Integration of Floating Solar Photovoltaic Systems with Hydropower Plants in Greece

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Abstract — **Floating solar photovoltaics in water bodies is a novel clean energy technology which has been developed rapidly during the last decade. The current work investigates the possibility and the potential of installing floating photovoltaic systems in the existing hydropower plants in Greece. Studies related with the use of floating photovoltaics in water reservoirs in Greece are limited so far. The characteristics of the existing 24 hydropower plants in Greece have been used for the estimation of the solar photovoltaic systems which can be installed in their water reservoirs. It has been found that the nominal power of these solar energy systems which can be installed in their water reservoirs, covering 10% of their water surface, is at 3,861 MWp while the annual generated electricity at 5,212.35 GWh corresponding at 10.04 % of the annual electricity demand in the country. The capacity factor of the integrated solar and hydro power systems is increased by more than 20%. The research indicates that the existing hydropower plants in Greece can host, in their water dams, floating photovoltaic systems generating significant amounts of green electricity while they also result in many environmental benefits. These novel solar energy systems can contribute, together with other benign energy technologies, in the achievement of the national and EU target for net zero carbon emissions by 2050.**

Keywords — **Electricity, Floating Solar Photovoltaics, Greece, Hydropower Plants, Water Reservoirs.**

I. Introduction

Use of solar energy for electricity generation is growing rapidly worldwide replacing gradually the conventional fossil fuels. Floating photovoltaics (FPVs) located on water bodies consist of a novel and clean energy technology which grows rapidly having many benefits compared to ground-mounted PV systems. However, studies regarding their application in Greece are lacking. Additionally, there are not currently installed FPV systems in existing hydro-electricity dams. The current work investigates the possibility of installing FPVs in existing hydropower plants in Greece taking into account the multiple benefits of such hybrid energy systems. Existing hydropower plants in various regions in Greece can host FPV systems increasing the total solar photovoltaic capacity in the country and contributing to the achievement of the national and EU target for carbon free societies by 2050. Our research is important since it investigates the potential of FPV systems which could be installed in water reservoirs in Greece as well as the green electricity which can be generated by them. It is aiming to fill the existing gap regarding the deployment of this novel benign energy technology in the country. The work is going to contribute to the existing knowledge concerning the possibility of installing floating solar-PV systems in water reservoirs of hydropower plants in Greece instead of installing them on the ground or the rooftops of buildings. It can be useful to policy makers, to local and regional authorities, to the owners of the hydropower plants as well as to companies who are willing to invest in these clean and novel energy systems in Greece.

Aim of the current research is the estimation of the nominal power and the electricity generation from floating photovoltaic systems which can be installed in water reservoirs of the existing 24 hydropower plants in Greece.

The paper is structured as follows: After the literature review and the description of the floating photovoltaic systems the existing hydropower plants in Greece and their characteristics are presented. Following that the nominal power of FPVs which can be installed in the water dams and the solar electricity that can be generated are estimated. Next, the benefits due to installation of FPVs in hydropower plants in Greece are mentioned while the paper ends with discussion of the findings, the conclusions drawn, and the citation of the references used.

II. Literature Survey

The literature survey is separated in two sections. The first is related with floating photovoltaics and hydropower plants worldwide while the second is focused on floating photovoltaics and climate change in Greece.

A. Floating Photovoltaics and Hydropower Plants

Farfan and Breyer [6] have studied the pairing of FPVs with hydropower stations. The authors stated that the existing hydropower reservoirs worldwide, at 1,170 GW installed capacity, can host FPVs at 4,400 GW with water surface coverage at 25%. They also mentioned that these flexible hybrid energy systems can be considered as “virtual batteries” generating solar electricity during peak irradiation hours and hydroelectricity during low irradiation hours. Cazzaniga *et al.* [4] have studied the integration of FPVs with hydroelectric power plants. The authors have analyzed the 20 largest hydropower plants worldwide. They stated that when covering 10% of the water surface with FPVs the energy generation is increased by 65%. They also mentioned that by covering 2.4% of the existing hydropower water basins with FPVs the energy generation will be increased by 35.9%. Mahmood *et al.* [13] have studied the pairing of FPVs with hydropower plants in Australia. The authors stated that only two hybrid hydropower-FPV plants exist in the world. They also mentioned that there are not studies related with the potential of hybrid solar-hydropower plants in Australia so

