A Score-Based Evaluation Model for Rehabilitation of Existing Pumped Storage Hydropower Plant Construction

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Abstract

As the proportion of new and renewable energy increases, power control demands are becoming more frequent due to variability in power generation. As a complementary means against this, the pumped storage hydropower plants (PSHP) are attracting attention as energy storage systems (ESS), but it has high construction costs. Therefore, this study aims to improve the economic feasibility by developing the evaluation model of the existing infrastructure into an upper/lower dam suitable for PSHP. The concept of upper dam capacity is newly defined, and the evaluation index is constructed using normalization. A new evaluation system is presented for five factors: environment, stability, energy, capacity, and economy. Finally, it is tested in the pilot area in Korea. Several candidates, including the PSHP in operation, are found to have been distributed with higher scores. These results will help to satisfy the selection of candidates during the preliminary feasibility study phase, and programming them will enable more accurate and rapid assessment.

Keywords: pumped storage hydropower plant (PSHP), score-based evaluation, economic feasibility, energy storage, optimal location

1. Introduction

Currently, the international community recognizes the seriousness of the climate change problem and is working to solve it. The Paris Agreement was adopted in 2015. It recommended each party establish a “long-term low greenhouse gas emission development strategies (LEDS)” by 2020 from the perspective of a long-term vision of policies for responding to “2050 Long-term low greenhouse gas emission development strategies (2050 LEDS).” Through these strategies, the renewable portfolio standard (RPS) system was introduced, and the ratio of renewable energy gradually increased.

However, since renewable energy is greatly affected by weather and climate, there is a disadvantage in that power generation variability is high. Frequent power control due to power generation variability can lead to large-scale blackouts while reducing the efficiency of renewable energy capacity [1]. Therefore, the pumped storage hydropower plants (PSHP) role as an energy storage system (ESS) is attracting attention.

A PSHP is a facility that can store energy and generate electricity when needed. These features and the fast generation time allow the PSHP to take charge of emergency power for the power system. Unlike other ESS, PHSP has the disadvantage of being large in scale and requiring high construction costs. However, the technology level of other ESS is lower than that of PSHP, so PSHP currently occupies most of the ESS market [2-3]. For this reason, in Korea, in the 8th Basic Plan for Long-

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term Electricity (BPLE) (2017-2031), an additional construction plan for PSHP was established for the first time as a backup function for renewable energy. In addition, this policy stance continues in the latest 10th BPLE (2022-2036). Therefore, the expansion of PSHP is essential for carbon neutrality and is expected to contribute to the stable expansion of renewable energy.

There are many concerns about the new PSHP construction, such as the high initial cost of new construction and environmental destruction. There are also safety-related problems such as the occurrence of industrial accidents. To increase the economic feasibility of PSHP, a new construction method that converts existing reservoirs and/or dams into PSHP is proposed as a solution. Connolly et al. [4] developed a program to select reservoir sites suitable for PSHP.

Görtz et al. [5] presented criteria for evaluating suitable PSHP sites based on rivers and coastal areas, but both papers lacked economic items. Tao et al. [6] used an abandoned mine as a reservoir to utilize the PSHP site and 15 evaluation indicators for site selection were built. Menéndez et al. [7] also conducted an analysis to utilize an abandoned mine as an underground reservoir for PSHP. However, since most underground mines in Korea are small in scale, it is unreasonable to use abandoned mines as reservoirs [8]. Kusre et al. [9] used watershed-related data to simulate potential locations for hydropower.

Larentis et al. [10] developed a geographical information system (GIS) based methodology for selecting suitable sites for hydroelectric power generation, but the scope of the studies was limited to hydroelectric power generation. Fitzgerald et al. [11] proposed a potential evaluation model for converting existing hydroelectric dams and reservoirs into PSHP.

Rojanamon et al. [12] developed a siting system for small-scale hydroelectric power plants by considering the economic, environmental, and social impacts of the hydroelectric plant sitting. Larson and Larson [13] ranked the social, economic, and energy sectors by the index. Both papers deal with items other than design when selecting a site, but have limitations in that they do not deal with direct construction costs.

However, since most of these studies are for new construction, studies on the utilization of existing reservoirs are insufficient. Even one of the great advantages of PSHP using existing infrastructure is improved economic feasibility, however, previous studies do not have factors to evaluate economic feasibility in common.

According to the International Energy Agency (IEA), among the types of ESS currently available, the PSHP is the most suitable method considering technology, risk, practicality, and commerciality [2]. Therefore, this study proposes a practical and reasonable model for evaluating the suitability of PSHP by reducing the constraints of locational limitations and environmental destruction induced by PSHP.

2. Energy Storage Systems

ESS is a system that stores electricity when demand is low and supply becomes high to improve energy use efficiency and stabilize power supply. As renewable energy increases, the importance and capacity of ESS is also increasing globally.

2.1. General types of ESS

ESS is a system that stores electricity when demand is low and supplies it when becomes high to improve energy use efficiency and stabilize power supply. There are various types of ESS other than PSHP. For example, there are chemical methods such as batteries and physical methods such as compressed air ESS, flywheels, and PSHP. Among them, PSHP has lower investment costs than other methods [2]. In addition, given the maturity of energy storage technologies, PSHP has good commercialization and stability as shown in Fig. 1.

