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Review Article

Integration of PV floating with hydroelectric power plants

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ABSTRACT

The integration of floating a PV plant (FPV) with a Hydroelectric Power plant (HPP) is studied and it is shown that several advantages come from this hybridization. The FPV power potential is analysed for the first 20 largest HPPs in the world and it is shown that when covering 10% of the HPP basin surfaces the HPP energy production is increased by 65%. The experience of China Longyangxa basin and of its connected PV power plant is examined together with the suggestion to install a FPV whose rated power is equal to HPP rated power. This hypothesis is applied to an analysis of the geographic potential worldwide and it is shown that covering 2.4% of the existing HPP basin surfaces the energy produced by HPP will be increased by 35.9%. The advantages of the coupling of the two power production technologies are discussed.

1. Introduction

Renewable Energy Sources (RES) are rapidly evolving and their cumulated installed power in the last few years has been continuously increasing as shown in Fig. 1, based on data reported in [1], where total installed power is given together for the three main RES technologies: hydroelectric, wind and photovoltaic. Biomass technology (waste, wood, etc.) covers only 5% of the installed power in 2017 and so is not reported in Fig. 1. One of the most noticeable pieces of information that comes from a first view of the graph is the significant rapid increase of the PV plants installed, which in less than 10 years have reached a cumulated power about 75% of the wind capacity. .

Due to the different nature (e.g. variability, availability, programmability) of the renewable sources reported in Fig. 1, the installed power is not sufficient to evaluate the real impact of the different RES on worldwide electric energy production. In fact, the hydroelectric power plants (HPP) have a more important role with respect to wind and PV technologies; at the end of 2017, HPP accounted for 16.4 % of the worldwide electric energy production with increasing investments especially in China and the equatorial regions (see Fig. 2). PV and Wind energy production reached 1564 TWh in 2017, which is just 37.6% of the energy produced by hydro which is 4185 TWh.

So, the contribution of HPP to worldwide electricity production is overwhelming. This is due to the different energy output over a period of time of Hydro power plants compared with PV or Wind power plants. To characterize the difference between hydro and PV or Wind plants we can adopt the Full Load Hours (FLH), the electric energy output of the power plant over one year divided by its rated power (in hours), or the Capacity Factor which is the FLH normalized to the yearly hours, 8760, in %.

In Table 1 there is a comparison of FLH and CF for the main renewable technologies considering the global worldwide data ([2] [3],).

Currently the average value of FLH for HPP is 3652 h and this value should be compared with solar PV (1102 h) and wind farms (2051 h); the only higher value is that of biomass whose FLH reaches almost 5000 h.

Therefore, if we look at the renewable energy sector, there has been a strong increase of PV, which covers 17.7% of the renewable energy power; however, its contribution to the production of energy is only 7.1%. Conversely, energy produced by biomass, which covers only 5% of the installed electrical power, reaches 8.3% of the energy production thanks to the larger CF value.

Notwithstanding this limit, PV is still expanding and companies in the electricity energy sector are looking for new areas where to install utility scale PV plants. There is a strong interest in installing the PV plants coupled to HPP thanks to the easy integration of the two technologies. A further improvement in the integration of solar and hydro energy is constituted by the floating PV plants (FPV) [4]. See also [5] for a specific analysis of the "virtual battery" storage potential.

In this paper a detailed analysis is given of the advantages of coupling FPV plants with HPP. The possibilities of doubling the power of a HPP using FPV is analysed and we show that with a coverage of only 2.4% on average of the water basins surface this target can be achieved thus increasing the energy production of the HPP by about 34%.

