Overview of the Coupling between Floating PV and Hydroelectric Power Plants

An evaluation of the European energy potential

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Abstract— **One of the recent solutions leading forward the optimization of the renewable energy sources consists in the implementation of hybrid systems: floating photovoltaic integrated with hydroelectric plants. Floating solar photovoltaic (FPV) coupled with the existing hydro-power entities are becoming an impactful competitive option; however, the technology is still nascent, and many potential companies have questions about the inherent technology, its benefits, and how to analyse it appropriately. FPV systems are often installed on storage basins of hydroelectric plants to obtain various advantages deriving from this coupling. Many of those, but not limited to, are the reduction of water evaporation rates that allow the usage of saved water for further pumping or production, the mutual complementarity, which avoids the intermittence due to This paper provides with an overview of FPV, and its hybridization with the hydro-power generations, their concepts, comparisons with the conventional plants and results coming from the already existing global widespread literature. Many evidences to the common technical-environmental problems have been discussed. The FPV energy potential was analyzed by studying the largest hydroelectric plants in 29 European countries, assuming three different percentages of coverage of the surface of the basins considered, 5%, 30% and 50%, using two different technologies of photovoltaic panels, multicrystalline and monocrystalline with respective yields of 17.3% and 21.4%. This study showed how much energy production increases exponentially thanks to the allocation of floating photovoltaic panels on basins of pre-existing hydroelectric plants.**

Renewable energy, floating photovoltaic, hydroelectric power plant, maximization of resource, optimal energy management.

I. Introduction

Energy needs of all the countries around the globe are growing due to their large scale industrial expansions and continuous increase in energy consumption per capita. The energy asset is widely accessible to purchase energy, thanks to the presence of countless players who enter the market and offer energy packages at competitive prices. Renewable sources are increasingly used to meet this growing demand and among these the production of solar energy stands out. [1]. In 2040 two thirds of the world's population will live in areas where the average per capita energy consumption will still be low, which will lead to the need for more energy. Growth in transport demand is slow relative to the past and gains compared to the renewable green energy represent the fastest growing source of energy and promoted to be the largest source of power by 2040 [2]. In line with this objective, RES such as solar, wind, biomass, micro-hydro, and geothermal are being converted into electrical energy and delivered either to demand centers or utility grids [3]. The floating photovoltaic system has attracted a tremendous attention all over the world, due to its numerous advantages. It has a relevant power generation, with a higher efficiency compared to the conventional landed PV plants, and is a system with zero soil occupancy that reduces the water evaporation of the water basin it is located on. Floating photovoltaic arrays are devices that can utilize the mostly unused water surfaces and the abundant solar energy from the sun [4]. A further advantage is the better long-term yield of the FPV thanks to the cooling effect of the water [5]. In 2018, the cumulative floating photovoltaic (FPV) power capacity installed in the world was attended to 1097 MWp with almost 0.78 GW realized only in that last year. But the potential is much wider: in the very conservative hypothesis of the study approached in [6] to cover with photovoltaic panels a very small part (1%) of the total area available on artificial water basins worldwide, equal to 404,000 square km, at least there could be installed 400 GW of floating PV parks, with an annual electricity production estimated at over 521,000 GWh.

In [7] confirming what was previously stated, a comparative analysis was carried out between a 1 MW PV ground system and a 500 KW floating photovoltaic system. The comparative study, conducted over a period of six months, showed how much the energy yield and efficiency of a floating photovoltaic system is higher, with the same climatic conditions and solar radiation, than a traditional terrestrial system. Although on-site photovoltaic (PV) systems can help customers reduce their maximum demands, PV system alone may not be sufficient to reduce the peak demands satisfactorily due to its intermittent output. The key role of this last generation floating system is the coupling with an already existing and compatible electrical generation infrastructure. In literature, like in [8] has been showed that floating photovoltaic, in fact, finds its best place in the closed water basins and in the fusion with the hydroelectric finds the maximum realization in terms of complementarity, as the solar energy compensates for the production decrease of the hydroelectric due to the drought in the driest seasons, while, in rainy seasons, the natural accumulation of water from the catchment area will maximize the potential for piezometric jump and therefore hydroelectric producibility, which will allow duality with respect to the period of minimum production of the floating photovoltaic system. The over time energy complementarity is proposed with a numerical index, evaluated between two types of energy sources, in different or same positions. In the end, the results of the application of this index refer to solar and water availability in the state of Rio Grande do Sul in southern Brazil.