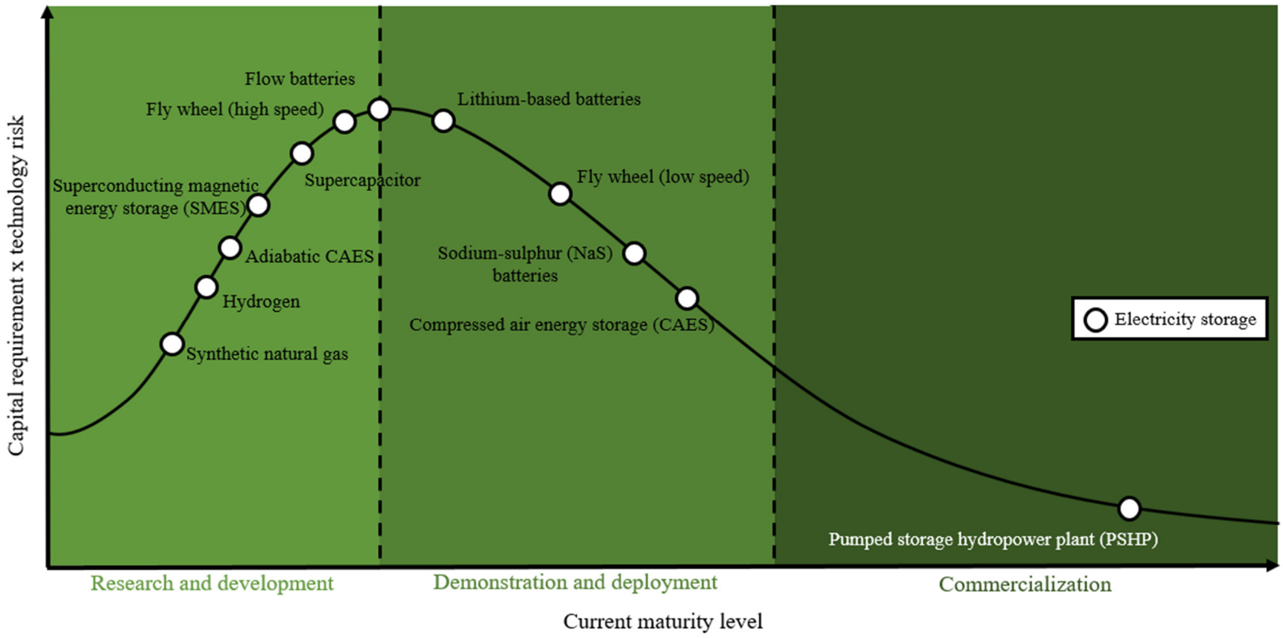


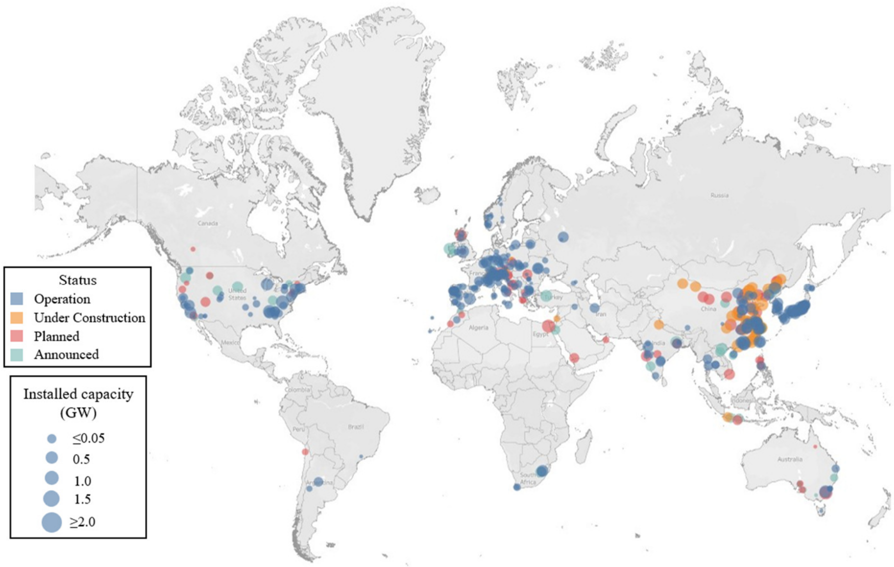
Fig. 1 Maturity of energy storage technologies [2]

2.2. *PSHP status*

The total capacity of grid-connected ESS capacity is about 174 GW worldwide, and among the types of ESS, PSHP accounts for about 97.62% [3]. Among these, 7 PSHP units with a capacity of 4,700 MW are in operation in South Korea, and 3 additional units are scheduled to be built.

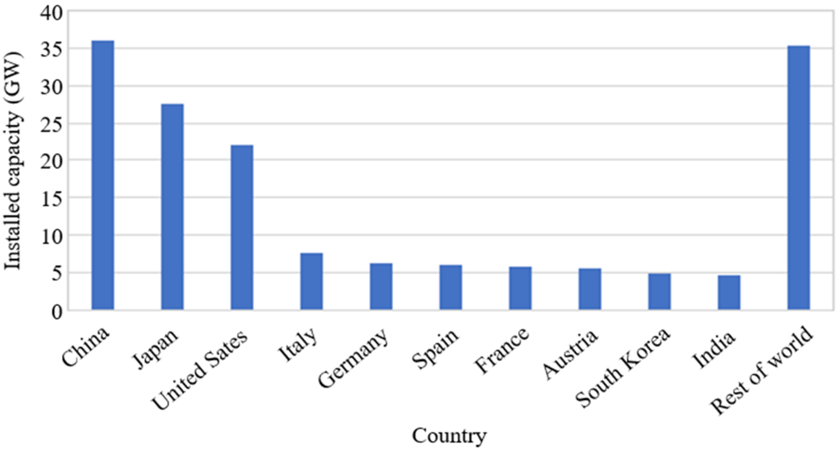
(1) PSHP in global

The total capacity of grid-connected ESS capacity is about 174 GW worldwide, and among the types of ESS, PSHP accounts for about 97.62% [3]. The region where PSHP is being built most actively is China, with plans to increase capacity to 120 GW by 2030 [14]. In addition, India is using only 4.75 GW out of the 96.5 GW potential capacity of pumped storage power plants, so the government is providing various support such as forming a committee and providing funding [15]. Austria is working on two pumped storage power plant projects, and Uzbekistan has also announced a project to build a pumped storage power plant [16]. PSH construction projects are being carried out in various countries. Fig. 2 below shows the installed capacity and status of PSHP.



(a) Status of PSP [17]

Fig. 2 Global status and installed capacity of PSHP



(b) Installed capacity of PSHP

Fig. 2 Global status and installed capacity of PSHP (continued)

(2) PSHP in South Korea

In South Korea, seven PSHPs with a capacity of 4,700 MW are in operation, from Cheongpyeong PSHP in 1980 to Yecheon PSHP in 2011. In addition, three PSHPs are planned to be constructed by 2034. Table 1 shows the recent status of PSHP in South Korea.

