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Approximate formulae for the assessment of the long-term economic impact of environmental constraints on hydropeaking

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ABSTRACT

The establishment of more severe *hydrological environmental constraints*, usually *minimum flows* and *maximum ramping rates*, on hydropower operation is a growing trend in the world. This paper presents the results of an attempt to assess the long-term economic impact of the above-mentioned constraints by three approximate formulae which quantify their effects, both separately and jointly, on a hydropower plant characterised by two parameters. The formulae are the result of three regression models developed from the solutions of 476 deterministic long-term hydro-scheduling problems corresponding to ten hydropower plants located in Spain. They were tested with 98 additional problems corresponding to two other Spanish hydropower plants. The formulae have a final average relative error of 8.2% and a final relative error of 19% with a confidence interval of 95%. This paper also offers some insight about the difficulties for tracking the energy prices when these constraints are present. Finally, the analysis of the hourly results indicates some additional effects of these constraints on hydropower operation related to the energy generated by the plant, the amount of water spilled from the reservoir, and the number of operating hours and of start-ups and shut-downs of the hydro units.

1. Introduction

Hydroelectricy has become the fourth largest source of primary energy in the world and the first one among renewable energies [10]. Unfortunately, hydropower plants usually have negative effects on the fluvial ecosystems where they are located. One of their most characteristic environmental impacts arises because their operations tend to follow the energy price profile (*hydropeaking*) and, as a result, their water releases disturb the natural flow regimes in the rivers [37]. The said operation pattern can be more pronounced in power systems with high penetration of intermittent renewable energy [18] and is therefore expected to increase in the next future both in Europe [12] and United States [19], among other countries.

In order to mitigate the above-mentioned impact, new environmental regimes have been imposed or are intended to be imposed on hydropower operation in various parts of the world, including the United States of America [20] and the members of the European Union [13]. Indeed some international institutions such as the World Bank are promoting them [21]. It is worth pointing out that these latter regimes may need to be modified periodically as a consequence of climate change or merely of variations in land-use activities [2]. The most common expressions of these *environmental constraints* are: *minimum flows* (ϕ), minimum values of water release, and *maximum ramping rates* (ρ), maximum rates of change of flows.

As it seems obvious, both ϕ and ρ cause economic impacts in hydroelectric production and consequently their quantification, as well as a sensitivity analysis of them [34], are important in implementing processes of new environmental regimes [28] and in relicensing negotiations [32]. As demonstrated in [26], ρ and specially ϕ can even cause significant impacts on the power system operation costs.

However, to the best of our knowledge, no analytical expression for the calculation of those impacts has been suggested yet despite its growing necessity and the number of studies devoted to this topic in the last two decades. Among those studies, the following are the most relevant to compare with:

- **Veselka et al.** [39]: it is a report on support an environmental impact statement on power marketing at the Salt Lake City Area

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Nomenclature

Abbreviations

F	flow released by the hydropower plant and the reservoir [m^3/s].
V	stored volume of water in the reservoir [hm^3].
ε	long-term economic impact(s) [%].
ϕ	minimum environmental flow(s) [%].
ρ	maximum ramping rate(s) [h].

Acronyms

DDP	discrete dynamic programming.
IDP	incremental dynamic programming.
MILP	mixed integer linear programming.
PDC	power-discharge piecewise linear curve(s).

Constants

f_c	conversion factor [0.0036 hm^3/h/m^3/s].

Indexes

c and $ç$	curve of the PDC.
hu	hydro unit of the plant.
i	initial V of the subproblem.
j	initial F of the subproblem.
k	problem stage.
l	final V of the subproblem.
m	final F of the subproblem.
s	segment of the PDC.
s^{hu}	first segment of the hu -th hydro unit in ascending order of flow discharged [m^3/s].
t	hour within the stage.

