

Multi Criteria Analysis for the assessment of the environmental and social impacts of hydropower plants: review of outcomes and critical points of a recent application

Giovanni Frosio
Studio Frosio S.r.l.
Via P. F. Calvi, 11
25123 - Brescia
Italy

Eliseo Marchesi
Studio Frosio S.r.l.
Via P. F. Calvi, 11
25123 - Brescia
Italy

Luigi Lorenzo Papetti
Studio Frosio S.r.l.
Via P. F. Calvi, 11
25123 - Brescia
Italy

Introduction

At Hydro 2018 in Gdansk we presented a paper describing a recent development of Multi Criteria Analysis (MCA) applied to Environmental Impact Assessment procedures in a region of Northern Italy, to evaluate, on the basis of objective criteria and measurable quantities (energy, velocities, areas and so on), the effects of different alternatives of ecological flow releases downstream of existing weirs and dams of hydropower plants and of new plants as well.

At that time, we were lacking some data and indicators, especially on the environmental (habitat and landscape preservation) side, so in our paper we couldn't draw the expected conclusions on the evaluations. Now, 2 years later, the outcomes of the MCA are mostly available and they will be summarised and discussed in this paper.

In the end we'll look back at the underlined strengths and weaknesses of the method and the possible improvements thereof proposed in 2018, drawing some remarks about this instance of MCA application.

1. Background

A brief summary of the issues presented in 2018 is essential to understand the outcomes and critical points discussed in this paper.

1.1 About MCA

Multi Criteria Analysis (MCA) evaluates the outcomes of a given set of alternatives in terms of multiple decision criteria simultaneously applied. For each alternative project or scenario, it must be possible to obtain a measure of its effects in terms of each individual criterion considered.

To avoid any kind of arbitrary evaluation, such measures should generally be quantitative. However, for certain aspects that could be difficult to quantify, the method also admits measures of a qualitative nature, which may be expressed through appropriate point-scores: nevertheless, the use of measurable criteria is strongly recommended. In either case, the measure of each effect must be determined prior to performing concordance analysis.

1.2 Allein HP

The hydropower plant of Allein, located in the Autonomous Region of Valle d'Aosta in Northern Italy, diverts water from the Artanavaz stream by a fixed weir with lateral intake, followed by a small basin and a steel penstock leading to the powerhouse, which hosts two horizontal Francis turbines, directly coupled to synchronous generators.

The main features of the plant are the following:

- | | |
|------------------------------|------------------------|
| • maximum diverted flow rate | 3.10 m ³ /s |
| • yearly average flow rate | 1.58 m ³ /s |
| • nominal (gross) head | 98.49 m |
| • nominal (~average) power | 1,523.70 kW |
| • rated capacity | 2.5 MW |

At the beginning of 2016 the Cooperative Society *Forza & Luce Aosta*, the Owner and Operator of the plant, started a 5 years experimentation, agreed with the administration, environmental protection agency and fishery support consortium of the Region, aimed at determining the quantity of reserved flow to be released and monitoring the ecological effects on the stream of the envisaged increase (from 2.0 to the aforesaid 3.1 m³/s) of the maximum flow rate diverted by the plant.

During each of the 5 years of experimentation, different scenarios of reserved flow release (both fixed and variable on a monthly basis) will be assessed with respect to four points of view: energy production, company revenues, suitability for river fauna and visual perception of the riverine landscape. So at the end of 2020, on the basis of the experimentation outcomes, the regional administration will decide whether to confirm or not the increased maximum flow diverted by the plant and will establish the quantity and possible time modulation of the reserved flow to be released at the intake works.



Fig. 1. Position of Valle d'Aosta Region in Northern Italy, with the red dot representing the plant location