Table 1 PSHP in South Korea

Name	Location	Year of completion	Capacity (GW)
Pocheon (Planned)	Pocheon-si, Gyeonggi-do	2034	0.7
Yeongdong (Planned)	Yeongdong-gun, Chungcheongbuk-do	2030	0.5
Yecheon	Yecheon-gun, Gyeongsangbuk-do	2011	0.8
Cheongsong	Cheongsong-gun, Gyeongsangbuk-do,	2006	0.6
Yangyang	Yangyang-gun, Gangwon-do	2006	1
Sancheong	Sancheong-gun, Gyeongsangnam-do	2001	0.7
Muju	Muju-gun, Jeollabuk-do	1995	0.6
Samnangjin	Samnangjin-eup, Miryang-si, Gyeongsangnam-do	1985	0.6
Cheongpyeong	Gapyeong-gun, Gyeonggi-do	1980	0.4

3. Criteria for Selecting PSHP

To select a suitable area for PSHP, various PHSP selection criteria were investigated. In the case of Korea, the selection criteria were not made public, so the selection criteria for suitable dam sites were referred to, and in the case of the United States, the standards of the Electric Power Research Institute were referenced.

3.1. USA criteria

The United States began storing electric energy on a large scale through The Rocky River Pumped Storage Hydroelectric Plant in 1929. In the pumped-storage planning and evaluation guide, the US Electric Power Research Institute (EPRI) classified criteria for site selection for PSHP [18]. Table 2 shows the 5 stages of the PSHP construction plan proposed by EPRI [15].

Table 2 Stages of the construction plan

Order	Stages	Purpose
1	Reconnaissance	Site identification and screening
2	Prefeasibility	Site selection
3	Feasibility	Project planning
4	Regulatory	Agency consultation and license application
5	Regulatory	License processing

Fig. 3 represents the general process of selecting suitable candidate sites for PSHP presented by EPRI. The “MUST (INDISPENSIBLE)” criteria are essential ones to consider when selecting a suitable site, which means items that can be objectively quantified, and examples of the “MUST (INDISPENSIBLE)” criteria are summarized in Table 3. After the “MUST (INDISPENSIBLE)” criteria are examined, candidates for suitable sites for PSHP are selected based on evaluation scores and weights of the “WANT (DEMANDING)” criteria, which means items that are difficult to quantify, such as costs, flooding expectations, and technical difficulties.

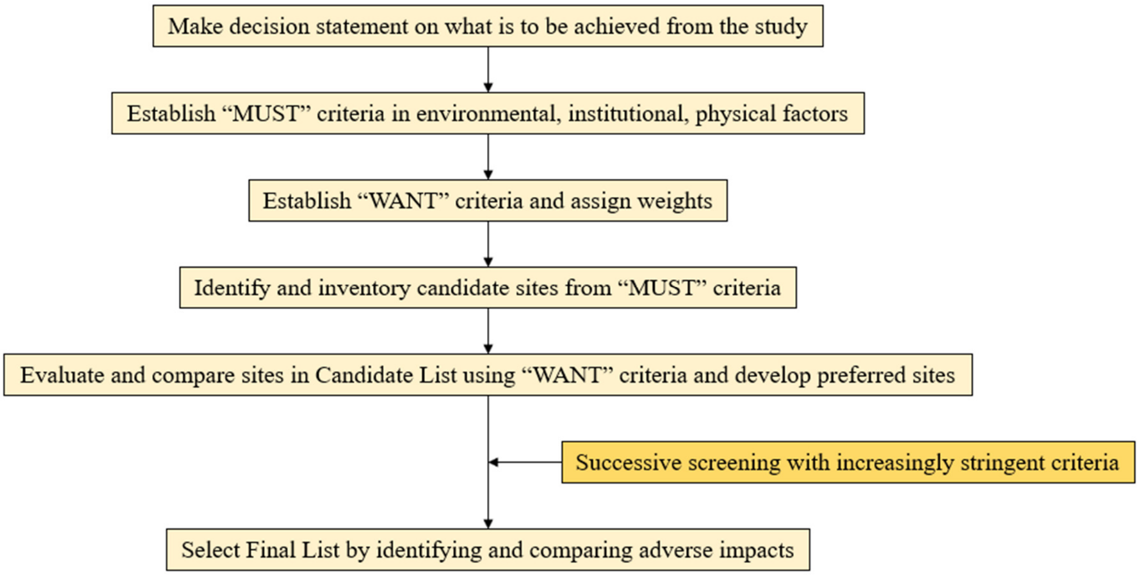
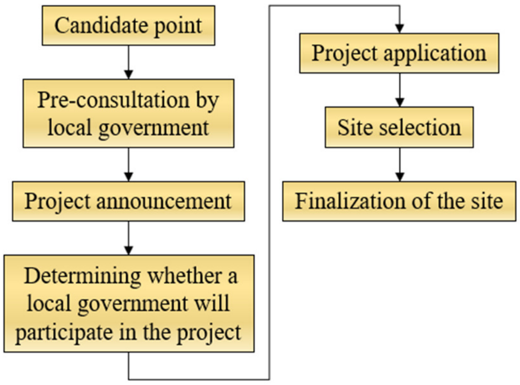


