Mechanisms and global deployment of different types of hydroelectric power generation

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Abstract. For the purpose of our research, we aim at explaining the principles of different types of hydropower and providing an overall review on global deployment. We searched for related and authoritative articles, reports and statistics and then made comparison about these data. Overall, different types of hydro power generation are used worldwide, with run-of-river, conventional storage and pumped storage being the main types of hydro power generation. Each method has its own virtues and drawbacks. In addition, developing countries have the features of abundant resources and huge economic effects by using hydropower but lack of fund support and environmental issues. For developed countries, complete and ripe hydropower systems are set however there is less potential to develop new sites. Therefore, we suppose that governments of developing countries should attach importance to and promote large scale hydropower generation by investing more funds whilst that of developed countries should maintain the current situation and keep devoting in refining new hydropower technologies and finally implement them.

Keywords: Hydropower, Mechanism, Global deployment, Advantages and disadvantages.

1. Introduction

As global energy demand continues to rise and concern about climate change are gradually increases, generating electricity by hydropower grabs public's attention. Hydropower is one of the largest and the most developed sustainable renewable energy sources in the world. In the year of 2020, global installed hydropower capacity reached to 1308 gigawatts [1]. In 2021, approximately 4.4 terawatt hours of energy were produced from hydro power plants worldwide [2]. It produces electricity by harnessing the energy from water flow, which has a great deal of benefits that include: Clean Energy Production, reliability, environmental sustainability and so on.

Our research aims at exploring and analyzing the mechanisms and global deployment status of various types of hydroelectric power generation. To be more specific, the research will delve into the fundamental principles behind hydroelectric power generation, examining the different technologies and mechanisms employed in this field. Furthermore, it will assess the environmental impact, economic feasibility, social implications and other aspects associated with these different types of hydroelectric power generation methods.

The significance of this study lies in its potential to provide valuable insights into the effective utilization and deployment of hydroelectric power globally as there are still blanks on providing an overall analysis of global situation. By understanding the mechanisms and exploring the challenges and opportunities, governors can make informed decisions regarding the implementation of hydroelectric power projects. To accomplish these objectives, this paper will adopt a comprehensive approach, integrating literature reviews, case studies, and data analysis. Various sources, including academic journals, scientific publications, industry reports, and government documents, will be consulted to ensure accuracy, reliability, and relevance of information.

To conclude, the objectives of this study are to provide information on how various forms of hydro power generation can be deployed around the world. The aim of this report is to give a comprehensive understanding of the vital source of renewable energy sources through an examination of technology developments, environment and socioeconomic factors. Therefore, in order to mitigate the effects of climate change this research is part of a larger objective which aims at building a stable and resilient energy landscape.

2. Methods of Hydropower Generation

2.1. Run-of-river hydropower

Run of river hydropower is a method of small hydropower generation with roughly 15MW to 75MW power output according to their sizes. The systems are often set in the running streams, where flowing water are channeled into a device called penstock [3]. The penstock are often pipes and channels that will transmit the running water into generating house where turbines are spun and then drives the generator. Thus, energy can be generated by conveying kinetic energy (or some gravitational potential energy) to electric energy. After all these steps, water is released back to the river. The run of river system doesn't contain reservoir typically. For some special conditions, a small dam and a reservoir are set to ensure there is enough water to enter into this system. However, the water storage is only used for the same day with no preparation for future usage.

Compared to other types of hydropower generation, there is a number of advantages to use run of river system. Firstly, lower constructing cost and time is needed to build such a system compared to that is needed to build large-scale dam-type hydropower plants. Secondly, less environmental restrictions need to be considered if manufacturer decides to erect run of river hydropower system. This is because conventional large dams are built based on some special terrains such as the Three Gorges of the Yangtze River in China.

Nevertheless, the real output of run of river hydropower generation is relatively low. In addition, the environmental impact it produces should not be ignored. To be more specific, the project may restrict the abundance of living animals and limit the reproductive process of them due to producing barriers of animal's migration [4].