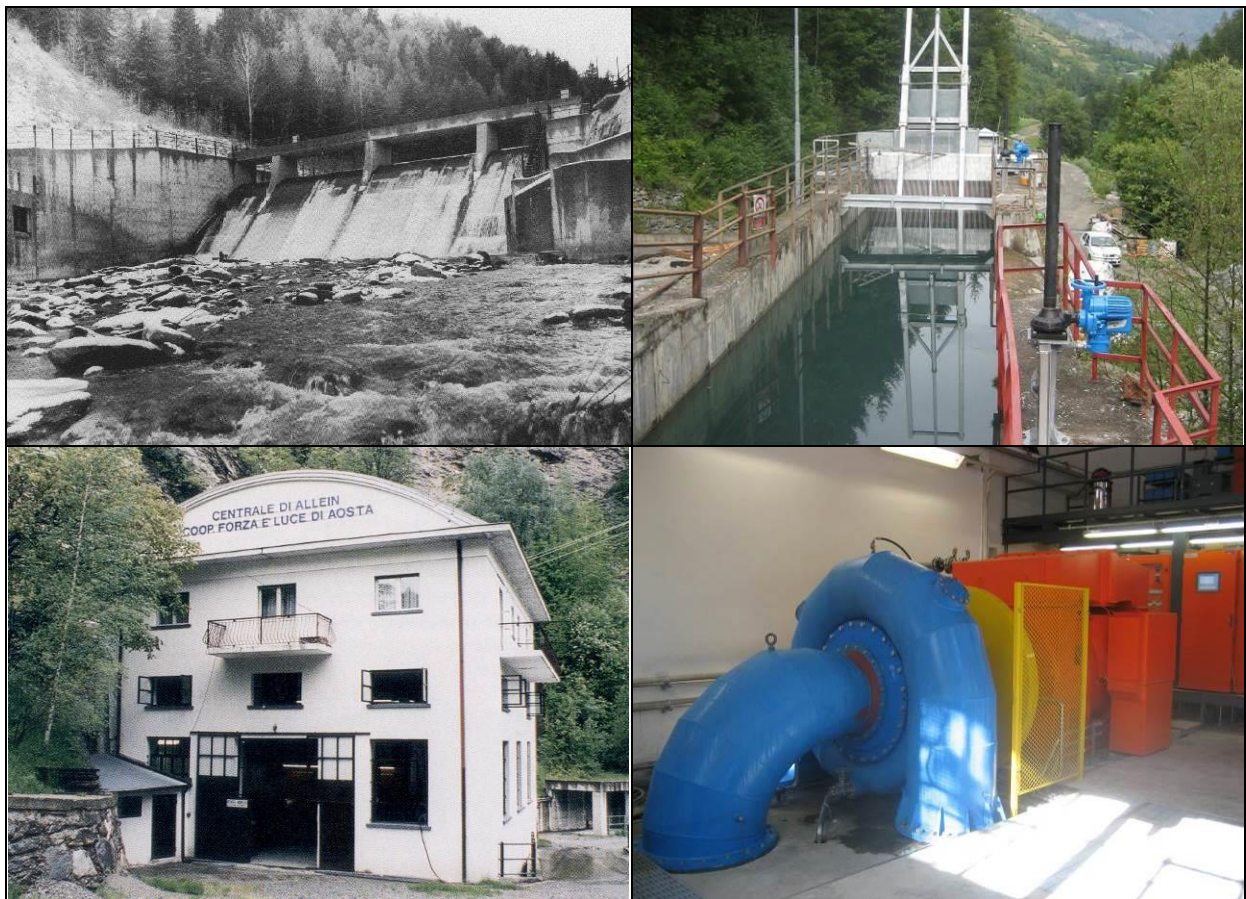


Fig. 2. Diversion weir, forebay, powerhouse and generating unit of Allein HPP

1.3 Method, procedure and software

Recently the MCA method has been officially adopted in the Autonomous Region of Valle d'Aosta (Northern Italy) to evaluate the effects of different alternatives of ecological flow releases downstream of existing weirs of hydropower plants and of new plants as well, in order to provide a common platform to increase the quality of decision making about a topic which is often a source of disputes among agencies, investors and other stakeholders.

This instance of MCA largely relies on the MesoHabSim method to evaluate the environmental outcome of an alternative project or scenario. This method, as suggested by the complete name *Mesohabitat simulation model*, is designed to predict the response of an aquatic community to its habitat modifications; basically the changing spatial distributions of physical attributes of a river as a result of variations in flow and the biological responses of aquatic species to these changes provide the basis for simulating the consequences of ecosystem alteration.