Fig. 3 Site identification and screening

Table 3 “MUST (INDISPENSIBLE)” criteria

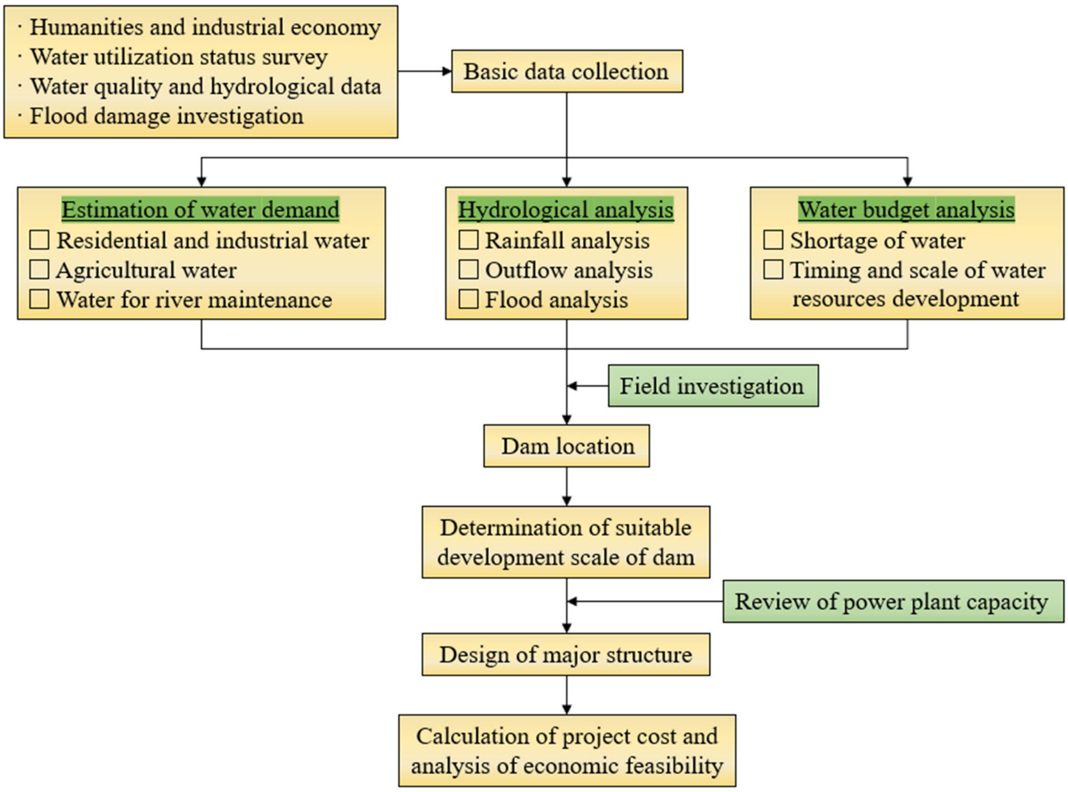
<table>
<tr><th>Factor</th><th>List</th></tr>
<tr><td>Legal and environmental</td><td>National parks, wild, critical habitat, protected rivers, urban areas, sites involving significant wetlands, federal/state highways, etc.</td></tr>
<tr><td>Geotechnical</td><td>Volcanism and landslides risk area, seismic and faulting risk area, soluble rock material, etc.</td></tr>
<tr><td>Economical</td><td><table>
<tr><th>Head (ft)</th><th>Maximum L/H ratio</th></tr>
<tr><td>200-300</td><td><5</td></tr>
<tr><td>300-500</td><td><7</td></tr>
<tr><td>500-750</td><td><10</td></tr>
<tr><td>750 and above</td><td><12</td></tr>
</table>
Or Unit cost of capacity with 10 hours of energy storage at $1,000/kW
Benefit/Cost ratio at 0.8 or more</td></tr>
</table>

3.2. South Korea criteria



(a) Site selection process for PSHP

Fig. 4 Procedure for site selection of PSHP and dam in Korea [20]



(b) Site selection process for dam

Fig. 4 Procedure for site selection of PSHP and dam in Korea [20] (continued)

The construction process of PSHP in South Korea generally proceeds to the project preparation stage (approximately 37 months), the construction preparation stage (29 months), and the construction stage (77 months) [19]. In the project preparation stage, whether it is possible to secure a construction site, an environmental impact assessment, and a basic construction plan are carried out.

In particular, through the strategic environmental impact assessment conducted under Article 9 of the Environmental Impact Assessment Act in the Ministry of Environment, the adequacy and location of the plan are reviewed from an environmental perspective. Fig. 4(a) is a diagram showing the site selection process of PSHP. However, since there are relatively few construction cases, the process of selecting the site of PSHP is not specific. Therefore, to develop a methodology for assessing the existing infrastructure, the dam siting process (Fig. 4(b)) was referenced.

4. Evaluation System

Four evaluation items were presented to evaluate the suitability of PSHP. Evaluation methods for environmental feasibility, safety, ESS/power generation, and economic feasibility were presented, and the evaluation methods were applied to the pilot field.

4.1. Methodology

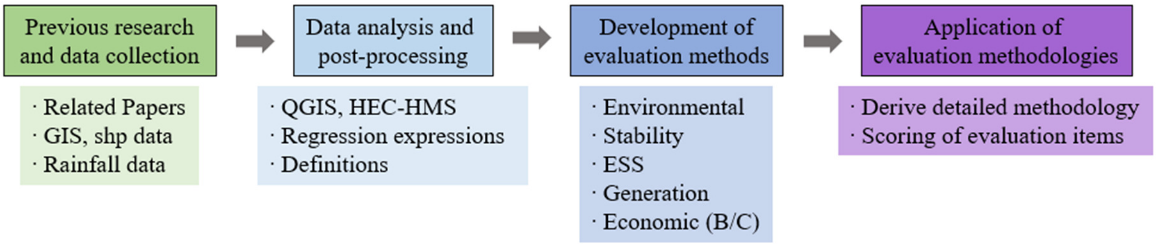


Fig. 5 Methodology of research

Before conducting this study, data were collected by analyzing studies in similar cases. Data were processed through data processing techniques so that the collected data could be used for research. Values of evaluation factors (environmental, stability, ess, and generation) were scored through normalization, and a scoring system using economic values as weights was developed. After that, the developed method was applied to the pilot area. Fig. 5 shows the methodology of this study.

4.2. Selection of evaluation target

Similar cases were investigated to select upper and lower dams. However, since there was no clear standard for the distance between the upper and lower dam, different standards were applied to the distance between the dams, such as 5 km and 20 km, depending on the researcher [11, 21]. Therefore, considering the distance between the upper and lower dams of Korea's PSHPs and the average distance of municipalities, 10 km was adopted. In addition, the minimum capacity of the upper and lower dams of the PSHP was set at 1,000,000 m^3 [11]. The upper and lower dams are dams/reservoirs registered with the water resources management information system (WAMIS) and the Korea Rural Community Corporation.

