Renewable and Sustainable Energy Reviews 77 (2017) 229–238

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Cost estimate of small hydroelectric power plants based on the aspect factor

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ARTICLE INFO

Keywords:
Small hydroelectric plants (SHPs)
Aspect factor (AF)
Unit cost of SHP
Physical scheme
Cost estimates

ABSTRACT

Hydroelectric power plants help to reduce greenhouse gas emissions, expand renewable energy generation, and distribute national energy generation. This is particularly true for small hydroelectric plants (SHPs). However, the development of SHPs is dependent on the economic and financial feasibility, which must be evaluated by cost estimates before starting construction. The parameterization of these costs with satisfactory precision can be difficult or even impossible due to the particularities a project or region. Thus, this study presents the aspect factor (AF), which is as a parameter based on the least squares method that represents the physical characteristics of a plant scheme. This factor was applied to determine the unit cost of SHP projects in Brazil and India. The results were evaluated using statistical tests. The cost estimate equations found in the literature were also revised and compared with the AF to characterize its applicability to other regions of the world.

1. Introduction

The production of power using falling or in flowing water is quite old and has experienced a large growth in demand since the Industrial Revolution. At the beginning of the 20th century, many small hydroelectric power plants were commercially built in various parts of the world. As power plants became larger, dams began to be designed for additional purposes, such as flood control, irrigation, and navigation [50].

Hydraulic generation is used a source of clean and renewable energy in more than 150 countries, representing more than 20% of all electricity produced in the world [25]. In Brazil, the percentage is larger at nearly 71% of the electricity consumed in the country [6]. According to the International Energy Agency [17], use of this renewable source of electricity is increasing throughout the world, and it is the second highest in total capacity. It is also the most proven form of renewable generation technology thus far [26].

Several countries have not fully developed hydroelectric generation to its full potential. For example, 64% of the electricity in Turkey is generated by hydroelectric generation [5]. The Malaysian government is planning to develop 490 MW of small-scale hydroelectric plants [52]. Fig. 1 shows the total and potential hydroelectric generation available worldwide for plants with more with than 10-MW capacity, which indicates great remaining potential. According to Capik et al. [8], the world potential is 14,060 TW h/year when only technical feasibility is considered and 8905 TW h/year when economic attractiveness is considered.

There are no uniform criteria for classifying small hydroelectric plants (SHPs) between countries. According to Zhang et al. [53], definitions for SHPs by power capacity range from < 1 [MW] in Germany to < 50 [MW] in Canada. In Brazil and India, plants with capacities of 1–30 [MW] and 2–25 [MW] are classified as SHPs, respectively [10,29]. However, the present study uses the convention adopted by the European Small Hydropower Association [11]:

- Low head plants: $2 < H < 30$ [m].
- Average head plants: $30 < H < 100$ [m].
- High head plants: $H > 100$ [m].

Hydrogeneration classified based on the process used to convert the kinetic energy released [9]. The hydraulic power can be calculated by thermodynamic analysis of the discharge, and the maximum usable potential in a river basin is 50% of the theoretical power potential [39]. The maximum usable potential is calculated based on the volumetric discharge at the mouth and on the average slope of the basin. There are four main types of SHP arrangements in which this process can be applied, which are also shown in Fig. 2 [29,38,48]:

(i) *Hydroelectric power plant dams*: These are deployed on stretches of a river and have a jumper between the dam and the powerhouse.
(ii) *Run-of-river hydropower plants:* These are typically deployed on a stretch of river that is relatively large and has good slope and

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http://dx.doi.org/10.1016/j.rser.2017.03.134
Received 6 April 2016; Received in revised form 15 February 2017; Accepted 31 March 2017
1364-0321/

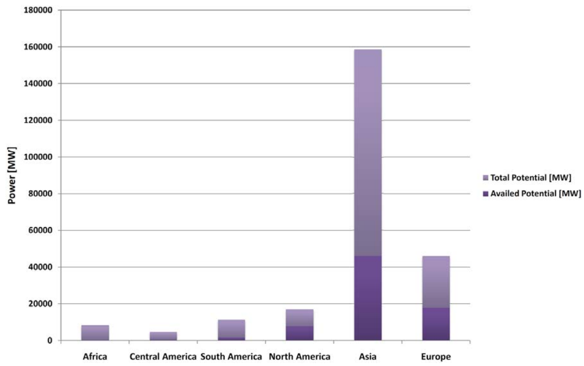

Fig. 1. World hydropower potential. Source: UNIDO e ICSHP [47].

