A Study on the Historical Trends in Load Factor of General Hydropower Plants

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Abstract

Hydropower comprises the largest proportion of renewable energy. Having a stable electricity generation pattern, it is widely used as a low-carbon base-load power source, though its output is susceptible to the abundance and scarcity of water. In Japan, the capacity of hydropower plants has increased by approximately 5000 MW since the 1970s, but their electricity output has not increased by as much. A possible cause of this gap in increase between plant capacity and electricity output is phenomena such as aging degradation, which causes the electricity output per unit plant capacity to decrease over time. This paper discusses the impact of temporal factors such as aging degradation on general hydropower generation. Specifically, it analyzes the effect of “water flow rate” and “time” on the load factor of general hydropower plants of general electric utilities.

Though the analysis results vary depending on the utility, the coefficient for water flow rate is generally about 0.4, which means that the utilization factor will increase by 0.4% when the water flow rate increases by 1 point. The time trend, which is a coefficient that is related to time, varies between −0.39 and −0.14. They are always negative, which implies that the load factor may be decreasing monotonously over time. This suggests that the load factor is being pushed down by 0.14 to 0.39 points each year, which would add up to a non-negligible drop of over 5% over the next 10 to 20 years from the current load factor of approximately 40%. Possible causes of this phenomenon include a drop in efficiency of the turbines within the hydropower plants, decrease in electricity output due to sediment deposition, and a drop in efficiency as the number of sites suitable for development decreases. General hydropower plants have been developed and constructed in stages since before World War II, and despite the progress in technology and the continuous maintenance efforts by the utilities, the effects of time may have been starting to show.

The correlation between the number of years of operation of the plants, weight-averaged by plant outputs, and the time trend coefficient produces a correlation factor of −0.629, which indicates a correlation between the number of years in operation and the time trend coefficient. This implies that utilities with older power plants without refurbishment are more susceptible to a decrease in load factor. Although continuous maintenance and refurbishment are needed, the total repair expenses of general electric utilities have tended to shrink continuously since peaking in the mid-1990s. The utilities may not be able to generate the necessary funds for additional investment and maintenance as their applications for permission to raise tariffs are undergoing rigorous reviews. Further, with the effects of abnormal weather being raised during the reviews as a cause of

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output fluctuations, new issues are emerging that must be considered for the future.

It is difficult to maintain the output of hydropower, which can provide perhaps the most stable output among the renewable energies, unless it is monitored carefully. While it is difficult to measure the future impact of hydropower, an unintended drop in output of this valuable low-carbon base-load power source could have unexpected negative effects on achieving the target renewable energy levels in the Strategic Energy Plan.

1. Trends in Electricity Output and Plant Capacity of General Hydropower

Hydropower comprises the largest proportion of renewable energy. Having a stable electricity generation pattern, it is widely used as a low-carbon base-load power source, though its output is susceptible to the abundance and scarcity of water. The Strategic Energy Plan approved by the Cabinet aims to expand the use of renewable energies. In addition to solar PV and wind power, which are the main components of the Plan for promoting renewable energies, hydropower must also be operated steadily as the foundation for renewable electricity generation if ambitious numerical goals are to be met.