II. MAIN TEXT

2.1 Energy optimization in hybrid systems

Thanks to the complementarity and synergy of the two resources, the coupling factor can be increased and the PV power production curve leveled.

Hybrid systems are created by allocating floating photovoltaic modules in pre-existing hydroelectric plants that must be mounted on floating structures which are made of polyethylene [9]; the floating platforms occupy an area that would not be used in a better way, thus also helping to reduce the evaporation of water [10].

A case study was carried out in a basin in southern Brazil where there was already a hydroelectric power plant and with a relatively large water surface. The total coverage of the latter would have involved the use of a photovoltaic generator with a capacity of just over 100 MW, and since the hydroelectric potential was much smaller, it was decided to consider the use of photovoltaic panels which would have added power comparable with the existing hydroelectric plant. In fact, floating structures with an installed power of 60 kW were considered. This shows how dams, used for water supply, represent an untapped hydroelectric potential; this can be exploited in combination with floating photovoltaic modules on the water surface, so as to be both operating in a hydro-photovoltaic hybrid system [11].

In [12] studies were conducted to compare the power and energy density between HPP and FPV; the quantities ρP, H and ρE, H (for hydroelectric plants) and ρP, FPV and ρE, FPV (for floating photovoltaic plants) were defined, the results obtained showed that the factor ρE, FPV is much greater than the ρE, H. These, therefore, allow us to see how energy production can improve considerably thanks to the FPV coverage of hydroelectric basins; it is possible to double the power of a hydroelectric plant by covering only 2.4% of the surface of the basins with FPV, increasing the energy production of the HPP plant by 34%.

To carry out the comparative study between floating photovoltaic systems and ground photovoltaic systems, two factors are taken into account: the efficiency of the module and the efficiency gain. This is because the positioning of the panels on the water compared to the panels on the ground reduces the temperature of the same and increases their efficiency. [13] A comparison was made between the operation of a 10 kW FPV system and a 10 kW PV system; the results obtained show that losses, due to the increase in temperature, in FPV systems were reduced by 3% in winter and 9.6% in summer [14]. In another comparison between a 100 kW floating photovoltaic system and a 1 MW ground-level photovoltaic system, it was found that the energy efficiency due to the cooling of the panels is greater than 11% [15].

2.2 Advantages of HPP and FPV coupling

There are several advantages that lead to the coupling of floating photovoltaic systems and hydroelectric plants:

- Connection to the grid is one of the main advantages: the hydroelectric basins, natural and otherwise, have in fact energy generators and direct connection to the grid, and it is therefore possible to exploit the pre-existing systems with the consequent reduction of installation costs of transformers and grid connections for floating photovoltaic systems.
- In temperate regions, photovoltaic panels give the maximum yield in the warm seasons, this period coincides with the seasons in which the hydroelectric plants record a reduction in power; there is therefore a reduction in the annual fluctuations in electricity production.
- The floating photovoltaic systems have a much higher ease of installation and disposal than the classic panels on the ground, their installation also does not involve irreversible effects of any kind.
- Traditional photovoltaic systems, due to the thermal shock, lose efficiency during the summer seasons unlike floating photovoltaic systems which, thanks to the presence of water, are able to produce 10% more energy during the calendar year. [16]
- Floating photovoltaic systems installed in hydroelectric basins involve the non-use of land except for the installation of electrical panels, and this is very important in agricultural areas. [17].
- The total or partial coverage of basins involves the reduction of surface water evaporation, this depends on the percentage of surface covered and the climatic conditions of the area where the basin is located.
- The terrestrial albedo varies from 40% for the roofs of buildings, to 50% in desert soils and 20-30% for areas used for pastoral activities; the allocation of terrestrial photovoltaic systems further modifies the albedo of the land [18]. The floating modules do not produce this effect as the albedo of the water is quite similar the one on panels which is approximately 5% thus not altering the energy balance [19].