4.3. Environmental evaluation

Before plans for large-scale infrastructure in South Korea, a strategic environmental impact assessment conducted by Article 9 of the Environmental Impact Assessment Act is proceed. Through the evaluation, the appropriateness of the plan and the feasibility of the location are reviewed from the environmental point of view. Therefore, to identify the environmental impact, the environmental evaluation was constituted as one of the factors of evaluation. The environmental evaluation was conducted based on the data from the environmental conservation value assessment map (ECVAM). ECVAM is data that provides comprehensive and scientific environmental information on land (Table 4). Considering the large-scale construction of PSHP and its impact on the environment, the average rating of ECVAM within a 1 km radius of the upper and lower dams was calculated using a quantum geographic information system (QGIS), an open-source geographic information system.

Table 4 Ratings of ECVAM (the higher the value, the easier to build.) [22]

Rating	Criteria
1	Designated as the highest grade among 62 legislative evaluation items (water source protection area, ecological landscape conservation area, etc.) and 8 environmental ecological evaluation items (species diversity, recurrence, naturalness, etc.)
2	
3	
4	
5	

4.4. Stability evaluation

Accidents in large-scale social overhead capital (SOC) plans are likely to lead to major accidents, and stability after construction is also important. Therefore, a rough evaluation of the possibility of industrial accidents during construction and stability evaluation for effective maintenance of the PSHP after construction were conducted. Most of the PSHP projects are conducted in mountainous areas, so stability evaluations were carried out using the landslide hazard map (LHM) from the Korea Forest Service (Table 5). LHM is data that provides vulnerability of the area by evaluating its susceptibility to landslides due to its location in the mountainous region. Similar to environmental evaluation, the average rating of LHM within a 1km distance of the upper and lower dams was calculated using QGIS.

Table 5 Ratings of LHM (the higher the value, the easier to build) [23]

Rating	Criteria
1	An area where the probability of landslides occurring is significantly higher compared to other regions.
2	An area where the probability of landslides occurring is higher compared to other regions.
3	An area where the probability of landslides occurring is lower compared to other regions.
4	An area where the probability of landslides occurring is significantly lower compared to other regions.
5	An area where there is no probability of landslides occurring.

4.5. Energy evaluation

This factor evaluates the expected energy stored capacity of PHSP when converting the existing reservoir into the upper and lower dam of the PSHP. After that, the economic evaluation of the PSHP is conducted based on the energy stored capacity for benefit.

(1) Evaluation method

The energy stored capacity in PSHP is an important evaluation factor, as the pumping process significantly impacts the power grid's stability for energy stabilization. The amount of energy storage that PSHP can store is expressed as [11].

$$E = \frac{\eta \rho g H V_p}{3.6 \times 10^9} \tag{1}$$

where E is the energy stored capacity (GWh), η is the efficiency of power generation, ρ is the density of water (t/m^3), g is the gravitational acceleration (9.8 m^3/s), H is the head (m), and V_p is the upper dam capacity of PSHP (m^3). In this study, η was assumed to be 85% according to practical guidelines for water resources (Dam) design, and the H was calculated through DEM [20].

(2) Upper dam capacity of PSHP (V_p)

Since most of the reservoirs in Korea are agricultural reservoirs, it is necessary to consider the capacity that can be used for farming. Therefore, before using the upper dam capacity of PSHP (V_p), the capacity to be used as PSHP should be additionally considered. In this study, V_p was calculated through the average reservoir storage rate over the past 30 years and the hydrological analysis of the watershed. QGIS was used to divide the watershed into reservoir units. In addition, the average rainfall in each reservoir basin was calculated through the Thiessen polygon method and the hydrologic modeling system of the hydrologic engineering center (HEC-HMS), a rainfall-runoff program of the US Army Corps of Engineers. The upper dam capacity of PSHP is expressed as,

$$V_p = RV + Q_{da} t \tag{2}$$

where R is the average reservoir storage rate over the past 30 years, V is the effective capacity, Q_{da} is the daily average runoff, and t is the day (86,400s).

4.6. Capacity evaluation

The capacity evaluation factor evaluates the expected installed capacity of PHSP when converting the existing reservoir into the upper and lower dam of the PSHP similar to Energy stored capacity. After that, the economic evaluation of the PSHP is conducted based on the estimated annual power generation cost. PSHP drops water to the lower dam to generate electricity when electricity demand increases. Electricity is generated in the same way as hydroelectric power, which converts the potential energy of water into electrical energy, and the installed capacity is expressed as:

$$P = \sum_{t=1}^{n} \eta \rho g H Q / 10^6 \tag{3}$$

where P is the installed capacity (GWh) and Q is the turbine discharge (m^3/s). The turbine discharge (Q) is calculated by [24].

$$Q = \frac{V_p}{T} \tag{4}$$

where T is the operation times of the turbine (21,600 s). In this study, the operation time of the PSHP was assumed to be 6 hours which is the minimum daily average operation time [25].

4.7. Economic evaluation

In this study, the benefit-cost (B/C) method, which is the most commonly used economic evaluation method, is used. However, studies related to the economic evaluation of the PSHP are limited, so it is difficult to quantify the costs and benefits of PSHP. Because of this situation, in this study, benefit and cost are derived with the following assumptions as shown in Table 6.

Table 6 Economic evaluation lists

B/C	List
Benefit	Benefit from opportunity cost, power generation benefit, indirect benefit
Cost	Construction cost, operation and maintenance (O&M), pumping cost

(1) Economic value conversion

The B/C is a method of analyzing the feasibility of a project by comparing the costs required for construction and operation with the benefits obtained during operation. The following factors are used to convert costs and benefits to present values.

(i) Future value of an annual sum (FA)

$$FA = \frac{(1+i)^r - 1}{i} \tag{4}$$

(ii) Future value of a present sum (FP)

$$FP = (1+i)^r \tag{5}$$

(iii) Present value of an annual sum (PA)

$$PA = \frac{1-(1+i)^{-r}}{i} \tag{6}$$

where i is the discount rate over the period and r is the number of periods. To Korea’s general guidelines for conducting a preliminary feasibility analysis, a 4.5% discount rate is applied.