Summarising the procedure:

- mesohabitat types are defined by their hydromorphological units (HMUs) such as pools and rapids, geomorphology, land cover and other hydrological characteristics;
- mesohabitats are mapped under multiple flow conditions at extensive sites along the river;
- fish or invertebrate data is collected in randomly distributed mesohabitats where habitat surveys are also conducted;
- this data is used for developing mathematical models that describe which mesohabitats are used by animals more frequently;
- this allows for evaluating habitat availability at a range of flows, expressed by rating curves, which represent the changes in a relative area of suitable habitat in response to flow and allow for the determination of habitat quantity at any given flow within the range of surveys. Rating curves can also be used to evaluate the benefits of various restoration measures on the entire fish community, both for the entire river and for specific sections;
- in combination with hydrologic time series, rating curves are used to create Uniform Continuous-Under-Threshold (UCUT) curves for the analysis of frequency, magnitude and duration of significant habitat events. UCUT curves evaluate continuous durations of unsuitable habitat under a specified threshold. UCUT curves serve as a basis for the development of "ACTograms", diagrams representing graphically the activity and response of the target species to habitat changes such as flow reductions, that managers can use to determine how long a given species can tolerate unsuitable conditions depending on its life stage.

The principal benefits of the MesoHabSim method are the following:

- it offers flexibility, open architecture and effective simulation capabilities thanks to its GIS framework;
- it is designed to address habitat needs of entire aquatic communities (fish and micro-invertebrates) and it operates at the meso-scale, that's more relevant for river management and less affected than micro-scale by coincidence in snap-shot observations in the validation phase;
- the model is established on a solid ecological background, but its outputs are designed to be comprehensible and convincing to non-scientists;
- it offers a quantitative assessment and produces quantitative restoration endpoints;
- it offers the ability for trade-offs between habitat structure and flow quantity.

SESAMO is a decision support method based on the MCA methodology, that allows the user to manipulate also graphically all the objects - criteria and alternatives, utility functions and weights - in order to get the final ranking of the alternatives and to analyse the composition of the results, performing sensitivity analyses as well.

Specific panels in the graphical interface of the software represent all the 7 phases of a MCA decisional process:

1. organisation of criteria in a decision tree;
2. filling evaluation matrix with alternatives;
3. application of technical aggregation;
4. application of utility functions;
5. allocation of weights;
6. final ranking;
7. sensitivity analysis.

It's worth reminding that SESAMO has been developed to assess and compare alternative scenarios of reserved flow release; therefore, even if its structure is flexible and can be applied to different cost-benefit analyses, the indicators illustrated below are referred to the trade-off between economic and environmental issues.

The MCA application in the case of Allein is aimed at defining the optimum quantity and modulation of the reserved flow to be released in the Artanavaz stream downstream of the plant intake works.

The alternatives scenarios analysed for Allein HPP are the following:

0. no release (theoretical scenario, only for comparison)
1. modulated release (in the range 250 - 500 l/s) on a monthly basis
2. 280 l/s fixed release
3. 350 l/s fixed release
4. 250 l/s fixed release + 10% of the instantaneous river flow

It must be pointed out that these releases are not actually implemented during the experimentation, except for the 280 l/s fixed release which is provided for by the current water concession; they're analytically applied to the long term Flow Duration Curve to evaluate the indicators described below.

The analysed indicators for each scenario are listed and classified as follows

Energetic

- IEn = energetic index, representing the percentage loss of energy production with respect to the theoretical scenario of no release and maximum production.

Economic

- IEc = economic index, representing the percentage loss of income with respect to the theoretical scenario of no release and maximum production and income
- NPV = net present value [€] of the scenario
- CD-BIM-SER = acronyms for various fees and levies related to the water concession
- RCS-REC = social and economic repercussions (environmental monitoring and management, road maintenance, supply of services, royalties and taxes) of the plant operation on the community.

Environmental

- IH = habitat integrity index, which quantifies the available area for fish fauna according to the MesoHabSim method, divided in 5 main steps
 1. identification of the stretch to be analysed, according to its morphology, hydraulic features (flows, slopes...) and riverbed sediment;
 2. choice of the hydrologic conditions (at least 4 with different flow rates) for the execution of the hydro-morphologic surveys;
 3. description of the riverine habitat in different hydrologic conditions, through a (georeferenced) 3D survey of the points representing the wetted perimeter and characterisation of the mesohabitat, by means of many variables (river flow rate, water surface slope, longitudinal connectivity, presence of shadow and cover...) whose values can be stored and represented on GIS software;
 4. application of the biologic models of habitat adequacy, with respect to the target fish species and the relevant statistic models evaluating the probability of presence and abundance on the basis of the surveyed parameters;
 5. analysis of the time and space variations of the riverine habitat.