Considering the previously analyzed advantages that can be drawn from the coupling between the two electricity production systems, it is evident that in many areas, from the economic to the environmental through energy optimization, better results can be obtained, compared to traditional energy production systems.

2.3 Energy potential analysis

The addition of large photovoltaic plants in hydroelectric basins to offset the production of hydroelectric plants could reduce the intermittent production of photovoltaic energy sources and improve the net power flow. In a case study in Sao Francisco River, Brazil, simulations were carried out considering the installation of a floating photovoltaic system in a river that already has a hydroelectric power plant. After having hypothesized to connect both sources of energy to the electrical system through the same cabin and having carried out various simulations, the results obtained by the latter suggested a significant increase in energy production due to the coupling of the two systems, which varies from 51.2% to 105.6%. To incorporate the energy results into already existing electricity system optimization algorithms, the possibility was presented to create a method that considers the energy produced by FPVs as an inflow to be added to the natural flow of the river and its energy production, to obtain the total inflow that coincides with the flow of the hybrid power plant. It emerged that the ability of the FPV to integrate the hydroelectric plant is much higher in dry periods in which the equivalent inflow is greater than the natural flow of the river. This approach hypothesized in Brazil represents a valuable opportunity to exploit more water for the hydroelectric plant in cold seasons and to reduce the dependence on thermoelectric power plants to meet energy demands. [20]

The largest hydroelectric power plants of each European state were analyzed, present on the database [21], and various hypotheses were proposed, with two different technologies, of installable power.

Assuming to use a photovoltaic panel, with multicrystalline cells, [22] of (1.98*1.00) m with a cell efficiency of 17.3% and knowing that this, after accurate calculations, has a production capacity up to 342.54 W which, considering the support of the panel (about 10% total), we will assume equal to 308.29 W.

P_{max} = (Cell efficiency / 100) x (E / A_c) = (17,3 / 100) x (1000 W / m^2 / 1,98 m^2) = 342,54 W - 10% = 308,29 W; where E is the incident radiant flux and A_c the collector area.

Assuming to use a photovoltaic panel, with monocrystalline cells, [23] of (2.27*1.13) m with a cell efficiency of 21.4% and knowing that it has a production capacity up to 548.93 W which, considering the support and the frame of the panel (12.5% of the total surface), we will assume equal to 480.31 W.

P_{max} = (Cell efficiency / 100) x (E / A_c) = (21.4 / 100) x (1000 W / m^2 / 2.56 m^2) = 548.93 W - 12.5% = 480.31 W; where E is the incident radiant flux and A_c the collector area. It is therefore possible to calculate the power that can be installed in the largest hydroelectric plants in Europe with three different coverage hypotheses (5%, 30% and 50%).

This study is clearly showed as reported below in Table I and in Table II.

The installable power per surface unit has been calculated. $P_{inst,surf.unit}$ = Installable power [W] / occupied surface [m^2].

For the silicon panel with multicrystalline cells it will be 155.7 W / m^2, for the panel with monocrystalline cells it will be 187.6 W / m^2.

III. Overview of FPV-HPP

The unpredictability of rain patterns and the increase of drought over the years have led to the installation of a large number of traditional power plants which, as is well known, significantly increase coal emissions.

These problems can be avoided by integrating photovoltaic systems with hydroelectric power plants. The hybridization gives the possibility of integrating the FPV system into the basin of a hydroelectric power plant.