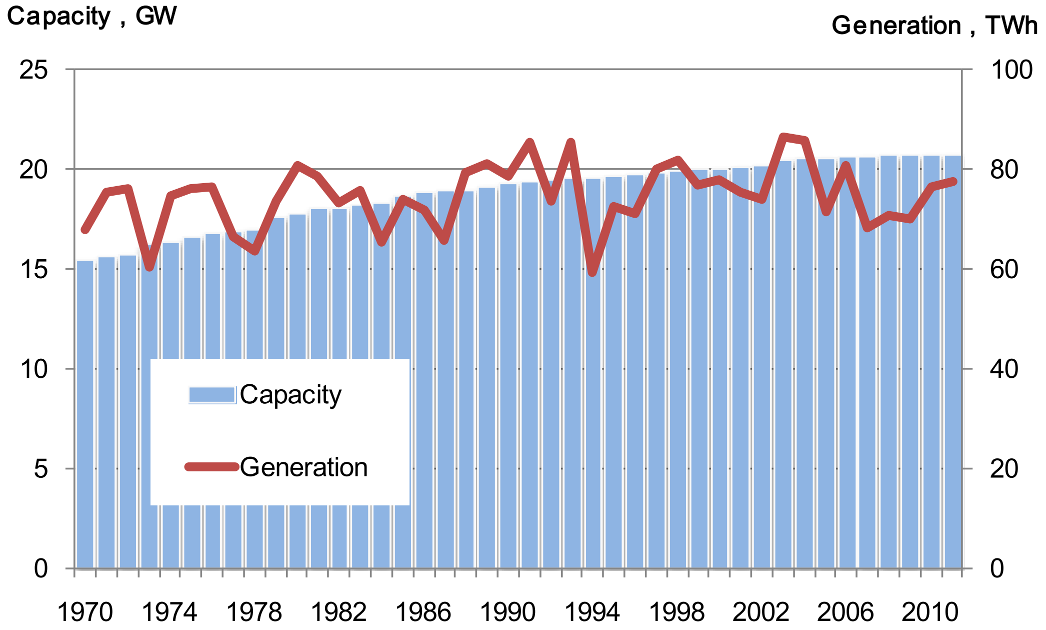
Hydropower can be grouped roughly into general hydropower and pumped-storage hydropower, which acts like a battery cell. General hydropower consists of the run-of-river type, regulating reservoir type and reservoir type [1] power generation, and includes generation technologies that can respond to fluctuations in electricity demand. In Japan, hydropower was the main type of electricity generation plant developed after World War II. Even after FY 1963 when thermal power surpassed hydropower in terms of electricity output and became the main generation technology, hydropower output has remained steady overall, though the pace of development of large-scale hydropower plants is slowing. Since the Oil Shocks, the development of pumped-storage hydropower has been promoted as it can respond flexibly to fluctuations in electricity demand.

Fig. 1-1 shows the trends in plant capacity and electricity output of general hydropower plants. While the capacity of general hydropower plants has increased by approximately 5000 MW since the 1970s, its electricity output has not increased by as much.[(1)] There are several hypotheses to explain this: one is that the output did not increase as much as capacity because much of the increase in capacity was from regulating reservoir type and reservoir type power plants; the other is the occurrence of some sort of phenomenon, such as aging degradation, that is causing the electricity output per unit plant capacity to decrease over time. Regarding the former, the data from the Electric Power Civil Engineering Association[(2)] show that the ratio of run-of-river power generation of general electric utilities to the entire general hydropower, in terms of capacity, was about 19% in 1970 and around 23% in 2011, and that regulating power plants did not add any share in terms of capacity. This means that the overall output of general hydropower remained flat despite the increase in the ratio of run-of-river plant capacity, and suggests that the utilization factor

[1] FEPC (in Japanese) http://www.fepc.or.jp/enterprise/hatsuden/water/

of run-of-river hydropower might be gradually falling. Based on the above, this paper discusses the latter possibility, which is the possible effect of time factors such as aging degradation on general hydropower generation.

Fig. 1-1　Capacity and Generation Output of General Hydropower Plants (general electric utilities total)



Source : Prepared based on the Energy White Paper, Agency for Natural Resources and Energy (ANRE), Ministry of Economy, Trade and Industry (METI)

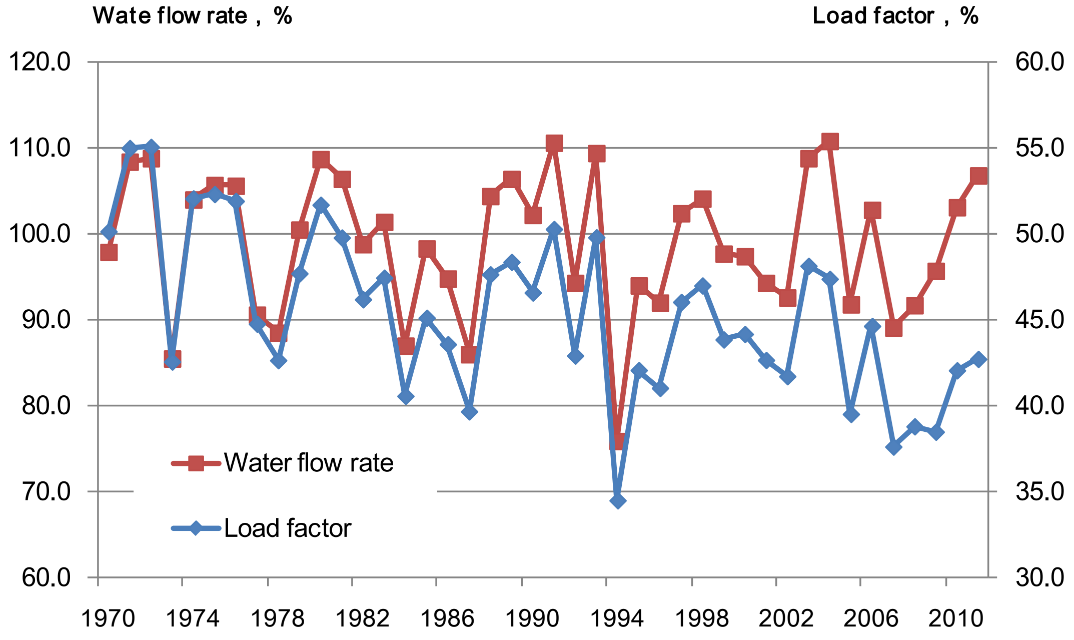
2. Trends in Load Factor of General Hydropower Generation and their Analysis Method