IH is equal to **0** for the maximum negative effect of the water diversion on the hydro-morphologic river components and increases up to **1** (no impact) for decreasing negative effects.

Landscape

- TP = landscape protection level, representing the modifications of the landscape perception related to the quantity of water in the diverted stretch. This indicator is an evolution of the "Tyrol landscape indicator" developed by the University of Innsbruck, modified to account for the context (natural, environmental and cultural emergencies, laws and constraints, etc.) of the Valle d'Aosta Region. Its evaluation follows 3 steps:
 1. identification of homogeneous (from the point of view of visibility) stretches within the diverted reach and definition of the "constraint factor";
 2. attribution of release coefficients and relevant protection level, definition of the "release factor";
 3. analyses of pictures taken in different hydrologic conditions and definition of the "visual factor".

For each stretch TP is equal to the sum of the three aforesaid factors.

The final value for the diverted reach is the length-weighted average of the TP values for each stretch.

As mentioned before, the energetic and economic indicators are evaluated *a priori*, i.e. by inserting the alternative release scenarios in a long period Flow Duration Curve to obtain the expected energy production, then applying the energy selling prices and the operating costs, both recorded and provided by the plant operator.

The landscape and environmental indicators are evaluated in a similar way, but they're not computed by analytical formulae; therefore, before inserting the release scenarios in the FDC, the utility functions of these two indicators must be constructed, relating the actual flow rates measured in the diverted stretch with the state of the investigated ecological components.

1.4 Outcomes and conclusions as of 2018

Halfway through the experimentation, in 2018 we observed that the MCA carried out with SESAMO seemed a promisingly simple and user-friendly tool, which clearly showed the composition of results and the effects of the chosen indicators and relevant weights on the final result.

Our remarks at that time concerned the following issues:

- the economic indicators were more than the others, but some of them represent the economic repercussions on the community, while other ones represent the repercussions on the plant owner and operator;
- RCS and REC are quite difficult to evaluate and in this case they have been computed in a simplified way, as suggested by the guidelines [1] developed within the SPARE programme for the definition of indicators relevant to MCA of alternative reserved flow scenarios;
- the environmental and landscape indicators need expert judgement; in particular IH is computed with a long (compared to other indicators) technical procedure, while the evaluation of TP is quite subjective, especially in the last of the three steps described earlier in this paper;
- it's important to have also high flow recorded, in order to evaluate the environmental indicator IH with the MesoHabSim methodology in a “balanced” way, that is not too unfavourable and punitive for hydropower production.

2. Developments and updates

With respect to the situation depicted in the previous chapter, some changes have occurred in different aspects of the experimentation, as described in the following chapters.

2.1. Scenarios

Following the first evaluations, which provided low values of the environmental indicator IH, a new scenario was introduced, with a fixed release of 590 l/s, later modified in a modulated release of very high flows necessary to achieve good results in terms of habitat integrity according to the MesoHabSim method.

Furthermore, additional scenarios were introduced, either according to the criteria established by the current Water Protection Plan (*Piano di Tutela delle Acque* - PTA) of the Valle d'Aosta Region or for maximising some indicators:

- a fixed release of 712 l/s, which has been eliminated by the regional authorities (probably for being too similar to other scenarios) after a short time;
- a monthly modulated release (quite higher than the existing scenario n. 1) computed according to PTA;
- a fixed release of 590 l/s for maximising the indicator IH, replaced after a short time by a much higher modulated release, varying on a monthly basis from 553 to 4,677 l/s;
- two monthly modulated releases aimed at achieving respectively a sufficient/good value of the indicator TP.

Lastly, the scenario with the instantaneously modulated release (identified as n. 5 in § 1.3) has been eliminated as well, due to the practical difficulty of its implementation.

Consequently, the alternative scenarios to be evaluated in the end are:

0. no release (theoretical scenario, only for comparison)
1. 280 l/s fixed release
2. modulated release (in the range 250 - 500 l/s) on a monthly basis
3. PTA 2 → monthly modulated release (ranging from 208 to 2,236 l/s)
4. IH max → monthly modulated release aimed at $IH \geq 0,8$
5. TP top → monthly modulated release aimed at $0,55 \leq TP \leq 0,79$ (good)
6. TP medium → monthly modulated release aimed at $0,30 \leq TP \leq 0,55$ (sufficient)

Only the first three of these seven scenarios are present since the beginning of the experimentation.

