost reductions. This phase is followed by a steady state (production or commercialization) phase, where cost reductions per cumulative output is often lower than in the R&D phase. One example is the progress ratio for electricity produced in the US., which was 0.71 between 1930-50, and 0.77 between 1950-70.

Table 1. Range of progress ratios for three types of products/technologies and economies of scale.

	High	Average	Low
Big Plants[a]	0.80	0.87	0.90
Modules[b]	0.70	0.83	0.95
Continuous operation[c]	0.64	0.78	0.90

[a]Based on: Nuclear,[9] gas turbines,[10] steam turbines,[11] coal burning generating units[12]
[b]Based on: Electronics, [13,14,15] consumer durables,[16,17] Model-T Ford,[18,19] air-frames[20]
[c]Based on: Alcohol production,[21] refineries,[22,23] plastic production,[24,25] metal production[26]

[9]M. B. Zimmerman, "Learning effects and the commercialization of new energy technologies: the case of nuclear power", *The Bell Journal of Economics*, Vol. 13, No. 2:297-310, 1982.

[10]P.R. MacGregor, C.E. Maslak, and H. G. Stoll, *The Market Outlook for Integrated Gasification Combined Cycle Technology,* General Electric Company, Schenectady N.Y., USA, 1991.

[11]D. R. Clair, *The Perils of Hanging on,* European Petrochemical Association 17th Annual Meeting Monte Carlo, September 28-28, 1983.

[12]P.L. Joskow, and N. L. Rose, "The effects of technological change, experience, and environmental regulation on the construction cost of coal-burning generating units", *Rand Journal of Economics,* Vol. 16, No. 1:1-27, 1985.

[13] F. Krawiec, and J. Thornion, *Investigation of Learning and Experience Curves,* Solar Energy Research Institute, Golden Co, USA, April 1980.

[14] D.R. Clair, *The Perils of Hanging on,* European Petrochemical Association 17th Annual Meeting Monte Carlo, September 28-28, 1983.

[15] Bonneville Power Administration, *Comparative Electric-generation Study,* Final report, Volume II, Golden Co, USA, 1980

[16]F. Krawiec, and J. Thornion, *Investigation of Learning and Experience Curves,* Solar Energy Research Institute, Golden Co, USA, April 1980.

[17] F.M. Bass, "The relationship between diffusion rates experience curves and demand elasticities for consumer durable technological innovations", *Journal of Business,* 53(2):S51-S67, 1980.

[18] W.J. Abernathy, and K. Wayne, "Limits of the Learning Curve", in: *Readings in the Management of Innovation,* M.L. Tushman and W.L. Moore (eds), Ballinger Publishing Company, 1982.

[19] Bonneville Power Administration, *Comparative Electric-generation Study,* Final report, Volume II, Golden Co, USA, 1980.

[20]D.L. Bodde, "Riding the experience curve", *Technology Review,* March/April 1976:53-59.

[21]Figures from alcohol production in Brazil, J. Goldemberg, Universidade de Sao Paulo Instituto de electrotécnica e energia, private communication, 1994

[22]F. Krawiec, and J. Thornion, *Investigation of Learning and Experience Curves,* Solar Energy Research Institute, Golden Co, USA, April 1980.

[23]J.C. Fisher, *Energy Crises in Perspective,* John Wiely & Sons, New York, 1974.

[24]F. Krawiec, and J. Thornion, *Investigation of Learning and Experience Curves,* Solar Energy Research Institute, Golden Co, USA, April 1980.

[25]D.R. Clair, *The Perils of Hanging on,* European Petrochemical Association 17th Annual Meeting Monte Carlo, September 28-28, 1983.

[26]F. Krawiec, and J. Thornion, *Investigation of Learning and Experience Curves,* Solar Energy Research Institute, Golden Co, USA, April 1980.

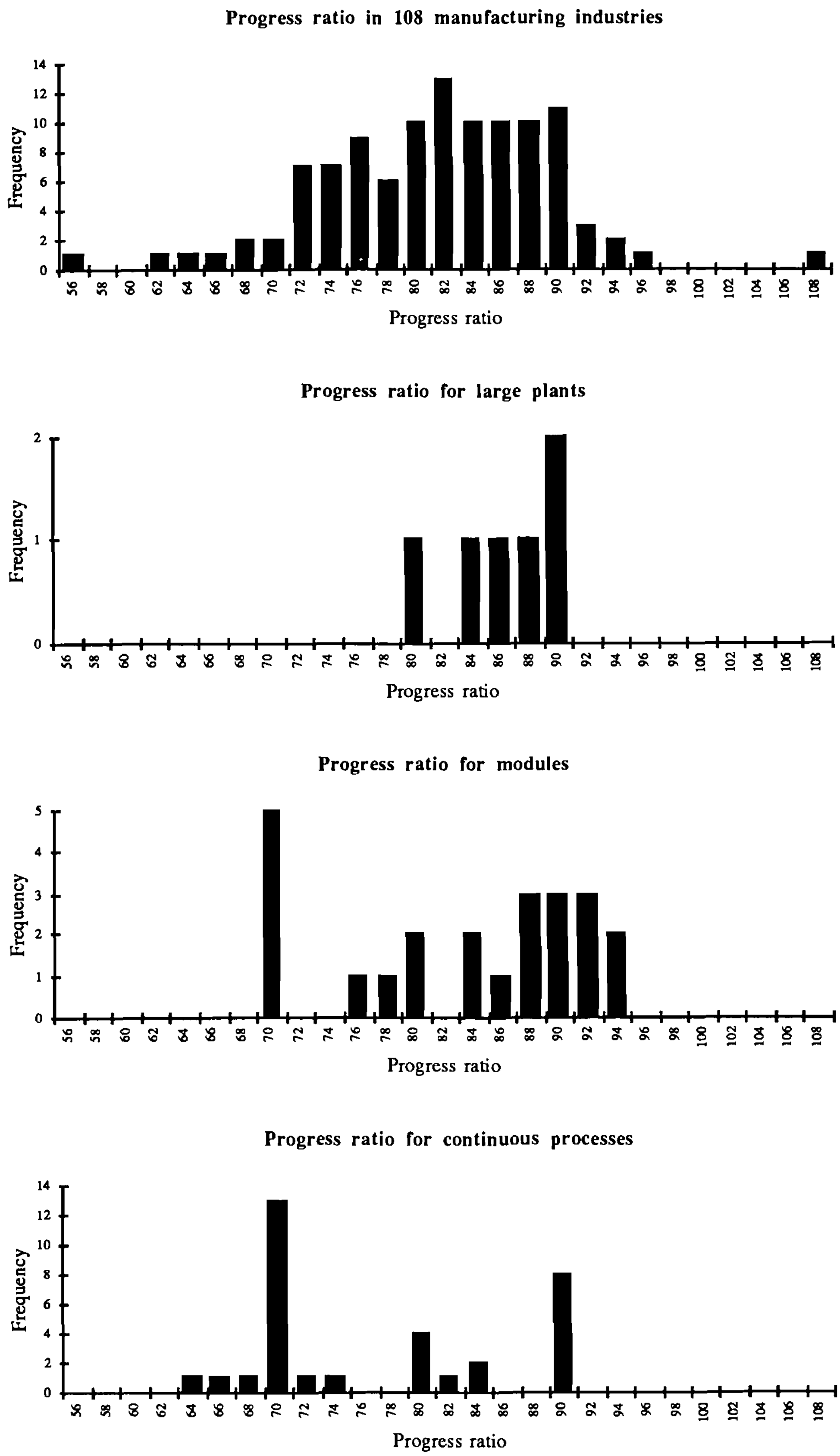

Figure 1. Distribution of progress ratios for 108 manufacturing industries (Argote and Epple 1990), big plants, modules, and continuous processes (see also Table 1).