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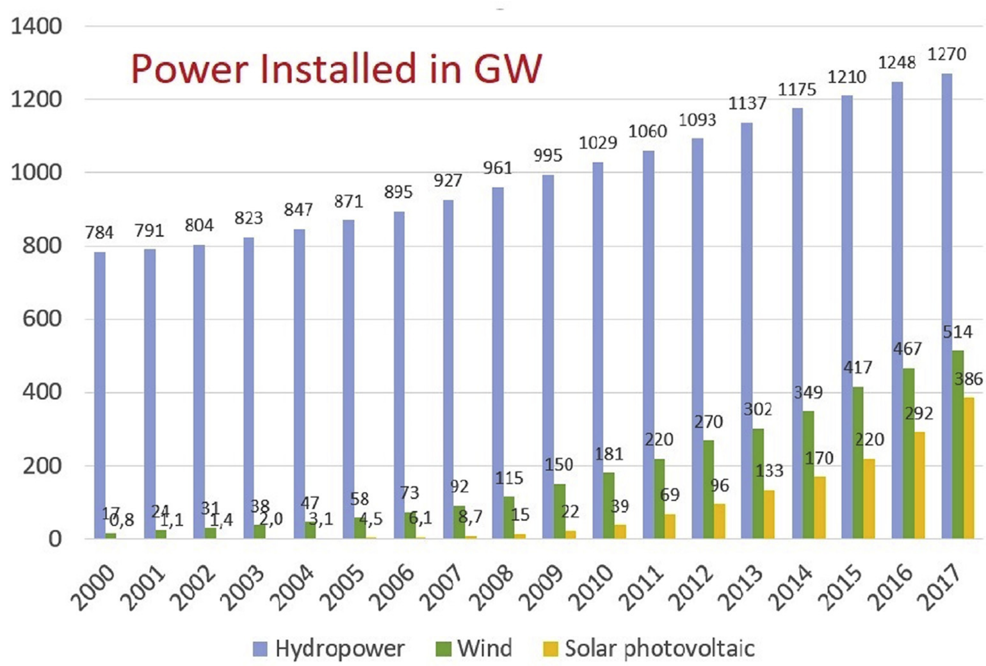

Fig. 1. Worldwide installed power in GW for the main RES [1].

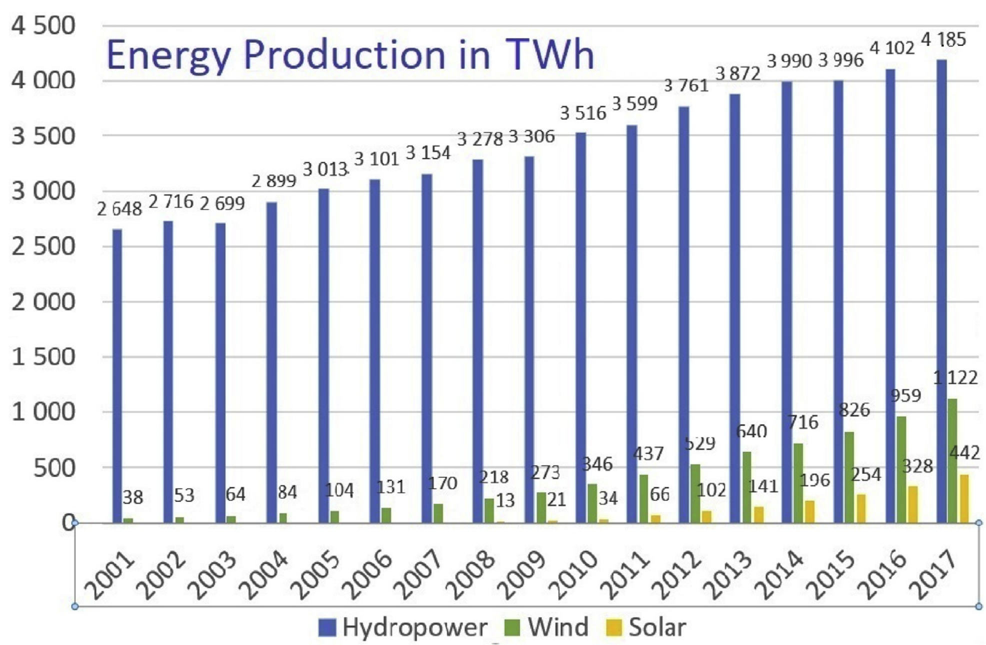

Fig. 2. Worldwide energy production in GWh for the main RES [1].

Table 1
Full Load Hours and Capacity Factor for the main renewable energy sources.

Year	2013		2014		2015		2016		2017	
Technology	FLH (hrs)	CF(%)	FLH (hrs)	CF(%)	FLH (hrs)	CF(%)	FLH (hrs)	CF(%)	FLH (hrs)	CF(%)
Biomass	4987	56,9%	4988	56,9%	4943	56,4%	4454	50,8%	5046	57,6%
HPP	3671	41,9%	3652	41,7%	3549	40,5%	3347	38,2%	3539	40,4%
Wind	2122	24,2%	2051	23,4%	1981	22,6%	2051	23,4%	2118	24,2%
PV	1008	11,5%	1102	12,6%	1109	12,7%	1086	12,4%	1164	13,3%

2. Main Text

2.1. Advantages of coupling FPV and HPP

Several factors suggest the advantages of coupling PV plants with hydroelectric power stations, as analysed by several authors [6, 7, 8]. In short, we can summarize the benefits gained by a hybrid PV-Hydro coupling as follows.