Thanks to the advantages deriving from the integration of these two systems, various benefits can be obtained, such as:

1. an increase in the energy collected due to the FPV, thanks to natural cooling.
2. FPV systems compared to GPVs installed in the vicinity of a hydroelectric power plant, are certainly more advantageous in terms of construction as they do not interfere with any surfaces of soil intended for agricultural use or for breeding. The ground could have an uneven surface and the installation would be more complex while the uninstallation irreversible.
3. allows the use of the existing transmission infrastructure, such as transformers and connection to the electricity grid, obtaining cost savings related to the additional infrastructure.
4. it is possible to avoid power variations in FPV due to the intermittent solar radiation profile.
5. FPV output can compensate power reduction from hydropower plants especially during droughts.
6. power output from FPV prevents the consumption of water from hydropower plants which can be otherwise used during peak load conditions.

Hybridization for example in [12] increases the overall coupling factor of the system. They declare that covering only 2.4% the increase in energy production is 35.9% raising the CF value from 3343 to 4450 hours. This analysis can be extended to other situations and to smaller HPP basins where the CF factor is lower, i.e., around 2000 hours. In this case, the benefits of the hybrid FPV-HPP couplings are more important, and the increase in energy can reach 50%.

By exploiting the potential of the FPV-HPP hybrid system, from the study proposed in [24] it is possible to obtain a global installable power ranging from 3.0 TW to 7.6 TW depending on the proposed scenario. This is equivalent to an energy production of 4,251 TWh to 10,616 TWh per year.

Thanks to the synergy between FPV-HPP systems, from an energy point of view, in a Brazilian scenario, the energy gain by the hybrid system is 76%, while the capacity factor increases by an average of 17.3% [20].

Thanks to the complementarity of the energy sources, that is water and solar radiation, there is the possibility of reducing the unavailability and intermittence of HPP plants [25].

TABLE I. COVERAGE HYPOTHESIS

			Hypothesized percentage coverage		
State	**Boosted HPP**	**Surface (km²)**	**5% (km²)**	**30% (km²)**	**50% (km²)**
Albania	Fierzë Hydroelectric Power Station	72,5	3,62	21,75	36,25
Armenia	Vorotan Cascade	10,80	0,54	3,24	5,40
Austria	Kölbrein Dam	2,55	0,13	0,76	1,27
Azerbaijan	Mingechevir Hydro Power Plant	605,00	30,25	181,50	302,50
Belarus	Osipovichi Hydroelectric Station	12,00	0,60	3,60	6,00
Bosnia-Herzegovina	Rama Hydroelectric Power Station	14,74	0,74	4,42	7,37
Bulgaria	Ivaylovgrad Dam	15,20	0,76	3,36	7,60
Czech Republic	Slapy Reservoir	11,63	0,58	3,49	5,81
Denmark	Tangeværket Dam	3,25	0,31	1,87	3,12
France	Petit-Saut Dam	365,00	18,25	109,50	182,50
Germany	Eibenstock Dam	3,70	0,18	1,11	1,85
Greece	Kremasta Dam	81,00	4,05	24,30	40,50
Hungary	Tisza Dam	119,00	5,95	35,70	59,50
Iceland	Búðarháls Power Plant	7,00	0,35	2,10	3,50
Ireland	Poulaphouca Reservoir	22,26	1,11	6,68	11,13
Luxemborg	Esch-sur-Sûre Dam	3,50	0,17	1,05	1,75
Montenegro	Mratinje Dam	12,00	0,60	3,60	6,00
North Macedonia	Kozjak Hydro Power Plant	13,50	0,67	4,05	6,75
Norway	Ulla-Førre	84,48	4,22	25,34	42,24
Poland	Solina Dam	22,00	1,10	6,60	11,00
Portugal	Cabril Dam	20,23	1,01	6,07	10,11
Romania	Bicaz-Stejaru Hydroelectric Power Station	310,00	15,50	93,00	155,00
Russia	Zhiguli Hydroelectric Station	6450,00	322,50	1935,00	3225,00
Serbia	Iron Gate I Hydroelectric Power Station	104,40	5,22	31,32	52,20
Spain	Mequinenza Dam	75,40	3,77	22,62	37,70
Switzerland	Gran Dixence Dam	4,00	0,20	1,20	2,00
Turkey	Atatürk Dam	817,00	40,85	245,10	408,50
Ukraine	Kremenchuk Hydroelectric Power Plant	2250,00	112,50	675,00	1125,00