2.2. Storage hydropower

Storage hydropower is also called impoundment hydropower which is the most common and well-established methods of hydropower generation worldwide. As of 2021, total installed capacity of conventional storage hydropower generation reached to 1300 gigawatts, accounting for approximately 94% of total installed capacity of hydropower [5]. The annual total electricity generated is around 5000 terawatt hours, occupying for 11.6% of global electricity generation [5]. The conventional hydropower plants often have a larger scale than run of river system. Their power output can vary between a few megawatts to hundreds of thousands of megawatts according to their sizes. For example, the Three Gorges in China has an annual output of 1.1 trillion kilowatts hours [6]. The mechanism of impoundment hydropower generation is a bit difference from run of river hydropower generation. Typically, a dam is installed to store the water in the reservoir. At the beginning, the gates of the dam will be opened to release the water in order to generate the electricity. Then, the running water is channeled into the penstock and delivered to the generating house. However, the major difference between conventional storage and run of river hydropower system is that the rate and amount of water flow is controlled at any time when using the conventional type, which means it is regulatable.

The conventional storage hydropower plant requires some special terrains such as mountains and canyons. Nevertheless, it will bring about some impacts on the nearby environment. Firstly, in order to construct the reservoir, lands are replaced which will affect the original ecosystem. In addition, as the dam may blocks the way of upstream and downstream, the migration, reproduction and living environment of underwater species may be affected seriously. Not only that, the influence to the local community is also a critical problem. The change in the land may cause the hardship and eventually migration of local residents as there is lack of natural resources and source of livelihood. Last but not least, the construction of reservoir will destruct and bury a lot of plants which will then be decomposed under water and produce some greenhouse gas such as methane.

Despite issues above, there are still some advantages such as longer service life with more than 80 years, being dispatchable and relative larger output.

2.3. Pumped storage hydropower

Pumped storage hydropower is known as “the world’s water battery”, accounting for 94 percent of installed world’s total energy storage capacity [7]. Compared to conventional storage hydropower system, pumped storage hydropower generation has no significant difference in general. To be more specific, the pumped storage system has two reservoirs, usually one high and one low. The power would be generated whilst the water in the higher reservoir is released down and pass through the turbine in the lower reservoir. This process usually happens in the period of peak-hour. During the period of low demand of energy, the water is pumped up through pipes from the lower reservoir to the upper reservoir. However, the major difference between conventional storage hydropower and pumped storage hydropower is that the latter uses the same amount of water from beginning to end. There are two main types of pumped storage system, open-loop and closed-loop respectively. The flow of water in former is controlled by electricity demand while that of latter is controlled by the water level of the reservoir. According to their distinct mechanisms, each system has its own advantages and disadvantages. For the open-loop system, it has the facts of simple and lower cost but inflexible. For the closed-loop one, the advantage of this system is its high flexibility and the ability to control water flow based on the water level of the reservoir, making it easier to adapt to the needs of the power grid. However, it has a relatively higher cost and needs multiple devices to control.

Like all the systems do, pumped storage hydropower generation has its own strengths and weaknesses. For the merits, the pumped storage hydro plants have a unique feature which is the ability to store water compared to the other types of hydropower generation. This characteristic can solve the intermittency of energy at some extent as excess electricity can be stored and released when needed to meet energy needs optionally. This means that the controllability of the system will be improved, as it is possible to adjust its energy consumption by hand. In addition, hydropower is, in fact, the most famous clean energy source in the world. More accurately, it has negligible contribution to air pollution as almost no greenhouse gases are emitted during the generating process. Furthermore, lower operating cost and longer serving life are also the reasons of why pumped storage hydropower is so popular. Commonly, pumped storage hydropower plants are expected to have a lifetime of 80-100 years with only minimal maintenance. Nevertheless, some disadvantages are encountered. First of all, the initial constructing cost is extremely higher than other types of hydropower plants. In addition, despite their low operating costs, the time it takes for a dam to pay for itself varies greatly. Most of pumped storage power plants take 2 to 5 years to build, and even more so, some of them take more than 10 years to build. Furthermore, environmental impacts should be the biggest issues of utilizing pumped storage hydropower system. To be more accurate, the construction may disrupt the surrounding ecosystems due to flooding the original land and reconstruct large facilities such as pipes, transmission towers and so on. Not only that, this measure will drive local residents out of the area owing to the devastation of indigenous job opportunities such as farming and grazing. Also, the residential and living areas may be compelled to be vanished.

