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Accurate estimation model for small and micro hydropower plants costs in hybrid energy systems modelling

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ABSTRACT

In last decades, more and more complex models have been developed to investigate hybrid energy systems in order to define optimal size and management strategies. However, the results accuracy of these analyses is strictly related to the accuracy not only of the models but also of the input data, among which one of the most important is a proper assessment of investment costs.

Even though small deviations from real investment costs are expected due to the peculiarities of each energy system, the meaningfulness of optimization analyses is affected by the availability of cost correlations characterized by sufficient accuracy. Although some technologies are characterized by standardized costs, other ones, as small hydro power plants, are characterized by investment costs that cannot be properly estimated with too simplified models, based on power and net head.

This paper proposes a new approach for the estimation of the electro-mechanical equipment cost, according to which the final cost is divided into three terms with a distinct dependence not only on power and net head, but also on design flow rate. The resulting cost estimation correlations for Pelton, Francis and Kaplan turbines were characterized by mean errors smaller than those of the best performing literature correlations.

1. Introduction

In last decades, the awareness about the need of a responsible use of the fossil reserves and of an increasing share of renewable energy sources has favoured the development of hybrid energy systems, mainly based on renewable energy sources. In particular, in developing countries, the exploitation of renewable sources represents a great opportunity for increasing the number of people having access to electricity with an adequate grade of availability and reliability. This has favoured the increasing diffusion of small plants and distributed generation, not only allowing for the use of low-density distributed renewable sources (biomass, wind, solar, mini-hydro) but also providing energetic self-sufficiency for small communities (isolated or not) with a consequent reduction of transmission losses and grid congestion problems. The exploitation of renewable energy sources was also demonstrated to have a positive socio-technical influence even on the evolution of the local energy systems, as verified by Hauber and Ruppert-Winkel [1] in three different case studies. Even single technology based energy systems have been considered an excellent option for rural electrification in remote and decentralized areas, characterized by a proper potential [2] or by existing irrigation systems by means of small hydro power plants [3].

Several studies have been carried out in literature to support the design and management of individual or micro-grid energy systems fed by multiple energy sources, only including renewable energy sources IRES (Integrated Renewable Energy Systems) or integrated with fossil fuels to overcome the geographical and temporal variability of wind and solar resources (hybrid energy systems) [4–11].

Even though the models adopted to analyse energy systems have become in the years more and more complex and accurate, the same attention has not always been paid to increase the accuracy of the model input data, among which one of the most important for a proper economic analysis is certainly represented by the investment costs. Although some technologies considered in hybrid energy systems are characterized by standardized costs that can be estimated with good accuracy without complex estimation models, other technologies, as for example small hydro power plants, are

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characterized by investment costs that cannot be estimated with too simplified models. For example, Akella et al. [12] presents the results of an optimization carried out on different IRES models in an Indian State. Unlike the detailed input data regarding energy demand and energy resources availability, investment costs were based on old and approximate data provided in 1993 by Ramakumar et al. [13] for a selection of technologies. This was particularly evident for hydropower plants, for which the lack of accuracy is due not only to the aged reference data set (costs of hydropower plants installed in the US during the period from 1983 to 1986), but also to the lack of a cost differentiation among the different types of hydraulic turbines, as will be shown in the next section (see Section 2).

Difficulty in finding an accurate estimation of small and micro-hydro power plant costs was also highlighted by Bracken et al. [14], whose analysis carried out on UK sites for small scale production was not able to identify a direct relationship between cost and power output. On the basis of this estimation model, searching for a simple power output dependency, they assumed the cost of small hydro power plants to be very dependent on local conditions. However, this cost is the sum of the cost of civil engineering works (infrastructure, land purchase, dam construction, weir and intake, penstock, etc.) and of the electro-mechanical equipment. The civil works are really country and region dependent and vary considerably depending on the type of project, difficulty of access, labour and commodity prices for cement and steel. For this reason, the most accurate correlations for estimating the civil costs need accurate details of the plant project (length and diameter of pipelines and penstock, concrete volume required in the dam walls, concrete volume required in the intake, specific costs of all the materials, etc.) [15] which are generally not known and hence not modelled in preliminary analyses for supporting design and management of individual or micro-grid energy systems.