1. **Grid connection.** Artificial and non-artificial hydroelectric basins are equipped with power generators and are grid connected, so it is possible to exploit the existing infrastructure reducing the cost of a floating PV plant.
2. **Reduction of power fluctuation.** In temperate regions, Italy for example, PV panels give the maximum energy yield during the hot season when the HPP registers a reduction of power due to the seasonal water cycle. This partial anticorrelation allows an important reduction in the yearly fluctuations of electrical energy production. Furthermore, an active control system could be used where the HPP is decreased during the day when the PV plant is operational and increased during the night, cloudy conditions or at times of peak demand to ensure power is produced to match demand without the need for battery or other storage equipment often associated with PV plants.
3. **No land occupancy.** The main advantage of floating or submerged PV plants is that they do not take up any land, except the small area necessary for electrical cabinets. Floating PV plants are not merely more economical than land-based plants, but they provide a crucial way to avoid competing with agricultural or green zones [9]. Also, unlike land-based PV plants, floating or submerged plants have a limited impact on the landscape as the surface occupancy is reduced.
4. **Installation and decommissioning.** Floating PV plants are more compact than land-based plants, their management is simpler and their construction and decommissioning straightforward. The main point is that no fixed structures exist, and the mooring of floating systems can be installed and removed in a totally reversible way, unlike the foundations used for a land-based plant which are far more intrusive and permanent.
5. **Water saving and water quality.** The partial coverage of HPP water basins has additional benefits such as the reduction of water evaporation. This result depends on climate conditions and on the percentage of the covered surface. A parallel advantage is the containment of the problem of algae bloom, which is especially serious in industrialized countries [10]. The partial coverage of the basins and the corresponding reduction of light on biological fouling just below the surface can solve the problem of algae blooms.
6. **Cooling and Tracking.** The floating structure allows the implementation of a simple and cheap cooling and tracking mechanism. As is well known, one of the limits of PV plants is that they lose efficiency during the hot season because of the thermal drift effect. In the case of a floating or submerged PV plant, this effect can be substantially reduced by the presence of water cooling, thus gaining 10% or more in yearly energy harvesting [11]. Moreover, a floating PV plant equipped with a tracking system has a limited additional cost, whilst the gain in energy can range from 15 to 25%. In several cases the technical effort necessary to implement this solution gives a sizeable reduction of the final kWh cost.
7. **Radiation balance.** Land-based PV plants strongly modify the land albedo. Land albedo ranges from 20% for grassland to 20–30% for roofs to 40%–50% for desert land [12]. Instead, PV modules are built in a way to reduce as much as possible the radiation reflection and so they absorb about 95% of solar radiation. This imbalance can give rise to local temperature modifications and microclimate changes and modifies the mean radiation balance. This effect is not present for the floating plants since the water albedo is on average about 5%, approximately equal to the PV modules albedo, thus leaving the energy balance unchanged [13].

2.2. Hybrid FPV-HPP and geographic potential

Hydroelectric power is mainly based on the construction of dams and on the creation of large basins. Run-of-the-river systems (ROR) cover only a small part of hydroelectric production and are important mainly in the mini and micro-installations. In general most hydroelectric power comes from the potential energy of artificial water reservoirs created by a dam, which in several cases are equipped with a pumping system which enables pumped storage for use during high peak demands [14].

2.2.1. Power and energy density

We want to compare the power and energy density for HPP and FPV. To do this we define the quantities ρP,H and ρE,H (power density and energy density for hydro power plant) and correspondingly the same densities for FPV, specifically ρP, FPV and ρE,FPV.

- $\rho_{P,H} = P_H/S_B$, where P_H in GW is the peak power of the hydroelectric plant and S_B in km^2 is the basin surface. The unit measure is GW/km^2 or kW/m^2.
- $\rho_{E,H} = E_H/S_B$ where E_H is the yearly energy production in GWh. The unit measure is GWh/km^2/y or kWh/m^2/y

The ratio of the two densities allows us to calculate the factor $FLH_H = E_H/P_H$ (hours) which for HPP has values ranging from 2000 to 5000 depending on the basin characteristics.

The corresponding quantities for FPV are $\rho_{P,FPV}$ and $\rho_{E,FPV}$ which depend on the geometrical structure of the FPV plant and on the local radiation. The FLH_{PV} ranges typically from 800 to 1800 h depending mainly on the latitude and on the mean weather conditions.