2.2. Indicators

The economic indicators NPV, CD-BIM-SER and RCS-REC have been eliminated, thus keeping only the economic index IEC to gauge the repercussions of the release scenarios on the economic balance of the plant.

Consequently, now there are just 4 indicators:

- the energetic index IEn
- the economic index IEC
- the habitat integrity index IH
- the landscape protection level TP.

It is worth highlighting that, with respect to the standard definition, a new definition was given to the economic index IEC, in order to take into account the peculiar economic situation of the cooperative company: this company was born with the purpose of producing and distributing electricity to its members, and when the production exceeds the energy needs of the members, the excess energy is sold to the DSO; on the other hand, when the energy need of the members exceeds the produced energy, the remaining energy is bought from the same DSO. While the standard definition of the index considers only the gross revenues, the new definition assumes the income to be compared as the difference between the gross revenues and the cost related to the purchase of energy needed to fulfill the energy demand of the members.

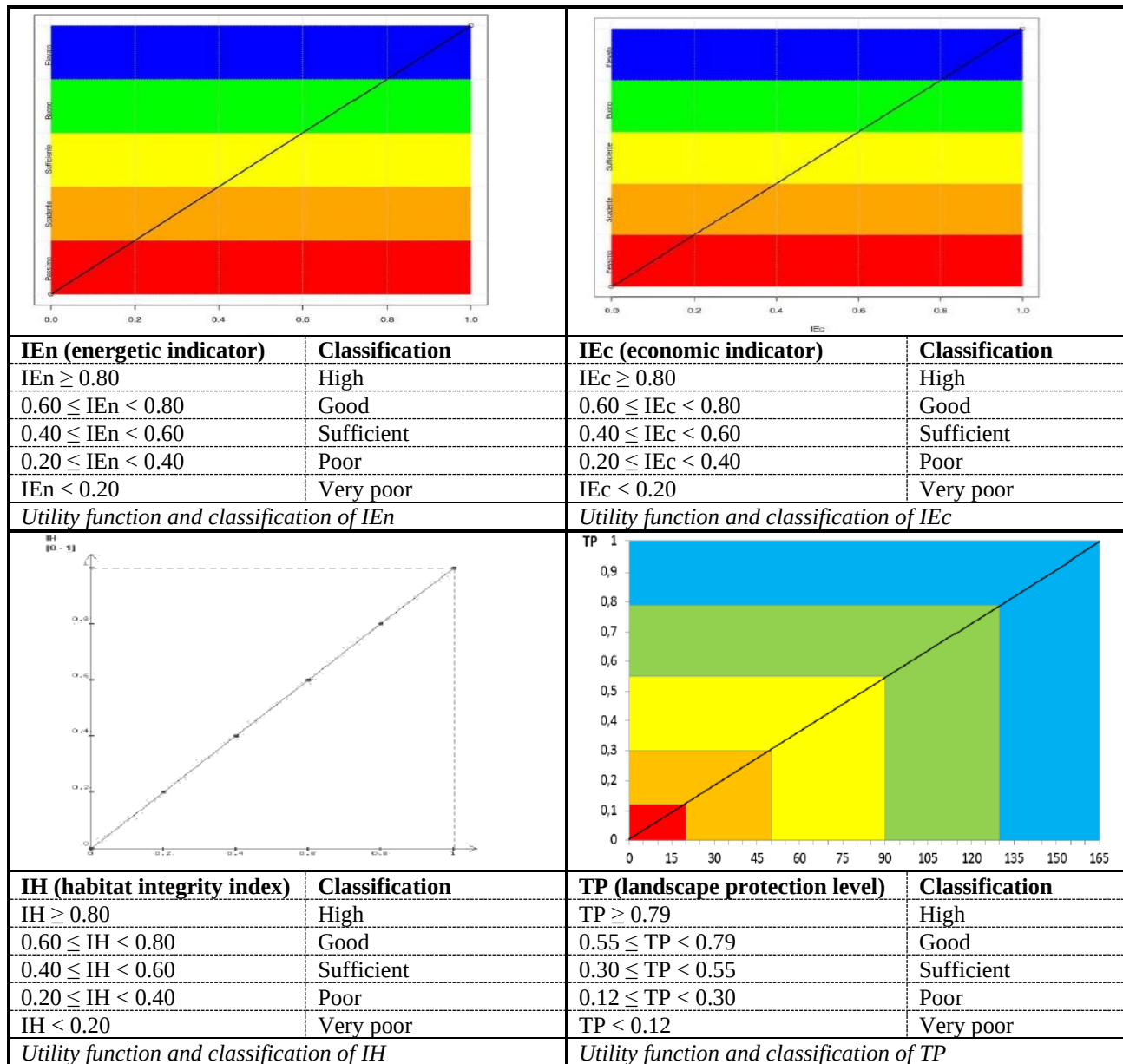


Table 1. Utility functions and classification rules of the four indicators taken into consideration

2.3. Method, procedure and software

The evaluation tool is no more the software SESAMO, but an online application, developed by the Regional Agency for Environmental Protection (ARPA) and accessible by anyone provided with credentials.

Anyway, the method and procedure are practically the same as described in § 1.3.

2.4. Outcomes

Following to the modifications in the scenarios and indicators described above, the physical variables (e.g. plant production and income) and related indicators have seen a change in their values.

The following tables summarise the resulting values of