It is noteworthy that the highest learning effects are to be observed for continuous operation processes that combine economies of scale effects (big plants) and economies from mass production of standardized units (modules). In the most extreme case of Table 1 unit costs decline 36 percent for each doubling of cumulative output (progress ratio: 0.64). Conversely both big plants and modules display less dynamic learning effects, with the distribution of progress ratios for modules being wider compared to big plants. This simple taxonomy of progress ratios may be useful to derive scenarios for possible learning effects of new technologies.

However, it should also be pointed out that the use of experience curves has its limits. The theory of experience curves assumes a standardized product that remains largely unchanged over the time period of the experience curve (a typical example would be a particular aircraft model). This is not always the case, as products change over time.[27,28] For instance, prices can also rise with cumulative production. This would be the case when, for example, costs cannot be reduced as fast as costs are added through design changes and product performance improvements. One example of this is the cost of the Ford car, which has increased since the 1930s (i.e. *after* the spectacular declines in costs and prices of the Model T Ford).[29] Ever since, design changes such as improved comfort, performance, and safety -as reflected in frequent model changes- have tended to rise costs. Another example of increasing costs with cumulative production is the increased generating costs of electricity ever since the 1970s, due to *inter alia* due higher oil and energy prices.[30]

3. Changes in Energy Supply

In the last two centuries there have been important changes in the world's energy system. Energy sources have shifted from wind, water and wood to coal, oil, and natural gas. The fundamental driving forces for the switch from traditional energy resources to steam-power technologies in the 19th century and electricity systems in the late 19th century are related to industrialization, electrification, and changes in consumption patterns.[31] Figure 2 presents these shifts in the structure of global primary energy over time.

The success of a future shift to renewable energy sources and environmentally friendly technologies is difficult to predict. How fast and how far these new energy technologies could penetrate the energy market depends on how integral they are to current (and future) patterns of industrial development. One of the reasons why renewable energy technologies have not made an impact so far is that they are not able to compete with cheap fossil-based technologies. For that reason is it important to look at the cost reduction potential and at the institutional factors that could promote or restrict the application of new renewable technologies.

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[27] F. Krawiec, and J. Thornion, *Investigation of Learning and Experience Curves*, Solar Energy Research Institute, Golden CO, USA, April 1980.

[28] C. Burnet, "The effect of aircraft size and complexity on the production learning curve", in: Industrial Applications of Learning Curves and Progress Functions, *Proceedings No. 52 Institution of Electronic and Radio Engineers*, pp. 147-159, London, 1981.

[29] W. J. Abernathy, and K. Wayne, "Limits of the learning curve", in: *Readings in the Management of Innovation*, M.L. Tushman and W.L. Moore (eds.), Ballinger Publishing Company, 1982.

[30] J. C. Fisher, *Energy Crises in Perspective*, John Wiely & Sons, New York, 1974.

[31] A. Grübler, Industrialization as a Historical Phenomenon, Working Paper 95-29, IIASA, Laxenburg, Austria, March 1995.

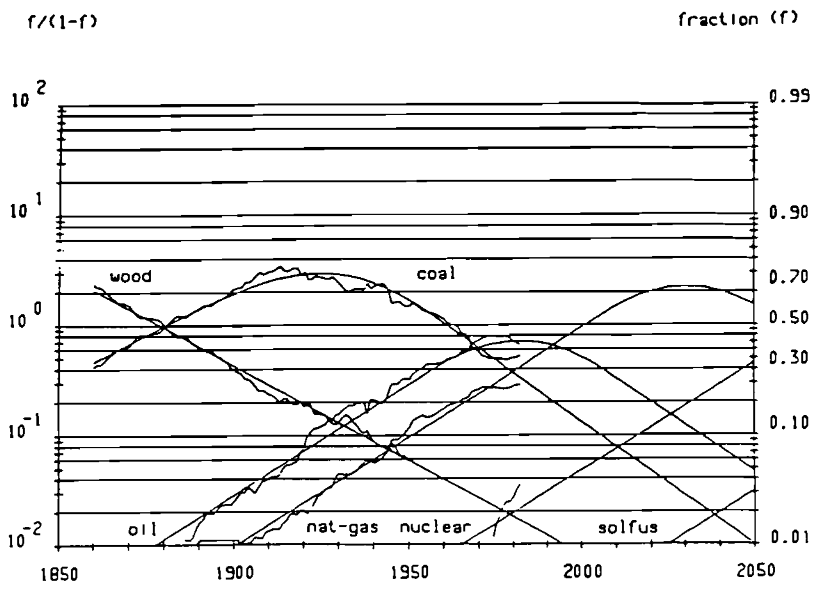

Figure 2. Substitution of primary energy sources in the world: 1850-2050.[32]

The most promising renewable energy resources are hydro, solar, wind, and biomass. At present hydropower provides close to 20% of the world's electricity[33], but hydro resources could represent a larger potential for the world energy supply in the future. With regard to wind, solar, and non-traditional biomass, their technologies have emerged on the energy market only very recently. However, the energy supply potential for these new energy resources is in the range of hydro, see Table 2.

Table 2. Annual renewable energy potentials by 2020-2030, and 2100. The figures present the results of a literature review where potentials in the upper boundary are chosen to represent the maximum potential of secondary or primary energy (see Appendix A). Energy use in 1985 is from Dessus 1992.[34]

	Hydro (Sec) (TWhe)	**Wind** (Sec) (TWhe)	**Solar** (Sec) (TWhe)	**Solar** (Prim) (Mtoe)	**Biomass** (Prim) (Mtoe)
1985	2020	5	-	18	890
2020	4500	4900	1400	500	3200
2100	14000	7600	20900	4700	7900

Note: Total primary energy use in 1990 was about 9000 Mtoe.

[32]N. Nakicenovic, *Decarbonization: Doing More with Less*, Working Paper 93-76, IIASA, Laxenburg, Austria, December 1993.

[33]IPCC, Working Group IIa, *Energy Supply Migration Options*, Zero order draft, 4 May 1994, IPCC, Geneva.

[34]B. Dessus, B. Devin, and F. Pharabod, *World Potential of Renewable Energies*, Extraits de la Houille Blanche No. 1, Paris, 1992.