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far. Miah *et al.* [1] have investigated the integration of FPVs with hydropower plants in Bangladesh. The authors stated the multiple benefits of hybrid-hydropower plants. They also studied the techno-economic feasibility of a 50 MW_p FPV system integrated with a hydroelectric plant mentioning that its payback period is around nine years. Rasool *et al.* [24] have studied the integration of a FPV plant with a hydropower plant in Pakistan. The authors analyzed the installation of a FPV system at Taunsa Barrage, Pakistan where a low-head hydro power plant has been designed. They mentioned that the hybrid energy system had multiple benefits. Silvério *et al.* [17] have studied the use of FPVs in the hydropower plant in Sao Francisco river's basin, Brazil. The authors stated that the installation of the FPV system increases the energy generation by 76% while the capacity factor is increased by 17.3%. They also mentioned that solar electricity generation in hydropower plants compensates the lower hydroelectricity produced due to climate change, the lower water precipitation and the increasing water droughts. Quaranta *et al*. [22] have assessed the energy potential of retrofitting the European hydropower fleet. The authors stated that about 50% of the global hydropower plants were commissioned more than forty years ago. They mentioned that these old hydropower plants can be modernized while FPVs can be installed in the water dams. They estimated that modernization of the old hydropower plants can increase the electricity generation by 8-10%. Liu *et al.* [12] have evaluated the benefits of integrating FPV systems and hydro-pumped-storage systems. The authors stated that their integration maximizes the energy generation while it minimizes the energy imbalance at the same time. Additionally, it results in land and water conservation. Perez *et al.* [19] have studied the installation of FPVs in 128 hydropower reservoirs in USA. The authors estimated that FPVs can generate up to 100% of the USA electricity generation covering only a fraction of the water dams' surface. They also mentioned that large amounts of water can be saved while covering with FPVs only 1.2% of the water dams' surface in hydropower plants similar amounts of hydro and solar electricity can be generated. Zhou *et al.* [33] have studied the complementarity of hybrid FPVs and hydropower plants with the water-food-energy nexus. The authors developed an algorithm in their study focused on Shihmen reservoir located in northern Taiwan. They estimated that the hybrid FPV and hydropower plant improves the water-food-energy nexus increasing the water storage capacity by 13%, the food production by 13.3 % and the electricity generation by 15.1%. Puppala *et al.* [21] have studied the criteria for integrating FPVs with hydropower plants in India. The authors stated that the nominal power of FPV systems which could be installed in 134 hydropower plants in India varies between 47 GW and 458 GW depending on the surface coverage ratio of the water basins. They also mentioned that various parameters should be considered before the installation of FPVs including the electricity generation, the LCOE, the capacity factor, the elevation and the available area for the installation. Maraj *et al.* [14] have evaluated the hybrid FPV and hydropower plants in Mediterranean region. The authors experimented with a FPV system with nominal capacity at 500 KW_p installed on the water reservoir of Banja hydropower plant located in Albania.They estimated that the daily electricity generation varied between 1,786 KWh to 3,644 KWh, the daily electricity yield between 3,572 KWh/KW_p to 7,289 KWh/KW_p, the daily capacity factor between 14.9% to 30.4 % and the system efficiency between 17.4% to 17.9%. Maues [15] has studied the integration of FPV systems with hydropower plants in Brazil. The author has surveyed 22 hydropower plants in Brazil with capacity at 31.5 GW compared to the overall hydropower capacity in the country at 114 GW. He stated that FPVs at 34 GW_p can be installed in the water reservoirs of these hydropower plants generating 53.3 TWh/year which correspond at around 10% of the Brazilian electricity demand in 2018. Quaranta *et al*. [23] have studied the role of FPVs in retrofitting existing hydropower plants. The authors stated that integrated FPVs and hydropower systems can improve flexibility and increase the annual electricity generation. They also mentioned that additional hydroelectricity can be generated since the water volume is increased due to lower water evaporation while the capacity factor is increased by 20%. Ravichandran *et al.* [25] have investigated the use of FPVs in Aswan reservoir in Egypt. The authors stated that the total power of the two existing hydropower plants in Aswan reservoir is at 2.65 GW while two FPV systems, at 5 MW_p, each can be installed in the two dams. They also mentioned that the additional electricity generation from the installation of two FPV systems in the water reservoirs is at 11.9 GW and 11.3 GW. Baptista *et al.* [3] have investigated the use of FPV systems in southern European countries. The authors studied the use of a FPV system at 1 MW_p in Gouvaes dam included in Tamega hydroelectric complex, Portugal. They stated that although FPVs have many advantages compared to terrestrial PVs their main drawback is their higher installation cost while they estimated the payback period of the abovementioned investment at 14 years which is high for renewable energy projects. Lee *et al.* [11] have assessed the hybrid FPV and hydropower systems. The authors stated that the global potential of hybrid FPV and hydropower systems is in the range of 3.0 TW to 7.6 TW while their annual electricity generation in the range of 4,251 TWh to 10,616 TWh. They also mentioned that FPVs could play an important role in achieving the ambitious renewable energy targets in many countries while their future deployment requires further investigation related with their actual installation costs and the optimum system design. Kakoulaki *et al.* [10] have analyzed the benefits of pairing FPVs with hydropower reservoirs in Europe. The authors studied 337 hydropower reservoirs in the EU27. They stated that the installation of FPVs of equal installed capacity as the hydropower plants has the potential to generate 42.31 TWh covering 2.3% of the total reservoir area while large quantities of water could be saved by installing solar-PVs. Gonzalez-Sanchez *et al.* [8] have assessed the solar photovoltaics potential in existing hydropower reservoirs in Africa. The authors examined the installation of FPVs in the largest 146 hydropower reservoirs in the continent. They estimated that by covering with FPVs less than 1% of the dams' water surface the existing hydropower capacity can double while the hydro-electricity generation can increase by 58%. Shyam and Kanakasabapathy [26] have studied the feasibility of a FPV system integrated with a small-scale hydro-pumped-storage system in India. The author stated that the integrated energy system is attractive reducing the daily operating cost and the loss of load probability. Spencer *et al.* [27] have assessed the technical potential of FPVs on man-made water bodies in USA. The authors have identified 24,419 man-made water bodies in the country which are suitable for installation of FPV systems. They estimated that 2,116 GW of FPVs can be installed generating 9.6% of the annual electricity demand in USA. Pouran *et al.* [20] have studied the environmental and technical impacts of FPV systems as an emerging clean energy technology. The authors stated that the main advantages of FPVs are a) They do not occupy habitable and productive areas, b) They mitigate water evaporation increasing the water security in arid regions, and c) They have higher efficiency compared to terrestrial PVs due to cooling effect. However, their growth requires supporting policies and development of appropriate roadmaps which are lacking today. Essak and Ghosh [5] have reviewed the floating photovoltaic systems worldwide. The authors stated that by covering 1% of the water surface of the global reservoirs with FPV systems additional green power capacity at 404 GW_p can be achieved. They also mentioned that the main drawbacks of the FPVs are related with their higher installation cost, their unknown impacts on water quality and living organisms and the undesired humidity impacts on solar modules.