The output of general hydropower plants is affected significantly by water resources. The plants can produce enough electricity when water is abundant, but not as much as expected when water is scarce. Thus, the output fluctuates by year and by season. This fluctuation is represented by "water flow rate"[2], which must be considered when analyzing the electricity output over time. Fig. 2-1 illustrates the relationship between water flow rate and load factor. It shows that the trends of water flow rate and load factor are alike until the 1980s, but gradually part from around the mid-90s. Thus, we can assume that irrespective of the water flow rate, the load factor is increasing while the output is gradually slipping.[3]

2 Water flow rate = possible run-of-river power generation / average possible power generation. The average possible power generation prior to FY 2001 is the average of 58 years from 1942, and is the average of the recent 30 years for 2002 and later.

3 Based on the EIA data(4), a comparison between the 1990s and now shows that the load factor is decreasing also in the US and Canada, though not as significantly as in Japan. On the other hand, the utilization factor remains flat for Europe and China.

Fig. 2-1 Trends in the Load Factor and Water Flow Rate of General Hydropower Stations (of general electric utilities[4])



Source : Prepared based on the Energy White Paper of the ANRE (METI), and the "Electricity Business Database" of the Federation of Electric Power Companies of Japan (FEPC)

This study analyzes the effect on the load factor of general hydropower plants of the utilities separately for water flow rate and time. Two variables are used for the analysis: water flow rate and time trend. By performing a simple multiple regression analysis using these two independent variables, the effects of water flow rate and time on the load factor are identified. For the multiple regression analysis, the following equation was used:

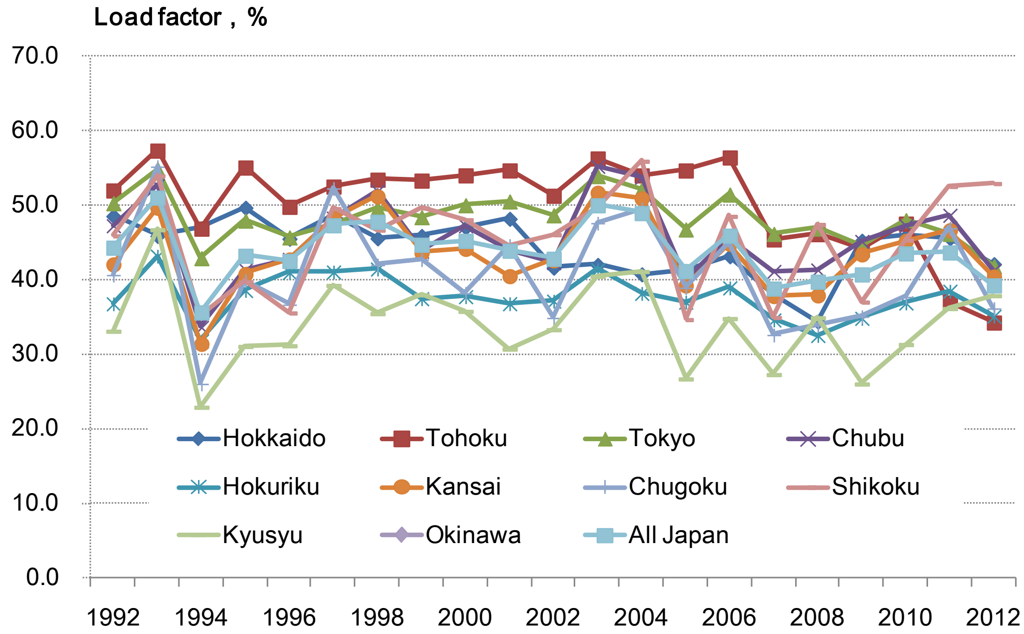
$$y_{i,t} = a + bx_{i,t} + cTIME + u_{i,t} \qquad (1)$$

y_t : load factor, x_t : water flow rate, TIME : time trend, $u_{t:}$: error, i : electric utility, t : year
a : constant term, b : water flow rate coefficient, c : time trend coefficient