TABLE II. EVALUATION: TWO DIFFERENT TECHNOLOGIES

		5%		30%		50%	
		Installable power related to efficiency (GW)					
State	**Boosted HPP**	**17,3%**	**21,4%**	**17,3%**	**21,4%**	**17,3%**	**21,4%**
Albania	Fierzë Hydroelectric Power Station	0,09	0,11	0,54	0,66	0,90	1,10
Armenia	Vorotan Cascade	0,11	0,14	0,66	0,84	1,10	1,40
Austria	Kölbrein Dam	0,12	0,14	0,72	0,84	1,20	1,40
Azerbaijan	Mingechevir Hydro Power Plant	4,71	5,68	28,26	34,08	47,10	56,80
Belarus	Osipovichi Hydroelectric Station	0,09	0,11	0,54	0,66	0,90	1,10
Bosnia-Herzegovina	Rama Hydroelectric Power Station	0,11	0,14	0,66	0,84	1,10	1,40
Bulgaria	Ivaylovgrad Dam	0,12	0,14	0,72	0,84	1,20	1,40
Czech Republic	Slapy Reservoir	0,09	0,11	0,54	0,66	0,90	1,10
Denmark	Tangeværket Dam	0,05	0,06	0,30	0,36	0,50	0,60
France	Petit-Saut Dam	2,84	3,42	17,04	20,52	28,40	34,20
Germany	Eibenstock Dam	0,03	0,04	0,18	0,24	0,30	0,40
Greece	Kremasta Dam	0,63	0,80	3,78	4,80	6,30	8,00
Hungary	Tisza Dam	0,93	1,12	5,58	6,72	9,30	11,20
Iceland	Búðarháls Power Plant	0,05	0,07	0,30	0,42	0,50	0,70
Ireland	Poulaphouca Reservoir	0,17	0,21	1,04	1,26	1,70	2,10
Luxemborg	Esch-sur-Sûre Dam	0,03	0,03	0,18	0,18	0,30	0,30
Montenegro	Mratinje Dam	0,09	0,11	0,54	0,66	0,90	1,10
North Macedonia	Kozjak Hydro Power Plant	0,11	0,13	0,66	0,78	1,10	1,30
Norway	Ulla-Førre	0,66	0,79	3,96	4,74	6,60	7,90
Poland	Solina Dam	0,17	0,21	1,02	1,26	1,70	2,10
Portugal	Cabril Dam	0,16	0,19	0,96	1,14	1,60	1,90
Romania	Bicaz-Stejaru Hydroelectric Power Station	2,41	2,91	14,46	17,46	24,10	29,10
Russia	Zhiguli Hydroelectric Station	50,21	60,51	301,28	363,06	502,10	605,10
Serbia	Iron Gate I Hydroelectric Power Station	0,81	0,98	4,86	5,88	8,10	9,80
Spain	Mequinenza Dam	0,59	0,71	3,54	4,26	5,90	7,10
Switzerland	Gran Dixence Dam	0,03	0,04	0,18	0,24	0,30	0,40
Turkey	Atatürk Dam	6,36	7,66	38,16	45,96	63,60	76,60
Ukraine	Kremenchuk Hydroelectric Power Plant	17,52	21,10	105,12	126,60	175,20	211,00
Total		**89,46**	**107,87**	**535,95**	**646,17**	**893,07**	**1076,81**

A study conducted in [26] states that, using a coverage rate of the basin of a hydroelectric power plant of 25%, the FPV system is able to provide 6270 TWh compared to 2510 TWh of hydroelectric power. Moreover, there is an availability of water in more than 6.3% thanks to the lack of evaporation of the basin due to the partial coverage. Assuming an HPP efficiency of 90%, pumping this 6.3% of water can potentially increase the energy collected by 142.5 TWh.

