The energy consumption of mankind has recently increased and economic development have increased the energy demand in many countries. As global fossil fuel reserves are limited, it is highly likely that the supply of fossil fuels will come under increased pressure and the development of alternative energies throughout the world will become essential. Assuming a Japanese population of 64 million in 2100 with a 20% increase of the power demand per capita from the present level, we studied the electric power supply and demand situation in 2100 by conducting the trial calculation of the maximum development potential of hydroelectric energy, a renewable energy produced in Japan. The findings indicate that the hydroelectric generation capacity can reach approximately 190 billion kWh/year, which is 1.97 times that of 2005 levels. This would be achieved by raising the height of existing dams and flexibly operating dams for power generation in harmony with the flood control and water supply for agricultural and other usage. Presupposing the completion as planned of the nuclear power plants currently under construction and a fivefold increase of the total output of wind power and other alternative power generation sources, it is concluded that a stable power supply will be possible in 2100 without dependence on fossil fuels.

KEYWORDS hydroelectric power generation; raising of the dam height; electric power output; fossil fuels.

INTRODUCTION

Electric power is generated by a variety of methods, including water power, nuclear power, oil-fired or coal-fired thermal power, LNG and others. Electric power generation methods in Japan have historically been selected primarily on the basis of the lowest cost at the time of development (Suzuki, 1993). Hydroelectric power generation currently deals with the peak load, utilising its ability to easily change the output in a short time.

The energy consumption of mankind has recently been accelerating at an unprecedented pace due to conspicuous development throughout the world, notably in BRICs (Brazil, Russia, India and China), causing concern in regard to an energy shortage in the near future given the limited fossil fuel reserves (Takemura, 2007). It is predicted that the mass consumption of fossil fuels will result in environmental deterioration on a global scale, such as global warming, due to the increased emission of CO\(_2\). There is growing awareness of the need for the worldwide application of preventive measures. As a society relying on fossil fuels cannot achieve sustainable growth, we face the challenge of urgently developing low carbon, alternative energy sources (IPCC, 2008). This study examines the maximum development potential of hydroelectric power to meet this challenge in Japan.

STUDY METHOD

The demand for electric power in Japan in 2100 was firstly estimated. Using the population estimate (based on a high birth rate and middle death rate) of the National Institute of Population and Social Security Research, the population in 2100 was set at 64 million. The electric power consumption per capita in 2100 was estimated to increase by 20% from 7.8 million kWh in 2005 in consideration of the expected shift to a more energy conservation-oriented social structure and the increased use of electric energy in the transportation sector. Consequently, the total demand for electric power in 2100 was estimated to be 600 billion kWh.

On the supply side, it was assumed that nuclear power would account for 360 billion kWh in 2100, an increase of some 20% from the present level, assuming that the nuclear power plants currently under construction will have been commissioned by 2100 in addition to nuclear power plants currently in operation. The power output of alternative energy sources, such as geothermal and wind, in 2100 was estimated to be 50 billion kWh, representing a fivefold increase from the present level, assuming that their development will accelerate in the coming years. The possibility of hydropower supplying the remaining 190 billion kWh was the subject of this study.

According to the Hydropower Development Promotion Policy announced by the Agency for Natural Resources and Energy (Agency for Natural Resources and Energy, 2006), hydropower generation potential of 104.6 billion kWh has already been developed or is in the process of development, leaving hydropower generation potential of 47.4 billion kWh untapped nationwide. Based on these figures, there will still be a shortfall of 38 billion kWh (NEDO, 2005). This study examined the possibility of redeveloping all existing dams in Japan with a height of 15 m or more by means of raising the height and conducting flexible operation. For this purpose, the maximum hydroelectric power development potential was estimated. Here, the flexible operation of dams means the use of the capacity of dams for both power generation and flood control. For flood control, preliminary discharge is the standard practice. Water use for irrigation and others are subordinate operations to power generation.
CALCULATION METHOD

The first step was the trial calculation of the electric power generation potential of 109 Class A river systems. Among Japan’s Class A river systems, 10 river systems, including the Sho River and the Kiso River (Figure 1), have hydroelectric dams which are constructed in a cascade (hereinafter referred to as “Type I rivers”). Raising the dam height at these river systems would result in the submersion of the dams upstream and, therefore, would have little redevelopment effect. For this reason, Type I rivers were studied separately from other rivers (hereinafter referred to as “Type II rivers”). Eight Type II rivers, including the Kushiro River and the Tsurumi River, were excluded from the scope of the study as their dam height is no higher than 15 meters or they do not have any hydroelectric power plants.

To calculate the electric power output of Type I rivers, the Sho River which has a large reservoir in its uppermost reaches and the Kiso River without such a reservoir were selected to represent groups of similar rivers. The existence of a dam in the respective uppermost reaches was then postulated and the relationship between the water use capacity of the dam and an increase of the electric power output was quantitatively established. The increase of the electric power output for the other eight Type I rivers was then calculated using the results for the representative rivers. To be more precise, Komaki Dam on the Sho River and the Inuyama point of the Kiso River were selected as “water use control points” (Figure 1) and water use calculation was conducted assuming the existence of a postulated dam. This was followed by the work to establish the relationship between the water use capacity of the postulated dam and the increase of the flow rate at the water use control point due to operation of the postulated dam (Figure 2). Here, the 95 day discharge was used as the control flow rate for storage. The electric power output was then calculated by multiplying the increased flow rate after the construction of the postulated dam by the energy conversion factor of discharge (maximum output/maximum water use). Figure 3 shows the relationship between the water use capacity of the postulated dam and the electric power output increase rate. In the case of the Kiso River, the output will increase in proportion to the water use capacity of the dam because of the current absence of large capacity dams. In the case of the Sho River, the increase rate will soon level off because of the existence of Miboro Dam with a water storage capacity of 330 million m$^3$. Based on these calculation results, it is assumed that the increase of the electric power output will level off at the 5% level for eight out of 10 Type I rivers, including the Sho River. In regard to the remaining two rivers, i.e. the Kiso River and the Tenryu River, an increase of the electric power output by 15% is assumed to be feasible by maximising the water use capacity of new dams. As a result, the electric power output for the 10 Type I rivers is estimated to be approximately 22.3 billion kWh a year.

For calculation of the electric power output of Type II rivers, Japan was firstly divided into 17 blocks (Figure 4) and the representative river system and the point where the mountainous topography changes to plain topography (typical measurement point) were

![Figure 1. Location of the Kiso River and the Sho River.](image1)

![Figure 2. Water use calculation for the Sho River.](image2)

![Figure 3. New dam volume and electric power increase rate.](image3)

![Figure 4. Type II river blocks. The Shaded parts show blocks where the flood storage volume is considered in addition to the required reservoir volume.](image4)
selected for each river system. At each typical measurement point, water use calculation using a postulated dam was conducted to establish the relational expression between the water use capacity of the postulated dam and the smoothing flow rate (Q) which would be secured with the supply of water from the dam. To be more precise, the flow rate range from 0 m³/sec to the maximum smoothing flow rate (Q_max) was divided into approximately 10 levels and the required water storage capacity for each flow rate level was determined. Here, Q_max is the maximum flow rate which can be sustained throughout the year with water supply from the dam and was calculated by dividing the total annual discharge by 365 days (Figure 5). The number of levels varies from one river to another and seven levels are used in the case of Figure 5. Through the analysis of such data with the least square method, the smoothing flow rate (Q) and the water use capacity (V) were approximated for each river by the following equation:

\[ Q = aV^b + c, \]  

(1)

where, a, b and c are the coefficients.

The maximum smoothing flow rate (Q_max) was calculated for each location where raising the existing dam height would be considered, using the equation applicable to the representative river system in the block where the dam in question is situated. This calculation used the specific flow rate shown in Figure 5 and the water use capacity (V_max) required to maintain Q_max was also calculated using Equation (1). As the sedimentation volume and other volumes must be considered at these dam sites, the dam storage volume is calculated by the following equation:

\[ V = V_{\text{max}} + V_s + V_f + V_u, \]  

(2)

where, \( V_s \): sedimentation volume, \( V_f \): flood control volume, \( V_u \): water volume for pumped storage power generation. In the study, the calculation (2) was only applied to dams in the Chugoku, Shikoku and Kyushu Regions located in the typhoon-prone south-western part of Japan and where the annual rainfall level is high. It is assumed that preliminary discharge will satisfactorily deal with the threat of flooding in other regions.

The increment \( (\Delta V) \) of the water storage capacity at each dam due to the raising of its height can be calculated by the following equation:

\[ \Delta V = \Delta H \times (A_0 + A_s(1 + \Delta H \times \frac{dA}{dH}/A_s))/2. \]  

(3)

where, \( H \): dam height, \( A_0 \): present reservoir surface area, \( A_s \): reservoir surface area.

Calculation of the value \( (dA/dH)/A_s \) for the 10 dams managed by the Ministry of Land, Infrastructure, Transport and Tourism produced an average value of 0.02. Using this value, the required height increase was calculated based on the dam storage volume calculated by Equation (2). The maximum height increase was set at 50 m. There are cases where raising of the dam height would be restricted by topographical or geological conditions, potential for large-scale submersion of houses or existence of major infrastructure facilities such as roads and railway lines. These factors were taken into consideration to reduce the height increase. Based on Figure 5 and Equation (3), the dam storage volume and the smoothing flow rate corresponding to the determined height increase were calculated for each relevant dam.