4. Experiences with Renewable Technologies

In recent years substantial progress has been made in the development and implementation of renewable energy technologies. In this section experience curves yielding cost reductions for two important renewable energy technologies, wind and photovoltaic (PV) will be analyzed.

4.1 Wind Technology

Since the mid-seventies, progress has been made in the development of wind turbines for electricity production, and in the early eighties the first modern grid-connected wind turbines were installed. Today approximately 20,000 high efficiency wind turbines are installed globally with a capacity of nearly 3,000 MW, of which approximately 1,500 MW is in the USA and 1000 MW in Europe.[35] [36]

Since the birth of the wind power industry in the mid-seventies, its innovation process can be described as a continuous chain of incremental product innovations. Over a few years, remarkable improvements in performance were gained, mainly due to improved design and production methods, higher towers (giving access to higher wind speeds), larger rotor diameters (i.e. larger swept areas), improved aerodynamic profiles of rotor blades, and optimization of rotor speeds and blade angles. At the same time, weight per installed kW was reduced to save materials and costs, reliability increased, and better wind resource estimation techniques enabled improved siting of wind turbines.

The efficiency of a wind power plant, measured as the fraction of the kinetic energy extracted from the air flow through the area swept by the wind turbine's rotor blades, has increased by about 50 percent as compared to the commercial wind turbines installed in the mid-1970s.[37] The maximum and average efficiencies of today's windmills are 45% and 35%, respectively .[38,39] Moreover, the technical availability (the capability to operate when the wind is higher than the starting wind speed of the machine) has increased to about 95-99%.[40]

Taken together, many small engineering improvements and a variety of other incremental improvements have led to steady cost reductions. Further cost reductions in the future can be achieved by both a reduction in capital cost and by increased energy output. Advances in wind turbine technology in the next 20 years will probably include new combinations of materials, advanced air foil designed, variable speed drive, technological improvements in production, less expensive transmission from remote wind turbine sites,

[35]World Energy Council, *Renewable Energy Resources: Opportunities and Constraints 1990-2020*, Report 1993, WEC, London.
[36]A.J.M. van Wijk, and J.P. Coelingh, *Wind Power Potential in the OECD Countries*, Utrecht, 1993.
[37]S. Frandsen, and C.J. Christensen, "Accuracy of estimation of energy production from wind power plants", *Wind Engineering* Vol. 16, No 5:257-268, 1992.
[38]S. Frandsen, and C.J. Christensen, "Accuracy of estimation of energy production from wind power plants", *Wind Engineering* Vol. 16, No 5:257-268, 1992.
[39]To increase the efficiency to the theoretical maximum, conventionally assumed to be 59%, would increase the marginal cost considerably. See S. Frandsen, in: IPCC WG IIa.
[40] IPCC, Working Group IIa, *Energy Supply Mitigation Options*, Zero order draft, 4 May 1994, IPCC, Geneva.

longer lifetimes, etc. Introduction of stall-controlled and variable speed rotors to take full advantage of different wind characteristics would allow an energy capture of approximately 50%.[41]

In the seventies two different strategies for designing windmills were followed. One concept was to produce an essentially new mill, implying a major technological advance. In countries like Germany, the USA, and Sweden, big windmills of about 1 MW were designed and built. However, none of these project were commercially successful. In some other countries, like Denmark and some parts of the USA, another more incremental strategy as followed, starting with small (about 10 kW), well-understood windmills of the early 70s, and upscaling them gradually over time (Table 3). This strategy enabled significant learning effects and cost reductions. As a result, wind turbines of up to 500 kW are today commercially available from several manufacturers.

In the future it would be conceivable to commercialize 600-1500 kW wind turbines in order to increase the installation of windmills in areas with scarcity of land. Today research in the European Community focuses on wind turbines with sizes exceeding 750 kW.[42] However, siting of wind turbines offshore in coastal regions is also an option for the future, that could provide for higher energy densities. Although wind is one of the fastest growing sources of electricity, the need for long-distance transmission can be a problem.[43] An alternative in the future to the long-distance transmission of electricity is the possible use of hydrogen as an energy carrier. The importance of reducing negative environmental effects of wind turbines like noise, disturbance of wildlife (e.g. birds), telecommunication interference, etc. must also be addressed.

Table 3. The size (kW) of commercial windmills in Denmark and California 1979-1991.

	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
Average size Denmark [44]	17	25	32	47	50	55	67	92	106	177	165	192	194
Average size California [45]			50						110			160	194
Size of new mills		(55)					(75-150)			(225-250)		(400-500)	

[41]P.D. Andersen, *En analyse af den teknologiske innovation i dansk vindmølleindustri*, Handelshøjskolen i København, Samfundslittreatur, Kopenhagen, Denmark, 1993.
[42]A.J. Cavallo, S.M. Hock, and D.R. Smith, "Wind energy: technology and economics", in: *Renewable energy - Sources of Fuels and Electricity*, T.B. Johansson, H. Kelly, A.K.N. Reddy and R.H. Williams (eds.), Island Press, Washington D.C., USA, 1993.
[43]A.J. Cavello, R.H. Williams, and G. Terzian, *Baseload Wind Power from the Great Plains for Major Electricity Demand Centers*, draft paper, Princeton University, Princeton, NJ, USA, 1994.
[44]P.D. Andersen, *En analyse af den teknologiske innovation i dansk vindmølleindustri*, Handelshøjskolen i København, Samfundslittreatur, Kopenhagen, Denmark, 1993.
[45]A. Loose, "The US wind energy Program", in: *Proceedings Amsterdam EWEC 91*, Elsevier, Amsterdam, The Netherlands, 1992, Part 2, pp. 191-195.

California
The Californian wind-power market boomed in the first part of the 1980s when installation rates increased from 10 MW in 1981 to 400 MW in 1984.[46] Tax incentives and favorable regulations supported the rapid installation of wind-power systems. One example was the PURPA Act, which mandated that utilities buy energy at its full avoided cost from independent generators, thus ensuring a market for wind generated electricity. During this time the US market accounted for 90% of the world market. The rapid market growth caused however also implementation of poor quality wind-power systems, but overall performance improved during the period.[47] In 1986 the state and federal tax credits were removed at the same time as the oil price declined. However, because of favorable wind resources and good electricity payback, the market was still there. At this time California started to import windmills from Denmark. The American market started to expand again in the late 1980s as a result of increasing environmental concerns, regained confidence in the technology and new and improved technology.[48]

Denmark
The wind-power industry in Denmark, founded in a stable home market, has been characterized by entrepreneurship and technological innovation in a large number of small enterprises. Government R&D programs for wind power were initiated in the mid-1970s, and a test station was established which later set the standard for windmills to ensure quality control. To stimulate a market, capital costs of a certified wind turbine was refunded. This subsidy was, however, gradually decreased as windmills became cheaper and more reliable. The Danish government also regulated the price the utilities had to pay for wind-generated electricity as well as the price paid by windmill owners for being connected to the grid.