Analyses were performed individually for each utility to identify their characteristics. Fig. 2-2 shows the trends in load factor of the general hydropower plants of each utility. The analyses are performed using these values and the historic water flow rate data of each utility.[(3)]

[4] In addition to those owned by the general electric utilities, J-Power, public, PPS and other wholesale electricity operators are included.

Fig. 2-2 Load Factor of General Hydropower Plants (per utility)



Source： Prepared based on the "Electricity Business Database" of the Federation of Electric Power Companies, and the Outline of the Electrical Power Development[(5)] of the Electricity and Gas Industry Department, ANRE

3. Results of Load Factor Analysis

The results of the multiple regression analysis on the general hydropower plants using load factor and water flow rate[(3)] are as follows. The analyses targeted a period of 20 years from 1992 to 2012. Note that the analyses exclude the period from 2011 to 2012 for Tohoku Electric when many of its hydropower plants stopped due to heavy rain in Niigata and Fukushima prefectures, and its impact lingered until the following year.[(6)] Further, additional analyses were performed for reference for the whole of Japan for the period from 1970 to 2010 using the data in the Energy White Paper. The results of the analysis were as follows.

Table 3-1 List of Coefficients Obtained Through Multiple Regression Analysis

Company name	Coefficient of water flow rate: $\hat{b}$	Coefficient of time trend	Constant	F-Value	Adjusted R^2	Note
Nationwide	0.455**	-0.225**	2.29	252.7**	0.965	Note 1
	(21.97)	(-7.30)	(1.06)			
Hokkaido	0.382**	-0.277**	14.85**	86.6**	0.895	
	(10.52)	(-6.18)	(3.55)			
Tohoku	0.529**	-0.304**	8.27	69.7**	0.884	Note 1
	(10.72)	(-5.27)	(1.57)			
Tokyo	0.435**	-0.243**	13.58**	61.8**	0.859	
	(10.41)	(-5.36)	(3.25)			
Chubu	0.453**	-0.239**	9.66**	185.3**	0.949	
	(19.25)	(-5.39)	(4.05)			
Hokuriku	0.345**	-0.179**	9.98**	87.6**	0.897	
	(12.22)	(-5.28)	(3.36)			
Kansai	0.454**	-0.187**	5.29*	195.7**	0.951	
	(19.78)	(-4.52)	(2.22)			
Chugoku	0.473**	-0.395**	10.70**	433.3**	0.977	
	(29.00)	(-10.16)	(5.95)			
Shikoku	0.439**	-0.136*	8.784**	164.2**	0.942	
	(17.98)	(-2.27)	(3.31)			
Kyushu	0.382**	-0.272**	7.34*	230.9**	0.958	
	(21.39)	(-6.37)	(3.72)			
Nationwide	0.461**	-0.207**	4.30**	622.5**	0.969	Note 2
(Reference)	(27.81)	(-18.2)	(2.55)			

Source : Prepared based on the “Electricity Business Database” of FEPC, and the Outline of the Electrical Power Development(5) of the Electricity and Gas Industry Department, ANRE. The data for nationwide (reference) were prepared from the Energy White Paper.

Note : Note 1. The data covers 1992-2010.
Note 2. Includes the data of those other than the general electric utilities. The data covers 1970-2010.
Okinawa Electric does not have any general hydropower plants. The values in brackets in the lower rows are t values; * means significant at the 5% level, and ** means significant at the 1% level. Unit root test conducted.

According to Table 3-1, the water flow rate coefficient varies among the utilities but is mostly around 0.4. This means that the load factor increases by 0.4% for every 1-point increase in water flow rate. Time trend, which is a coefficient that is related to time, varies between −0.39 and −0.14, and is always negative, which implies that the load factor may decrease monotonously over time. This suggests that the load factor is being pushed down by 0.14 to 0.39 points each year, which would add up to a non-negligible drop of over 5% over the next 10 to 20 years from the current load factor of approximately 40%.[5]

Possible causes of this phenomenon include a drop in efficiency of the turbines within the hydropower plants, decreased electricity output due to sediment deposition, and decreased efficiency as the number of sites suitable for development decreases. General hydropower plants have been

5 A time trend coefficient of 0.3 over 20 years suggests a decrease in load factor of 6%. This means that, of the total electricity output of general hydropower plants of 777 GWh for 2011 (load factor of 42.7%), 6% decrease in load factor results in 110 GWh loss of power generation.

developed and constructed in stages since before World War II, and despite the progress in technology and continuous maintenance by the utilities, the effects of time may be starting to show.

