Learning curve of wind power generation in Japan

Takemi Sato and Toshihiko Nakata

Abstract: Estimating technological progress of emerging technologies such as renewable energy technologies is essential for designing sustainable energy systems and drawing energy policies. Learning curve is a quantitative estimating method for describing the cost decline rate of technologies caused by technological progress and learning. The purpose of this study is to estimate learning curve and learning rate (LR) of capital cost in wind power generation in Japan. As a result, 11% of learning rate was obtained from the analysis using capital cost data, though it included some uncertainty caused by the lack of cost data. Moreover, the difference in correlation was analyzed when classified by the capacity or the country of wind turbine manufacturers. The LR obtained in the study was higher than the one in Germany and Denmark. The reasons behind cost reduction were discussed in the latter section.

1. Introduction

Estimating technological progress of emerging technologies such as renewable energy technologies is essential for designing sustainable energy systems and drawing energy policies. Learning curve (LC) is a quantitatively estimating method for describing the price or the rate of cost reduction caused by technological progress or accumulation of experience. It is necessary to understand the learning rate (LR) in advance, which is derived from learning curve and represents the rate of cost decline. The learning rate is used as an input parameter in analyses by energy-economic models that employ the learning curve to describe technological progress.

Several studies have estimated the LC of photovoltaic in Japan (IEA, 2004; Tsuchiya, 1999). However, the LCs of the other renewable energy technologies in Japan are unknown. As the capacity of wind power increases, the cost for the wind power declines in recent years. The purpose of the study is to estimate both the learning curve and the learning rate of the investment cost in wind power generation in Japan.

2. Learning curve

Learning curves or experience curves describe how cost declines with cumulative production. The cumulative production is used as an approximation for the accumulated experience in

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producing and employing a technology (Neij, 1999). This study examines the learning curve which describes the relation between the cumulative installed capacity of wind power generation in Japan and the investment cost per kW.

The learning curve for the cumulative installed capacity and the investment cost per kW can be described by the following function (Harmon, 2000).

\[
\text{Cost}(CUM) = \text{Cost}_0 * CUM^b
\]

(1)

\[
LR = 1 - 2^b
\]

(2)

Where Cost is the investment cost per kW, Cost\(_0\) is the cost of first unit, CUM is cumulative installed capacity, LR is learning rate, b is the learning index. LR shows the relative cost reduction for each doubling of cumulative capacity.

Fig. 1 shows an example of learning curves (Grubler, et al., 1999). The machine cost of wind turbine is analyzed in other studies. However, the machine cost as well as the total investment cost is necessary for the analysis using energy-economic models that include LCs and evaluate the penetration of wind power in the energy system on a national scale. In this study, LCs and LRs of the investment cost in wind power generation in Japan are estimated, using the whole investment cost data includes the cost for constructing wind power facilities such as the cost of civil engineering, transportation, grid connection, and machine cost.

3. Cost and cumulative capacity data for the analysis

The objective of the analysis is wind power facilities in Japan which were constructed since 1980’s. This analysis is based on the national data (NEDO, 2004) which describes the capacity of individual wind turbines and installed year. Costs for investment are given by wind turbine owners etc..

Total project cost was used as the investment cost including the cost of civil engineering, transportation, grid connection preliminary surveys, and machine cost such as wind turbines and generators.

Fig. 2 shows the annual installed capacity and the ratio of the cost data available. The cost data of 465.7MW wind turbines is known in 682.1MW of the total installed capacity from the year 1990 to 2003, which is equivalent to 68% of total installed capacity. In terms of the number of wind turbines, the cost data of 436 wind turbines is available in total number of 735 wind turbines. Following analyses were conducted using those data.

4. Results of estimating the learning curves and learning rate

4.1. Learning curves using cost data of individual wind turbines

Fig. 3 shows the leaning curve that resulted from regression analysis on 436 individual wind
turbines. The LR is estimated to be 10.5% and $R^2$ is 0.419 (significant at the 1% significant level). Some circles on the graph include multiple plots on the same point because wind turbines located in a wind farm have exactly the same cost and cumulative capacity data.

4.2. Learning curves from annual average investment cost per kW

Many other studies adopt the estimation method for LC using annual average price or the cost. The regression analysis by this method was conducted for comparison. The method, however, has the possibility to result in the different coordinate positions of plotted markers. The reason in choosing the different plotting position is shown as follows:

1. How the representative cumulative capacity of a year is chosen?; e.g. cumulative capacity at the end of the year or intermediate cumulative capacity between the beginning and end of the year;
2. How the boundary of a year is chosen for calculating annual average cost?; e.g. dominical year or fiscal year.

In the analysis, LCs, LRs, and $R^2$ were examined in four cases shown in Table 1. Fig. 4 shows the LCs in the each case and the one of PV in Japan for comparison (IEA, 2004). Table 2 shows the LR and R2 in each case. These results show that LR varies within the range of 11-13% by the way of plotting methods. The results in Section 4.1 and 4.2 show that the LC and LR may differ by the plotting methods even in the analysis of using the same data set.

4.3. Analysis of different size of wind turbines

There was no correlation between cumulative installed capacity and the investment cost when wind turbines are classified by capacity such as below 500kW, 500kW-1000kW, and above 1000kW.

4.4. Analysis of different countries of wind turbines manufacturers

There was no correlation between cumulative installed capacity and the investment cost when wind turbines are classified by the countries of wind turbines manufacturers.