The quantity $\rho_{E,FPV}$ depends also on the geometry of the plant (panels pitch and tilt) and has been discussed in reference [15] with the result that, for an optimal floating structure, the solar energy produced by modules in horizontal position should be increased for modules with optimal tilt and pitch. In the following, data is taken from PVGIS or the NASA data base, and evaluated with the program PVsyst.

For the purpose of this analysis, we define a typical FPV plant as having 16 PV modules are installed on a raft of 12 m × 4 m and we assume that the power of each module is 0.36 kWp. This corresponds to a typical value for the standard PV modules of 2 m^2 which in today's market have powers ranging from 300 to 440 kWp. So the power available on a 1 km^2 floating plant would be: $\rho_{P,FPV} = 10^6/(4.3 \times 12.3) \times 24 \times 0.44 = 199.6$ MWp/km^2 (200 W$_p$/m^2)

This value can change due to an increase of the power density of the PV modules (recently modules of 2 m^2 have been proposed with a power of 0.44 kW) and to a change in the raft geometry (see ref. [16], where a “gable” solution, suitable for equatorial regions, allows us to put 24 PV modules on a double raft of surface 4.3 × 12.3 m, catwalk included). In this case, using a high efficiency PV module of 0.44 kW the peak power density for a km^2 rises to $\rho_{P,FPV} = 10^6/(4.3 \times 12.3) \times 24 \times 0.44 = 199.6$ MWp/km^2 (200 Wp/m^2).

Table 2
Typical values of power and energy density for the first 20 HPP and the corresponding possible FPV plants (Elaboration of data from [17]).

		Units	Average value
HPP	$\rho_{P,H}$	MWp/km^2 or Wp/m^2	14,40
	$\rho_{E,H}$	GWh/y/km^2 or kWh/y/m^2	65,70
	FLH_H	hours	4545
FPV	$\rho_{P,FPV}$	MWp/km^2 or Wp/m^2	120
	$\rho_{E,FPV}$	GWh/y/km^2 or kWh/y/m^2	135,4
	FLH_{PV}	hours	1128

This possibility is very attractive since the compactness of the power PV plant is a positive factor, however in the following we will use the more conservative value of $\rho_{P,FPV}$ equal to 120 Wp/m^2.

In Table 2 typical values are collected for HPP and FPV plants.

We want to stress that the higher power density of FPV plants is reduced by the low CF value. However the FPV energy density remains higher than the HPP value by a factor 2 and the power density by a factor 9. This is because of the relatively large basin size required by the HPP; this area is also relatively unused and presents an ideal location for a FPV plant as discussed below.

2.2.2. *Data for the first 20 largest HPPs*

Data for the first 20 largest HPP in the world are shown in Table 3.

After the basic information about power and energy production we give the CF value, the flooded area and the energy production for km^2, defined above as $\rho_{E,H}$.

The last two columns give the energy yearly production per km^2 (which depends on the irradiation data) and the produced energy under the hypothesis that 10% of the basin is covered by a floating plant.

As evident, even limiting the coverage to 10%, the increase in energy production is sizeable and in some cases is more than the production of the HPP itself.

In Table 3 we can see also that large HPP generate power for more than 50% of the time which are on average 4,866 hours (55% of the hours in the year) if we exclude the flow river contribution. We remark that the value found for FLH is larger than the FLH quoted in Table 1. This is due to the storage capacity of the very large basins and to the fact that small basins have a lower FLH factor ranging from 2000 to 3000 h.

Another interesting parameter for our purpose is the power generated per m^2. Its value is on average 4.2 W/m^2 with large fluctuations; in fact, the power density ranges from 1 to 70 W/m^2 but in many cases it is below 5 W/m^2.

This value should be compared with the one obtained using PV plants and floating PVs. The installed power for a fixed land-based plant is about 70 W/m^2 whereas for a floating plant depending on the technical solution (fixed plants, plants with tracking, gable solution, etc.) this value rises in the range of 100–200 W/m^2. In conclusion we gain on average a factor of 30 in the power density per m^2.

The energy harvesting however is reduced and, averaging on the 20 PV plants, we get an FLH_{PV} value of 1128 MWh/MWp which is about 4 times lower than the FLH for HPP.

Using these values, we can see that the energy production, using a coverage of 10% of the basin, is 433.5 TWh, about 65% of that due to the hydroelectric power. This value is larger in the equatorial zone where solar energy yield is larger, and smaller at high latitudes but eitherways we can conclude that with a coverage of 10% the energy harvesting is substantially increased.