3. Global installation and application analysis

3.1. Developing country

Until now, there are millions of people in the developing countries are facing a problem of not being connected to the electric grid [8]. Therefore, the construction of hydropower plants has been much accounted of governments of the world and been in progress for several decades. In particular, in developing countries, an estimated 3 700 dams producing more than 1 MW are planned or under construction [9]. It's easy to understand why: hydropower is the world's largest renewable energy source, accounting for 71% of global renewable energy production, and only 22% of the world's potential has been exploited so far [6]. Up to the year of 2020, developing countries account for approximately 60% of the global installed capacity of hydropower, as shown in table 1 [10]. In

addition, total energy output of hydropower in developing countries reached to approximately 2276 TWh, occupying for 57% of global total output by hydropower [10].

Table 1. The deployment situation of some developing countries [11-20]

Countries	Total annual output (TWh)	Total installed capacity (MW)	Number of hydropower plants
Brazil	341	109446	649
China	1355	355000	944
India	174.5	51785	233
Russia	214.5	48859	105
Columbia	51.54	11917	12

There are several advantages of utilizing hydropower generation in developing countries compared to other countries around the world. The foremost strength is that plenty of waterpower resources can be found in some developing countries. For instance, the world's largest river Amazon River in the South America can reach a total drainage area of 6.9 million km², consisting of 160 thousand of tributaries [21]. Furthermore, an average river flow of 219000m³/s can be attained. In this case, a total of 158 dams were built and there are another 351 that have been suggested [22]. Among them, Belo Monte hydropower project, which is a typical type of run of river hydropower generation, achieved an installed capacity of 11.2 GW, ranking the first place in the world [23]. It is estimated that the Belo Monte project will deliver enough electricity to supply around 60 million people, accounting for about 10% of total energy demand [23]. For another example, the Three Gorges project in China, which is one of the largest storage hydropower plants among the world, also plays an important role in generating electricity. To be more specific, the Three Gorges Dam has a generating capacity of 22,500 MW [6]. In addition, the dam produced 113,8 kilowatt hours in 2020, setting a new world record for annual power production [6]. The electricity generated there are transferred to other provinces such as Henan, Hubei, Hunan, Jiangxi, Chongqing, Anhui, Jiangsu, Zhejiang, Shanghai and Guangdong, etc. Overall, abundance natural water resources in some developing countries provide numerous opportunities to develop and utilize hydropower generation.

Moreover, making use of hydropower generation would derive some economic effects. First of all, constructing and maintaining hydropower plants will provide a number of job opportunities. Skilled and unskilled labor is required for site preparation, dam construction, turbine installation, maintenance, and plant operations. These jobs directly contribute to reducing unemployment rates, enhancing household incomes, and stimulating local economies. For example, hydropower generation industries in China have provided more than 2 million of job opportunities [24]. Similarly, in the fiscal year 2019-2020, India's hydropower industry employed about 300000 people both directly and indirectly [25]. Secondly, hydropower projects provide a reliable source of revenue for developing countries. Energy produced from hydroelectric plants can be sold domestically or exported, generating income through electricity sales. This revenue can be reinvested in infrastructure development, education, healthcare, and other essential sectors, further driving economic growth and improving living conditions. Last but not least, hydroelectric power is relatively inexpensive once the initial construction costs are recovered. The operational costs are low, primarily comprising maintenance and overhead expenses. As a result, electricity generated from hydroelectric sources can be provided to consumers at competitive prices, making it affordable for domestic and industrial use. This affordability stimulates industrial growth, attracting investment and creating a favorable business environment.