B. Floating Photovoltaics and Climate Change in Greece

Zervas *et al.* [32] have assessed the Greek national plan of energy and climate change. The authors criticized various aspects of the energy plan including the absence of risk analysis and alternative scenarios, the proposed energy mix, the future energy prices, the energy savings and the energy storage. They proposed the delay of the energy transition for some years for a better preparation of the national plan. Vourdoubas [31] has estimated the solar electricity generation from FPVs in water reservoirs in Greece. The author estimated that the nominal power of the FPVs that can be installed in the existing 128 water reservoirs in the country, covering 10% to 30% of the water surface, varies between 4.77 GW to 14.31 GW while the annual solar electricity generation varies between 6,435.2 GWh to 19,305.6 GWh. Varlas *et al.* [29] have reanalyzed the precipitation data in Greece since 1950s. The authors stated that the trends were characterized by nonlinearity and inter-decadal variability. They mentioned that precipitation was increasing some decades while in others it was decreasing. Mimikou and Baltas [16] have assessed the climate change impacts in Greece. The authors studied various river basins in different Greek regions analyzing the hydrological data. They found that small decrease in the mean annual precipitation caused dramatic decrease of reservoirs' water supply and level as well as in hydroelectricity generation. Giannakopoulos *et al.* [7] have studied the climate change impacts in Greece in the near future. The authors stated that the annual precipitation changes are different in various regions in the country. They also mentioned that the general picture indicates small overall reductions in the annual precipitation for all the Greek territories. According to National Energy and Climate plan [18], it is foreseen that the nominal power of solar-PV systems in Greece will be increased at 14.1 GW in 2030 and at 34.5 GW in 2050 compared to current installations at 5 GW. It is predicted that the power of the hydro-pumped-storage systems in Greece will be at 2.5 GW by 2030 compared to current absence of these energy storage systems. Vourdoubas [30] has investigated the possibility of using FPVs in the hybrid energy system in the island of El Hierro, Spain and in the planned hybrid energy system in the island of Crete, Greece. The author stated that the installation of FPVs on the water reservoirs of the hybrid energy plant in El Hierro, with coverage ratio 30%, increases its annual electricity generation by 6.06% while in the planed hybrid energy system in Crete by 33.78%. A detail presentation of 128 water reservoirs in Greece has been published [28]. Some aspects of the hydropower plants of Greece have been reported [2].