This result is very important and for this reason the possibility of coupling floating PV plants to HPP plants is quite natural and has been analyzed from the very beginning of the research in this sector [18].

2.2.3. *Optimization*

Since the factor $\rho_{E,FPV}$ is much larger than $\rho_{E,H}$ it is quite evident that the coverage with FPV of part of the hydroelectric basins can strongly improve the energy production. Advantages are remarkable:

- Grid connection already exists and this of course reduces the costs
- Integration with a pumping system or simply a balance with the water turbines of the HPP is simple and allows us to exploit the solar energy without the problem of discontinuity since turbines of the HPP can supply the energy necessary to face the intermittent behavior of the PV plant.
- FPV uses the otherwise under utilized water basin of the HPP
- Installation is quick and can be done at a cost which is lower than 1000 $ per kWp

About this last point we have registered in the last few years a remarkable reduction in the cost of land based PV plants which is now around 700 $/kWp; in parallel several efforts have been made to reduce the cost of floating structures and up to now the suggested minimum cost is 800 $/kWp: see [19].

From reference [20] we can learn how profitable the coupling of HPP and FPV is. The authors present an analysis of the Longyangxia hydro–PV power plant. This plant consists of a large HPP (power 1280 MW) and by a large land-based PV plant (850 MWp). See Fig. 3. Main parameters of the plant are given in Table 4.

If we summarize data using our parameters we can say that $\rho_{E,H}$ = 19.8 GWh/km^2/y and that the PV plant occupies a surface which is 6.7% of the basin surface. Of course, for an equivalent FPV plant the surface would be much less and should not exceed 8 km^2, that is 2.7% of the flooded area.

The managing of this hybrid power station is very interesting. The power produced by the PV plant is fully used and the power of HPP is tuned gently to match the grid requirement. This can be easily done since

Table 3
The first 20 largest HPP in the world [17].

Name	P_H	E_H	FLH_H	S_B	Hydro $\rho_{E,H}$	FPV $\rho_{E,FPV}$	E_{FPV} (S_{FPV} = 0,1S_B)
	MW	TWh	h	km^2	GWh/y/km^2	GWh/y/km^2	TWh
Three Gorges Dam	22500	98,8	4391	1084	91,1	112,7	12,2
Itaipu Dam	14000	103,1	7364	1350	76,4	153,8	20,8
Guri	10235	53,4	5218	4250	12,6	185,6	78,9
Tucuruí	8370	41,4	4950	3014	13,7	180,6	54,4
Belo Monte	7333	39,5	5387	441	89,6	139,5	6,2
Grand Coulee	6809	20,0	2937	324	61,7	84,8	2,7
Xiangjiaba	6448	30,7	4761	95,6	321,1	97,4	0,9
Sayano–Shushensk	6400	26,8	4188	621	43,2	92,4	5,7
Krasnoyarsk	6000	15,0	2500	2000	7,5	154,8	31,0
Nuozhadu	5850	23,9	4085	320	74,7	105,7	3,4
Robert-Bourassa	5616	26,5	4719	2385	11,1	109,6	26,1
Churchill Falls	5428	35,0	6448	6988	5,0	100,6	70,3
Tarbela Dam	4888	13,0	2660	250	52,0	145,2	3,6
Bratsk	4515	22,6	5006	5470	4,1	92,5	50,6
Xiaowan Dam	4200	19,0	4524	190	100,0	121,2	2,3
Ust Ilimskaya	3840	21,7	5651	1922	11,3	165,6	31,8
Jirau	3750	19,1	5093	258	74,0	176,6	4,6
Jinping-I	3600	17,0	4722	82,5	206,1	159,6	1,3
Santo Antonio	3580	21,2	5922	490	43,3	181,5	8,9
Ilha Solteira Dam	3444	17,9	5197	1195	15,0	148,8	17,8
Total/Aver	**136806**	**665,6**	**4866**	**32730**	**65,7**	**135,4**	**433,5**

Fig. 3. Google earth map of the Longyangxa basin with the PV power plant.

Table 4
Relevant parameters for the Longyangxia hydro–PV power plant [20].

Hydropower reservoir Normal pool level	2600 m
Minimum outflow of a hydro unit	50 m^3/s
Maximum outflow of a hydro unit	292 m^3/s
Average hydraulic head	100 m
Installed power capacity	1280 MW
Average annual energy production	5940 GWh
FLH_H	4640 h
Basin surface	300 km^2
PV array installed capacity (land based)	850 MW
Average annual energy production	1494 GWh
FLH_{PV}	1756 h
Occupied area	20.4 km^2

the power peak and the energy production are considerably less than that of the HPP. Following reference [20], we remark that the hydroelectric power of the HPP can be tuned in a coarse way and can follow the variation of the PV plant. In this way the total output can match the grid requirements and the use of water resources is proportionally reduced.