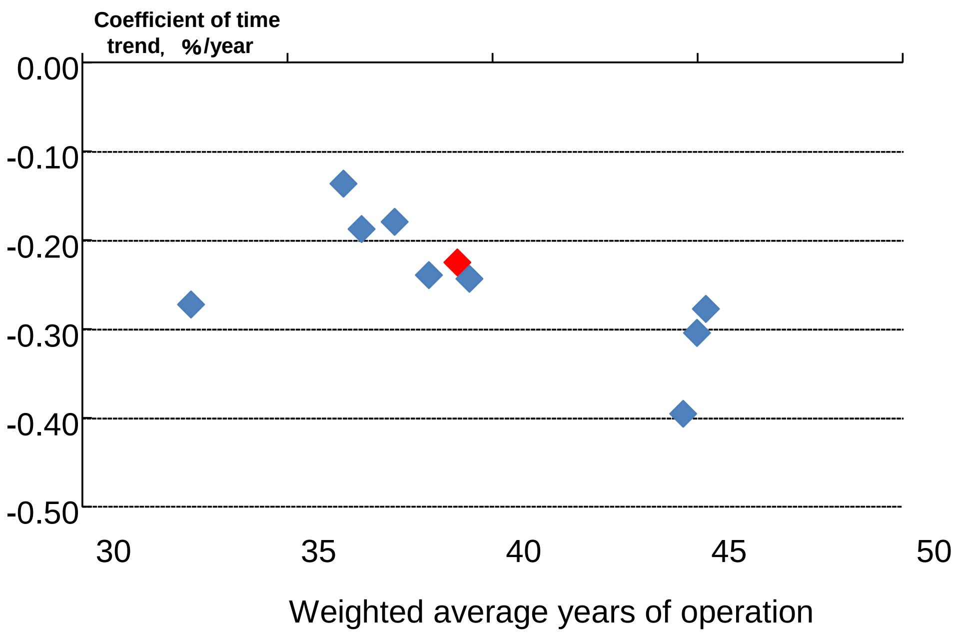
4. Discussion on the Temporal Change in Load Factor

The analysis results suggest that the load factor of general hydropower plants is falling over time. This chapter clarifies, in terms of temporal change and impact, the possible factors that are affecting the load factor, and discusses their impact. The impact of prolonged operation, as well as the growing difficulty of developing new hydropower plants due to the progress in hydropower resource development, is also discussed.

4-1 Years of Operation of Hydropower Plants and the Decrease in Load Factor

As described in the previous chapter, the magnitude of the decrease in load factor varies among the utilities. One possible reason is the difference in the years of operation. Fig. 4-1 plots the relationship between the years of operation of the plants[6], weight-averaged by their respective outputs, and the time-trend coefficient. In Fig. 4-1, the correlation coefficient between the weight-averaged years of operation and the time trend coefficient is −0.629, which indicates a correlation between the years of operation and the time trend. Though this may not apply to all cases as the correlation is likely to vary depending on the amount of regular repair and hence the speed of facility degradation, it implies that utilities with older power plants without refurbishment are more susceptible to a decrease in load factor.

Fig. 4-1 Time Trend Coefficients and Weight-Averaged Years of Operation



Source： Prepared based on the Hydropower Station Database, Electric Power Civil Engineering

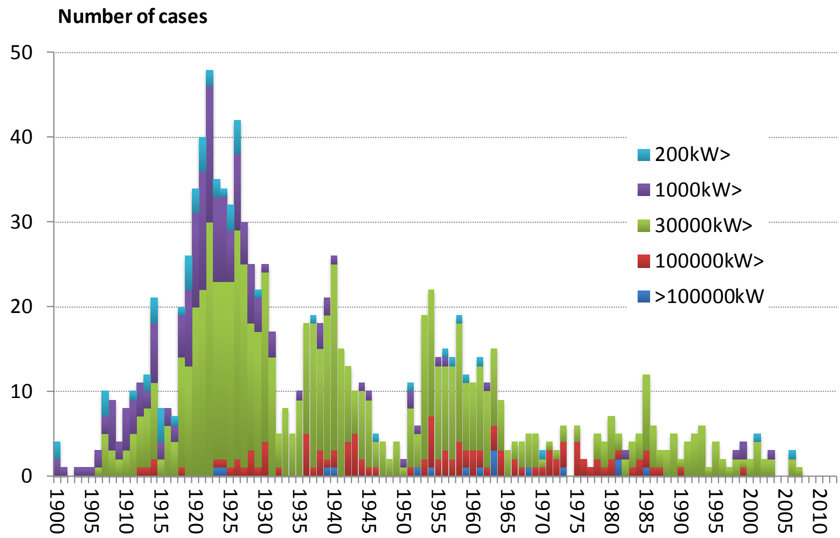
[6] For refurbished plants, the years after refurbishment are counted.

Association
Note : The red plots on the graph show the values for nationwide.

4-2 Difficulty in Developing New Large-Scale Hydropower Resources due to the Progress in Hydropower Resource Development

Resource development usually starts out at locations that are the easiest to develop, and thus it becomes harder to develop new resources as time passes. The same applies to hydropower, in which large-scale development projects presumably started out in areas where power could be efficiently generated. On the other hand, thanks to technological progress, efficient development may now be possible in locations which were once hard to develop. Fig. 4-2 shows the number of general hydropower plants by the year of start of operation and by capacity.

Fig. 4-2 Historical Trend in the Number of Hydropower Stations Launched (by plant capacity)



Source : Prepared based on the Hydropower Station Database, Electric Power Civil Engineering Association

As mentioned earlier, development projects tend to decrease over time both in number and scale as the locations suited for large-scale development are developed first. In terms of cost, the investment per kW usually rises as the facilities become smaller, but whether the load factor decreases as development becomes harder and facilities becomes smaller is difficult to observe from macroscopic data. As the unit price per kW tends to rise as facilities become smaller, it is necessary to raise the load factor and lower the electricity generation cost per kWh.[7]

As it is unlikely that large-scale hydropower will be developed in Japan in the future, to raise

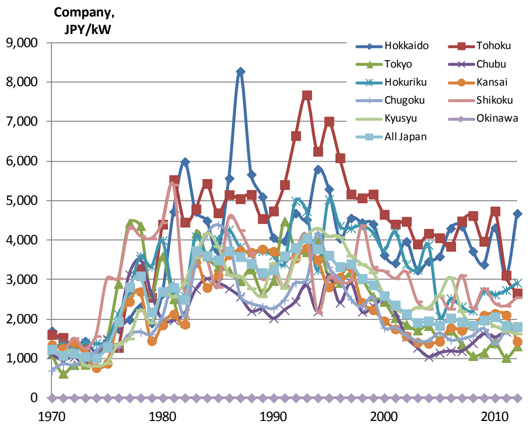
[7] The Cost Review Committee[(8)] assumes a plant capacity of 12 MW and a load factor of 45% for general hydropower plants, but a capacity of 0.2 MW and a load factor of 60% for low-head hydropower plants. “Potential Water Power Investigation”[(9)] by ANRE, METI also shows that the load factor becomes higher as the plants become smaller.

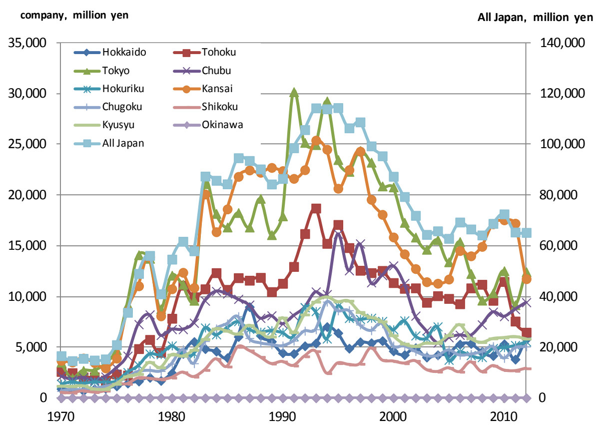
the overall load factor, it is important to repair existing facilities for larger plants; for smaller plants, which are likely to continue to be built, it is important to develop medium- and low-head hydropower plants which have a higher load factor.