In [27] a study on the evaluation of energy potential on 22 HPPs was carried out. The HPPs surveyed have significant water storage reservoirs and approximately the 28% of total hydropower capacity installed in Brazil i.e. 31.5 MW of 114 MW. A project to add 34 GW of floating PV systems on their reservoirs represents an additional CF of 20% MW to this installed hydro capacity per year, equivalent to almost 10% of the Brazilian electricity demand in 2018.

The Figure 1 shows an FPV-HPP hybrid system configuration.

IV. Environmental impact

The effect on the environment of the coupling between HPP and FPV is mainly due to the shading exerted by the panels, the sunlight reaching the water is therefore reduced by shading and prevents the growth of algae. [28] Algae in the basins play an important role as they use sunlight to activate the photosynthesis process to produce carbohydrates and are also the food for protozoa and zooplankton. [29] Obviously, failing these factors, there are deficits both for fishing and for habitat and therefore for wildlife and water birds. [30] Shading can also reduce the bloom of blue-green algae that produces the surface foam, have cyanobacteria (a cause for concern as they can produce serious toxins) and produce bad odors due to decomposition. [31]

4.1 Challenges and future scenarios

In the coming years there will be many challenges to be overcome to increase the production of electricity from hybrid plants: you will have to try to minimize the environmental impact due to the shading of the panels [32], it will be very important to design an adequate anchorage to reduce the impact of the wind on the FPVs, avoiding that due to the latter and the waves, micro-cracks are created that could lead to a loss of power in the modules. [33]

In addition, future scenarios could be related to the use of energy produced by hybrid plants as a key resource in the national and European framework and for this the production capacity of existing hydroelectric plants must be maximized before the installation of floating photovoltaic systems.

V. Conclusions

The coupling, between pre-existing hydroelectric plants and floating photovoltaic systems, gives rise to a significant increase in production of electricity from renewable sources with a lower economic and environmental impact than the construction of a new terrestrial photovoltaic system.

The strategy hypothesized in this article will make it possible to reduce the quantities of swirling water needed and depleted by the reservoir while still ensuring the injection of energy into the network even during peak daytime hours.

Recent climate changes, which have led to periods of drought, have reduced production from hydroelectric plants with a consequent return to the need to use electricity produced by thermal power plants based on conversion from fossil sources.

The allocation of floating systems on the HPP water surface will allow to reduce the quantities of water evaporated throughout the year, this is a factor as important as the power production of the site itself.

The power that can be installed in Europe is approximately 90 GW considering the hypothesis of less heavy coverage, aimed at minimizing environmental impacts, and the panels with lower efficiency; assuming the same percentage of coverage and the panels with greater efficiency, there will be an installable power of approximately 108 GW. Therefore, by evaluating the most efficient scenario with panels made with the latest technologies, the installable potential will have an increase in producibility of 20%; these hypotheses have been proposed for each state after having identified the hydroelectric plants of the most huge size.

The various hypotheses of coverage were conducted for an improvement of the harmonization of the floating system with respect to the flora and fauna of the sites considered.

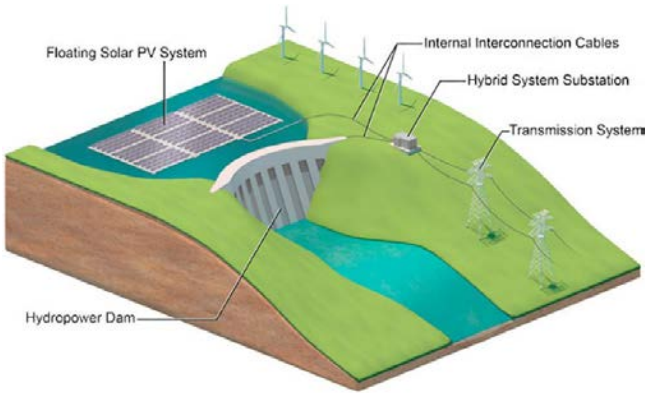

Figure 1. Schematic of a hybrid FPV-hydropower system

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