(2) Benefit

The most important factor when a business operator builds a PSHP is benefit. Therefore, calculating appropriate benefits is an essential procedure in building PSHP. Benefit evaluation consists of Benefits from opportunity cost, Power generation benefit, and Indirect benefit.

(i) Benefit from opportunity cost: This study assumed that benefits have been obtained since existing infrastructures have been utilized as upper and lower dams of the new PSHP. The cost of building a dam of PSHP is expressed as [26].

$$B_{oc} = \varsigma_{€} \times 7.88 \times 10^6 \times E \tag{8}$$

where B_{oc} is the cost of building a dam of PSHP (KRW) and $\varsigma_{€}$ is the exchange rate conversion factor (KRW/€).

(ii) Power generation benefit: PSHP is a facility that utilizes surplus electricity to pump water and generates power when electricity demand is high. In terms of electricity rates, these characteristics generate revenue by pumping when electricity rates are low and generating power when electricity rates are high. In this study, through Korea’s system marginal price (SMP) analysis (Fig. 6), the average value of the maximum and minimum electricity prices was calculated. The power generation benefit was assumed to be the maximum average SMP and was expressed as:

$$B_{pg} = SMP_{\max} \times P \times t_a \times PA \tag{9}$$

where B_{pg} = Power generation benefit, SMP_{max} = Maximum average SMP and t_a = year.

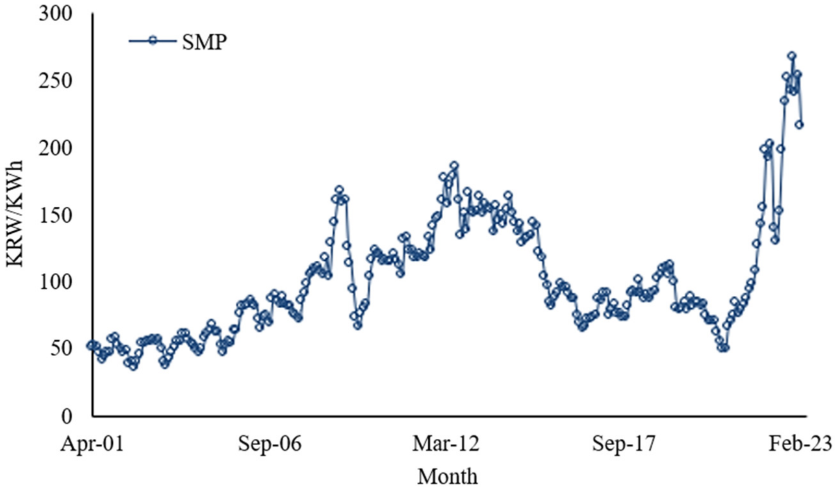


Fig. 6 System marginal price in South Korea

(iii) Indirect benefit: The need for new construction of PSHP is increasing due to the increasing role of ESS. For this reason, studies are being conducted to quantify the indirect benefits of ESS [27-28]. ESS has national benefits such as improving power system reliability and contributing to the stabilization of electricity rates. In this study, the calculation of ESS benefits was estimated at [28]:

$$B_{ib} = 7609 \times HN \times t_m \tag{10}$$

where B_{ib} is the indirect benefit (KRW), HN is the household number of upper and lower dam regions and t_m is the month.

(3) Cost

Cost evaluation is the process of analyzing the costs incurred while operating a PSHP. Costs were evaluated through the initial estimated construction costs of PSHP by capacity, operation, and maintenance (O&M) costs, and pumping costs for energy storage.

(i) Construction cost: The construction cost of PSHP is determined through several processes, from a preliminary feasibility study to contract signing, before construction begins. However, the purpose of this study is to determine the approximate construction cost in the preliminary feasibility analysis stage. Therefore, the construction cost equation of Korea's PSHP was presented through the construction cost equation of the dam and the methodology of the "PSH Cost Model" of the Oak Ridge National Laboratory (ORNL) in the United States [29]. Then, the amount was calculated by subtracting the construction cost of the original PSHP (formula below) and the construction cost of the upper and lower dams (Eq. (8)).

$$C_p = 2.057e^{2.663P} \tag{11}$$

where C_p is the construction cost of PSHP (10^{11} KRW). The estimated PSHP construction cost in Korea was converted to present value through a value conversion factor (Table 7). Afterward, regression analysis was conducted to derive Korea's PSHP cost curve, and the equation is shown in Fig. 7 and Eq. (11).

Table 7 Construction cost based on conversion

Name	Year of completion	Capacity (GW)	2022 Construction Cost (10^{11} KRW)
Yecheon	2011	0.8	14.35
Cheongsong	2006	0.6	10.06
Yangyang	2006	1.0	28.68
Sancheong	2001	0.7	17.54
Muju	1995	0.6	11.57
Samnangjin	1985	0.6	9.373
Cheongpyeong	1980	0.4	5.382

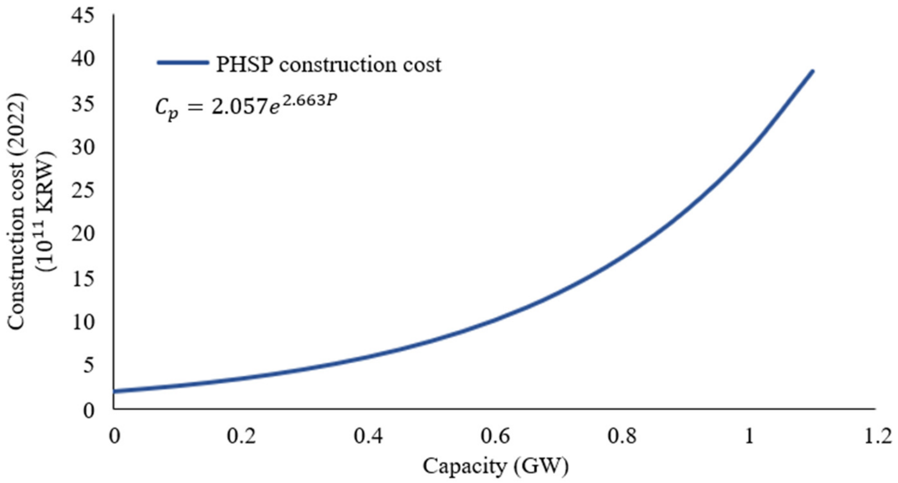


Fig. 7 Expected construction cost of PSHP

(ii) Operation and maintenance (O&M) cost: O&M costs are also referred to as the "Average Annual O&M costs" of the ORNL and were expressed through the formula below [29]. To calculate the total O&M cost, it was necessary to convert it into a present value after assuming the lifespan of the PSHP. The lifespan of the PSHP was set to 40 years, which is the standard lifespan of K-water's hydroelectric power generation facilities.

$$C_{OM} = 31\times10^3 \times \varsigma_{\$} \times P \times t_a \times PA \tag{12}$$

where C_{OM} is the cost of O&M and $\varsigma_{\$}$ is the exchange rate conversion factor (KRW/\$).