III. Floating Photovoltaic Systems

A floating photovoltaic system is consisted of solar-PV panels installed on a structure which floats on the surface of a water body. The structure is anchored to the sides or the bottom of the water body. The solar modules are usually crystalline silicon which work well in fresh water. The generated electricity is transmitted with underwater cables to an onshore power sub-station. It is often easier to install FPV systems on water bodies than installing terrestrial PVs. When the solar modules are placed on water bodies they are cooled, and their energy efficiency is increased compared to ground-mounted PVs. Floating photovoltaics installed on the surface of water bodies reduce the solar irradiance and the evaporation of water from the water bodies saving large amounts of water resources. This is important in water-scarce regions. Installation of floating photovoltaics on water bodies results in less land use which is required for the installation of terrestrial PVs. This is important for countries with high population density, high land prices or countries with limited land resources for food production. The impact of FPVs on water quality and on living organisms is not fully understood yet particularly when the solar panels cover a significant part of the water surface usually higher than 10%. Further research is required to shed light on this topic. The installation cost of floating photovoltaics is usually at 10% to 20% higher than the installation cost of similar terrestrial PVs but it is counterbalanced by their multiple advantages.

IV. Installation of Floating Photovoltaic Systems in Water Basins of Hydropower Plants

The concept of integrating FPV systems with hydropower systems is new and many hydropower plants worldwide have investigated the possibility of installing FPV plants on their water reservoirs. The new hybrid energy systems can co-generate solar and hydroelectricity achieving synergies and resulting in many benefits including: a) water saving which results in additional hydro-electricity generation, b) easy connection to the grid for the generated solar electricity, c) Reduced algae growth and better water quality, d) reduction of power fluctuation, and) less land occupancy. Solar electricity can be generated during the day complementing the hydroelectricity generated during the night.

Therefore, green electricity can be delivered more smoothly into the grid from the hybrid FPV and hydropower plant. It is estimated that there are over 9,000 hydropower plants globally covering a surface at around 265,000 Km^2 [5]. Floating photovoltaic systems can be installed in a) natural lakes or in man-made water reservoirs using the water for irrigation and domestic purposes, b) in water dams of existing hydropower plants, c) in water reservoirs of hydro-pumped-storage systems, and d) in water dams of hybrid energy systems including wind parks and hydro-pumped-storage plants.

V. Existing Hydropower Plants in Greece

Several hydropower plants exist already in Greece located in different regions of the country. The characteristics of the existing 24 hydropower plants are presented in Table I. The power of these hydropower plants varies from less than 1 MW_{el} to more than 400 MW_{el}. They are characterized as small-scale, medium-scale and large-scale power plants. The number of the existing hydroelectric stations, their power and the surface of their water reservoirs categorized per region in the country are presented in Table II. Almost half of the hydropower plants are located in Macedonia, northern Greece while around one fifth of them are located in Attiki-Sterea Ellada, southern Greece.