- the main technical and economic variables (*Table 1*)
- the energetic and economic indicators computed from those variables, as well as the environmental and landscape indicators evaluated with the longer procedures described in § 1.3 (*Table 2*).

Release	0	280 fixed	monthly modulation	PTA 2	IH max	TP top	TP medium	Unit of measure
Q _{avg_release}	0.798	1.032	1.058	1.358	1.809	1.353	1.283	m ³ /s
Q _{avg_plant}	1.782	1.549	1.524	1.267	0.824	1.244	1.308	m ³ /s
Q _{release} /Q _{nat}	27%	36%	36%	47%	63%	47%	44%	-
P _{avg}	1,482	1,337	1,328	1,295	1,227	1,231	1,236	kW
E _{year}	12,650	10,990	10,810	8,990	5,840	8,820	9,280	MWh
ΔE _{year}	0	-1,660	-1,840	-3,660	-6,810	-3,830	-3,370	MWh
ΔE%	0%	-13%	-15%	-29%	-54%	-30%	-27%	-
Income	690,000	580,000	570,000	440,000	170,000	410,000	450,000	€ per year
ΔIncome	0%	-16%	-17%	-36%	-75%	-41%	-35%	-

Table 2. Resulting values of the main parameters describing the plant operation and performance (2016-2019 average values)

Release	0	280 fixed	monthly modulation	PTA 2	IH max	TP top	TP medium
IEn	1.00	0.87	0.85	0.71	0.46	0.70	0.73
Class	High	High	High	Good	Sufficient	Good	Good
IEc	1.00	0.63	0.60	0.20	-0.72	0.08	0.22
Class	High	Good	Good	Very poor	Very poor	Very poor	Poor
IH	0	0	0	0	0.13	0	0
Class	Very poor	Very poor	Very poor	Very poor	Very poor	Very poor	Very poor
TP	0.26	0.32	0.30	0.43	0.69	0.55	0.54
Class	Poor	Sufficient	Poor	Sufficient	Good	Good	Sufficient

Table 3. Resulting values of the indicators for the alternative release scenarios (average values over the period 2016-2019)

The allocation of the indicators' weights hasn't been done yet, so the final ranking of the scenarios and the possible sensitivity analysis will take place later than expected, probably in the first half of 2021.

Anyway, the following graphs show the results, in terms of both indicators' performance and alternative ranking, in the hypothesis of allocating equal weights (0.25) to the four indicators.

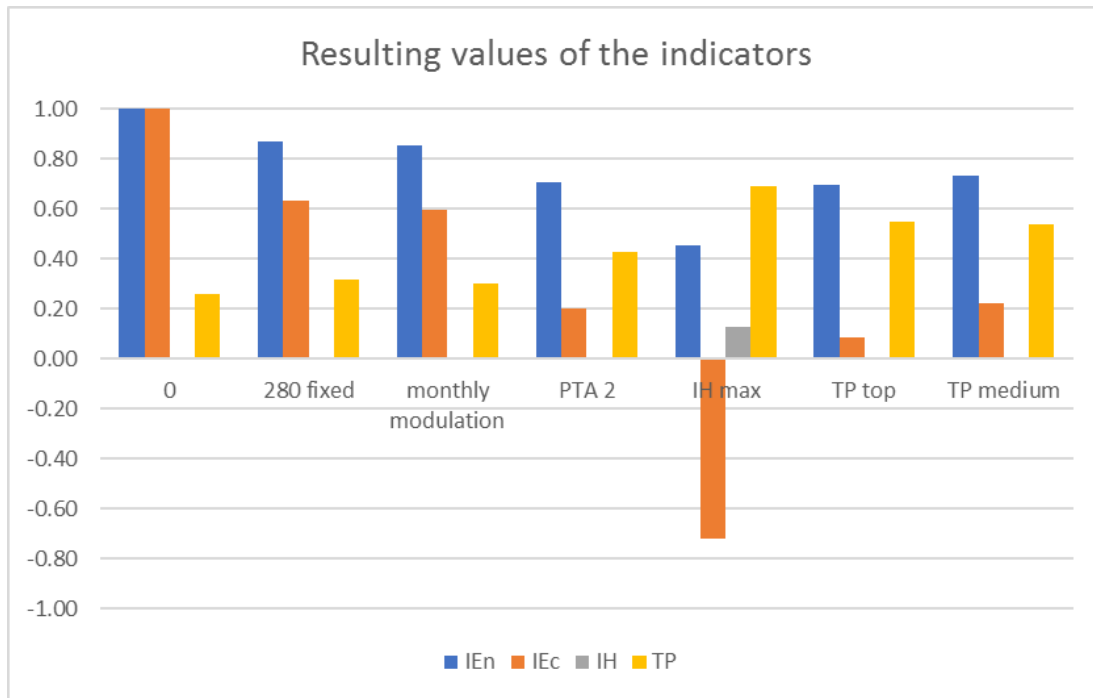


Fig. 3. Performance of the four indicators in the alternative scenarios taken into consideration