(iii) Pumping cost: The calculation of the pumping cost was difficult to quantify due to the uncertainty of PSHP and electricity prices that change every day. Therefore, similar to the power generation benefit, pumping cost was calculated as the minimum average SMP, and it is expressed in:

$$C_{pc} = SMP_{\min} \times P \tag{13}$$

where C_{pc} is the pumping cost and SMP_{min} is the minimum average SMP.

(4) Benefit-Cost ratio (B/C)

Assuming 40 years of operation, the benefit was calculated by adding the benefit from opportunity cost, power generation benefit, and indirect benefit. As for costs, costs were calculated by adding construction costs, O&M costs, and pumping costs. Then, B/C was calculated by dividing each value.

(5) Scoring system

The higher the value of all factors, the higher the value of PSHP. However, since the values of each factor have different units and scales, the values of each factor were normalized to relatively adjust the size of the data. The calculation of Min-Max normalization expresses the formula below, which is the most commonly used normalization method.

$$S^f_{norm} = \frac{x^f - x^f_{\min}}{x^f_{\max} - x^f_{\min}} \tag{14}$$

where S^f_{norm} is the normalized value (score of each factor), x^f is the value, x^f_{max} is the maximum value, x^f_{min} is the minimum value, and f represents factor (En: environmental, St: stability, Es: ESS, and Gn: generation)

B/C is usually used as an important value for economic evaluation in large-scale policy projects or SOC. Therefore, after adding the values of each normalized factor, the B/C value was finally used as a suitability factor. The scoring for calculating the final score of the suitability assessment is expressed as:

$$S = SF(\alpha^{En} S_{norm}^{En} + \alpha^{St} S_{norm}^{St} + \alpha^{Es} S_{norm}^{Es} + \alpha^{Gn} S_{norm}^{Gn}) \tag{15}$$

where S is the suitability score, and SF is the suitability factor (B/C ratio). In this study, it was assumed that the values of weight α are equal to 1.

5. Applications and Results

The suitability evaluation process for using existing infrastructure as upper and lower dams can be summarized as shown in Fig. 8. Economic feasibility (B/C) results are used as evaluation weights to calculate the final suitability score, with higher scores being considered more suitable for use as a PHSP.

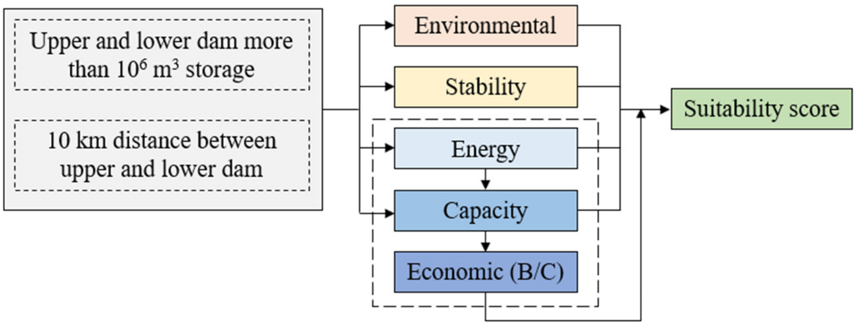


Fig. 8 Flowchart of suitability evaluation method

5.1. *Selection of pilot area*

To apply the evaluation methodology presented in this study to the pilot area, the study areas were investigated for a region in South Korea. Among them, Gangwon-do, where there are many mountainous areas and PSHP is in operation, was selected as the pilot area.

5.2. *Suitability evaluation*

12 pairs of upper and lower dam candidates in Gangwon-do including operating and planned PSHP were selected to apply the method mentioned in Section 5.1, and they are shown in Table 8. The case of Yangyang downstream/upstream dam is a PSHP that is operated in Korea.

Table 8 Candidate group of upper and lower dams

Lower dam	Upper dam
Gulun	Gaeun
Gaeun	Jwaun
Gungchon Gwiun	Heung-eop
Dallae	Samgyoji
Daeryong	Gulun
Daeryong	Wonchang
Dowon	Injeong
Inheung	Dowon
Chuncheon	Sinmae
Janghyeon	Obong
Yangyang (lower)*	Yangyang (upper)*

*Operating PSHP

For the upper and lower dams in Table 8, the suitability evaluation was conducted for each factor. Table 9 shows the evaluation results of candidate infrastructure for upper and lower dams in Gangwon-do that can be used as PSHP. Suitability Score indicates the final suitability of PSHP.

Table 9 Evaluation results of upper and lower dam candidates for PSHP

Group	Lower dam	Upper dam	S_{norm}^{En}	S_{norm}^{St}	S_{norm}^{Es}	S_{norm}^{Gn}	RF (B/C)	Suitability score
1	Janghyeon	Obong	0.8550	1.000	0.2424	0.2424	0.8396	1.965
	Gungchon Gwiun	Heung-eop	1.000	0.8960	0.0052	0.0052	0.9944	1.896
	Yangyang (lower)	Yangyang (upper)	0.000	0.6678	1.000	1.000	0.4537	1.210
2	Daeryong	Wonchang	0.3600	0.6192	0.1300	0.1300	0.8395	1.040
	Dowon	Injeong	0.1438	0.8840	0.0809	0.0809	0.7980	0.9492
	Inheung	Dowon	0.8289	0.1408	0.0213	0.0213	0.8297	0.8399
	Chuncheon	Sinmae	0.0137	0.5449	0.0562	0.0562	1.055	0.7078
3	Dallae	Samgyoji	0.2339	0.6484	0.0175	0.0175	0.5276	0.4839
	DaeryongNaju	Gulun	0.3294	0.1647	0.000	0.000	0.9710	0.4798
	Gulun	Gaeun	0.2677	0.1717	0.0115	0.0115	0.9162	0.4238
	Gaeun	Jwaun	0.3208	0.000	0.0025	0.0025	0.7176	0.2339