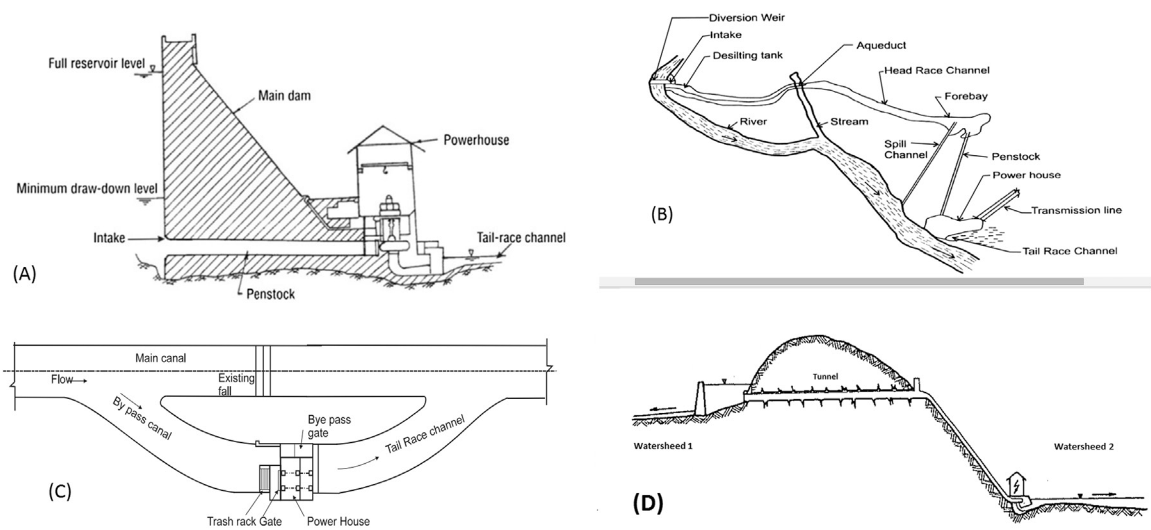

Fig. 2. Small hydropower schemes. A) Damping scheme, B) run-of-river scheme, C) canal-based power plant, and D) derivation power plant. Source: Modified from Schreiber [33], Signal and Saini [35,36], Singal et al. [37], and Varun et al. [48].

rapids. This type of plant requires a water level that is similar to that downstream. The dam and the canal are driven by a low pressure system, which should be scaled according to the technical, economic, and local environmental conditions.

(iii) *Canal-based power plants:* These plants use the head and flows in canals (main canals or by-pass canals) and may be integrated with an irrigation network.

(iv) *Derivation power plants:* In these plants, the bus is associated with one river and the discharge is output to another.

Usually, run-of-river plants are used for SHPs due their low environmental impact. SHPs may also be developed in a decentralized way to reduce transmission line losses and system operation risks [49]. According to the IEA [16] and Akella et al. [2], carbon dioxide emissions throughout the life cycle of these plants are on the order of 7–9 gCO_2/kW h, which is 100 times lower than that of fuels such as coal and wood. This emphasizes the importance of these plants in distributed generation, especially in rural and isolated areas [13,14,4,43].

There are several barriers to the development of SHPs around the world. For instance, the Brazilian market has been stagnant for years. According to Tiago Filho et al. [45], SHP growth in Brazil has been have limited by changes in the politics and economy of Brazil, which have been accompanied by some social opposition by NGOs. Furthermore, only a small percentage (1%) of the energy generated by SHPs was bought in Brazilian energy auctions between 2008 and 2016 [18]. According to Rangel [28], the costs of electricity generation by SHPs in Brazil varies between 53.43 and 87.5 USD/MW h. These costs are generally higher than the tariffs charged for SHPs. However, Jasper [19] emphasized that some factors have been improving the national SHP market, such as rising value of the energy reference tariff for SHPs and the acceleration of procedures related to environmental licensing.

To overcome the barriers to the economic feasibility of SHPs, several studies have investigated optimization methods of dimensioning such plants to maximize their economic benefits. Anagnostopoulos and Papantonis [3] presented a model that can be used to maximize the economic benefits, optimize energy production, and optimize the use of local discharge. Santolin et al. [30] presented an optimization model that considers seven factors: the turbine type, turbine dimensions, annual energy production, maximum installation height to avoid cavitation, engine cost, net present value (NPV), and the internal rate of return (IRR). Voros et al. [51] carried out a series of simulations that consider various potential sites and types of turbines. They obtained an empirical equation (Eq. (1)) for calculating the optimum turbine discharge Q:

$$Q = \left[\frac{\gamma q_{50}^*}{1+(\gamma-1)q_{50}^*}\left(1-\frac{q_{min}^*}{q_{max}^*}\right)+\frac{q_{min}^*}{q_{max}^*}\right]Q_{max}^* \quad (1)$$

where q_{50}^* is a parameter from curve of the discharge rate duration and defined as $\frac{Q_{50}^*}{Q_{max}^*}$; q_{min}^* is the minimum discharge rate duration curve parameter defined as $\frac{Q_{min}^*}{Q_{max}^*}$; q_{max}^* is the hydro turbine's maximum working discharge rate fraction; Q_{max}^* is the annual highest stream discharge rate (m^3/s); Q_{min}^* is the annual lowest stream discharge rate (m^3/s); and γ is a model parameter defined as 0.422 for Francis turbines, 0.369 for Pelton turbines, and 0.364 for axial discharge turbines [51]. To define the discharge limitations for SHPs operation, Santos et al. [32] presented a theoretical equation for calculating the maximum possible discharge for SHPs to determine economically viability. Mishra et al. [41] provide a more comprehensive review on the optimization methods of power plants using several types of cost data.

The physical aspects of SHPs influence the types of machines used and the civil works required for the deployment. These aspects therefore influence the cost and economic benefits generated by an SHP. Changing the physical characteristics of SHPs also changes the distribution of the costs (Fig. 3). Therefore, this study reviews several cost estimates for SHPs, particularly the aspect factor (AF) equation. Cost estimates based on the AF are then developed for Brazil and India, and then the effectiveness is evaluated by graphical and statistical analyses.