TABLE I: Several Characteristics of the Existing Twenty-Four Hydroelectric Plants in Greece

	Name of the hydropower plant	Location-Greek region	Volume of the water dam (mil. m^3)	Surface of the water dam (Km^2)	Height (m)	Hydroelectric power (MW_{el})
1	Lithotopos	Macedonia	345	75	16	2
2	Louros	Ipiros	1.1	0.37	22	10.3
3	Ladonas	Peloponnisos	57.6	4	56	70
4	Tavropos	Thesalia	400	25.20	83	129.9
5	Kremasta	Sterea Ellada	4,750	80.60	165	437.2
6	Kasrtrakiou	Sterea Ellada	165	24.20	96	320
7	Polifitos	Macedonia	2,244	74	112	375
8	Pornari	Ipiros	730	20.60	102	300
9	Asomata	Macedonia	53	2.60	52	108
10	Sfikias	Macedonia	99	4.30	82	315
11	Stratos	Sterea Ellada	14.9	8.40	26	156.2
12	Ilarionas	Macedonia	520	18	130	157.2
13	Pigon Aioou	Ipiros	180	11.50	78	210
14	Mesoxoras	Thesalia	358	7.80	151	161.6
15	Thisavrou	Macedonia	705	20	172	384
16	Platanobrisis	Macedonia	57	3.30	95	116
17	Pournari II	Ipiros	4.5	0.65	15	33.6
18	Evinou	Sterea Ellada	138	3.60	127	0.82
19	Smokovo	Thesalia	240	-	104	10.37
20	Sisani	Macedonia	0.82	0.11	35	0.32
21	Ag. Varvaras	Macedonia	3	0.92	20	0.92
22	Promoritsas	Macedonia	5.6	0.11	57	1.04
23	Papadias	Macedonia	14	0.60	67	0.55
24	Dafnozonaras	Sterea Ellada	2.55	0.34	28	8.5
	TOTAL	-	-	386.19	-	3,368.42

Source: [28]

TABLE II: Existing Hydropower Plants in Greek Regions

Greek region	Number of existing hydropower plants	Power of the existing hydroelectric stations (MW_{el})	%, of total	Surface of the water reservoirs in these hydropower stations (Km^2)	%, of total
Peloponnisos	1	129.90	3.86	4.00	1.03
Attiki-Sterea Ellada	5	922.72	27.39	117.14	30.33
Ipiros	4	553.90	16.44	33.12	8.58
Thesalia(1)	3	301.87	8.96	33.00	8.55
Macedonia	11	1460.03	43.35	198.93	51.51
Total	24	3,368.42	100	386.19	100

Source: [28]

An overview of the hydroelectricity generation in Greece is presented in Table III. The mean annual capacity factor is estimated as the ratio of the total actual annual electricity generation divided by the electricity which could be generated if the hydropower plants were operating continuously at full capacity according to (1).

$$\text{Capacity factor} = \frac{\text{annual hydroelectricity generation}}{\text{hydropower installed capacity} \times 24 \times 365} \quad (1)$$

It has been reported that the capacity factor of hydropower plants in Greece was estimated at 13% slightly lower than the value reported by PPC at 14.26% (Table III) [10].

TABLE III: Hydropower Potential and Hydro-Electricity Generation in Greece

1	Annual theoretical hydroelectricity potential = 80 TWh
2	Economically exploitable hydroelectricity potential= 12 TWh
3	Total installed capacity of hydropower plants = 3,217.4 MW_{el}
4	Average annual hydroelectricity generation=4,020 GWh (average 5 years)
5	Annual mean capacity factor = 14.26 %
6	Hydroelectricity generation in 2020 = 5,282 GWh

Source: Hydroelectric Power Plants in Greece, Public Power Company, 2013.

VI. Estimation of Electricity Generation from Floating Photovoltaic Systems Installed in the Existing Hydropower Plants in Greece

The nominal power of the floating photovoltaic systems which can be installed covering 10% of the surface of the water reservoirs in the existing hydropower plants in Greece in each region has been estimated and presented in Table IV. It has been assumed that the required water surface for the installation of FPV systems is at 10,000 m^2 per MW$_p$. In some regions the nominal power of the installed FPV systems is higher than the installed power of the hydroelectric stations while in others is lower. Taking into account that the total installed electric power in Greece, in 2020, was at 19,067 MW$_{el}$ [31] the estimated nominal power of the FPV systems, at 3,861 MW$_p$, corresponds at 20.25% of total installed electric power in the country.