*En: environmental, St: stability, Es: ESS, and Gn: generation

Among the lower and upper dams in Gangwon-do, Janghyeon, and Obong were evaluated as the most appropriate to use as upper and lower dams for PSHP. In particular, because of applying the methodology to PSHP in operation, it was confirmed that it was ranked in the first group. In addition, two candidate dams that can be used as upper and lower dams of PSHP were found. In particular, in the case of Janghyeon dam and Obong dam, most scores were ranked 1st to 3rd. As a result, it received higher evaluations than other candidates in comprehensive evaluations including environmental, stability, generation, and ESS.

5.3. Comparison with previous studies

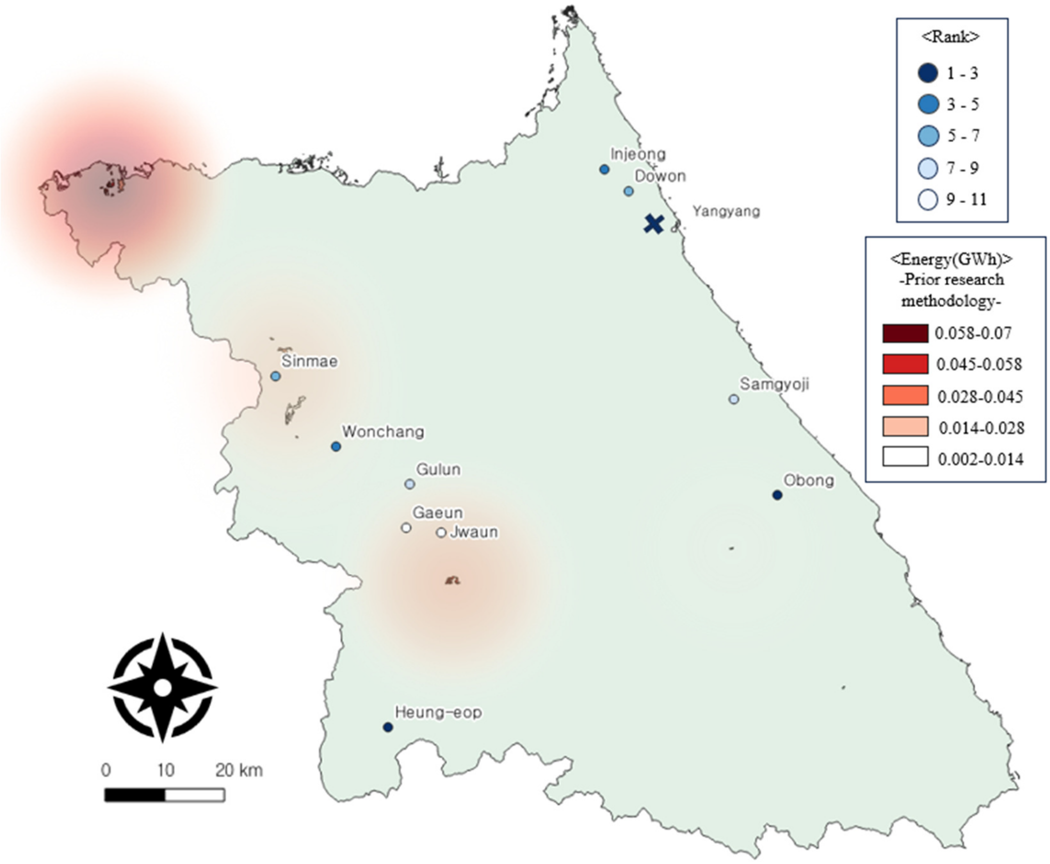


Fig. 9 Previous study and results of this study

A previous study was applied to the same pilot area and compared with the results of this study [11]. Most of the mountains in Korea have low elevations, excluding 150 m conditions [30]. As a result of applying the previous research methodology, the western region of Gangwon-do was found to be suitable. This was similar to the distribution of western locations in the results of this study (Fig. 9). However, according to the results of this study, the eastern and southwestern regions, where the top candidate sites and operating PSHPs are located, were very suitable. These differences appeared due to differences in evaluation items (height, dam capacity, etc.) and an evaluation item system that is not suitable for Korea.

6. Conclusion

With the score-based evaluation method for the rehabilitation of PSHP presented in this study, it is possible to make a primary environmental and technical judgment when evaluating the suitability of PSHP's upper and/or lower dams. At the same time, it is possible to determine an advantageous point for the construction of PSHP through economic evaluation. The process for evaluating the suitability of PSHP's upper and/or lower dams is described below:

(1) The environmental evaluation was conducted using the ECVAM. Assessing the possibility of an accident during the construction and operation of the PSHP was examined through the stability evaluation.

(2) The ESS and generation evaluations determined the expected installed capacity and energy stored capacity of PSHP. Through these evaluations, specifications such as the amount of power generation can be inferred.

(3) With the economic analysis, the expected benefits, and costs of PSHP were estimated including the operation and maintenance.

(4) The final suitability score was presented after multiplying the suitability factor (B/C ratio) with the sum of the normalization score of each factor.

The developed methodology was applied to the Gangwon-do region in Korea. From the results, a group of candidates suitable for use as an upper dam and lower dam were derived, which means that it was a facility suitable for use as a PSHP. In addition, the region where the existing PHSP is located was highly evaluated, and as a result of comparison with prior studies, it was confirmed that it was an appropriate methodology for Korea.

However, the possibility of conversion to upper and lower dams through the vulnerability evaluation of the PSHP facility has not been completely reflected yet. Therefore, more research on vulnerability evaluation should be conducted in the future. Lastly, in this study, the weighting of each factor was set to be identical, which related research to obtain specific weighting factors through surveys such as AHP would be requested.

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