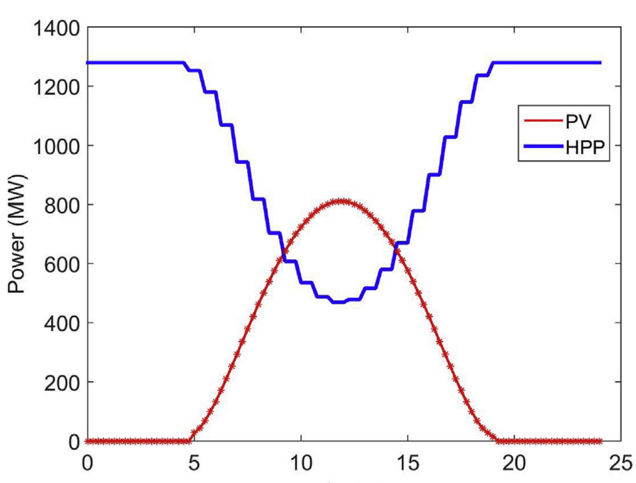

Fig. 4. HPP and PV power in MW during a sunny summer day for Longyangxia plant.

In the specific case of the Longyangxia plant we illustrate in Fig. 4 the behaviour of the two components of energy production during a sunny summer day where the PV production reaches its maximum. In this case the PV produces 6680 MWh to be compared to the HPP production of 24350 MWh. So PV supplies 21.5% of the total energy production of 31.030 MWh.

This result should be averaged along the year, considering also winter and cloudy day, but the global result is that the energy production of the HPP is increased and that PV plant generates 1494 GWh/y to be compared with 5940 GWh coming from the HPP, that is 20% more energy without any changes in the grid connections or to the basic infrastructure.

The question now is: what is the optimum choice for the coupling of a PV plant (possibly an FPV) with a large HPP?

In order to minimize costs and exploit as far as possible the advantages of this hybrid system we suggest installing a FPV able to supply, at its best, the power of the HPP itself. In the typical situation for a Mediterranean latitude (Catania for example), the daily average energy yield can be calculated for different months assuming that for 1 MW HPP an equivalent FPV of 1 MWp has been installed: averaging on the different months we find that the contribution to the energy production of the FPV for the month of July, April and January is of 33%, 26% and 17% respectively. These three months have been chosen as a typical example and a calculation throughout the whole year gives an average yearly contribution of 27%.

However this result underestimates the FPV contribution. In fact the large basins quoted in Table 3 have an average FLH value of 4,896 h whereas the FLH factor is much lower for Sicily HPP (approximately 2,500 h) so that the FPV contribution is actually much more important.

In conclusion, we list in Table 5 what would happen if the 20 largest HPP basins in the world were equipped with FPV plants of the same power. The first column gives the energy production of the HPP plant, the second gives the surface of an FPV plant with the same peak power, and the third column the energy produced by the FPV plant. The last three columns show the relative weight of FPV results over HPP and the final LFH value resulting from this hybrid system.

It is impressive to see that the surface occupied by the FPV plant (of equal power to HPP) is only a small fraction (3.5%) of the hydroelectric basin surface. The energy produced ranges between 15% and 52% of the energy produced by HPP, with an average contribution of 23%.

Table 5
Comparison between larger HPP and FPV plants of equivalent power.