On the other hand, the costs of electro-mechanical equipment follow world market prices [16] and hence are expected to be estimable by proper correlations. Because of this, some authors have even proposed to relate the uncertain civil costs to the electro-mechanical equipment cost, by means of proper multiplying factors depending on the expected site characteristics [17–20].

In such a context, some studies tried to increase the accuracy of the economic input data by adopting more refined analytical correlations, depending not only on power output but also on net head and turbine type.

For example, Santolin et al. [21] proposed a techno-economic method for optimal sizing of small hydro power plants in which the investment cost evaluation was based on Ogayar and Vidals's correlations with coefficients determined by interpolation as a function of the turbine type [22]. Cartelle Barros et al. [23] and Manfrida and Secchi [24] respectively analysed the economic sustainability of mini-hydroelectric power plants and of seawater pumped storage solutions for photovoltaic energy systems by using the economic correlations proposed by Kaldellis et al. [20] and Aggidis et al. [25].

In 2015, Carapellucci et al. [26] carried out techno-economic analyses of small hydro power plants, by adopting two different economic models to estimate capital and O&M costs of the plants. The first model was based on cost functions derived by interpolating plants data collected in 2010 [27], while the second one was aimed at updating capital and O&M costs prediction by taking into account economic statistics provided by the Hydro Data Initiative [28].

In 2016, Zema et al. proposed the results of a techno-economic feasibility analysis on micro hydro power plants in existing irrigation systems [3]. To estimate the cost of the electro-mechanical equipment, they adopted the correlations proposed by Papantonis [29] based on a European data set available in 2001. In addition, to refine the results they updated one of the coefficient of the previous correlation through a comparison with recent market values.

Although such refinements in investment model predictions, the considerable amount of techno-economic studies on hydro power plants still provide a wide range of investment cost estimations between 1300 $/kW and 8000 $/kW for smaller projects [30], testifying that capital costs of small hydro power plants cannot be estimated with too simplified models, calibrated on a country-dependent set of real cost data and considering a dependency of such investment costs on one or at the most two design parameters, such as power and net head.

Even though some deviations from the estimated costs are expected due to the specific characteristics of each plant, correlations that depend solely on power and net head do not appear to take properly into account all the different aspects (design flow rate, turbine size, etc.) which concur in the definition of the final cost of the electro-mechanical equipment.

Differently from the literature correlations, this paper proposes a new approach for the estimation of the cost of electro-mechanical equipment, according to which the final cost is decomposed into three terms, two of which represent the cost of mechanical equipment, and one the cost of electrical equipment. The final correlation, whose coefficients depend on the type of turbine selected, depend not only on power and net head, but also on design flow rate.

The rest of the paper is organized as follows. Section 2 presents an overview of the most performing correlations proposed in literature for estimating the cost of the electro-mechanical equipment. Section 3 presents in detail the new approach proposed for the estimation of the cost of electro-mechanical equipment. Sections 4, 5 and 6 propose the cost equations determined for Pelton, Francis and Kaplan turbines. Finally, section 7 presents a comparison between the proposed approach and other literature correlations.

2. Literature methodology for the estimation of electro-mechanical equipment cost

The cost of electro-mechanical equipment in small hydro power plants has a significant impact on the final budget (about 30–40% of the total sum) [31,32]. This estimation is even more important in the case of retrofitting of a small hydro power plant as the electro-mechanical equipment represents the main investment cost.

Several analytical correlations were proposed over the past years for the assessment of the electro-mechanical equipment costs (C), most of them being dependent on power (P) and net head (H) according to the following equation model:

$$C = aP^{b}H^{c} \tag{1}$$

where a, b and c are coefficients statistically determined on the basis of the available database of small hydro power plants (Table 1).

The first correlation, considering both power and net head, was proposed by Gordon and Penman in 1979 [17]. Their analysis focused on hydro power plants smaller than 5 MW and, on the basis of techno-economic data of power plants located in North America, the following empirical correlation was proposed for the cost determination of the electro-mechanical equipment:

$$Cost[\$] = 9000{*}P[kW]^{0.7}{*}H[m]^{-0.35} \tag{2}$$

In 1979, Lasu and Persson [33] developed a similar correlation, but based on the data of plants located in Sweden: