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Environmental reporting in the hydropower sector: analysis of EMAS registered hydropower companies in Italy

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Hydropower (HP) is a key source of renewable energy, but also poses significant environmental challenges, including habitat fragmentation, hydropeaking and perturbations of flow and sediment regime. This study analyzed how Italian companies managing HP plants, and registered to the European Eco-Management and Audit Scheme (EMAS) in 2022, evaluated their sustainability and publicly disclosed related data. The analysis was based on the environmental statements (ESs) of 206 hydropower plants (29% of Italian HP production in 2019). The applied methodology involved an inventory of the plants and their categorization about technical features and the reporting of technical, environmental, and social aspects. The results of the analysis revealed that the companies rarely described the environmental state of the site, even less frequently adopting quantitative indicators. "Soil contamination", "biodiversity", "waste production", "risk of environmental accidents", "water pollution and flow management", and "noise emissions" were the aspects considered most significant. No correlation was found among the significance of an aspect, the number of indicators used to describe the associated impacts, and the number of objectives set for reducing those impacts. "Biodiversity" was mostly described through irrelevant indicators (i.e., total site area) and 76% of the allocated budget was assigned to technical aspects without a clear connection with any environmental improvement. In particular, the specific impacts on the aquatic ecosystems were scarcely reported, mitigation measures were rarely mentioned and with few details. In conclusion, the results of the study highlight the need for specific guidelines, directed to the HP sector, for effectively reporting the environmental performances and the effectiveness of the adopted Environmental Management Systems, while providing valuable information to policymakers and researchers.

KEYWORDS

biodiversity, EMAS, environmental management system, environmental assessment, hydropower, renewable energy, sustainability

1 Introduction

Global energy consumption is rapidly increasing (AlQattan et al., 2018; Ma et al., 2021), and supplying environmentally friendly, fair, affordable, and secure energy is fundamental for sustainable development (Vera and Langlois, 2007). The United Nations' 2030 Agenda for Sustainable Development (United Nations, 2015) dedicated Sustainable Development Goal No. 7 to "ensuring access to affordable, reliable, sustainable, and modern energy for all".

The production of heat and electricity is the main responsible for global greenhouse gas (GHG) emissions, and in 2019 it accounted for 33% of total emissions (Climate Watch, 2019) due to the high share of fossil fuels (Ouda et al., 2016). Decreasing the carbon intensity of energy production is of foremost importance to reach carbon neutrality by 2050, defined "the world's most urgent mission" by the United Nations (United Nations, 2020) and "the heart of the European Green Deal" by the European Commission (European Commission, 2019). The European Green Deal acknowledges the key role played by renewable energy sources to achieve the objectives set for the reduction of GHG emissions, and defined a 40% minimum share of renewables in the EU energy mix as target for 2030.

Among renewable energy sources, hydropower (HP) is paramount; it has long tradition and significance in Europe, particularly in the Alps due to the presence of steep slopes and high water availability (Wagner et al., 2019; Vassoney et al., 2020). In the EU, HP accounted for 35.4% of total renewable energy production in 2020 (Vassoney et al., 2017), with 151 GW of installed capacity (IRENA, 2022). In Italy, 48.2 TWh of energy were produced from HP in 2020, corresponding to 42% of the national renewable energy production (IRENA, 2022). Italy's total installed HP capacity grew from 21.9 GW in 2012 to 22.7 GW in 2020 (+0.5% per year on average) (IRENA, 2022). Compared to other EU countries, Italy's increase was slower than global growth (2.8%/year from 2012 to 2020 on average) (IRENA, 2022) because water resources have been already extensively exploited for HP, and the interest in new plants has been mostly focused on small-scale run-of-the-river (RoR) installations (Vassoney et al., 2019; Algieri et al., 2020).

HP is generally characterized by limited GHG emissions throughout its life cycle (Almeida et al., 2019; Kumar et al., 2021), and is also a safe and reliable energy source, with low operating costs and long plants' operational life (Saw and Ji-Qing, 2019; Majumder et al., 2020; Quaranta et al., 2021). HP is also characterized by great flexibility, since dam reservoirs can store high amounts of energy at low cost (Hunt et al., 2020), and the associated plants can rapidly increase or decrease energy production to match the demand (hydropeaking) or to counterpart intermittent energy sources (Danso et al., 2021; Zhang et al., 2022). The capacity to store water in reservoirs can play an essential role in water supply for irrigation, residential and industrial use, flood regulation, and inland navigation (Hogeboom et al., 2018; Hecht et al., 2019).

However, HP faces various environmental challenges, as dams and weirs threaten numerous fish species (van Puijenbroek et al., 2019; He et al., 2021) by interrupting river continuity (Pini Prato et al., 2011; Calles et al., 2012), and thus hindering a crucial element for natural aquatic environments (European Commission, 2000). Fish migration can be enabled through fishways, but their application is not always feasible (e.g., high head dams), and design criteria are often based only on the swimming abilities of species with high socio-economic value (e.g., salmon) (Wilkes et al., 2019; Sánchez-Pérez et al., 2022). Furthermore, fishways' effectiveness is often below 70% for upstream passages and even lower for downstream passages (Noonan et al., 2012; Calles et al., 2013; Hershey, 2021). Regulated reservoirs also perturbate the natural flow regime and sediment transport, resulting in reservoir siltation, riverbank erosion, habitat degradation, and loss of biodiversity (Espa et al., 2019; Koutrakis et al., 2019; Vassoney et al., 2019). Reservoirs siltation is often tackled with sediment flushing, which can trigger undesired ecological effects (Nukazawa et al., 2020; Doretto et al., 2021). The flexibility in electricity production allowed by dam reservoirs induces hydropeaking, leading to significant changes to the hydrology, hydraulics, and sediment regime of the river on very short time scales, also affecting the river ecosystem (Bruder et al., 2016; Bejarano et al., 2018). Although RoR HP plants are perceived as more environmentally friendly than large HP plants with regulated reservoirs, they have been associated with numerous environmental impacts, especially when the river flow is diverted (Anderson et al., 2017; Kuriqi et al., 2021). Another critical challenge for the HP sector is the setting of ecological flows maintained downstream of the water withdrawal sites. Traditionally, the minimum in-stream flow (MIF) was defined as "the minimum amount of water downstream of any diversion that allows for the protection of the aquatic ecosystem" (Alecci and Rossi, 2020). In contrast, the ecological flow (EF) is described in the European Guidance on Ecological Flows as "the amount of water required for the aquatic ecosystem to continue to thrive and provide the services we rely upon" (European Commission and Directorate-General for Environment, 2016). The ecological flow follows a more holistic approach and focuses on maintaining the health and function of the aquatic ecosystem, which requires consideration of its biological requirements varying over time, the natural flow regimes, and hydrological patterns (Alpine Convention, 2009; Vezza et al., 2014). The constant minimum in-stream flow is primarily focused on ensuring a minimum level of water in the river downstream the dam to maintain the health of the aquatic ecosystem, while ecological flows also encompass a series of minimum flows variable through time to mimic the natural river flow variability.

Given the environmental concerns of the HP sector and the associated ongoing and increasing interest, especially in developing countries (Couto and Olden, 2018; Pracheil et al., 2019), the capacity to assess the overall environmental sustainability of HP plants remains remarkably limited. This study analyzes how the Italian companies managing HP plants and registered to the European Eco-Management and Audit Scheme (EMAS) in 2022 evaluated their sustainability. EMAS is the voluntary international standard for implementing environmental management systems (European Commission and Council of the EU, 2009), along with ISO 14001 (ISO, 2015). Despite the similarities between the two schemes, EMAS places more emphasis on public disclosure of environmental performance data and stakeholder engagement, requiring registered organizations to publish each year the relevant environmental information in an Environmental Statement (ES), after the validation by an independent verifier. Another significant difference between EMAS and ISO 14001 is that the former foresees also a formal institutional assessment by the National Competent Authority, which includes a check by the Environment Agency on the effective legal compliance to all applicable environmental requirements, thus enforcing the accuracy and robustness of the environmental information disclosed in the ESs.

The Italian HP sector was selected as a case study because it accounts for 15% of the total installed capacity in the EU in 2020 (IRENA, 2022), and 148 out of the 241 EMAS registered sites producing energy are located in Italy (European Commission, 2022).

This study was aimed at: i) analyzing how the companies managing existing HP plants describe their environmental performance; ii) identifying the metrics and indicators used to describe the environmental impacts; iii) assessing on which aspects, how, and to what extent are set the improvement objectives, if any; iv) analyzing how the companies describe their impacts on the hosting site and on biodiversity, with a specific focus on aquatic ecosystems, and what measures have been implemented or planned to mitigate these impacts.

The remainder of this paper is structured as follows: Section 2 presents the methodology adopted in this study, while Section 3 describes the results of the analysis, including the key significant aspects and related performance, the improvement objectives, and how the impacts on biodiversity are reported. The discussion in Section 4 summarizes the study's key findings and managerial implications and recommendations.

2 Methodology

The methodology applied in this study included three consequent phases: an inventory of the HP plants registered to EMAS in 2022 in Italy, the analysis of the information retrieved in the ESs on the technical, environmental, and social aspects disclosed by the companies managing the inventoried plants, and finally a sensitivity analysis of the analyzed data.

An inventory of the HP plants registered to EMAS in 2022 in Italy was created as an Excel database by analyzing the National Register of EMAS-certified sites (ISPRA, 2022) and cross-checking the sites with the NACE code "35.11" (i.e., production of electricity). The environmental statements (ESs) of the pre-selected plants were then screened to exclude sites referring to large combustion plants, photovoltaic power stations, and wind farms. Finally, the selected HP plants were individually assessed to confirm that it was possible to separate the data regarding HP plants from any other activities included in the ES.

Once the final sample of HP plants was delineated, the ESs were analyzed in detail focusing on the following 4 key elements:

- Technical features of the plants and production data
- Reporting on the environmental and socio-economic context
- Reporting on the key environmental, technical, and social aspects (significance, indicators, and improvement objectives)
- Reporting on the impacts on biodiversity and their mitigation

The technical characteristics of each HP plant were analyzed to identify the key features of the sample in relation to the water abstraction typology (dam, RoR, pumped storage), the HP plants characteristics (installed capacity, turbine type, available drop, average allowed outflow), and the energy production (gross and net electricity production, water volume fed to the turbines).

The ESs also allowed to retrieve the main characteristics and the related quantitative indicators used by the companies to describe the environmental and socio-economic context hosting the HP plants through 9 domains (or matrices): ecosystems, watercourses, fauna, aquifers, soil and subsoil, flora, geological and hydrogeological risk, population and socio-economic aspects, and landscape.

The ESs were finally scrutinized with regard to the following 18 key environmental, technical and social aspects: effects on biodiversity, soil contamination, emissions to air, water pollution and flow management, raw materials/energy/water consumption, odor/noise emissions, waste production, risks of environmental accidents, energy production, visual impact, radiations, stakeholder engagement, light pollution, transport, and process management. Specifically, data regarding those aspects were retrieved from the ESs, considering in sequence: the significance assigned by the companies to each aspect; then the metrics and indicators used to quantify each aspect; and finally, the objectives set to improve the environmental performances of the plant along the period 2017–2026, collecting the related actions, allocated budget, and metrics. EMAS requires organizations to evaluate the significance of each aspect based on its potential impact on the environment, considering the nature, scope, frequency, and severity of the impact, the sensitivity and vulnerability of the affected environment, regulatory requirements and public expectations, and the organization's objectives, targets, and environmental policy.

A specific focus was devoted to analyzing how companies reported on their impacts on biodiversity, with a particular attention on fluvial ecosystems, and the related mitigation measures taken or planned. Firstly, the selected ESs were examined to assess whether the impacts of hydropeaking and sediment deposition in reservoirs were described and if mitigation measures were implemented. Then, the mitigation measures for habitat fragmentation were considered by collecting information on fish passages and barriers for fish safeguard. Finally, data on the definition and quantification of the ecological flow were collected.

The presence of correlations among the significance of the aspects, the number of indicators used to describe each aspect, and the number of improvement objectives was then investigated with the Spearman and Kendall-Tau correlation tests.

3 Results

148 energy production sites were registered to EMAS in 2022, and 17 included HP plants. All 17 sites were selected after the screening, as it was possible to separate the data regarding HP plants from other activities (e.g., photovoltaic installations, wind farms). Each site included between 1 and 39 HP plants for a total of 206 installations producing in overall 14.1 TWh of electricity in 2019, corresponding to 29.3% of the total electricity produced by HP plants in Italy.

The most common plant type was run-of-the-river (58%), followed by dams (41%) and pumped storage (1%) (Figure 1). Although a large variability was observed among plants' installed capacity, produced electricity, available drop, and amount of water used, most of the plants were small-sized (60% below 10 MW), and the majority was characterized by high drops (53% above 90 m) and low average flow (60% below 5 m^3/s). As expected, Pelton turbines were implemented more frequently (35%) than Kaplan turbines (23%), as Pelton turbines are used for high drops while Kaplan for small drops. The most applied turbine type was the Francis (42% of the total), used for average drops and a wide range of flows and capacities.

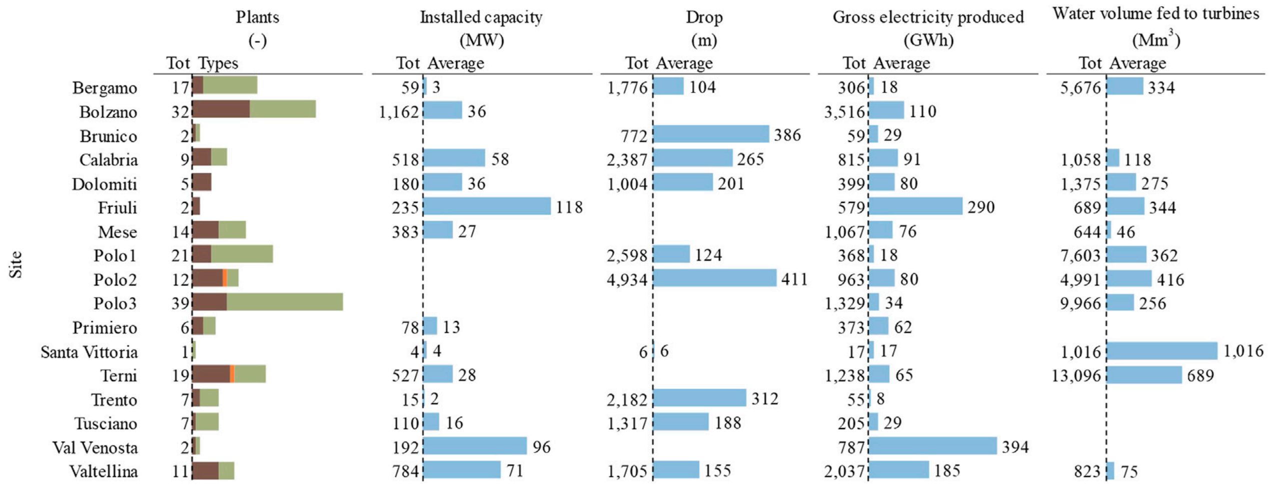

FIGURE 1
Technical features and production data of the analyzed sites. Tot refers to the entire site and average to the plants included in each site. Gross electricity produced and water volume used data are referred to 2019 (Brown = Dam; Orange = Pumped storage; Green = Run-of-the-river).

On average, each plant produced 68.5 GWh of gross electricity using 313 Mm^3 of water in 2019.

3.1 Environmental and socio-economic context

The ESs rarely described the environmental and socio-economic context hosting the HP plants (Table 1). The state of the matrix "ecosystems" was addressed 11 times, but just declaring the presence of natural protected areas of interest (e.g., Natura 2000 or UNESCO sites, Parks, *etc.*) in the watershed. Only one indicator was used to quantify the state of the ecosystems, and only in relation to macrobenthic communities. Information about the other environmental and socio-economic matrices was disclosed in less than half of the ESs, and only 10 indicators were used to describe their state. Population characteristics and landscape resulted more reported than watercourses, flora, and fauna, also related to the aquatic ecosystems impacted by the HP plants.

3.2 Reporting on the key environmental, technical, and social aspects (significance, indicators, and improvement objectives)

3.2.1 Key significant aspects and related performance indicators

Table 2 reports the data related to the 18 key environmental, technical and social aspects disclosed in the ESs. Although 11 aspects were listed in over 80% of the ESs, only 6 were considered significant in more than half of the ESs (soil contamination, biodiversity, waste production, risk of environmental accidents, water pollution and flow management, and noise emissions). All those aspects received attention in the literature, with a particular focus on "biodiversity" and "water quality" (Parish et al., 2019; Nautiyal and Goel, 2020; Roy and Roy, 2022). On the other hand, the technical aspects were rarely considered significant (only by less than 20% of the ESs), as well as "stakeholder engagement", "light pollution", "transport", and "odor emissions".

Four aspects (energy production, emissions to air, energy consumption, and waste production) were described by quantitative indicators in over 90% of the ESs, quantified by the highest number of indicators on average (1.9, 2.3, 2.9, and 5.2, respectively), and accounted for 65.3% of the 323 total environmental performance indicators. However, none of those aspects was considered significant and the detailed quantification found in the ESs might be related to other reasons. In line with a previous study on the waste-to-energy sector (Comoglio et al., 2022), "energy consumption", "waste production", and especially "energy production", could have been quantified with more indicators because of their direct relationships with operational costs. Monitoring waste production is mandatory by law, leading to a consistent data availability, while emissions to air was influenced by the reporting on avoided GHG emissions due to electricity production by the HP sector, reported in 16 out of 17 of the ESs.

On the contrary, the aspects "soil contamination" and "noise emissions" were described by indicators in less than 20% of ESs and quantified by only 0.2 indicators on average, despite being considered significant in 86.7% and 53.3% of the ESs, respectively. "Biodiversity" was also quantified in a limited number of ESs (53%) and by few indicators (0.9 on average), despite being considered the most significant aspect together with soil contamination. No correlation was found between the significance of an aspect and the percentage of ESs describing them with indicators or the number of indicators used.

Table 3 lists the environmental indicators most frequently found (at least in two different ESs) for each aspect and represents an initial reference set of metrics for the organizations that manage HP plants to describe their environmental performance. The complete list is reported in Table 1 of the Supplementary Materials. "Total annual gross electricity" was the only indicator reported in all ESs, followed by "total annual mass of waste produced", "total annual mass of

TABLE 1 ESs reporting on the environmental and socio-economic context. From left to right, the table reports: matrices described in the ESs; number of ESs that described the matrices; elements of the matrices described in the ESs and number of ESs that described such elements; number of ESs that used at least one indicator to quantify the matrix state; indicators used in the ESs and number of ESs that used the indicator.

Matrix	ESs with description	Elements (No. of ESs)	ESs with indicators	Indicators used (No. of ESs)
Ecosystems	11	Presence of natural areas of interest (11); Assessment of the state of macrobenthic communities (1); Degree of conservation of habitats in the site (1)	1	$\text{STAR}_{\text{ICMi},}$ inter-calibration common multimetric index, (1)
Population and socio-economic characteristics	8	Presence of tourism (5); Presence of industrial activities directly supplied by the plant (4); Description of the population (4); Agricultural activities that use the stored water (3); Degree of urbanization (3); Use of the reservoirs by fishermen (2)	4	Average income (3); Population density (1)
Landscape	7	Reservoirs as a positive factor (6); Landscape description (2)	0	—
Watercourses	6	Description of the watercourses in the hydrographical basin (4); Physical characteristics of the watercourses (3); Watercourses quality (2)	2	Watercourse quality class (1); LIM_{eco}, pollution level from macrodescriptors for the ecological state, (1)
Fauna	6	Description of fauna (4); Presence of species of particular interest (2); State of fish communities (1)	1	ISECI, ecological status index of fish communities, (1)
Geological and hydrogeological risk	6	Seismic risk (5); Presence of past floods (1)	5	Seismic risk category (5)
Soil and subsoil	5	Geological characteristics of the site (5); Instability causes (1); Riverbeds characteristics (1)	2	Riverbed permeability (2)
Flora	5	Dominant vegetation (5); Presence of species of particular interest (2)	0	—
Aquifers	1	Presence of springs (1)	0	—

non-hazardous waste produced", and "total annual mass of hazardous waste produced" found in 15 ESs. Notably, 14 of the 17 ESs reported data regarding the minimum in-stream flow release. On the contrary, 12 of the 15 indicators reported for "biodiversity" were not related to relevant impacts of HP plants on the watercourse and other environmental matrices but rather to quantifying the total site area (7 indicators) and the amount of that area allocated to different uses, e.g., "total built-up area", "total non-permeable area", "total nature-oriented area" (5 indicators) (Table 3). Regarding "waste production", 7 ESs disclosed data regarding waste production from materials substitution and maintenance, 2 ESs from screening residues, and 2 ESs from biological sludges.

3.2.2 Improvement objectives

"Visual impact" resulted the aspect with the highest number of improvement objectives set (30), followed by "energy production" (24), "energy consumption" (21), and "soil contamination" (19) (Table 4). The complete list is reported in Table 2 of the Supplementary Materials. Nevertheless, compared to the performance indicators, the improvement objectives were more spread across different aspects. Ten aspects had at least ten related improvement objectives, and nine had related improvement objectives in 40% of the ESs or more. The allocated budget was specified only for 41.4% of the 186 declared improvement objectives and accounted for 22.2 M€. "Energy production" was the aspect with the highest allocated budget (13.5 M€ and 60.8% of the total), followed by "process management" (2.5 M€) and "energy consumption" (1.2 M€). Again, no correlation was found between the significance of an aspect and the number of improvement objectives set or the total budget allocated for its improvement.

Despite their low significance, the technical aspects of "process management" and especially "energy production" had a high objective occurrence rate in the ESs. Those objectives were also characterized by a high average budget per objective (1.11 M€ for "energy production" and 0.35 M€ for "process management") due to expensive technical interventions such as turbines or generators substitution, refurbishments of plants, and the construction of a control center, leading to a combined allocated budget of 16.0 M€ (72.1% of the total) for the two aspects. "Visual impact", "energy consumption", and "stakeholder engagement" also received a high number of improvement objectives in several ESs despite their low significance. However, those aspects were characterized by a low budget per objective (0.07, 0.15, and 0.02 M€, respectively) related to inexpensive actions such as organizing plant tours, repainting buildings, and installing LED lights, accounting for a low total allocated budget (0.75, 1.23, and 0.06 M€, respectively).

On the contrary, either a few improvement objectives were set or a limited budget was allocated for the aspects defined with more frequency as significant in the ESs. For instance, a relatively high number of objectives were set to improve "risk of environmental accidents", "soil contamination", and "water pollution and flow management" (16, 19, and 16, respectively), but the average budget per objective was very low (0.08, 0.08, and 0.07 M€, respectively). This is because of relatively inexpensive actions such as installing leakage sensors, removing asbestos materials,

TABLE 2 Summary of the key aspects considered in the ESs, their significance assessment, and indicators used.

Aspect	Considered in the ESs (%)	Significant (%)	Described by indicators (%)	No. of indicators per ES (Avg ± SD)
Soil contamination	100.0	86.7	17.6	0.18 ± 0.39
Risk of environmental accidents	94.1	60.0	52.9	0.77 ± 0.90
Emissions to air	100.0	46.7	94.1	2.29 ± 1.21
Energy consumption	100.0	26.7	94.1	2.94 ± 1.64
Energy production	100.0	6.7	100.0	1.94 ± 0.56
Biodiversity	94.1	86.7	52.9	0.88 ± 1.11
Waste production	94.1	66.7	94.1	5.24 ± 2.28
Water pollution and flow management	94.1	60.0	82.4	0.82 ± 0.39
Noise emissions	82.4	53.3	11.8	0.18 ± 0.53
Raw materials consumption	82.4	26.7	76.5	1.88 ± 1.58
Visual impact	82.4	26.7	0.0	0
Water consumption	76.5	46.7	70.6	1.88 ± 1.83
Radiations	70.6	26.7	0.0	0
Stakeholder engagement	52.9	0.0	0.0	0
Light pollution	47.1	20.0	0.0	0
Process management	47.1	0.0	11.8	0.24 ± 0.75
Transport	29.4	0.0	5.9	0.06 ± 0.24
Odor emissions	29.4	0.0	0.0	0

and employing epoxy resin for transformers, leading to a limited total allocated budget (0.8, 0.7, and 0.5 M€, respectively). "Waste production", "biodiversity", and especially "noise emissions" had instead a lower number of objectives set for their improvement (11, 10, and 4), generally with a low total allocated budget, although the availability of budget data in the ESs was limited for those aspects.

Table 5 lists the objectives set in at least two of the analyzed ESs. Renovation of buildings to lower their visual impact was the one with the highest occurrence (16 ESs), followed by installing LED lights (14 ESs), purchase of lower emission vehicles (8 ESs), and removal of asbestos materials (8 ESs). It is notable that only 5 of the objectives set by the companies (i.e., "determination of the ecological flow", "modification of the water release procedures", "construction of a fishway", "flushing of sediments") might have a positive impact on biodiversity while, on the other hand, 12 objectives could have a negative effect. "Reducing waste production discharging water extracted from wells into the watercourse" could modify the water quality, while the "release of fish upstream of the plants" could represent an impact if the released fishes come from not accurately genetically selected hatcheries. The "construction of gabions to reduce the erosion of the banks" could alter the habitat diversity and availability, and "decreasing the released flow to increase electricity production" determines a clear alteration in habitat availability in the downstream river reaches and decreases the environmental sustainability of the plant. Lastly, "constructing a new HP plant" and "construction of a new weir", represent a new anthropic element causing an environmental impact upon the river ecosystems. With regard to "water pollution and flow management", most objectives were set to limit the risks of water contamination, but only one was associated with the "determination of the ecological flow" to be released downstream the dam. The lack of objectives associated with the determination of the EF can be related to its current limited and fragmented implementation in the regional water resources management policies in Italy (Moccia et al., 2020).

3.2.3 Reporting of the impacts on biodiversity and their mitigation

The impacts on biodiversity were scarcely reported, as summarized in Table 6.

Sediment management was mentioned only in 8 ESs, and 7 described its impacts. Furthermore, while all those 7 ESs stated operational problems (e.g., reduction of reservoir volume) and 2 ESs acknowledged issues related to security and efficiency decrease, only 1 ES described sediment management as an impact on biodiversity. It acknowledged potential fauna disturbance due to increased turbidity (assessed as comparable to flood events), and evaluated decreases in the macrobenthic community after flushing operations as temporary (2–3 months) without providing details about monitoring campaigns. Six ESs mentioned the reservoir management project, a document requested by Italian legislation for large reservoirs that describes the planned procedures for the

TABLE 3 List of the environmental indicators reported most frequently in the ESs (at least two different ESs).

Aspect	Indicator	Unit	No. of ESs
Emissions to air	Total annual avoided greenhouse gas emissions	t	11
Emissions to air	Total annual mass of pollutants emitted to air	t	7
Emissions to air	Total annual greenhouse gas mass emitted to air	t	7
Emissions to air	Total annual CO_2 mass emitted to air by source	t	6
Water pollution and flow management	Minimum in-stream flow released	m^3/s	14
Waste production	Total annual mass of non-hazardous waste produced	t	15
Waste production	Total annual mass of hazardous waste produced	t	15
Waste production	Total annual mass of waste sent to recycling	t	13
Waste production	Total annual mass of waste produced	t	12
Waste production	Total annual mass of waste sent to disposal	t	11
Waste production	Total annual mass of waste produced per produced energy	t/MWh	8
Waste production	Total annual mass of waste produced per typology	t	7
Waste production	Total annual mass of hazardous waste produced per produced energy	t/MWh	6
Energy consumption	Total annual electricity consumption	MWh	10
Energy consumption	Total annual oil consumption	t	9
Energy consumption	Total annual electricity consumption per produced energy	MWh/MWh	8
Energy consumption	Total annual methane consumption	t, Sm^3, MWh	5
Water consumption	Total annual water fed to turbines	m^3	10
Water consumption	Total annual water consumed for domestic use	m^3	7
Water consumption	Total annual water consumption per source	m^3	6
Water consumption	Total annual water fed to turbines per produced energy	m^3/GWh	5
Raw materials consumption	Total annual consumption of chemicals and materials	t	13
Raw materials consumption	Total annual consumption of chemicals and materials per produced energy	t/MWh	8
Biodiversity	Total site area	m^2	7
Biodiversity	Total site area per use	m^2	5
Energy production	Total annual gross electricity produced	GWh	17
Energy production	Total annual net electricity produced	GWh	14
Risk of environmental accidents	Total annual number of emergency events	—	8

removal of sediments from the reservoir in compliance with the quality objectives of the concerned water bodies. However, only 3 ESs described the sediment removal operations adopted. One ES reported that for smaller reservoirs operations were mechanical and that flushing was performed for larger reservoirs (Val Venosta). Another ES mentioned that flushing operations were conducted for one reservoir (Polo 3), and the last ES reported flushing of sediments scheduled every 3 years (Bolzano). None of the 3 ESs disclosed information on characterizations of the sediments. Although one ES stated that competent authorities authorized maximum turbidity and flow values during flushing operations (Bolzano), none of the ESs described any measure implemented to mitigate the impacts of sediments management. Two ESs defined improvement objectives to mitigate the impact from sediments management (Table 2 of the Supplementary Materials). The first ES (Bolzano) reported a dredging operation in 2020 aimed at reducing the impact on fish fauna. This operation was defined as “experimental” as sediments are currently flushed through the turbines. However, no information was provided regarding the cost or outcome of the experiment. The second ES (Polo3) reported an objective of increasing solid transport downstream of the plant by implementing sediments flushing through the turbines. Again, the ES lacked information on the effect of this action on the aquatic ecosystem as well as any financial data.

Only two ESs mentioned hydropeaking. Both ESs underlined the importance of hydropeaking to match the electricity demand

TABLE 4 Summary of the environmental improvement objectives set by the organizations and of budget allocation (cross: average; horizontal line: median).

Aspect	Significance (%)	Tot allocated budget (k€)	Budget per objective (k€)	ESs with objectives (%)	No. of objectives per plant (Avg ± SD)
Energy production	6.7	13,505	1,125	47.1	1.41 ± 1.84
Process management	0.0	2,450	350	47.1	0.71 ± 0.92
Energy consumption	26.7	1,230	154	64.7	1.24 ± 1.15
Risk of environmental accidents	60.0	1,104	92	47.1	0.88 ± 1.22
Visual impact	26.7	748	68	64.7	1.77 ± 2.31
Soil contamination	86.7	701	78	64.7	1.12 ± 0.99
Biodiversity	86.7	596	119	47.1	0.59 ± 0.71
Water pollution and flow management	60.0	533	67	58.8	0.94 ± 0.97
Waste production	66.7	510	510	29.4	0.65 ± 1.32
Water consumption	46.7	500	500	17.6	0.24 ± 0.56
Emissions to air	46.7	215	54	66.7	0.77 ± 0.83
Stakeholder engagement	0.0	57	19	29.4	0.29 ± 0.47
Raw materials consumption	26.7	40	40	11.8	0.12 ± 0.33
Odor emissions	0.0	0	—	0.0	0
Noise emissions	53.3	0	—	11.8	0.24 ± 0.66
Transport	0.0	0	—	0.0	0
Light pollution	20.0	0	—	0.0	0
Radiations	26.7	0	—	0.0	0

peaks but recognized its impact on aquatic fauna due to rapid changes in the wetted perimeter of the river, especially during fish breeding seasons. Furthermore, none of the ESs described any measure implemented to mitigate hydropeaking impacts, nor did they report any improvement objectives for the implementation of such measures.

Regarding habitat fragmentation, fish passages for upstream migration were reported only in 4 ESs and related to 10 HP plants (5% of the total, all fish ladders). Moreover, none of the mentioned fishways was described in terms of technical characteristics (e.g., specific typology, drop between pools, total drop, *etc.*) or passage efficiency. The presence of fish bypasses for downstream migration was reported for 3 HP plants (1.5% of the total). The use of screens at water intake structures was mentioned for 43 plants (21% of the total), but just as a mean for protecting intake structures and turbines from debris or logs rather than for preventing fish from accessing the turbines (Calles et al., 2013). Only one improvement objective was directed towards mitigating habitat fragmentation, consisting in the construction of a fishway for upstream migration to reduce the impact on the fish fauna (Val Venosta). The construction was expected to be concluded during 2021, with a total cost of 0.54 M€. No information on the design process and typology of this fishway was disclosed in the ES. The limited number of fish passage solutions mentioned in the analyzed ESs basically reflects the fact that in Italy the related legal framework is still limited and fragmented and the implementation of these mitigation measures can be a mandatory requirement only for new dams or a retrofit requested by the competent Authorities at the renewal of the water withdrawal license of existing sites.

Finally, 16 ESs mentioned and 14 quantified the minimum in-stream flows. Nevertheless, only 2 ESs mentioned the stricter ecological flow, and none of the ESs reported its value. Two ESs defined improvement objectives concerning flow regulation. One ES (Polo 3) reported a modification of the calculated minimum in-stream flow to reduce the environmental impact of the affected HP plant, but without quantifying such flow release modification nor the criteria used for its definition. Another ES (Calabria) aimed at calculating the ecological flow to ensure the health of water bodies, but this was considered experimental due to ongoing discussions with local regulatory bodies regarding the definition of a new regional regulation. Moreover, both improvement objectives lacked further details on associated investments or implementation plans.

In summary, the reporting of impacts on biodiversity and their mitigation was found to be surprisingly lacking in the analyzed ESs, with sediment management, hydropeaking, and habitat fragmentation being poorly described. Only a few ESs mentioned mitigation measures, and improvement objectives were scarce, highlighting the need for specific guidelines to improve reporting in the hydropower sector especially on the

TABLE 5 List of objectives and related actions set at least by two organizations.

Aspect	Objective	Action	No. of ESs
Visual impact	Improvement of the visual perception of the implant	Renovation of a building	17
Visual impact	Improvement of the visual perception of the implant	Demolition of a building	9
Visual impact	Improvement of the visual perception of the implant	Landscaping arrangement	2
Energy consumption	Reduction of electricity consumption	Replacing lighting with led technology	14
Energy consumption	Reduction of energy consumption	Building efficiency	6
Energy production	Increase of the electricity generation efficiency	Replacement of turbines and/or generators	11
Energy production	Increase of the electricity generation efficiency	Renovation of a plant	4
Energy production	Increase in electricity production	Construction of a new HP plant	6
Emissions to air	Reduction of emissions	Replacement of means of transport	8
Emissions to air	Reduction of greenhouse gas emissions	Improvements to the efficiency of the air conditioning system	4
Risk of environmental accidents	Reduction of the risk of asbestos dispersion	Removal of items	8
Risk of environmental accidents	Reduction of flood damage	Installation of submersible pumps	3
Soil contamination	Reduction of the risk of soil contamination	Reduction in the use of mineral oil	8
Soil contamination	Reduction of the risk of soil contamination	Interventions on underground tanks	4
Soil contamination	Reduction of the risk of spills	Adaptation of the containment tanks	3
Waste production	Improvement of waste management	Construction of a room for the collection and storage of waste	5
Water consumption	Reduction of the consumption of withdrawn water	Elimination of water leakage	4
Stakeholder engagement	Increased awareness	Organization of guided visits to the plants	4
Water pollution and flow management	Reduction of the risk of water contamination	Changes to the cooling system	3
Water pollution and flow management	Reduction of the risk of water contamination	Installing an oil detection system	3
Water pollution and flow management	Reduction of the risk of water contamination	Replacement of hydraulic components	3
Water pollution and flow management	Reduction of the risk of water contamination	Use of biodegradable oils	2
Water pollution and flow management	Reduction of the risk of water contamination	Installation of a de-oiling plant	2
Noise emissions	Reduction of the emitted noise	Installation of soundproofing systems	3
Process management	Improvement of monitoring systems		2
Process management	Increase of knowledge on safety and environmental issues	Organization of internal initiatives	2
Biodiversity	Reduction of the impact on fish fauna	Release of fish upstream of the plants	2

crucially important environmental impacts of the hydropower plants. Furthermore, the only significant investment for the mitigation of the impacts on biodiversity was the construction of a fishway for the upstream migration of fish fauna (0.54 M€). This investment accounted for 91% of the overall budget allocated to biodiversity by all the plants of the sample, but still represented only 2% of the total budget allocated by plant operators, which amounted to 22.2 M€.

4 Discussion

4.1 Key findings of the study

This work analyzed the environmental reports (the ESs) of 206 Italian HP plants managed by organizations registered to EMAS in 2020, discussing how the managing companies evaluated their sustainability. The key findings of the study are as

TABLE 6 Summary of the reporting of the impacts of HP plants on biodiversity in the ESs.

Site	Tot plants	Sediments management	Hydro-peaking	Fish passage	Fish bypass for downstream migration	Intake barrier	MIF	EF	No. of objectives for aquatic ecosystem	Total budget [M€]
Bergamo	17	I	-	6	1	17	Q	-	-	-
Bolzano	32	P, I, O	M, I	-	-	-	Q	-	1	-
Brunico	2	M	-	1	-	1	-	-	-	-
Calabria	9	-	-	-	-	-	M	M	1	-
Dolomiti	5	-	-	-	-	1	Q	-	-	-
Friuli	2	-	-	-	-	-	Q	-	-	-
Mese	14	-	-	-	-	-	Q	-	-	-
Polo1	21	P, I	-	2	1	3	Q	-	-	-
Polo2	12	P, I	-	-	-	1	Q	-	-	-
Polo3	39	P, I	-	-	-	1	Q	-	1	-
Primiero	6	-	-	-	1	-	M	-	-	-
Santa Vittoria	1	-	-	1	-	-	Q	-	-	-
Terni	19	P, I	-	-	-	19	Q	M	-	-
Trento	7	-	-	-	-	-	Q	-	-	-
Tusciano	7	-	-	-	-	-	Q	-	-	-
Val Venosta	2	P, I, O	M, I	-	-	-	Q	-	1	0.54
Valtellina	11	-	-	-	-	-	Q	-	-	-

The improvement objectives were defined as related to the aquatic ecosystem if addressing the following areas: environmental flow, hydropeaking, habitat fragmentation, and sediment management (M = Mentioned; P = reservoir sedimentation management plan described; I = Impacts described; O = Operations described; Q = Quantified; MIF = Minimum in-stream Flows; EF = Ecological Flow).

follows. Firstly, the ESs rarely described the environmental state of the site hosting the HP plant. Specifically, only 1 company described the ecosystems using a relevant indicator, and the watercourses, flora and fauna were considered less than population characteristics and landscape. The impacts on biodiversity were scarcely reported and 12 of the 15 indicators found in ESs were not related to relevant impacts of the HP plants. In details, of the 17 ESs, only one described the impacts of sediment management on biodiversity, 2 mentioned hydropeaking, 4 reported fish passages, and only 2 defined the ecological flow, although 14 defined the minimum in-stream flow. A key finding of our study is that there is a significant gap between what the HP plant operators report in their ESs and the information necessary for an effective assessment of the environmental impacts of the HP plants upon the aquatic ecosystems. This gap can be attributed to the fact that the organizations primarily focused on the reporting of environmental aspects with legally binding targets, such as waste management, and directly related with operational costs, for instance energy production and consumption. Therefore, those aspects were addressed in the ESs with more detail than more significant aspects such as "biodiversity", for which the legal framework in Italy is still limited and fragmented.

No correlation was found between the significance of an aspect, the number of indicators used to quantify the impacts, and the budget that the companies invested in reducing them. This is in contrast with previous studies based on the analysis of the environmental reporting of companies registered to EMAS managing biodegradable waste treatment plants (Castelluccio et al., 2022) and waste-to-energy plants (Castelluccio et al., 2022; Comoglio et al., 2022), where a strong positive correlation between the significance of a single aspect and the total number of indicators used was found.

Considering the economic efforts, the companies managing the analyzed HP plants dedicated 76% of total budget to the improvement of technical aspects ("process management" and "energy production") due to expensive technical interventions lacking a clear implication towards any environmental improvement. On the contrary, few improvement objectives were set for the aspects defined more significant, or a limited budget per objective was allocated. This is substantially consistent with the findings of the mentioned studies related to the biodegradable waste management (Castelluccio et al., 2022) and waste-to-energy (Castelluccio et al., 2022; Comoglio et al., 2022) sectors.

The findings of this study have important implications for the management of HP plants. Firstly, the unexpectedly low level of reporting on the environmental state of the sites hosting the HP plants suggests that more attention needs to be paid to environmental monitoring and assessment. This could include the development of standardized metrics that are relevant to the impacts of the sector, particularly in relation to the physical and ecological characteristics of the impacted watercourse.

Secondly, the lack of correlation between the significance of an aspect and the budget that the companies invested in those aspects highlights the need for more targeted investments. HP plant managers should prioritize environmental performance indicators that are most relevant to the sector and allocate sufficient budget to meet those objectives.

This study suggests that organizations managing HP plants could benefit from adopting environmental management systems such as EMAS. However, to be effective, these systems need to be supplemented with specific reporting guidelines for the HP sector. The implementation of these guidelines would have practical implications for policymakers and industry stakeholders, as it would enable more informed decisions and more appropriate measures to mitigate the environmental impacts of the sector, with a specific focus on the biodiversity of aquatic ecosystems. Furthermore, our findings have significant value for future research. The definition of environmental reporting guidelines specifically for the HP sector would address the focus on the most significant environmental aspects and allow researchers to better quantify its environmental impacts.

4.2 Novelty compared to prior research

The available literature has considered the sustainability assessment of the HP sector since about 25–30 years ago (Goodland, 1994; Kaygusuz, 2002), and it is mostly devoted to the sustainability assessment of new HP installations through site-specific indicators (i.e., “soil contamination”, “biodiversity”, “waste production”, “risk of environmental accidents”, “water pollution and flow management”, and “noise emissions”). The applied approach usually compared the status of the site before and after the construction of the HP plant (Lopes et al., 2022; Roy and Roy, 2022), while much less focus is dedicated to the impacts associated to existing plants. A recent study that assessed the ecological impacts of HP plants in operation proposed an ecological impact scorecard based on four criteria: environmental flow, hydropeaking, fish protection and passage performance, and sediment management (Alp et al., 2020). This study is particularly relevant because it suggests an integrated approach to evaluate the sustainability of existing HP plants in relation to aquatic ecosystems using an internationally recognized regulatory context. Other authors reviewed the indicators used in previous studies (Nautiyal and Goel, 2020; Pimentel Da Silva, 2021), and established environmental assessment frameworks. Some researchers also suggested subsets of indicators (Kumar and Katoch, 2014; Tahseen and Karney, 2017; Parish et al., 2019) to improve the efficiency of the assessment. Additionally, various frameworks relevant to the sustainability assessment of the HP sector have been developed. Richter et al. (1996) established a method for assessing the degree of hydrologic alteration attributable to human influence within an ecosystem. Bratrich et al. (2004) designed a concept for evaluating environmentally compatible hydropower production, while McManamay et al. (2020) proposed a toolkit for assessing the most relevant impacts of hydropower on river ecosystems. However, various authors documented shortcomings of the existing studies on the topic, including the lack of standardization (Tahseen and Karney, 2017), the bias towards global aspects due to limited use of local metrics (Mortey et al., 2019), the unavailability of data (Nautiyal and Goel, 2020), and the inadequate description of some impacts (Nautiyal and Goel, 2020). The established frameworks for the sustainability assessment of the HP sector also present limitations. For instance, some methods necessitate data spanning several decades before and after a particular impact to accurately determine changes in flow variability (Ma et al., 2014; Timpe and Kaplan, 2017). Other frameworks have been criticized due to the exclusion of important criteria that play critical roles in river ecosystem functions (Kunz et al., 2013).

In summary, our literature analysis highlighted three knowledge gaps: i) the limited standardization in the evaluation of the environmental performance of existing HP plants; ii) the limitations of some of the established frameworks, such as the scarce use of metrics relevant to the impacts of the HP sector and data availability; and iii) the lack of emphasis on how HP organizations evaluate their sustainability. Compared to the existing literature, this study is characterized by two main novelties. Firstly, it focused on the environmental performance of existing HP plants disclosed by the managing companies. Our first research question was related to how the environmental performances are quantitatively assessed, and if the companies planned to contain the environmental impacts through improvement objectives and mitigation measures. Secondly, this study explored the role of the adoption of an environmental management system (EMAS in our case) in supplying data useful for an environmental assessment of the HP sector. Therefore, our second research question investigated the reliability and consistency of the environmental reports associated to an environmental management system (EMAS) in providing a useful base of data to evaluate the sustainability of the HP sector.

4.3 Future directions of the research

The results of this study showed that the ESs of EMAS-registered organizations are not sufficient to evaluate the sustainability of the managed HP plants. There is an urgent need of specific environmental reporting guidelines for the HP sector, addressing the focus on the most significant environmental aspects, and particularly on the physical and ecological characteristics of the impacted watercourse, also defining a minimum set of performance indicators relevant to the HP sector to quantify its environmental impacts. To establish the reporting guidelines for the HP sector, it is recommended to reference the already developed frameworks for the assessment of the environmental impacts of HP plants on the aquatic ecosystem

(Bratrich et al., 2004; Alp et al., 2020; McManamay et al., 2020). This could allow to use ESs, and environmental reporting in general, as tools for the evaluation of the sustainability performance of organizations (Barón Dorado et al., 2022).

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found in the Environmental Statements concerning the analyzed plants, which can be obtained by contacting the managing companies or visiting their websites. For any further information, please contact the corresponding author.

Author contributions

SC: investigation, data curation, visualization, writing—original draft; CC: conceptualization, methodology, supervision, writing—original draft, writing-review and editing; SF: conceptualization, methodology, writing-review and editing. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2023.1178037/full#supplementary-material

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