Name	E_H TWh	S_{FPV} km^2	E_{FPV} TWh	S_{FPV}/S_B %	E_{FPV}/E_H %	$FLH_{FPV,H}$ h
Three Gorges Dam	98,8	188	21,1	17,3%	21%	5330
Itaipu Dam	103,1	117	17,9	8,6%	17%	8646
Guri	53,4	85	15,8	2,0%	30%	6765
Tucuruí	41,4	70	12,6	2,3%	30%	6455
Belo Monte	39,5	61	8,5	13,9%	22%	6549
Grand Coulee	20,0	57	4,8	17,5%	24%	3644
Xiangjiaba	30,7	54	5,2	56,2%	17%	5573
Sayano–Shushenskaya	26,8	53	4,9	8,6%	18%	4958
Krasnoyarsk	15,0	50	7,7	2,5%	52%	3790
Nuozhadu	23,9	49	5,2	15,2%	22%	4966
Robert-Bourassa	26,5	47	5,1	2,0%	19%	5632
Churchill Falls	35,0	45	4,5	0,6%	13%	7286
Tarbela Dam	13,0	41	5,9	16,3%	45%	3870
Bratsk	22,6	38	3,5	0,7%	15%	5777
Xiaowan Dam	19,0	35	4,2	18,4%	22%	5534
Ust Ilimskaya	21,7	32	5,3	1,7%	24%	7031
Jirau	19,1	31	5,5	12,1%	29%	6565
Jinping-I	17,0	30	4,8	36,4%	28%	6052
Santo Antonio	21,2	30	5,4	6,1%	26%	7435
Ilha Solteira Dam	17,9	29	4,3	2,4%	24%	6437
Total/average	**665,6**	**1140**	**152,5**	**3,5%**	**23%**	5994

We further remark that for small HPP plants with low FPH factor (in the range of 2000–3000 h) the average contribution of the FPV plants should rise to about 45%.

2.3. A worldwide analysis

A similar but more detailed analysis can be done for the USA. We use the data published by [21] about 100 HPP in USA.

In this case the main results are synthesized in Table 6.

As evident the high value of $\rho_{E,FPV}$ ($\rho_{E,FPV}/\rho_{E,H} = 191/5.02 = 38$) implies that covering on average 1/38 = 2.5% of the hydroelectric basins we can double the produced energy.

However, we simply want to install FPV of power equal to that of the HPP. In this case the surface of the basin occupied by FPV would be 1.19% of the whole basin surface (32574/120 = 271 km^2 i.e. 1.19 % of 22736 km^2) and the energy produced would be 40.5% of the hydroelectric energy production (191/5.02*1.19% = 40.5%).

A more general analysis can be made using a world wide database for water resources. We refer to [22] for the free fresh water surface and to the AQUASTAT database [23] for information about manmade reservoirs and hydroelectric basin surfaces. See also [[24] for the Digital Water Atlas database. The main results are collected in Table 7.

We start from the analysis done in reference [4] and [25]: the fresh water surfaces are taken from ref. [22] and the data are collected for large geographic areas. Man-made reservoirs and HPP basin surfaces are taken from Aquastat database. A careful analysis has been completed and some small corrections have been made to the Aquastat data, the key conclusions are as follows:

- The Man-made water reservoirs represent 12.6% of the entire fresh water surfaces, and the surface of HPP basins represent 66% of the man-made total. This last percentage depends on orographic configuration and a specific case is Japan where the presence of many HPP basins at high altitude and with small surface areas pushes this ratio below 10%.

Table 6
Data for 100 USA HPP (total values and average data).

Power MW	Basin surface km^2	$\rho_{P,H}$ MW/km^2	$\rho_{E,H}$ GWh/km^2	$\rho_{P,FPV}$ MW/km^2	$\rho_{E,FPV}$ GWh/km^2
32574	22736	1.43	5.02	120	191

Table 7
Worldwide analysis of water reservoirs.

	Fresh Water km^2	ManMade reservoirs km^2	HPP surfaces km^2	ManMade/all %	HPP-Surfaces/ManMade res. %
Africa	540,030	46,499	24,197	8.6%	52%
America Central	58,801	4,161	2,899	7.1%	70%
America South	381,710	65,000	53,863	17.0%	83%
Asia South East	153,490	32,231	22,929	21.0%	71%
Asia South without India	48,320	1,283	1,081	2.7%	84%
Australia + New Zealand	58,920	4,965	1,216	8.4%	24%
Canada	891,163	97,914	95,224	11.0%	97%
China	270,550	12,979	7,454	4.8%	57%
Europe (North)	178,156	30,267	24,724	17.0%	82%
Europe (South)	19,612	3,091	2,066	15.8%	67%
India	314,000	102,775	13,361	32.7%	13%
Japan	13,430	1,394	130	10.4%	9%
Middle East	140,190	26,259	10,775	18.7%	41%
Russia	720,500	85,408	84,761	11.9%	99%
Turkestan	76,110	17,247	14,582	22.7%	85%
USA	685,924	43,904	21,686	6.4%	49%
Total	**4,550,906**	**575,377**	**380,948**	**12.6%**	**66.2%**

- 380,948 km^2 of water basins originated by dams for HPP power plant are available around the world.

Now the question is: how large is the FPV surface necessary to install an equivalent power? And how much is the energy produced?

Table 8 answers these questions under the hypothesis discussed in section 3.

