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GIS-based approach for assessing the energy potential and the financial feasibility of run-off-river hydro-power in Alpine valleys

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HIGHLIGHTS

- An open-source tool to plan hydropower production is proposed.
- The GIS-based model accounts for spatial changes in physical, morphological, legal and financial variables.
- In the case of hydro-power potential raster and vector data have to be combined.
- Site-specific model has been validated by comparing model output with the local knowledge and historical decisions.
- Available sites in Alpine valley are often in isolated areas and civil work engineering cost can arise.

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ABSTRACT

In the last decade, European attractive policies are favoring the construction of new run-off hydro-power plants. The realization cost of these plants is quite low in mountain areas thanks to small water discharges and high gross heads. For this reason, small rivers have been strongly exploited without considering an optimal use of the resource. Nowadays, available sites are often in areas with low accessibility and a greater specific cost of civil engineering works. However, during the planning of new small hydro-power plants, the dependency of physical, technical, legal and financial variable on space is often not assessed. The tool presented in this paper addresses this gap to support the planning of run-off-river plants. The method improves on previous approaches by (1) integrating all the legal, technical and financial analysis in a GIS tool, and (2) trying to validate the site-specific model with local knowledge. The tool is applied to the Gesso and Vermenagna valleys in the Alps. Information and data were collected and discussed with local stakeholders in order to improve the model results.

1. Introduction

While estimating the feasibility of a renewable energy development project and plan, a first challenge is to define the availability of the natural resource. Only theoretically all the available energy in the nature could be used [1,2]. In the planning process, further restrictions to exploit the natural resource (e.g. technical, environmental, legal, social and financial constraints) should be considered [2–10].

In the case of hydro-power, defining the availability of the natural resource and its potential firstly depends on the technical installation. They can mainly be divided in two kinds, reservoir and run-off hydro-power plants (i.e. just a weir and no water storage). Dams and reservoir plants, hence big hydro-power plants, have already covered more than the 50% of European hydro-power potential [11]. They have a significant role, along with other renewable energy, since they can deliver valuable peak-load power. More favorable and convenient sites for big hydro-power plants have been already utilized and future increases could be provided only by small hydro-power projects as highlighted by the Word Energy Council for the Italian case. Nowadays, European attractive policies are in fact favoring small hydro-power supply that in most cases correspond to run-off plants. The estimation of their energy potential is then relevant for a sustainable planning.

In mountain areas, usually, run-off hydro-power plants primary use the head to generate power and the flowing water is channeled from a river through a canal or penstock to spin a turbine. Consequently, in order to estimate the energy potential, elevation and discharge data have to be combined. Palomino Cuya et al. [1] evaluate the energy potential in function of the mean annual discharge of each river section and the mean elevation calculated from the hypsographic curve. They obtain the hydro-power potential at river scale. Kusre et al. [12]

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Nomenclature

List of symbols

Δh	gross head
ϵ	roughness height
η	global efficiency
Φ_{inst}	installed power
ψ	life of the hydro-power plant
ρ	water density
ς	progressive coordinate along the pipelines
A	cross sectional area of flow
A_c	area with planning constraints
A_v	view-shed or visibility area
C	yearly cost
c	specific cost
D	diameter of the penstock
d	distance between two plants
e_{price}	price of the electricity
f	Darcy-Weisbach friction coefficient
g	gravity acceleration
h	elevation
k_s	Strickler coefficient
l	rivers exploited segment
n	number of full-load hours equivalent
P	energy potential indicator
p	value between 0 and 1
Q	yearly discharge
R	yearly revenue
r	interest rate
R_h	hydraulic radius
Re	Reynolds number
s	progressive coordinate along the river
v	velocity

List of subscripts

b	sub-basin
$comp$	compensation costs
d	derivation channel
em	electro-mechanical costs
$excv$	excavation cost
fin	financial evaluation
fix	fix costs
grd	grid connection
i	i-th plant
j	j-th bank of the river
l	supply and installation cost
loc	singular losses
lu	land use
net	net value accounting for losses
o	operating costs
p	penstock
pl	power line
$plan$	planning evaluation
st	power station costs
tec	technical evaluation
$theo$	theoretical evaluation
tr	tributes for expropriation
vup	tributes for wooded areas

pinpoint three criteria for identification of sites: order of stream, bottom gradient and minimum hydro-power site interval. They deepen the hydrological model to assess the flow rate, but they do not deal with spatial planning and site-specific financial aspects. Yah et al. [13] summarize the steps for assessing small hydro-power projects by underlying the importance of site identification and of preliminary analysis to evaluate the technical, environmental and economic (with an accuracy of circa 30%) feasibility of the project. These considerations are still not integrated in the hydro-power potential assessment and GIS analysis.

Müller et al. [14] present a webGIS tool to siting hydro-power infrastructures based on topography. Their algorithm mainly maximizes the product between the gross head and the catchment area without accounting for the spatial variability of the discharge due to existing water diversion. However, the spatial energy planning mechanisms should take into account environmental criteria as well as socio-economic aspects, including other water uses [15]. In the WebGIS tool, they introduce a financial assessment of hydro-power projects but their analysis neglects the cost factors related to hydraulic head, geometry of the infrastructure and site accessibility. Müller et al. [14] and Basso and Botter [16] simplify the cost as a power law of the electrical capacity. Ogayar and Vidal [17] highlight that most of the authors use an analytical expression for the calculation of the cost of electro-mechanical equipment depending on electrical capacity and net head. The power law coefficients are, however, related to the geographical, space or time field in which they are used and this spatial dependency should be introduced in the site-specific financial assessment. This cost of the equipment is a high percentage of the investments on hydro-power plants. Despite, the cost for civil works is around 40% of the total budget of the plant. Kaldellis et al. [18] underline as the specific cost of civil engineering works, including infrastructure, land purchase, dam construction, weir and intake, water canal, forebay tank, penstock depends on the local situation of every specific site. More specifically, the characteristics of topography, geology, road access and local electricity grid of each site have such an influence that each project becomes a prototype.

Table 1 summarizes the main works on energy potential assessment and on feasibility analysis of new hydro-power plants. It can be noticed as the two research topics are not integrated in a unique tool able to deal with the main advantages of GIS analysis and accounting for feasibility and site-specific financial aspects. However, the site specificity and the integration of this analysis in GIS tools become particularly important for planning new run-off plants at network scale but it has been scarcely investigated by the scientific literature and by policy makers.

This gap is particularly evident in Italian Alpine valleys where subsidies are favoring the construction of new run-off plants also in areas with low accessibility. A wrong planning of hydro-power exploitation can rise environmental, social and financial issues.

This study investigates a new model able to consider the spatial variability of energy potential, legal and planning constraints, and above all site-specific financial variables. All the input data are spatially explicit and the algorithm, to siting hydro-power infrastructures, includes the spatial variability of the flow rate. The model comprehensively estimates direct and indirect costs accounting for their spatial variability rarely undertaken in other studies as shown in Table 1. The GIS tool was developed within the recharge.green project co-financed by the European Regional Development Fund in the Alpine Space Programme.

As reported by Refsgaard and Henriksen [20], a model is a simplified representation of the natural system it attempts to describe. They define the following terminology:

- *Conceptual model*, i.e. mathematical description and flow processes.