The new output \( (P) \) and the annual electric power output \( (W) \) (kWh) were calculated by the following equations using the smoothing flow rate, height increase and effective head of the existing dam (New Energy Foundation, 2002):

\[ P = \eta \times g \times H \times Q, \]  

(4)

\[ W = 24 \times 365 \times P, \]  

(5)

where, \( \eta \): generating efficiency, \( H \): effective head = effective head of the existing dam + height increase \( \times 2/3 \) (only two-thirds of the raised height are considered to produce an effective head to increase the electric power output), \( Q \): smoothing flow rate.

The calculation results are shown in Table I. An annual total electric power output of approximately 41.9 billion kWh is predicted for 91 Type II rivers. All Class B rivers are Type II rivers. In regard to dams on Class B rivers, an increase of the electric power output due to an increase of the dam height by 10 m will be equal to approximately 10% of the total electric power output from dams on Class A rivers. Accordingly, the total electric power output for Class B rivers is calculated to be 10% of the corresponding figure for Class A rivers. The estimated output is approximately 4.19 billion kWh. This makes the estimated total output of Type II rivers (of both Class A and Class B rivers) ap-

![Figure 5. Smoothing flow rate and specific storage volume](image)

Table I. Annual electric power output by region.

| Region       | Electric power output (100 million kWh) |
|--------------|----------------------------------------|
| Hokkaido     | 28                                     |
| Tohoku       | 59                                     |
| Kanto        | 36                                     |
| Hokuriku     | 125                                    |
| Chubu        | 34                                     |
| Kinki        | 33                                     |
| Chugoku      | 20                                     |
| Shikoku      | 27                                     |
| Kyushu       | 57                                     |
| Class A total| 419                                    |
| Total (Class A + Class B) | 460                                   |

Based on the relational expression between the water use capacity of the postulated dam and the smoothing flow rate in the representative river system in each block, the potential for increasing storage capacity and dam height was calculated, and the increased electric power output was obtained using equation (4).
Table II. Same as in Table I but for each river type (Unit: 100 million kWh/year).

| River system category | Type I | Type II | Total |
|-----------------------|--------|---------|-------|
| Electric power output (existing) | 203    | 138     | 341   |
| Electric power output (new)       | 223    | 461     | 684   |
| Increase of Electric power output | 19     | 323     | 343   |

Table III. Predicted hydroelectric power output for 2100 (Unit: 100 million kWh/year).

| Category                  | Electric power output |
|---------------------------|-----------------------|
| Existing electric power output | 952                   |
| Estimated power output increase | 343                   |
| Run-off river increase     | 14                    |
| Under construction         | 94                    |
| Undeveloped                | 475                   |
| **Total**                  | **1,878**             |

CONCLUSIONS

The study calculated the development potential of hydropower energy, assuming the continued use of existing dams, in preparation for the eventual depletion of fossil fuels while positioning hydroelectric power generation as the core power generation method along with nuclear power generation.

The study attempted to determine the maximum level of hydroelectric power development through the appropriate raising of the existing dam height and flexible dam operation. The study found that it will be possible for hydroelectric power generation alone to supply some 190 billion kWh of electric energy in 2100, including new output of some 34.3 billion kWh, by the redevelopment (i.e., raising the height and flexible operation) of existing dams. The study produced a possible scenario where the total power demand of some 600 billion kWh in 2100 based on a population size of 64 million and a 20% increase of the power demand per capita from the present level could be fully met by hydropower generation, nuclear power generation and power generation using non-fossil alternative energy sources (Table III and Figure 6). The electric power output at currently undeveloped sites was taken from data published by the Agency for Natural Resources and Energy (2006). The rate of output increase at run-off-river dams was assumed to be 5% based on the relevant result for the dam height increase on the Sho River. In addition, the future trend of the electric power output by power source in 10 year intervals was predicted on the basis of the following assumptions. The output of nuclear power will increase at a constant rate from 2010 and will level off in 2060 and thereafter. The output of geothermal and other alternative power sources will increase by 35% every decade from 2010 and will level off in 2090 and thereafter. The output of oil, coal and LNG-fired power generation will decrease by 15–40% every decade from 2010 and will reach zero in 2100.

Hydroelectric power is both an old and new source of energy (Okano, 2006). While its importance has changed with the times, it has greatly contributed to Japan’s development as a 100% domestic, renewable and clean energy (Hydropower Power Generation Research Committee, 2008). The role of hydroelectric power generation in the future will be increasingly important because of the predicted shortage of fossil energy and the growing severity of global warming. It is essential for Japan to make the best use of its hydroelectric power generation potential provided by its unique climate and topography through the efficient operation and raising of the height of existing dams while responding to the need for a stable water supply for other water usage and environmental conservation.

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