4-3　Maintaining and Improving the Load Factor

Fig. 4-3 (left) shows the repair expense per unit output of hydropower plants, derived from the financial statements(7) of the respective power companies. The repair expenses in the financial statements are for the entire hydropower generation, and thus include pumped-storage hydropower. As pumped-storage hydropower has a large output, it is assumed to have lowered the repair expenses per unit output between 1970 and 2000 when it was being actively introduced. However, repair expenses have decreased since peaking in the mid-1990s. Fig. 4-3 (right) also shows that repair expenses peaked in the 1990s in terms of the total amount. While this could be partly due to rationalizing inspections, the continuing decrease in the total amount of repair expense is not good for conducting facility maintenance and aging degradation prevention measures with enough leeway.

Fig. 4-3　Trends in Repair Expenses of Hydropower Plants
(left: per unit output of hydropower plants; right: total amount)

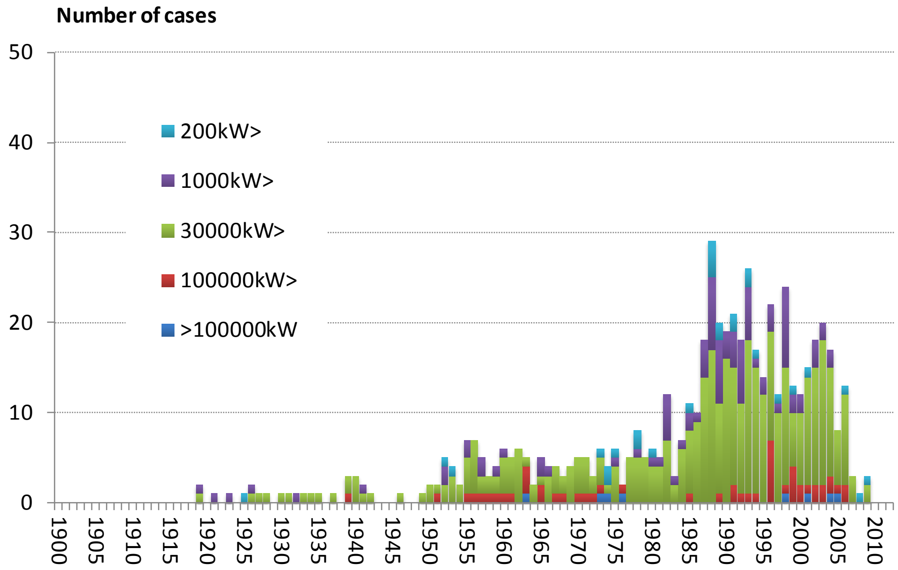




Source :　Prepared based on the financial statements of each utility.
Note :　The figures in the graphs are nominal, but the trend would not change even if converted to real-terms by GDP deflator.

Even hydropower stations, which have a stable output, will lose their efficiency over time unless continuous efforts are made. However, utilities are currently facing tough circumstances, and each utility applying for permission to raise its electricity tariffs (application for revising the electricity supply stipulation) is undergoing rigorous reviews of its facilities investment and repair expense plans by the Expert Committee on Reviewing Electricity Rate of the ANRE. Among the utilities that have recently applied for raising electricity tariffs, including Tokyo Electric, some have increased their hydropower station repair budget while others were forced to cut it(10), showing the efforts of the utilities to find ways, despite the rigorous reviews, to utilize hydropower as a valuable resource.

Fig. 4-4 Historical Trend in the Number of Hydropower Plants That Have Started Operation Following Facility Repairs (by capacity)



Source : Prepared based on the Hydropower Station Database, Electric Power Civil Engineering Association

In some cases, the drop in load factor is being mitigated by replacing the power generation equipment through major refurbishment and plant investment, in addition to regular repairs. While the launch of hydropower plants peaked in around 1920 (Fig. 4-2), the number of plant refurbishments began to increase in the early 1990s (Fig. 4-4), suggesting that many of the plants were refurbished about 60 to 70 years after starting operation. The number of refurbishments has dropped since the collapse of Lehman Brothers. As many of the plants were launched in the 1940s after the 1920s, assuming that the refurbishment cycle is approximately 70 years, these plants will also soon need refurbishment. The plant investment needed for refurbishment, however, might be postponed, as the utilities operating nuclear power plants are currently allocating much of their funds to safety measures for their nuclear plants, and are tending to cut investments for other plants. Considering the very high cost of fossil fuel imports caused by the shutdown of nuclear power plants, the utilities will inevitably have to cut additional investment and maintenance resources to minimize the rise in electricity tariffs, yet there are concerns over its long-term impact such as a drop in load factor of hydro power stations.