However, making use of hydropower generation in developing countries may faces some problems. To beginning with, Dam construction and reservoir formation may lead to issues such as population migration, ecosystem damage, and flood risk. These issues need to be carefully addressed to balance the benefits of hydroelectric power generation with the protection needs of the social environment. Also, Large hydroelectric power projects require significant investment. Developing countries may face the challenge of funding shortages as they also require significant funding in other areas such as education, healthcare, and infrastructure.

3.2. Developed country

Compared to the deficient hydropower generation system in developing countries, mature hydropower systems have taken shape in developed countries, as shown in table 2. In addition, hydropower often occupies a very large proportion of electricity generation among the countries. For instance, Norway has the most advanced hydropower system in the world. More accurately, it had an installed capacity of 33391 MW with 1439 MW of pumped storage hydropower capacity up to the year of 2021 [33]. In addition, it has generated about 143.70 TWh of the whole year of 2021, which accounted for more than 90% of total power output in Norway [33]. Another example is Japan. Japan has a well-developed and advanced hydropower generation system over a hundred years of progressing. Japan also represents one of the world's largest consumes of hydropower. In the year of 2022, the total number of hydropower plants reached to 1760 which accounted for 2% of world's total hydropower capacity [29]. In addition, electricity produced by hydropower was stood at approximately 78-terawatt hour, which was the second most productive renewable energy sources in japan [28]. Compared to developing countries, pumped hydropower plants are gradually set up. This is because pumped storage system can solve the problem of electricity intermittency caused by the widening gap of demand for energy between daytime and nighttime. Furthermore, there are diversified types of hydroelectric power projects in developed countries. Including large dams, small hydropower stations, tidal power generation, and ocean power generation. Some countries have also begun to use new technologies, such as tidal and wave power generation, to improve the efficiency of hydropower and reduce environmental impacts. For example, micro hydropower devices are favored by Japanese government due to the reason of lack of potential to build large scale plants. Micro hydro is a type of run of river hydropower system, whose output is less than 100 kilowatts. The systems are often set in the running streams or in the farmlands. Even though they didn't contribute for a large percent of Japan total output, numerous advantages such as negligible carbon emission, higher efficiency, almost suffering no influence by weather, etc., can be seen.

However, developed countries are facing some problems. First of all, the developed countries can take almost no further steps on building large scale hydropower plants as nations have used up all the potential sites for constructing them. In addition, many facilities of hydropower systems are getting too old among the developed countries. Hydroelectric power has an ageing fleet, almost half of its worldwide generation capacity is over 30 years old and approximately one third above the age of 40 [37].

Table 2. The deployment situation of some developed countries [26-36]

Countries	Total annual output (TWh)	Total installed capacity (MW)	Number of hydropower plants
USA	260	101943	1429
Japan	78	49050	1760
Switzerland	37	15610	693
Norway	143.7	33391	291
Canada	377	82300	553

4. Conclusion

In this study, our research aimed to explore the mechanisms of different types of hydropower generation and their implications in both developing and developed countries. We adopted a literature review approach to gather relevant articles, reports, and data. The data analysis process involved synthesizing key findings and comparing them across different countries. The most important finding of our research is that each type of hydropower generation has its own advantages and drawbacks due to the difference of principles. Therefore, when plan to construct a hydropower plant, the government should consider multiple aspects such as costs, geographical positions, environmental impacts and so on. In the further study, we analyze the reasons, benefits brought and challenges facing of using hydropower in both developing and developed countries. Hence, we found that the potential of utilizing hydropower is huge for developing countries meanwhile a larger number of problems need

to be solved compared to developed countries. These results are consistent with our research objective and support the importance of hydropower as a renewable energy source. The significance of our research lies in providing insights into the principles of different types of hydropower and global deployment situation. It fills gaps in existing research and provide useful information for governments and researchers in the energy sector. However, we only finished a review on the general situation while there are many special cases in each region that have been ignored. Therefore, further research should be more precise and all-round on providing global situation by collecting and analyzing more thorough data.

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