The Danish wind-power market has been stable over time except for the period 1984 to 1988, when Danish turbines supplied half of the Californian market. Danish firms with well-established competence had a significant success in California, acquiring approximately 60% of the market share in 86/87.[49] However, the declining dollar and the withdrawal of wind subsidies in California created severe financial difficulties for the Danish wind-power industry. In 1991 Denmark completed the first offshore wind farm with 11 turbines, each with a power of 450 kW.[50] The cost for these offshore mills is, however, twice as high as that for land-based windmills. However, at the same time they produce twice as much energy.[51]

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[46]M.J. Grubb, and N.I. Meyer, "Wind energy: resources, systems, and regional strategies", in: *Renewable Energy - Sources of Fuels and Electricity*, T.B. Johansson, H. Kelly, A.K.N. Reddy and R.H. Williams (eds.), Island Press, Washington D.C., USA, 1993.
[47]R. Kemp et al., *Technology and the Transition to Environmental Stability - Continuity and Change in Technological Systems*, Report, MERIT, Maastricht, the Netherlands, May 1994.
[48]P.D. Andersen, *En analyse af den teknologiske innovation i dansk vindmølleindustri*, Handelshøjskolen i København, Samfundslitteratur, Kopenhagen, Denmark, 1993.
[49]P.D. Andersen, *En analyse af den teknologiske innovation i dansk vindmølleindustri*, Handelshøjskolen i København, Samfundslitteratur, Kopenhagen, Denmark, 1993.
[50]M.J. Grubb, and N.I. Meyer, "Wind energy: resources, systems, and regional strategies", in: R*enewable Energy - Sources of Fuels and Electricity*, T.B. Johansson, H. Kelly, A.K.N. Reddy and R.H. Williams (eds.), Island Press, Washington D.C., USA, 1993.
[51]S. Frandsen, Risø National Laboratory, Denmark, personal communication, 1994.

4.2 Photovoltaic (PV) Technology

Photovoltaic (PV) modular systems convert sunlight into DC electricity by solar cells that consist of semi-conductive materials. These modular systems can be located near the end user, and reduce transmission and distribution costs while increasing the reliability of service. In contrast to other energy technologies, photovoltaic modules have no moving parts and operate quietly, with no emissions. Also, the modules are small-scale systems, do not require on-site personnel continuously and need only modest maintenance.

Photovoltaic applications were introduced on the energy market in the early 1970s.[52] From then until 1985 the US dominated the PV market. However, in 1990 when world-wide PV sales reached 48 MW, Japan was the leading country on the PV market with 16,8 MW installed compared to the US (14.8 MW), Europe (10.2 MW), and the rest of the world (4.7 MW).[53]

Since the introduction of PV systems, improvements have been made in materials, conversion efficiencies, and manufacturing technologies. The efficiency of the first photovoltaic cells was not more than 10%, but in 1985 newly designed silicon cells reached conversion efficiencies above 20%.[54] Today the conversion efficiency of single crystal PV system reaches a peak of 30% .[55] Parallel to the efficiency improvements, unit costs of the PV modules have declined fifty-fold since 1970, to around $6,000 per kilowatt peak.[56] The cost of the inverter and control systems required in PV installation has also been reduced significantly by recent advances in solid-state electronics.

From the single crystal PV, two new classes of PV technologies have been developed that offer good prospects for future improvements and reductions in PV costs. One is thin film modules which are used in flat-plate PV systems, where a thin film of active material is placed on a carrying substance.[57,58,59] The other new technology is concentrating modules[60], using low-cost optical systems to concentrate sunlight on comparatively small, high-efficiency cells. The conversion efficiency of single crystal PV systems today

[52]Before that date PV cells were used already within the US space program.

[53]P.D. Maycock, "International PV markets, development and trends", *10th European Community PV Solar Energy Conference*, May 1991, European Community, Brussels, pp. 1396 ff.

[54]J.J. Loferski, "The first forty years: a brief history of the modern photovoltaic age", *Progress in Photovoltaics*, vol. 1, No. 1, Jan. 1993.

[55]World Energy Council, *Renewable Energy Resources: Opportunities and Constraints 1990-2020*, Report 1993, WEC, London.

[56]D. Anderson, and R.H. Williams, *The Cost-effectiveness of GEF Projects*, Working paper Number 6, GEF Documentation (Global Environment Facility), Washington D.C., USA, 1993.

[57]Thin film PVs are suitable for use in central stations or distributed applications in many areas that have even moderate insulation.

[58]K. Zweibel, and A.M. Barnett, "Polycrystalline thin film photovoltaics", in: *Renewable Energy - Sources of Fuels and Electricity*, T.B. Johansson, H. Kelly, A.K.N. Reddy and R.H. Williams (eds.), Island Press, Washington D.C., USA, 1993.

[59]D.E. Carlson, and S. Wagner, "Amorphous silicon photovoltaic systems", in: *Renewable Energy - Sources of Fuels and Electricity*, T.B. Johansson, H. Kelly, A.K.N. Reddy and R.H. Williams (eds.), Island Press, Washington D.C., USA, 1993.

[60]E.C. Boes, and A. Luque, "Photovoltaic concentrator technology", in: *Renewable Energy - Sources of Fuels and Electricity*, T.B. Johansson, H. Kelly, A.K.N. Reddy and R.H. Williams (eds.), Island Press, Washington D.C., USA, 1993.

is 23-33 %.[61] The thin film cells have been developed in order to lower prices by applying only small amounts of PV active material. However, for this PV system, consisting of amorphous silicon on metal, glass or plastic substance, conversion efficiencies are somewhat lower, at about 12%.[62] Hence, thin film PV systems are less efficient than concentrating systems; on the other hand, they are less capital intensive.

The main goal of future PV technology R&D is to reach higher efficiencies and lower costs. Silicon point contrast cells have already reached 30% peak efficiency and higher figures can be achieved in a multijunction cell, where every layer collects a different part of the solar frequency spectrum.[63] Concerning thin-film devices, new materials under development show good prospects for achieving higher efficiency as well. For concentrator systems, future efficiency depends both on the improvements of efficiency of the optical concentrators and on the improvements of efficiency of the cell. Efficiency will no doubt increase in future technologies, because the efficiency of commercial PV cells is about half the efficiency of cells demonstrated in recent laboratory tests, and far below theoretical limits.[64]

To reduce costs it is important to find new materials as well as to find ways to mass-produce large amounts of active PV material. The thin-film systems are especially well-suited for high volume manufacturing because the costly batch process of single-crystal production can be replaced by a continuous process. However, the price reductions of PV systems also depend greatly on such low-technology problems as weatherproofing cells and mounting them in the field. Another interesting development is systems that can follow the sun, capturing significantly more energy than fixed systems.

4.3. Experience Curves for Renewable Technologies.

The experience curve of windmills in the US is presented in Figure 3. The progress ratio of the curve is 0.84, i.e. for each doubling of cumulative sales costs are reduced by 16 percent. This US figure corresponds well to progress ratios estimated for windmills by Eldringe and Jacobsen in 1980. A comparable progress ratio for Danish windmills is not so easy to estimate, considering that prices of Danish windmills have fluctuated greatly. The reason for these price fluctuations could be the interaction of learning effects, resulting in decreasing costs, vis-à-vis quality improvements, the increasing size of mills, and the employment of more expensive lightweight materials.