4-4 Suggestions on the Issues to be Considered

At the Expert Committee on Reviewing Electricity Rate of the ANRE, an interesting point was made about hydropower by Chubu Electric[(11)]. For its electricity tariffs application, Chubu Electric reported its hydropower output estimate as the average of the past 3 years, instead of the usual 10 years. As the basis for proposing 3 years as the appropriate value, Chubu Electric cited: (1) the increase in overflow power[8] caused by the flooding-induced shutdown of electricity generators resulting from the increase in brief, torrential downpours, and (2) the rebound from a temporary drop (2002-2007) in the amount of work abandoned due to the rationalization of water-wheel generator maintenance. As a result of the review, the proposal was rejected and the average of the past 10 years was adopted, as usual, to be reflected on the cost, but Chubu Electric's proposal provided an interesting hint in relation to this analysis: it might be possible to reduce costs and improve the load factor at the same time by improving the efficiency of maintenance through technology and ideas; further, not only facility degradation but also abnormal climate might affect the hydropower output. This study cannot discuss whether the phenomena encountered by Chubu Electric were caused by the effect of climate change, but considering the effect of torrential downpours on Tohoku Electric in 2011, if the probability of abnormal weather rises in the future, it could affect the operation of hydropower plants, which to date have been considered stable.

Hydropower is expected to serve as a stable renewable electricity source. We should not be optimistic that hydropower will continue to operate far into the future, but we may need to find ways to maintain the current efficiency, taking into account the impact of facility degradation and weather.

5. Conclusion

This study analyzed the temporal change in the electricity output of general hydropower plants. In particular, regarding the load factor, it was suggested that the utilization factor may decrease due not only to water flow rate but also to time factors. As hydropower plants deteriorate with time like other power plants, hopefully, this study has provided useful material to consider the direction of maintenance and plant investment in the future.

In the discussions on the Strategic Energy Plan, the share of renewable energies in the "generation mix" is likely to attract much attention. Hydropower is expected to continue to steadily generate electricity as the core of renewables. Though it is easy to assume that hydropower will continue to produce electricity steadily without taking particular measures, it too may be affected by aging degradation, as described in this paper. Thus, general hydropower requires well-prepared repair and investment plans. In addition, we must carefully monitor the impact of climate change from now on, otherwise it may be difficult to maintain the output of hydropower, which can provide perhaps the most stable output among the renewable energies. While it is difficult to measure the future impact of hydropower, an unintended drop in output of this valuable low-carbon base-load power source could have unexpected negative effects on achieving the target renewable energy levels in the Strategic Energy Plan and the GHG emissions reduction target.

[8] The amount of water that overflowed (discharged downstream through the gate) without generating electricity due to facility repair, accident, or flooding, converted into the amount of electricity.

〈References〉

(1) Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry, 2013 *Annual Report on Energy (Energy White Paper 2013).*

(2) Electric Power Civil Engineering Association, *Hydropower Station Database*, http://www.jepoc.or.jp/hydro/.

(3) Federation of Electric Power Companies, *FEPC INFOBASE*, http://www.fepc.or.jp/library/data/infobase/index.html.

(4) U.S. Energy Information Administration (EIA), *International Energy Statistics*.

(5) Electricity and Gas Industry Department, Agency for Natural Resources and Energy, *Outline of Electrical Power Development* (issued each year).

(6) Tohoku Electric Press Release, *Status of Recovery of Hydropower Stations*, August 10, 2011, http://www.tohoku-epco.co.jp/news/normal/1183453_1049.html.

(7) General electric utilities, *Corporate Financial Reports* (issued each year).

(8) Energy and Environment Council, *Various Documents of the Cost Verification Committee*.

(9) Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry, *Potential Water Power Investigation*, as of March 31, 2010.

(10) Expert Committee on Reviewing Electricity Rate Electricity and Gas Industry Committee, Advisory Committee for Natural Resources and Energy, *Various Documents*.

(11) Expert Committee on Reviewing Electricity Rate, Electricity and Gas Industry Committee, Advisory Committee for Natural Resources and Energy, *Draft Policy on the Review of the Application for Revising the Electricity Supply Stipulation from Chubu Electric Power Company*, March 14, 2014.

(12) Yuhji Matsuo, Yuji Yamaguchi, Tomoko Murakami, *Historical Trends in Japan's Long-Term Power Generation Costs by Source: Assessed by Using Corporate Financial Statements*, Energy Economics, 39(4), (2013), pp. 48-66.