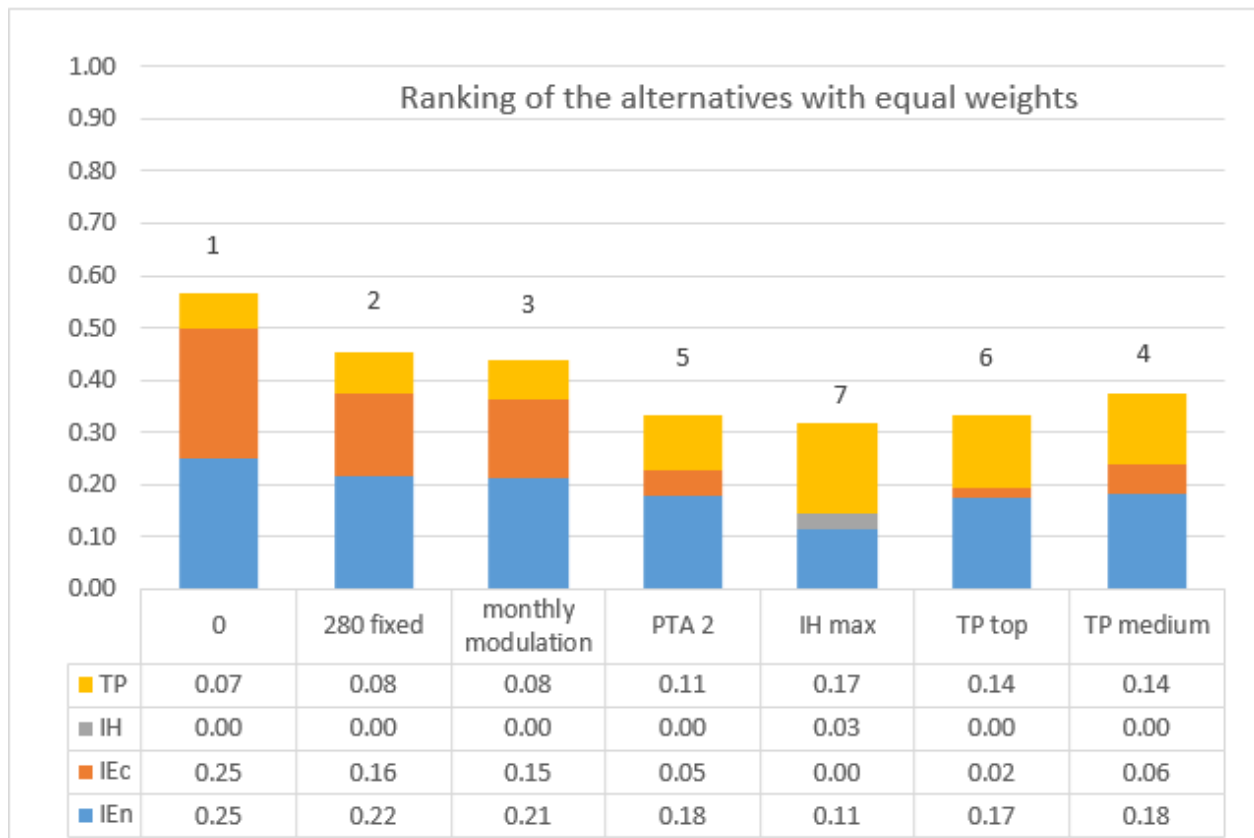


Fig. 4. Ranking of the alternative scenarios in the hypothesis of allocating equal weights to the indicators (the negative value of the economic indicator IEc in the "IH max" scenario has been manually set to zero)

3. Conclusions

As we are approaching the end of the experimentation, after two more years of discussions about the release scenarios, the evaluation method and the relevant indicators, the following remarks can be drawn:

- First, the possible introduction of further scenarios at any moment of the 5 years experimentation may be a little confusing, because until the very end it's not possible to make any reasonable prediction on the final outcomes, as we learned by ourselves writing about this experimentation in different years.
- On the other hand, most of the economic indicators have been eliminated, summarising all the economic outcomes (O&M costs, energy production and sale vs purchase) in IEC; therefore, presently there's just one indicator for each category (economic, energetic, environment and landscape) which makes it simpler to combine and weigh the alternatives.
- As we expected and predicted in our paper in 2018, the evaluation of the environmental indicator IH with the MesoHabSim methodology based on the ordinary flows of the river (i.e. without considering the highest flow rates, more difficult to record) is very unfavourable and punitive for hydropower production.
- The environmental indicator IH is appropriate only for river sections with an unmodified stretch upstream, otherwise it always provides very low values. In this case study, as there are many diversions upstream of the intake works of Allein HPP, the IH indicator has values as low as zero for all the scenarios, except the one with maximum release, which has just a **0.13** value.

In the end this instance may be considered as a first step towards a more effective application of MCA; in particular the following lessons have been learnt:

- The indicators IH, which was tested in this case study, should be modified if we want to avoid a situation where all scenarios are judged bad except for the ones without any water diversion (in a MCA we want the indicators to take different values according to the scenarios and not to be constant).
- Since the scenario "IH max" would lead to a negative economic index IEC, it would be useful to modify this alternative in order to guarantee a high IH value without excessively penalize the cooperative company (this scenario change is under examination).
- Before starting the experimentation, it may be worth spending more time defining the scenarios, so they won't be modified too often subsequently.
- We can't pretend that the scenarios won't ever be modified after beginning the experimentation, because the possibility of adjusting the scenarios according to the resulting values of the indicators - which can't be known *a priori* - is inherent to the nature of this method, and actually this can be an advantage in terms of flexibility, in case one or more scenarios are found to be useless or to give poor results for some indicators.
- Probably it would be even more important to define the indicators' weights prior to the experimentation, which hasn't been done in Allein's case, where the final allocation of weights with the indicators already evaluated might become a source of discussion and arguments, in addition to being a conceptually incorrect application of the MCA method.

If these issues are kept in mind for the following applications, this method may deploy its strength and potential for a flexible and user-friendly implementation of Multi Criteria Analysis for the assessment of the environmental and social impacts of hydropower plants.

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The Authors

Giovanni Frosio: environmental engineer, he joined Studio Frosio in 2010. He is currently Deputy CTO and in charge of hydrological and hydraulic issues, numerical analysis of steady and unsteady flow, design and supervision of works for hydropower projects.

Eliseo Marchesi: hydraulic engineer, he joined Studio Frosio in 2019. He is currently in charge of hydraulic and hydrological analyses of hydropower projects. He's also responsible for the pumped storage development at Studio Frosio.

Luigi Lorenzo Papetti: hydraulic and chemical engineer, involved in the design and supervision of small hydropower plants since 1990. He is currently the Chief Technical Officer and Chief Executive Officer of Studio Frosio.