TABLE IV: Nominal Power of floating Photovoltaic Systems that could be Installed on The Water Reservoirs in the Existing 24 Hydropower Stations in Greece (coverage ratio of the water surface at 10%)

Greek region	Total water surface of the existing 24 hydropower reservoirs (Km^2)	Surface of FPVs that can be installed in 10% of their water surface (Km^2)	Nominal power of the installed solar photovoltaics (MW$_p$)	Power of the existing hydroelectric stations (MW$_{el}$)	%, power of FPVs to the installed hydro power
Peloponnisos	4.00	0.4	40	129.90	30.79 %
Attiki-Sterea Ellada	117.14	11.71	1,171	922.72	126.91 %
Ipiros	33.12	3.31	331	553.90	59.76 %
Thesalia(1)	33.00	3.30	330	301.87	109.32 %
Macedonia	198.93	19,89	1,989	1460.03	136.23 %
Total	386.19	38.62	3,861	3,368.42	114.62 %

(1) The water surface in Smokovo hydropower station (at 104 MW$_{el}$) has not been included in the estimations.

The annual electricity generation from the floating photovoltaics which can be installed covering 10% of the surface of the water reservoirs in the existing hydropower plants in Greece in each region has been estimated and presented in Table V. The total solar electricity generation at 5,212.35 GWh/year is higher than the electricity generated by the existing hydropower plants at 4,020 GWh/year (Table III). Taking into account that the total electricity demand in Greece, in 2020, was at 51,900 GWh/year [31], the estimated annual solar electricity generation corresponds to 10.04 % of the total annual electricity demand in the country. It should be noted that Spencer *et al.* [27] have estimated that installation of FPV systems in water reservoirs in USA can generate electricity equal at 9.6 % of the annual electricity demand in the country.

TABLE V: Annual Electricity Generation from Floating Photovoltaic Systems that could be Installed on the Water Reservoirs in the Existing 24 Hydropower Stations in Greece (coverage ratio of the water surface at 10%)

Greek region	Nominal power of the installed solar photovoltaics (MW$_p$)	(1) Annual solar electricity generation (GWh/year)
Peloponnisos	40	54
Attiki-Sterea Ellada	1,171	1,580.85
Ipiros	331	446.85
Thesalia	330	445.50
Macedonia	1,989	2,685.35
Total	3,861	5,212.35

(1) Annual solar-PV electricity generation = 1,350 KWh/KW$_p$.

The initial mean capacity factor of the hydropower plants in Greece at 14.26 % (Table III) has been increased with the installation of the FPVs covering 10% of the water surface, at 35.76%. Therefore, the installation of FPVs covering 10% of the reservoirs' surface increases the initial capacity factor of the existing hydropower plants by more than 20%. It should be noted that additional hydroelectricity will be generated in the hydropower stations by the water which will be saved due to the reduced incident irradiance after the installation of FPV systems. The additional generated hydroelectricity has not been included in our estimations.

VII. Benefits due to Installation of Floating Photovoltaic Systems in the Existing Hydropower Plants in Greece

Installation of floating photovoltaic systems in hydropower plants has advantages and drawbacks compared to ground-mounted PVs. Their advantages include:

a) Valuable land is not occupied and can be used in agriculture,
b) Mitigation of water evaporation from the reservoirs,
c) Higher electricity yields due to cooling effect,
d) Less soiling,
e) Easy installation,
f) Reduced algae bloom in the water reservoir,
g) Additional solar electricity generation increasing the overall green electricity generation in the hydropower station using the same infrastructure for grid connection,
h) Solar electricity complements hydro-electricity generation increasing the capacity factor and delivering more smoothly electricity into the grid,
i) Additional hydroelectricity can be produced from the water that will be saved due to the installation of FPV systems.

Their drawbacks include:

a) Higher installation cost,
b) Unknown effect on water quality and living organisms,
c) Undesired humidity impacts on solar modules.

The benefits related with the installation of solar photovoltaic systems in the existing twenty-four hydropower stations in Greece (covering 10% of the water surface) are presented in Table VI. For the necessary estimations the following assumptions have been made:

a) The electricity generation of FPVs is at 5% to 10% higher than the electricity generated from similar terrestrial PVs,
b) The required land surface of ground-mounted PVs is 20% higher than the surface occupied by FPVs,

c) The annual water evaporation savings is around 15,000 M^3/MW_p.