The experience curves of PV cells in the US and in Japan are presented in Figure 4. The progress ratios of the PVs in the US and in Japan are estimated as 0.82 and 0.81, respectively, i.e. learning effects and cost reductions in PV technologies operate at similar rates in the two countries.

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[61]E.C. Boes, and A. Luque, "Photovoltaic concentrator technology", in: R*enewable Energy - Sources of Fuels and Electricity*, T.B. Johansson, H. Kelly, A.K.N. Reddy and R.H. Williams (eds.), Island Press, Washington D.C., USA, 1993.
[62]J.J. Loferski, "The first forty years: a brief history of the modern photovoltaic age", *Progress in Photovoltaics*, vol. 1, No. 1, Jan. 1993.
[63]World Energy Council, *Renewable Energy Resources: Opportunities and Constraints 1990-2020*, Report 1993, WEC, London.
[64]H. Kelly, "Introduction to photovoltaic technology", in: R*enewable Energy - Sources of Fuels and Electricity*, T.B. Johansson, H. Kelly, A.K.N. Reddy and R.H. Williams (eds.), Island Press, Washington D.C., USA, 1993.

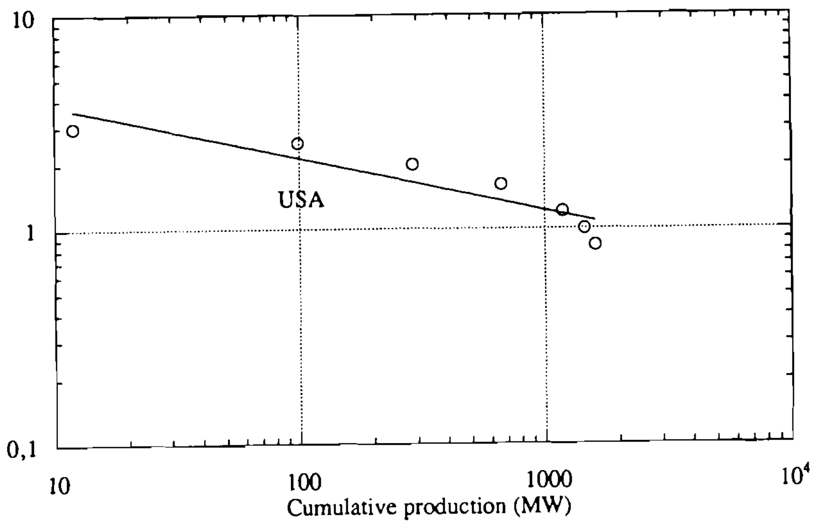

Figure 3. Experience curve of windmills in the US 1981-1987.[65]

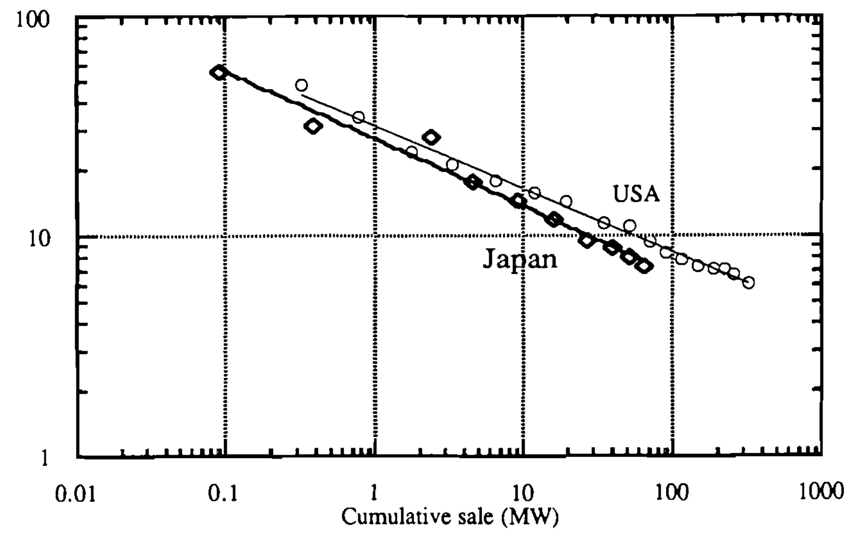

Figure 4. Experience curves of PV cells in the US 1976-1992[66] and in Japan 1979-1988.[67]

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[65]World Energy Council, *Renewable Energy Resources: Opportunities and Constraints 1990-2020*, Report 1993, WEC, London.

[66]R.H. Williams, and G. Terzian, *A Benefit/cost Analysis of Accelerated Development of Photovoltaic Technology*, Center for Energy and Environmental Studies, Princeton University, Report No. 281, Princeton, NJ, USA, 1993.

[67]H. Tsuchiya, *Photovoltaics Cost Analysis Based on the Learning Curve*, Research Institute for Systems Technology, Tokyo, Japan, 1992.

4.4. Cost data

Forecasts of future costs for new energy technologies have been made in several studies, in order to analyze the possible introduction of new renewable energies. In Table 4 a survey of present investment costs (1990) and assessments for future investment costs for gas turbines, windmills, and photovoltaic cells are presented. Prices have also decreased compared to 1990. One example is the investment cost of wind technology, where in 1993 the cost of an average new wind technology investment was approximately 1200 $US/kW and the cost of the best new technology was 900 $US/kW. In Table 4 costs for offshore windmills are not included, but it ought to be mentioned that their price is twice that of onshore windmills.

Table 4. Average and range of investment for gas turbines, windmills, and PV cells in 1990 and cost estimates for the future. Cost data from IIASA's CO2DB database[68].

Technology		Cost ($/W) average	Cost ($/W) range
Gas turbines	*1990*	0.65	0.35-1.0
	Future	0.45	0.25-0.70
Windmills	*1990*	1.5	1.3-1.9
	Future	1.3	0.85-1.9
PV cells	*1990*	9.0	8.0-10.5
	Future	3.0	1.0-4.5

5. Analysis

Diffusion of renewable energy technologies will depend *inter alia* on technology improvements and cost reductions, i.e. learning effects. As shown in Figures 3 and 4 the experience curves of wind and PV technologies point to progress ratios of 0.84 and 0.81-0.82, respectively. However, these progress ratios may differ slightly for different countries and producers. As mentioned before, the future rate of learning can decline as well as rise. However, some measures can be made to affect the accumulation of field experience and organizational learning. One measure would be to accelerate RD&D investments, which would result in technological improvements and a steeper initial learning curve, i.e. an increase of cost reduction related to the increase of cumulative installation of new technologies.[69] The development of new technology can also be supported by special science and technology programs, and cooperative networks can be created between technology suppliers and research institutes.

In addition to stimulate learning, i.e. influencing the slope of the experience curve, to promote the diffusion of renewable energy technologies, costs can also be reduced through demand and market stimulation. This could be complemented with government procurement programs, regulation, tax policies, investment subsidies, utilities' payment of privately produced wind energy, etc. Especially with regard to renewable energy technologies, it could be useful to commit utilities to produce a certain amount of energy

[68]S. Messner, and M. Strubegger, *User's Guide to CO2DB: The IIASA CO2 Technology Data Bank Version 1.0*, Working Paper 91-31a, IIASA, Laxenburg, Austria, October 1991.
[69]R.H. Williams, and G. Terzian, *A Benefit/cost Analysis of Accelerated Development of Photovoltaic Technology*, Centre of Energy and Environmental Studies Princeton University, Princeton NJ, USA, 1993.

by means of different renewable energy technologies, or acquire a certain amount of renewable power capacity, in order to stimulate technological learning. However, the goal of speeding up the diffusion of renewable energy technologies has to be accompanied with developments in the infrastructure.

Concerning renewable energy technologies, niche markets could be a promising way to influence diffusion of renewable energy technologies. In these niche markets experience can be gathered to help firms to further improve the product. In a study made by Foray and Grübler (1990), it was pointed out that an early start of diffusion within specialized market niches is of extreme importance for RD&D so that, at a later stage, technologies can become cost effective and start to diffuse in the entire market.[70] Niche markets for wind and PV technologies have already appeared in areas where the energy requirements are small and therefore the costs of conventional electricity supply, either by grid extension or by diesel generators, are very high. An extension of niche markets for renewable energy technologies could lead to a cost reduction of the technology due to an increased market, but also to enhanced learning by both producers and users of the technology, i.e. to steeper learning curves.

Based on above-mentioned possible driving forces of technological learning and cost reductions, a sensitivity analysis of the cost reduction potentials of wind and PV technologies was performed. In Tables 5 and 6 the parameters "progress ratio" and "market growth" are varied for calculating (hypothetical) future costs of the technologies for the years 2025 and 2100. In this analysis wind is considered as a "big plant" technology (see Table 1); hence the progress ratio is varied between 0.8 and 0.9. This assumption of progress ratios is consistent with the average progress ratio of 0.84 measured in the US, see Figure 3. The market growth is assumed to be between two and five percent per year, where five percent represents powerful government intervention to increase the market for wind power. The future cost reduction scenario is based on data from year 1990 when installed wind capacity was approximately 2000 MW and average cost of wind technology 1.45$/W.

As can be seen from Table 5, the calculated cost decreases for wind technology compared to the average costs for 1990 vary from 10 to 42 percent in 2025, and from 28 to 81 percent in 2100. Taking into consideration that the prices of wind technology in 1990 varied from 1.25 $/W to 1.8 $/W, the variation in future cost reduction from Table 5 is in the same range.

Conversely, PV technologies are considered as "modules" technology (i.e. modular mass produced units) in the terminology of Table 1 given above. However, slightly narrower limits for the progress ratio are used in the sensitivity analysis here compared to Table 1 (progress ratios of between 0.70 to 0.90 instead of the range between 0.70 to 0.95 given in Table 1). The lower end of the assumed progress ratios for PV of 0.70 corresponds to the observed progress ratios of electronic circuits and heliostats, i.e. technologies that are structurally quite similar (eligible for economies of mass production and standardization). However, it must be pointed out that the progress ratio of PVs today is in the range 0.81-0.82 (see Figure 4). As in the case of wind technology, a market growth of two and five percent is assumed in the sensitivity analysis, and future cost reductions scenarios start

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[70] D. Foray, and A. Grübler, "Morphological analysis, diffusion and lock-out of technologies: ferrous casting in France and the FRG", *Research Policy*, Vol. 19 No. 6:535-550, 1990.

from data of the year 1990. For PV, the 1990 installed capacity is assumed to be 200 MW[71], and the average investment cost are assumed to amount 8.90 \$/W based on the data of the IIASA CO2DB[72].

Table 5. Investment cost (\$/W) of wind technology in 2025 and 2100 corresponding to the theory of learning curves. Initial cost of 1990 is set at 1.45 \$/W[73] and in installed capacity at 2000 MW[74].

WIND	Year	Market growth 2% per year	Market growth 5% per year
	2025		
Progress ratio: 0.80		1.16	0.84
Progress ratio: 0.85		1.23	0.97
Progress ratio: 0.90		1.31	1.12
(Cumulative GW)		*(4)*	*(17.5)*
	2100		
Progress ratio: 0.80		0.72	0.27
Progress ratio: 0.85		0.87	0.41
Progress ratio: 0.90		1.04	0.64
(Cumulative GW)		*(11)*	*(430)*

Table 6. Investment cost (\$/W) of PV cells in 2025 and 2100 corresponding to the theory of learning curves. Initial costs of 1990 are set at 8.9\$/W[75] and installed capacity at 200 MW[76].

PV	Year	Market growth 2% per year	Market growth 5% per year
	2025		
Progress ratio: 0.70		6.23	3.70
Progress ratio: 0.75		6.68	4.38
Progress ratio: 0.82		7.30	5.46
Progress ratio: 0.85		7.57	5.96
(Cumulative GW)		*(0.6)*	*(1.5)*
	2100		
Progress ratio: 0.70		2.90	0.56
Progress ratio: 0.75		3.60	0.96
Progress ratio: 0.82		4.77	1.91
Progress ratio: 0.85		5.34	2.53
(Cumulative GW)		*(2.5)*	*(60)*

[71]This figure is based on cumulative world photovoltaic shipments 1971-90, presented by C. Flavin in: *Vital Signs 1992 - Trends that are Shaping our Future*, eds. L.R. Brown, C. Flavin, H. Kane (eds), Worldwatch Institute, Washington D.C., USA, 1992.

[72]S. Messner, and M. Strubegger, *User's Guide to CO2DB: The IIASA CO2 Technology Data Bank Version 1.0*, Working Paper 91-31a, IIASA, Laxenburg, Austria, October 1991.

[73]S. Messner, and M. Strubegger, *User's Guide to CO2DB: The IIASA CO2 Technology Data Bank Version 1.0*, Working Paper 91-31a, IIASA, Laxenburg, Austria, October 1991.

[74]World Energy Council, *Renewable energy resources: Opportunities and Constraints 1990-2020*, Report 1993, WEC, London.

[75]This figure is based on cumulative world photovoltaic shipments 1971-90, presented by C. Flavin in: *Vital Signs 1992 - Trends that are Shaping our Future*, L.R. Brown, C. Flavin, H. Kane (eds), Worldwatch Institute, Washington D.C., USA, 1992.

[76]S. Messner, and M. Strubegger, *User's Guide to CO2DB: The IIASA CO2 Technology Data Bank Version 1.0*, Working Paper 91-31a, IIASA, Laxenburg, Austria, October 1991.