5. Discussions
5.1. Reasons behind cost reduction

Both LRs of wind turbines in Denmark from 1990 to 1998 and in Germany from 1982 to 1997 are 8% (Neij, 1999; McDonald, et al., 2001). The LR in Japan obtained from this study is higher than those in Denmark and in Germany.
Table 2 shows the share of the wind turbine manufacturers’ nationality in wind turbine market in Japan. The wind turbines from Denmark and Germany occupy a significant market share. Therefore LR of wind turbines imported from Denmark and Germany could have an impact on the LR of wind power in Japan. From the analysis in Section 4.2, the LR in Japan is higher than the one in Denmark or Germany.

A main reason of the difference in the LR is the range that the cost data include. While the other studies on the wind turbines made in Germany and Denmark used only the wind turbines price data, the cost data used in this study include costs related to the construction as well as the cost of the wind turbines as mentioned above.

Fig. 5 shows the percentage of the large-scale wind farms and the annual average investment cost per kW in both the small-scale and large-scale wind farms. The “Large-scale wind farm” means that the one has more than four wind turbines in a location. While the percentage of the large-scale wind farms is quite low before the year 1998, it has been increasing rapidly after that. The increase in the large-scale wind farms caused the decline in the cost of the civil and electric engineering cost per unit. That is one of the main causes of the lower average cost per kW in the large-scale wind farms compared with the one in the small-scale wind farms, leading the higher LR in Japan.

5.2. LR in the near future

The one of the main purposes of the LC analysis is utilizing the results in the design or evaluation of the future energy systems. It is considered reasonable that adopting the trend of LR in recent years as a baseline for the anticipated technological progress in the near future.

Fig. 6 and Table 3 shows the LCs and LR obtained by the analysis using data from the year 2000 to 2003 in order to understand the recent trend of LC and LR. The LR in near future was estimated to be 9% or lower based upon the result.

6. Conclusions

The study estimated the LC and LR of wind power generation facilities installed in Japan and obtained the following results;

1) The average LR is estimated to be 11% from the year 1990 to 2003.
2) The LR obtained from the average investment cost is 11-13%.
3) The LC and LR can differ by the way of plotting methods.
4) The LR obtained from the average investment cost data from the year 2000 to 2003 exhibits a 6-9%. Therefore recent LR is on a declining trend.
In the future work, LC for the biomass energy technologies is required to be investigated, though there are difficulties in analyzing variety of biomass resources and energy conversion technologies.

Reference


Table 1  Cases for choosing the plotting positions

<table>
<thead>
<tr>
<th>Case name</th>
<th>Representative cumulative capacity of a year</th>
<th>Boundary of a year</th>
</tr>
</thead>
<tbody>
<tr>
<td>End/deminical</td>
<td>The value at the end of a year</td>
<td>Deminical year</td>
</tr>
<tr>
<td>Mid/deminical</td>
<td>The middle value of a year</td>
<td>Deminical year</td>
</tr>
<tr>
<td>End/FY</td>
<td>The value at the end of a year</td>
<td>Fiscal year</td>
</tr>
<tr>
<td>Mid/FY</td>
<td>The middle value of a year</td>
<td>Fiscal year</td>
</tr>
</tbody>
</table>

Table 2  Learning rate and $R^2$ in different ways of plotting cumulative capacity, and PV module’s learning rate and $R^2$

<table>
<thead>
<tr>
<th></th>
<th>End/deminical</th>
<th>Mid/deminical</th>
<th>End/FY</th>
<th>Mid/FY</th>
<th>PV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Learning rate (%)</td>
<td>12.4</td>
<td>11.3</td>
<td>12.9</td>
<td>12.9</td>
<td>13.1</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.860</td>
<td>0.880</td>
<td>0.792</td>
<td>0.792</td>
<td>0.792</td>
</tr>
</tbody>
</table>

Table 3  Share of the wind turbine manufacturers’ nationality in the wind turbine market in Japan (NEDO, 2004)

<table>
<thead>
<tr>
<th>Nationalities of manufacturers</th>
<th>Capacity (MW)</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denmark</td>
<td>372.6</td>
<td>55.0</td>
</tr>
<tr>
<td>Germany</td>
<td>101.3</td>
<td>14.9</td>
</tr>
<tr>
<td>Netherlands</td>
<td>89.5</td>
<td>13.2</td>
</tr>
<tr>
<td>United States</td>
<td>67.8</td>
<td>10.0</td>
</tr>
<tr>
<td>Japan</td>
<td>44.7</td>
<td>6.6</td>
</tr>
<tr>
<td>Others and unknown</td>
<td>2.0</td>
<td>0.3</td>
</tr>
<tr>
<td>Total</td>
<td>677.8</td>
<td>100.0</td>
</tr>
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</table>

Table 4  Learning rate and $R^2$ using price data from 2000 to 2003

<table>
<thead>
<tr>
<th></th>
<th>End/deminical</th>
<th>Mid/deminical</th>
<th>End/FY</th>
<th>Mid/FY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Learning rate (%)</td>
<td>8.0</td>
<td>6.6</td>
<td>8.5</td>
<td>8.5</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.589</td>
<td>0.418</td>
<td>0.921</td>
<td>0.921</td>
</tr>
</tbody>
</table>
Fig. 1 Learning curves (Grubler, et al., 1999).
Fig. 2  Available cost data by year.

Fig. 3  Learning curve plotting cost data of individual wind turbines.
Fig. 4  Learning curves in four plotting ways and photovoltaic module in Japan. Prices are averages over annually (FY or dominical year) installed capacity. Plotted cumulative capacities are the values of the end or middle of the year.
Fig. 5 Investment cost per kW and the share of installed capacity in large-scale and small-scale wind farms.

Fig. 6 Learning curves from the year 2000 to 2003.