Abstract ID#: 16

Title of Paper: Impacts of floating solar panels: The Magat reservoir as reference case

Session: 177
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1. Introduction

Transition and transformation of society for energy decarbonization requires an approach where environmental, socio-economic, and socio-cultural aspects are addressed to achieve a sustainable and just industry. Hybrid hydro – floating solar energy production (FPV) represents an innovative technology, and a potential for increased renewable power production (Essak and Ghosh 2022; Scatec 2022). The possibility to place solar panels on reservoirs compared to on land means reduced land utilization, decreased dependence on inflow for power generation, and the possibility for a more resilient water management regime. However, few studies have been undertaken where primary data are collected for the analysis of possible impacts of floating panels on environmental, socio-economic and socio-cultural aspects (Bax et al. 2022; Pouran et al. 2022). There is hence a need to better understand impacts on different stakeholders and beneficiaries in society and to enhance potential co-benefits and address adverse impacts.

The Hydrosun project involves collaboration between research and industrial partners for knowledge development to enable efficient design and operation of hydro and FPV-hydro hybrid power plants (FPV-H-HPP), and to increase understanding of FPV impacts and possible co-benefits (Hydrosun 2024; Scatec 2022). This paper presents research carried out in 2021 – 2024 on possible effects of covering the water surface with solar panels, (i) on the natural environment, and (ii) the direct and (iii) the indirect effects on socio-economic and socio-cultural values.

The Magat dam in the Philippines was selected as a case study for the ex-ante impact assessment, as there is an existing hydropower plant in operation since 1982. The local research partner has provided historical hydrologic data and facilitated engagement with local authorities and actors.

This paper presents a conceptual framework for an ex-ante impact assessment that enables an evidence based, and holistic approach including engagement of stakeholders. Possible effects on environmental variables are quantified through biogeochemical lake modelling; possible effects on society are explored by identifying water users and users as part of focus group discussions with local stakeholders. The environmental simulations are given for two scenarios, a realistic FPV coverage and an unrealistic large coverage, with reference to a baseline scenario without FPV. Drawing on focus group discussions and bilateral discussions with industry partners, activities to enhance co-benefits and reduce adverse impacts of floating solar energy production are presented. The degree that the results have generic relevance is discussed.

2. Methods and material

2.1 The case area

The Magat reservoir (16°49'30"N 121°27'14"E, 15 km2, Fig. 1) is located on the Magat river in the Province of Isabela, Philippines. The catchment (4 463 km^2) covers areas within the administrative jurisdiction of the provinces of Nueva Vizcaya, Quirino, Isabela and Ifugao (Elazegui and Combalicer 2004; Sarmiento et al. 2010). The elevation range of the catchment is between 100 to 1595 masl while the maximum depth of the reservoir is 80.5 m. The Magat dam was constructed between 1975-82 for irrigation, flood control and hydropower generation, with policy priority for irrigation purposes. The reservoir impounded areas along the boundary of Ifugao and Isabela provinces. Originally owned and operated by the government of the Philippines through the National Power Corporation (NPC), the Magat powerplant was acquired by SN Aboitiz Power (SNAP) in 2007 through a privatisation program as mandated by the 2001 EPIRA Law. In 2019, SNAP installed a 280 kWp FPV pilot project on the reservoir. Two case villages, one upstream of the dam, and one downstream were selected for closer study (Fig. 1). The indigenous communities in the Province of Ifugao, were not included in this study as the authors did not receive permission to collect data in this area.