For PV technologies the calculated decrease of cost varies from 15 to 58 percent in 2025 and from 40 to 94 percent in 2100 (see Table 6). Taking into consideration a cost variation of PV's in 1990 between 7.7 $/W to 10.0 $/W, the calculated decrease of cost varies from 15 to 52 percent in 2025 and from 40 to 93 percent in 2100. As can be seen, the results depend very much on the assumed progress ratios and market growth, and less on the initial cost uncertainties. The cumulative installed MW required for the calculated cost reductions are in the range of 0.6 GW to 60 GW. For comparison, the nuclear installed capacity in 1990 globally amounted to some 360 GW, and for hydropower to some 600 GW.

Another point to be emphasized is that the commercialization of renewable technologies depends on the cost of energy produced. Renewable technologies will not be commercialized until the cost of produced energy for renewables is as low as the cost of energy produced from already commercialized (i.e. fossil) energy technologies. To what extent renewable technologies would have to be installed to decrease energy cost depends on the slope of the learning curve as illustrated in Tables 5 and 6 above. However, the cost of produced energy will not only depend on technology costs (i.e. investment costs) alone, but also on operation and maintenance cost, fuel cost, and, for renewables, the availability of sun, wind etc. However, to simplify the analysis in this paper only a comparison of investment costs was made to estimate the amount of installed capacity of wind and PV technologies required to make these technologies commercially viable. In a next step of the analysis, investment costs for wind and PV technologies are compared to the investment costs of gas turbines (Table 7).

Table 7. Increase in cumulative capacity (GW) required for wind power to decrease the investment cost of wind power to the current average investment cost of gas turbines (i.e. to 0.65 $/W, data from IIASA CO2DB). The initial investment costs for wind turbines in 1990 are given as average, higher and lower values, again based on the CO2DB.

WIND	Cost, lower bound (1990): 1.25$/W	Cost average (1990): 1.45$/W	Cost, upper bound (1990): 1.80$/W
Progress ratio: 0.80	15	20	50
Progress ratio: 0.85	30	60	150
Progress ratio: 0.90	150	400	1600

The average investment costs for gas turbines is estimated to be 0.65 $/W in the CO2DB.[77] In Tables 7 and 8 the calculated increase of installed capacity needed to commercialize wind and PV is presented. In other words, the tables present calculated increases in installed capacity needed to decrease investment costs via a range of progress ratios to the current average value of gas turbines (i.e. to 0.65 $/W). In the sensitivity analysis presented in the tables, both the progress ratio as well as initial costs in the base year 1990 is varied.

The results indicate that low progress ratios combined with high initial investment costs require a rather high cumulative capacity to be installed before the break-even point of

[77]S. Messner, and M. Strubegger, *User's Guide to CO2DB: The IIASA CO2 Technology Data Bank Version 1.0*, Working Paper 91-31a, IIASA, Laxenburg, Austria, October 1991.

equal investment costs with gas turbines is reached. Major barriers to introduction are discernible for wind technology if the progress ratio is only 0.9 (Table 7). For PV technology the corresponding value is 0.75 (Table 8) that is in fact more optimistic than the progress ratio of PV observed today. This indicates that with currently observed progress ratios for wind and PV, wind technology would come onto the market, but not PV technology.

Table 8. Increase in cumulative capacity (GW) required for PV cells to decrease the investment cost of PV cells to the current average investment cost of gas turbines (i.e. to 0.65 $/W, data from IIASA CO2DB). The initial investment costs for PV cells in 1990 are given as average, higher and lower values, again based on the CO2DB.

PV	Cost, lower bound (1990): 7.7$/W	Cost average (1990): 8.9$/W	Cost, upper bound (1990): 10$/W
Progress ratio: 0.70	35	45	55
Progress ratio: 0.75	100	150	200
Progress ratio: 0.82	1600	2600	4000
Progress ratio: 0.85	10000	20000	32000

However, using only the investment costs of gas turbines as a measure for required installation of renewable energy capacity is rather conservative, because energy costs from gas turbines depends greatly on fuel prices. The cost of electricity generated by wind and PV, on the other hand depends more on solar hours, the possibility to use diffuse solar light, wind potentials, prospects of using windmills when wind speed is relatively low or relatively high, land cost etc.. All technologies also require maintenance costs, which are generally assessed to be relatively low for PV's.

Using the theory of experience curves, an investment subsidy for promoting the diffusion of one technology rather than another can be calculated. Considering two different technologies with two different experience curves, the two curves will cut each other at a point where the unit cost of the technologies will be the same. The required installed capacity will depend on the progress ratio and the initial conditions of cost and installed capacity. The difference in total cost required to install such capacity can be calculated, indicating an investment subsidy to allow technological learning required for ultimate diffusion of one technology instead of another.

When comparing wind and PV technologies it can be shown that major investments are required to press the cost of PV technologies down to the cost of wind technologies. Even assuming a progress ratio of 0.9 for wind technology and 0.7 for PV technology, an additional ca. 1000 billion $US would need to be invested to lower the costs of PV technology to the same level as for wind technology. The PV cost after such a massive program stimulating technological learning would be 1.0 $/W, and the cumulative capacity that would need to be installed before reaching that break-even point amounts to approximately 20 GW. To decrease the investment cost of wind turbines to the same level as for gas turbines 1300 billion $US would be required, assuming a value of 50,000 MW gas turbines installed in 1990 and progress ratios of 0.85 and 0.91 for wind and gas turbines, respectively. The obtained break-even investment cost would be 0.56 $/W, and the cumulative wind capacity to be installed to reach the break-even point would amount to approximately 160 GW.

5. Conclusion

The analysis presented here indicates that experience curves can be used for estimating future cost reductions for renewable energy technologies and possibly for the timing and rates of their diffusion. However, the possibilities of predicting future progress ratios and market growth are limited. For that reason this study was constructed more as a sensitivity analysis than as an attempt to accurately forecast the diffusion of renewable technologies. In that way the analyses provided some insights on future possibilities and obstacles for the diffusion of renewable technologies. Furthermore, costs considered in the analysis presented here were only investment costs. This means that the results presented are preliminary as fuel costs for gas turbines were not included, nor were maintenance costs, land costs, solar and wind potentials etc..

The progress ratio, which represents the accumulation of experience and organizational learning leading to cost reductions, turns out to have a major influence on the future costs of renewable technologies and thus influences their diffusion potential. Wind technology, which today displays a progress ratio of 0.85, shows a tendency towards entering the energy market to a larger extent. PV technology according to this analysis, however, has to rely on better progress ratios of 0.7-0.75, than the progress ratio observed today, 0.81-0.82, in order to enter the commercial market. One measure for affecting the progress ratio would be to accelerate RD&D investments, which would result in technological improvements and steeper experience curves. Another possibility could be to focus on niche markets to increase technological learning. With regard to wind turbines, improved efficiency to reduce the land area required for windmills should be a priority.

How or to what extent the experience curves will or can be changed in the future is impossible to predict. However, it is shown that RD&D and niche markets increase the slope of the learning curve. In turn past experience suggests that when the technology enters the commercialization phase, the slope of the learning curve decreases. For simple gas turbines the commercialization phase started at 600 cumulative MW, and the progress ratio changed from 0.87 to 0.91.[78] Where the break point will be for wind and PV at present cannot be determined with any accuracy. If the gas turbine technology serves as a guide, the possible inflection point to a less steep learning curve could have been reached already for wind, with about 2000 MW installed in 1990, but not for PVs, with about 280 MW installed in 1990.

In addition to steeper experience curves, diffusion will depend on market growth. As has been shown in Table 2, the market potentials for renewable energy are large indeed and significantly surpass current global energy needs. Especially for PV technology, the potential market in the long run could be considerable. As has been shown in the analysis, a high market growth for PV technology would influence cost reductions considerably.

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[78]P.R. MacGregor, C.E. Maslak, and H.G. Stoll, *The Market for Integrated Gasification Combined Cycle Technology*, General Electric Company, Schenectady, NY, USA, 1991.

The cost calculations in this analysis show that costs estimates that incorporate learning effects can be lower than future cost estimates published in the literature (see Table 4). For PV, for example, costs decline rapidly with increased progress ratios and market growth. Subsidized investments in the initial learning phase can influence the costs of technologies. Before to decide in which technologies money should be invested, further studies are however needed to investigate how experience curves change over time and how they can be affected. Changing the experience curve and influence rates of technological learning however are key strategies to affect introduction and diffusion potentials of new technologies.

Future research must also further focus on the reasons for changing learning curves and the importance of RD&D and niche markets. It is also crucial to point out possible "take back effects", e.g. examples where costs do not decrease in "protected" niche markets as firms have no incentive to lower the costs which governments subsidize anyhow. In addition to studying how the rapid introduction of renewable energy technologies can be encouraged, attention must also be paid to different implementation policies.

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Appendix A

Annual renewable energy potentials by 2020/2030 ("reserves")

2020 -2030	Hydro[1] (Sec) (TWhe)	Wind[2] (Sec) (TWhe)	Solar[2] (Sec) (TWhe)	Solar[3] (Prim) (Mtoe)	Biomass[3] (Prim) (Mtoe)
1 NAM	729	2100	300	40	377-446
2 LAM	1185	603	150	60	776-1083
3 WEU	662	225	24	20	182-337
4 EEU	75	18	5	2	70
5 FSU	400	836	67	28	276
6 MEA	89	32	93	80	27
7 AFR	206	95	126	60	492-693
8 CPA	407	318	141	50	270
9 SAS	160	191	228	40	296
10 PAS	404	132	204	60	370
11 PAO	150	382	57	30	50
Total	4467	4931	1395	470	3146-3918

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Annual renewable energy potentials (maxima) by 2100 ("resources")

2100	Hydro[4] (Sec) (TWhe)	Wind[5] (Sec) (TWhe)	Solar[6] (Sec) (TWhe)	Solar[7] (Prim) (Mtoe)	Biomass[7] (Prim) (Mtoe)
1 NAM	969	3247	1800	497	734-**888**
2 LAM	3348	936	1564	425	2078-**3252**
3 WEU	945	348	1293	344	405-**635**
4 EEU	154	23	880	167	151-**331**
5 FSU	3338	1293	2104	628	599-**1326**
6 MEA	139	50	1484	322	**35**
7 AFR	1308	148	1548	265	1551-**2168**
8 CPA	2035	492	3775	654	730-**781**
9 SAS	443	295	1420	314	576-**857**
10 PAS	1085	205	4675	894	804-**571**
11 PAO	216	541	337	153	239-**320**
Total	13980	7578	20880	4663	7902-**11164**

Notes and references:

1. World Energy Council, Energy for tomorrow's world - High Growth Scenario 'A' (999 Mtoe hydro PE globally), ISBN 0 7494 1117 1 September 1993. Figures for EEU and PAO were corrected as WEC A 2020 production (EEU: 27 TWh and PAO: 58 TWh) was below 1990 output (EEU: 41 TWh, PAO: 127 TWh). New potentials for EEU from S. Fillipov, Cost analysis of the world's hydropower resources and technologies, Working paper forthcoming, 1994. For PAO exponential interpolation between 1990 production and 2100 potential for PAO was used to derive potential for 2020/2030. WEC A potential for SAS in 2020 (91% of exploitable capability, i.e. of 2100 potential) were reduced from original 409 TWh to 160 TWh, assuming exponential interpolation between 1990 production and 2100 potential. WEC A potential for FSU in 2020/2030 (only 15% higher than in 1990) was replaced by estimate of Fillipov, 1994. World totals equal global totals of WEC A.

2. Joel Swisher, Renewable energy potentials, in N. Nakicenovic Long-term strategies for migrating global warming, Special Issue Energy The International Journal, Vol 18 No 5 May 1993.
- Practical potentials renewable energy sources in 2030, p. 449.

3. Wood (commercial and non-commercial), biomass, urban waste, and rural waste: B. Dessus, B. Devin, F. Pharabod, 1992, World potential of renewable energies, Extraits de la Houille Blanche, Paris, France. For CPA and SAS Dessus' figures have been corrected, because Dessus' non-commercial renewables are lower than renewables used in 1990. (Non-commercial renewables for 1990 for CPA are 224.9 and for SAS 155.9 Mtoe). For MEA current use of biomass and waste is used plus potential given by Williams, 1994 (Ref. 7). Also a higher potential (if greater than given by Dessus) from ref. 7 (Robert H. Williams 1994) for the year 2025 is given for comparison. Preferred value is denoted by bold.

4. Exploitable hydropower capability: World Energy Council, Survey of energy resources 1992.

5. Joel Swisher, Renewable energy potentials, in N. Nakicenovic Long-term strategies for migrating global warming, Special Issue Energy The International Journal, Vol 18 No 5 May 1993.
- Maximum technical potentials of renewable energy sources in 2030, p. 448.

6. Intermittent (from ref. 7) minus wind (from ref. 5); except for NAM and PAO where solar potentials are from ref. 5.

7. Wood (commercial and non-commercial), biomass, urban waste, and rural waste. Robert H. Williams, A low carbon dioxide emission scenario (LCDES) for global energy (low-nuclear variant) Working draft, Prepared for the Intergovernmental Panel on Climate Change Second assessment report working group IIa, Energy supply mitigation options, Princeton University, March 1994. In case LCDES is lower than 2020/30 potentials from Dessus, 2020/30 potential are assumed as minumum value (cf. figures >xx). Biomass: lower range values from Williams, 1994. High range values from EPA, 1990, RCWR scenario. Preferred value is denoted in bold. Regional dissegragation for EEU and FSU, and PAS and SAS proportional to lower range potential of Williams, 1994. (United States Environmental Protection Agency, Policy Options For Stabilizing Global Climate - Report to Congress Technical Appendices, 21P-2003.3, December 1990.)

Note: Solar potentials are not necessarily additive between secondary (electricity) and primary total (thermal), as from two different sources. For modeling purposes, however, it is suggested to treat the two potentials separately (additive).