Parameters

C	number of the PDC of the subproblem.
e^s	maximum extent of the s-th segment of the PDC of the subproblem [m^3/s].
H^{max}	maximum operating gross head [m].
H^{min}	minimum operating gross head [m].
$H^{\%}$	percentage of the range of operating gross head that must be “covered” by each PDC.
HU	number of hydro units of the plant.
K	number of weeks per problem.
p^{max}	maximum hydropower plant power output of the subproblem [MW].
$p^{min,ç}$	minimum hydropower plant power output according to the $ç$-th PDC of the subproblem [MW].
q^{hu}	plant flow above which the ($hu + 1$)-th hydro unit starts-up [m^3/s].
q^{max}	maximum plant flow of the subproblem [m^3/s].
q^{min}	minimum plant flow of the subproblem [m^3/s].
Q_k^{ec}	ϕ at week k [m^3/s].
Q^{max}	maximum plant flow [m^3/s].
Q^{maxbo}	maximum flow through the bottom outlets [m^3/s].
Q^{min}	minimum plant flow [m^3/s].
$r^{s,ç}$	slope of the s-th segment of the $ç$-th PDC of the subproblem [MW/m^3/s].
RR^{down}	down ρ [m^3/s/h].
RR^{up}	up ρ [m^3/s/h].$S =$ number of segments of the PDC of the subproblem.
T	number of hours per stage.
v^c	water content of the reservoir above which d_t^c is equal to 1 [hm^3].
v^{maxf}	maximum feasible water content of the reservoir corresponding to h^{maxf} [hm^3].
$V^{0,f}$	V at the beginning and end of the period of study [hm^3].
V^{max}	maximum useful volume of the reservoir [hm^3].
V_k^{inf}	volume of water inflow to the reservoir during week k [hm^3].
w_t	water inflow to the reservoir during hour t [m^3/s].
W^{avg}	average river flow during the year [m^3/s].
α	wear and tear costs of hydro units due to variations in the generated power [€/MW].
β	start-up and shut-down costs for hydro units [€/ud].
π_t	energy price during hour t [€/MWh].
Π_k	mean of the energy prices during week k [€/MWh].
ϕ^{max}	maximum of the considered ϕ [m^3/s].
ρ^{max}	maximum of the considered ρ [h].

Non-negative variables

d_t^c	binary variable that takes the value 0 during hour t if v_t is lower than the c-th PDC or the value 1 in other case.
f_T^{dec}	decrease in flow through the hydropower plant and the reservoir during hour T [m^3/s].
f_T^{inc}	increase in flow through the hydropower plant and the reservoir during hour T [m^3/s].
F_k	F at the beginning of the week k [m^3/s].
F_{k+1}^m	F corresponding to the node m at the end of the week k [m^3/s].
h^{maxf}	maximum feasible gross head of the subproblem [m].
h^{minf}	minimum feasible gross head of the subproblem [m].
off_t^{hu}	binary variable which is equal to 1 if the hu-th hydro unit is shut-down during hour t.
on_t^{hu}	binary variable which is equal to 1 if the hu-th hydro unit is started-up during hour t.
p_t	generated power during hour t [MW].
p_t^{dec}	decrease in generated power between hours t and $t+1$ [MW].
p_t^{inc}	increase in generated power between hours t and $t+1$ [MW].
$P_k^{i,l}$	approximate generated power corresponding to the decision to go from V_k^i to V_{k+1}^l linearly interpolated in the generation characteristic from the weekly average values of both the net head and the plant operating flow [MW].
q_t^{bo}	flow through the bottom outlets during hour t [m^3/s].
q_t	plant flow during hour t [m^3/s].
q_t^s	plant flow corresponding to the s-th segment of the PDC during hour t [m^3/s].
$T_k^{ope,i,l}$	number of operating hours corresponding to the decision to go from V_k^i to V_{k+1}^l [h].
u_t^{hu}	binary variable which is equal to 1 if the hu-th hydro unit is on-line during hour t.
v_t	water content of the reservoir at the end of the hour t [hm^3].
v_T^{dec}	decrease in water content of the reservoir respect to the value obtained in the estimation step during hour T [hm^3].
v_T^{inc}	increase in water content of the reservoir respect to the value obtained in the estimation step during hour T [hm^3].
V_k	V at the beginning of the week k [hm^3].
V_k^i	V corresponding to the node i at the beginning of the week k [hm^3].