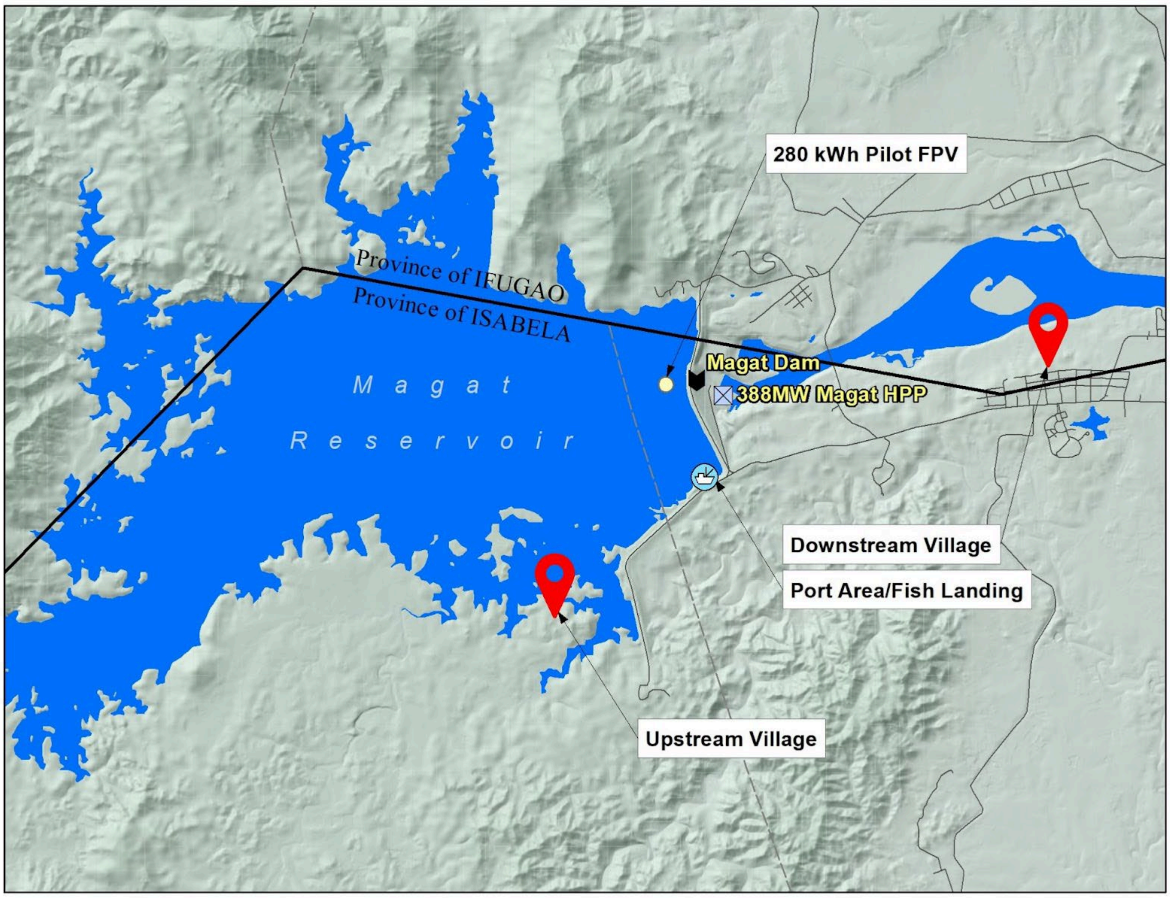

Figure 1. Location map of Magat reservoir with upstream and downstream village, port area and 280 kWh pilot FPV.

2.3 Analytical framework

A methodological framework is developed for ex-ante sustainability impact assessment of FPV-H-HPP. The framework is adapted from an approach considering land use policies and sustainable development in developing countries (McNeill, Nesheim, and Brouwer 2012). Three main phases are included: (i) a pre-modelling phase to identify the system addressed, select scenarios and indicators, (ii) a modelling phase to assess the impacts on indicators and (iii) a post-modelling phase to analyse the impacts on society based on selected indicators, and to identify activities to enhance co-benefits and reduce adverse impacts. Involvement of stakeholders and actors occurs during the pre-modelling and post-modelling phases.

2.2 Methods and data collection

The study involved combining various methods and approaches to assess the impact of FPV on environmental and socio-economic factors. The study does not aim for generic results, but rather to provide a case study benchmark. Most of the data collection occurred within three 7–10-day field visits to the case villages and the reservoir during June 2022 to June 2023.

The pre-modelling phase

Environmental factors. Data collection included point measurements of nutrient concentrations (Total Nitrogen and Total Phosphorus), oxygen concentration and water temperature for each field visit near the FPV pilot and near the turbine intake. During the first visit, two chains of thermistors were installed to record hourly water temperature at various depths over the next year, one located below the FPV unit and one 50 m away. The collected data was used for model validation in the modelling phase.

Socio-economic issues. Literature reviews were conducted in 2021 to get overview and describe the history, the institutional, and the socio-economic and socio-cultural situation in the Isabela Province. Primary data collection involved Key Informant Interviews (KIIs) and focus group discussions (FGDs) with local authorities and villagers, respectively. A map-based approach was used to identify water users and users, and to locate this on the map.