It is remarkable that the surface necessary to install an FPV power equivalent to that of the HPP is only on average 2.38% of the basin surfaces and that in only three cases it is larger than 10%, for example in the case of Japan.

Table 8
Worldwide analysis of hydroelectric basins.

	HPP			FPV			
	S_H	P_H	E_H	S_{FPV}	E_{FPV}	$S_{FP}V/S_B$	E_{FPV}/E_H
	km^2	GW	TWh	km^2	TWh	%	%
Africa	24,197	34.4	114.1	287	41.28	1.2%	36.2%
America Central	2,899	7.7	23.0	64	9.24	2.2%	40.2%
America South	53,863	161	589.8	1342	193.2	2.5%	32.8%
Asia South East	22,929	44.8	143.4	373	53.76	1.6%	37.5%
Asia South without India	1,081	17.6	65.5	147	21.12	13.6%	32.2%
Australia	1,216	14	43.9	117	16.8	9.6%	38.3%
Canada	95,224	81	388.2	675	97.2	0.7%	25.0%
China	7,454	333	1,162.8	2775	399.6	37.2%	34.4%
Europe (North)	24,724	68	196.7	567	81.6	2.3%	41.5%
Europe (South)	2,066	85.9	175.3	716	103.08	34.6%	58.8%
India	13,361	47.6	128.8	397	57.12	3.0%	44.3%
Japan	130	12	91.3	100	14.4	76.9%	15.8%
Middle East	10,775	15.87	19.8	132	19.044	1.2%	96.2%
Russia	84,761	51	186.6	425	61.2	0.5%	32.8%
Turkestan	14,582	12.7	51.7	106	15.24	0.7%	29.5%
USA	21,686	103	261.8	858	123.6	4.0%	47.2%
Total	**380,948**	**1089.57**	**3,642.7**	**9,079.8**	**1307.5**	**2.4%**	**35.9%**

Even more important is the fact that the rise in energy yield is on average 36%. This result is related to the fact that the FLH factor of FPV ranges between 900 and 1200 h with an average value of 1060, whereas the FLH_H is on average 2950 h.

2.3.1. Evaporation reduction

A byproduct of the FPV plant consists in a strong reduction of evaporation from the water surface covered by rafts supporting the PV modules. The floating PV array can have features (e.g. floating structures and geometry of the deployment of the PV modules) that determine a different impact on the water evaporation and on the energy balance of the covered part of the basin [25]. The results of this study show that by covering only 10% of water surface it is possible to reduce evaporation from 6 to 18%. Floating systems, with modules anchored to a tubular buoyancy system, allow a greater ventilation of the modules and therefore a good evaporative cooling [26]. In [16] the evaporation reduction is approximately 80% respect with the uncovered water basin.

As an example, we take the parameters of Longyangxia hydro–PV power plant. Let's imagine that the full PV plant was an FPV plant occupying a surface of approximately 10 km^2 and that we save 2 m^3 of water per m^2 because of the reduction of the evaporation rate [25]. The amount of water saved in one year would be 20 million m^3 which with an average head of 100 m gives rise to a production of 5.4 GWh.

This reduction is very relevant if we are in arid zones or for example for waste water basins where an adequate water coverage can save from 10,000 to 20,000 m^3 per ha. Several calculations have been done using Penman model [19] and experimental findings of several authors (see for example [27] and [28]) support this rough estimate. However, in the case of HPP, saving water is not the main concern so this is mentioned for completeness but not a major factor compared to the potential increase in energy production from FPV.

3. Conclusions

Coupling of FPV and hydroelectric power plant allows a considerable increase in RES energy production.

The cost of FPV is comparable to that of a land-based PV plants and is further reduced because of the presence of infrastructure and the existence of a grid connection for existing HPP. There are major potential advantages combining the natural energy storage system of HPP with the relatively high power but sporadic power production of FPV.

The strategy suggested consists in installing a FPV power plant equal to the existing HPP power plant and to reduce the hydro turbines energy production during the sunny hours maintaining the energy fed into the grid at an approximately constant level, this could also be fine tuned to match peaks in demand.

Using this approach, the worldwide HPP basins surface covered by FPV would only be 2.4 % but the increase in energy production would be 35.9% raising the FLH value from 3,539 to 4,800 h.

This analysis can be extended to other situations and to smaller HPP basins where the FLH factor is lower, i.e. around 2000. In this case the benefits of the hybrid FPV-HPP coupling are even greater and the increase in energy can reach 50%.

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Additional information

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