TABLE VI: SEVERAL BENEFITS RELATED WITH THE INSTALLATION OF SOLAR PHOTOVOLTAIC SYSTEMS IN THE EXISTING TWENTY-FOUR HYDROPOWER STATIONS IN GREECE (COVERAGE RATIO OF THE WATER SURFACE AT 10%)

Nominal power of floating photovoltaics	3,861 MW_p
Annual solar electricity generation	5,212.35 GWh/year
Land area saved	46.34 Km^2
Annual water evaporation savings from the reservoirs	57.91 mil. M^3 per year
Increased electricity generation due to cooling effect compared to electricity generation from similar terrestrial PVs	260.62 - 521.62 GWh/year

Source: Own estimations

VIII. DISCUSSION

Our estimation regarding the total installed power of the existing hydropower plants in Greece at 3,368.42 MW_{el} is slightly higher than the power reported at 3,217.4 MW_{el} [2]. The nominal power of the floating photovoltaic systems which can be installed on water dams of hydropower plants in Greece has been estimated and the solar electricity that can be generated has been evaluated. The nominal power of FPVs which can be installed in the water dams of Greek hydropower plants, with surface coverage ratio at 10%, is slightly higher than the installed power capacity of these plants. The solar electricity that can be generated annually from these FPV systems is around 30% higher than the annual hydro-electricity generation. Installation of FPVs in the hydro-power plants increases the capacity factor of these plants by more than 20%. Additionally, installation of FPVs in hydropower reservoirs results in many co-benefits including less water evaporation, higher electricity yields, and less use of valuable land compared to terrestrial PVs. However, the installation cost of floating photovoltaics is higher than the cost of ground-mounted PVs. Our findings indicate that FPVs can be installed in the existing hydropower plants in the country generating both hydro and solar electricity. They can increase the share of solar energy in the energy mix in Greece facilitating the de-carbonization of the country while they increase significantly the capacity factor of the hydropower plants. They also result in many environmental benefits related with water savings and less use of land resources. Our results are similar with relative studies implemented in other countries which also indicate the multiple benefits of the floating photovoltaic systems. Kakoulaki *et al.* [10] have reported that in 337 hydropower plants in EU27 installation of FPVs of equal power with the existing power of the hydroelectric plants occupies 2.3% of their water surface. Farfan and Breyer [6] have stated that the power of FPV systems which can be installed in the existing hydroelectric plants globally, covering 10% of the water basins, is slightly higher that the installed power of the hydroelectric plants. Gonzalez-Sanchez *et al.* [8] have estimated that installation of floating photovoltaics in the largest 146 hydropower reservoirs in Africa, with total surface coverage less than 1%, doubles the existing power capacity of the hydroelectric plants. Our estimations are based on published data regarding the characteristics of the existing hydroelectric plants in Greece [28]. The accuracy of our estimations depends on the accuracy of the data which have been used. Further research should be focused on the implementation of feasibility and techno-economic studies regarding the installation of floating photovoltaic systems in several small-scale, medium-scale and large-scale hydropower plants in the country assessing their profitability.

IX. CONCLUSION

The possibility of installing floating photovoltaic systems in water reservoirs of the existing hydropower plants in Greece has been investigated. Although the global applications of floating photovoltaic systems have grown rapidly during the last decade, realized mainly on Asian countries, there is a lack of relative studies published so far for Greece. The total installed power capacity in the existing twenty-four (24) hydroelectric plants in the country has been estimated at 3,368.42 MW_{el} while the nominal power of the floating photovoltaic systems which can be installed in their water reservoirs, covering 10% of their surface, at 3,861 MW_p corresponding at 20.25% of the total installed electric capacity in Greece. The annual electricity generation by these FPV systems has been evaluated at 5,212.35 GWh/year which corresponds at 10.04% of the electricity demand in the country in 2020. Integration of FPV systems with hydroelectric plants in Greece increases significantly their initial mean capacity factor from 14.26% to 35.76%. It also increases the share of solar energy in the energy mix in Greece assisting the de-carbonization in the country by 2050 according to the national and EU targets for climate change mitigation. Use of this novel carbon-free energy technology has additional environmental benefits related with water saving and less use of land resources. Our research indicates that installation of FPV systems in the existing hydropower plants in Greece has multiple benefits. Therefore, this clean energy technology should be promoted and supported by the government with various ways.

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