The modelling phase

Environmental factors. We developed a fully integrated physical-biogeochemical reservoir model (based on Norling et al. 2021) to simulate impacts of FPV on evaporation, heat exchanges (based on Lindholm et al. 2022), light penetration and gas (O_2, CO_2 and CH_4) exchanges at the water surface. The model is driven by daily weather, inflow and outflow observations provided by the hydropower company and provides daily water level, evaporation, water temperature, nutrients, and dissolved gas concentrations in the epi- and hypolimnions. The Magat reservoir is modelled with measured bathymetry by two adjacent, fully connected layered basins, one of which can be partly or entirely covered with FPV mounted on soft membrane in direct contact with water. The horizontal mixing between basins is controlled by a user-defined parameter. We considered three cases, no FPV coverage (baseline), realistic commercial scale with FPV, and unrealistic large FPV coverage (Fig. 2).

Socio-economic issues. Indicators to assess the effect of the FPV interventions were addressed in focus group discussions in the case villages in June and in November 2022. The qualitative data formed the basis for the further analysis of effects. Participants in the workshops were local villagers, both men and women, and in total 40- 50 participated in workshops from each of the two case villages.

The post-modelling phase.
Measures to reduce adverse impacts and enhance co-benefits considering both environmental and socio-economic cultural issues were discussed with the project's industry partners in Norway and in the Philippines, and with local authorities in Isabela during our last visit.

3. Results

3.1 The pre-modelling phase results

The main water users and uses of the reservoir are fishing for subsistence and sale, aquaculture production, agriculture irrigation, transportation (boat operators), tourism, and energy production (Table 1). The reservoir is also important for different types of recreational activities, particularly boating. A fish sanctuary declared by the National (NIA) as a no fishing zone is delineated and covers the zone within 1 km from the Magat dam embankment (Fig. 2).

Road construction is strictly restricted in the upstream villages where rehabilitation efforts are located to minimize disturbance in the watershed. On the north-eastern side of the reservoir, which is under the administrative jurisdiction of the province of Ifugao lies indigenous cultural communities (ICCs; Fig. 1). During the FGD of the upstream village, the research team was informed of several activities which are related to the socio-cultural heritage of the Ifugao ICCs. These include cleansing rites and baptisms, and "gulgul". Several rules adopted with the construction of the dam, do not permit the activities mentioned, such as boat race, boat parade, and swimming competition.

The catchment is characterised by economic development and urbanization. *Policy drivers* include the use of Magat reservoir as a source of renewable power generation, and irrigation for agriculture. Other drivers in the catchment include technological development and climate change.

The scenarios for impact assessment. The assessment addresses three scenarios (2010-2022), 1. a baseline that considers policy drivers, as technological development, and irrigation policies. 2. A realistic commercial scale FPV implementation; and 3. An unrealistic high FPV coverage scenario. The scenarios consider the same underlying drivers as in the baseline. We considered fourteen different water and land use functions (Table 1) corresponding to the environmental, the economic and the socio-cultural sustainability dimensions.

Sustainability dimensions	Water and land use functions	Beneficiaries, actors
Environmental dimension	Provision of water availability (quantity)	National level authorities: DENR, NPC, NCIP, Isabela and Ifugao province authorities, Local Government Units. NGOs, CBOs, People's Committees, Society, the Energy company
	Provision of good water quality	
	Provision of biotic resources, biodiversity	
	Reduction of GHG emissions	National authorities
	Maintenance / Provision of ecosystem processes	Civil society and different sectors and industries.
Economic dimension	Industry and physical production	Province authorities, Local Government Unit authorities. Aquaculture farmers, Fishermen, Agriculture farmers, Families renting out boats
	Provision of employment	
	Accessible infrastructure - transportation	Responsible authorities, villagers
	Provision of electricity	NPC, Energy company, Industries
	Enabling flood control	Responsible authorities, villagers downstream
Socio-cultural dimension	Provision of food security	Provincial and local authorities, marginalised people
	Provision of social cohesion	Civil society and households, children, youth, elderly people,
	Provision of recreation opportunities, quality of life	
	Access to cultural heritage	NIPC, Civil society, religious people, indigenous people

Table 1: Water and land use functions associated with key beneficiaries and actors.

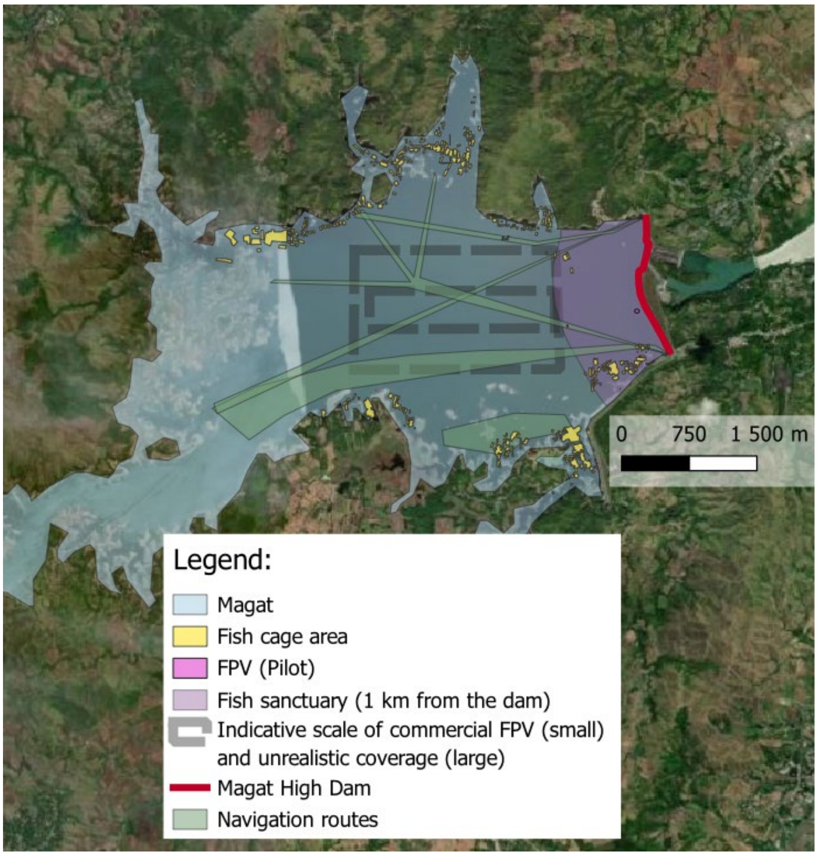

Figure 2: Indicative locations of commercial scale FPV and unrealistic FPV coverage along with other spatial constrains.

3.2 Modelling phase, effects of FPV

Expected effects on environmental variables.

FPV installation showed small impacts under normal conditions, even for the unrealistic large coverage. On average, evaporation was 3% (64 mm yr^{-1}) and 12% (220 mm yr^{-1}) lower for the realistic and unrealistic cases, respectively, compared to no FPV coverage. However, the amount of water saved represents only 0.01% and 0.05% of the total yearly inflow, respectively. Similarly, water temperature in the epilimnion was 0.02°C and 0.12°C higher, and oxygen concentrations were slightly lower than without FPV. Nevertheless, under selected extreme events, such as prolonged low water level, the presence of FPV can significantly increase the numbers of days where O_2 concentration falls below 5 mg L-1 or temperature rises above 35°C, considered as thresholds with some impacts on fish growth (Abd El-Hack et al. 2022).

Expected effects on economic and socio-cultural values.

Both FPV cover scenarios are expected to have negative effects on several water users upstream as the FPV panels will reduce area for other uses, and the current port area will be used for FPV installations (Table 2). Aquaculture production yields and transport on the reservoir will particularly be affected. Regarding possibilities for recreational activities, there will be some reduced area for boating. Most recreational activities and cultural heritage activities as cleansing rites, baptisms, occur along the shore away from the panels. The degree that the presence of FPV, including light reflection and changes in the landscape reduce peoples' recreational experiences, and the value of cultural heritage activities was not addressed in this study.

Positive effects are expected on industries due to construction of the technologies and economic ripple effects can be expected (Pouran et al. 2022). Higher local power production might also result in more economical activities for local energy transmission company and better grid connectivity with more households benefiting from power supply. New local employment opportunities such as for cleaning and maintenance of the panels are planned (Scatec, 2022).

<table>
<tr><th colspan="2" rowspan="2">Water and Land use functions/ Indicators</th><th colspan="3">Scenarios</th></tr>
<tr><th>Baseline</th><th>Indicative commercial FPV scale</th><th>Unrealistic high FPV coverage</th></tr>
<tr><td rowspan="5">Environmental dimension</td><td>Provision of water availability (quantity)</td><td>Access to irrigation water for 6 months per year</td><td>No impact. Much higher coverage is needed to see positive impacts (Essak and Ghosh 2022)</td><td>Possible positive impact depending on operation regime: more irrigation water.</td></tr>
<tr><td>Provision of good water quality</td><td>Drinking water from ground water. Water ecological status: acceptable</td><td>No impact under normal conditions but low risk of more frequent low O2 concentrations and high temperature.</td><td>Negative impacts on oxygen availability. High risk of more frequent low O2 concentrations and high temperature</td></tr>
<tr><td>Biodiversity / biotic resources</td><td>National agencies authorities (ref describe biodiversity reduction</td><td>No impact under normal conditions but low risk of more frequent low O2 concentrations with impacts on fish growth</td><td>Negative impact due to reduced oxygen with high risk of more frequent low O2 concentrations with strong impacts on fish growth and possibly reproduction.</td></tr>
<tr><td>Climate change mitigation GHG emissions</td><td>Relatively low GHG emissions dominated by downstream CH_4 degassing.</td><td>Uncertain impact. Possible higher downstream degassing (higher CH_4 concentrations) but lower surface emissions.</td><td>Uncertain impact. Possible higher downstream degassing (higher CH_4 concentrations) but lower surface emissions.</td></tr>
<tr><td>Ecosystem processes</td><td>Low water level in reservoir dry season has negative effect on O2 availability</td><td>No impact. Much higher coverage is needed to see positive impacts (Essak and Ghosh 2022)</td><td>Reduced algal growth</td></tr>
<tr><td rowspan="5">Economic dimension</td><td>Industry and physical production</td><td>Upstream: High aquaculture annual production, and high fishing yields.</td><td>Upstream, less aquaculture farmers and yield.</td><td>Upstream: substantially less aquaculture farmers and yield; less fishermen and sale of fish.</td></tr>
<tr><td>Provision of employment</td><td>The majority villagers upstream are employed in agriculture & aquaculture sectors.</td><td>New local employment opportunities such as for cleaning and maintenance of the panels are planned</td><td>Change in distribution of employment.
Positive effects on industries as economic ripple effects can be expected (Pouran et al. 2022).</td></tr>
<tr><td>Access to transportation</td><td rowspan="3">Upstream villagers use boats for transport for most daily activities.
There is not sufficient security of energy supply.
Flooding occurs annually, high flooding occurs every 5-10 years.</td><td colspan="2">Long; - longer transportation time for youth to go to school, increased fuel expenses.</td></tr>
<tr><td>Provision of electricity</td><td colspan="2">Increased security of energy supply</td></tr>
<tr><td>Enabling flood control</td><td colspan="2">Flooding control depend on operation regime, this is not controlled by the energy company.</td></tr>
<tr><td rowspan="4">Socio-cultural dimension</td><td>Provision of food security</td><td rowspan="3">Local Gov. Unit provides support, ca. 50% of household in reference village receive support.
There have previously been some conflicts among aquaculture farmers. Currently low conflict level.
Boating is important upstream, also downstream villages go to the reservoir.</td><td>Less subsistence from fishing, and sale of fish – more support from Local Gov. Unit for unemployed.</td><td>Little subsistence from fishing, and sale of fish – large expenses for support from Local Gov. Unit to households without employment</td></tr>
<tr><td>Provision of social cohesion</td><td>Some conflicts can be expected, particularly among aquaculture farmers.</td><td>Conflicts can be expected among villagers upstream. Lack of social cohesion.</td></tr>
<tr><td>Recreation and quality of life</td><td>Not addressed</td><td>Not addressed</td></tr>
<tr><td>Cultural heritage</td><td>Cleansing rites, baptism, “gulgul”, and parades on the lake. Not all activities are permitted by rules.</td><td colspan="2">Reduced protection and value on cultural heritage.</td></tr>
</table>

3.3 Post-modelling phase: possible mitigating activities

Covering the reservoir can compromise space for other activities as transportation and fishing, and recreational activities. Drawing on FGDs and KIIs, the activities to enhance co-benefits and reduce adverse impacts of floating solar energy production are presented in Table 3. The degree of coverage also corelates with the environmental impact (Pouran et al. 2022; Essak and Ghosh 2022). The placement of the FPV intervention appears as a key measured to reduce adverse socio-economic and environmental impacts. Similar conclusions have been drawn regarding the impacts of a FPV pilot in the Netherlands (Bax et al. 2023). Mitigation activities (Table 3) have been identified to address adverse almost all environmental impacts and their implementation seems promising.

On one hand, allowing space between the panels for air-water exchanges, and to allow for boat transportation is one important and effective action. In addition, if needed, water circulation below the FPV can be artificially increased to avoid low O_2 conditions. A possible co-benefit situation was identified related to the possibility to upgrade the fishing port for the local area with a freezer providing better fish conservation and higher sales.

On the other hand, co-benefits related to reduced evapotranspiration from covering the lake with FPV, is not expected, because little water is saved. A much higher coverage is needed to see significant impact (Essak and Ghosh 2022). Furthermore, the complex dam operation regime is strictly regulated by authorities. In addition, no mitigation activity was identified to address the remaining challenge of competition for space for aquaculture production.

Table 3: Measures to enhance co-benefits and reduce adverse effects.

Water and land use functions	Possible adverse effects	Measures to address adverse effects	Measures to enhance co-benefits
Provision of water availability (quantity)	Possible negative effects of panels on water circulation under panels, water temperature increase, low O_2 concentrations and impacts on fish growth and possibly reproduction, reduced biodiversity.	Ventilation below the panels to reduce hypoxia and improve water quality, and to avoid impacts on fish and other aquatic life. Optimize space between FPV units to allow for optimal air-water exchanges and water circulation below FPV.	With low and intermediate cover, only marginal water saving. Utilization of saved water depends on dam operation regime. Maximize water savings by adapting dam operation regime.
Provision of good water quality			Not applicable
Provision of biotic resources, biodiversity.			Not applicable
Reduction of GHG emissions			Develop a CH_4 isolation method to recover natural gas from high CH_4 water downstream of turbine
Maintenance / Provision of ecosystem processes			Not applicable
Industry and physical production	Reduced nr. aquacultural farmers, and yields. Some reduced fishing & income for households. Longer transportation time. Increased expenses for fuel.	Optimize space between panels to allow for navigation, boats. Identify other areas for aquaculture production.	Construct port to replace old, cold storage beneficial for fish sale. Facilitate for tourism.
Provision of employment			Employ local people to work on FPV
Accessible infrastructure - transportation			Co-design new port area with local users for more efficient transport.
Provision of electricity	Not applicable	Not applicable	Promote local grid connectivity
Enabling flood control	Not applicable	Not applicable	Depends on operation regime
Provision of Food security	Reduced sources for subsistence	*Not identified*	*Not identified*
Provision of social cohesion	Potential increase in conflicts aquaculture farmers	*Not discussed.*	
Provision of recreation opportunities & quality of life	Some reduced area on the reservoir for boating. Glare from panels may be an issue.	Optimize space between panels to allow for navigation, boats.	Educational trips to the FPV panels for schools.
Access to cultural heritage	The degree that FPV and glare will reduce the value of cultural heritage rituals was not addresses, also the study did not address the situation for the Ifugao indigenous people.	*Not discussed.*	

Discussion & conclusion

The study shows that while FPV represents a promising technological development for renewable energy provision, covering the reservoir can imply compromising space for other activities. Yet, the commercial FPV scale scenario where space between the FPV units is optimized to allow for ventilation and navigation – would be a solution where co-benefits would be enhanced, and adverse impacts would be limited. In sub-tropical and tropical regions, large water bodies often provide important ecosystem services for society, and important sources of livelihood for vulnerable groups (Sterner et al. 2020), hence it is important to upfront include activities enhancing co-benefits and reducing adverse impacts. In fact, a higher level of community trust in FPV project can be achieved when the socio-economic benefits are promoted early in the planning phase (Bax et al., 2023).

Regarding the generic relevance of the results from this study, our results agree with the fact that the percentage of FPV cover on a water body will determine the system's impact on water quality and biodiversity (Essak and Ghosh 2022). For now, more research supported by field data and modelling is needed to conclude on potential negative effects and provide generic guidance on FPV impacts. It is however expectable that impacts will be stronger in shallower waterbodies, with higher coverage and will differ depending on FPV design. Finally, the effects of FPV on socio-economic and socio-cultural factors in a specific case will depend on water and land uses in each respective area and should be investigated for each specific context.

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