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Studies on Installation of Floating Photovoltaic Systems in Water Reservoirs of Several Hydropower Plants in Greece

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Abstract

Use of solar photovoltaics for electricity generation is growing rapidly in Greece replacing the use of fossil fuels in energy generation. The possibility of installing floating photovoltaic systems in water reservoirs in ten hydropower plants in Greece has been studied. Installations of floating photovoltaics in water reservoirs in Greece have not been reported while published studies regarding their applications in the country are limited so far. It has been found that the integration of floating photovoltaic systems with hydropower plants in Greece increases, by average, their initial capacity factor by 42.32%. It has been also estimated that, in the ten hydropower plants studied, by covering 9.39% of the water dams' surface with floating photovoltaics the installed hydropower capacity is doubled while by covering 12.22% of their surface with floating photovoltaics the annual solar electricity generation is equal to the hydroelectricity generation. The additional hydroelectricity generation due to installation of floating photovoltaics in two hydropower plants varies in the range of 0.035% to 0.43% of the initial hydroelectricity generation. Our results indicate that floating photovoltaic systems can be integrated with hydropower plants in Greece generating significant amounts of solar electricity consisting of a complementary alternative technology to terrestrial photovoltaics which are mainly used to day. The results are useful to policy makers who are willing to increase the contribution of solar energy in energy generation, to investors in sustainable energy technologies and to the owners of hydropower plants in Greece who can increase the electricity generation and their energy efficiency integrating them with floating photovoltaic systems.

Keywords: floating photovoltaics; Greece; hydropower plants; water reservoirs.

1. Introduction

Floating photovoltaic (FPV) systems installed on water bodies consist of a novel solar photovoltaic (solar-PV) technology alternative to terrestrial solar-PVs. Their use is increasing rapidly worldwide due to their benefits compared to ground-mounted photovoltaics [1]. Installed FPV systems do not exist today in Greece while studies regarding their future use in the country are limited [2]. However, there are many natural or artificial water reservoirs including natural lakes, man-made water reservoirs, hydropower dams and reservoirs of hydro-pumped-storage systems which could be used for the installation of these systems [3].

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The annual solar irradiance in Greece is high making the use of solar photovoltaic systems very attractive and profitable. The Greek national plan for energy and climate change foresees that solar photovoltaic systems are going to play a dominant role in the future in the replacement of fossil fuels with renewable energy sources [4]. Installation of FPV systems on water reservoirs in existing hydropower plants increases its electricity output allowing the generation of both hydro and solar electricity [5, 6, 7, 8, 9].

Aims of the current research are:

a) *The investigation of the possibility of installing floating solar photovoltaics in water dams of hydropower plants in Greece,*
b) *The estimation of the increase of the capacity factor in several hydropower plants in Greece after the installation of FPV systems,*
c) *The % covering of the water reservoirs' surface with FPV systems in several Greek hydropower plants having equal hydro and solar power,*
d) *The % covering of the water reservoirs' surface with FPV systems in several Greek hydropower plants generating annually equal amounts of hydro and solar electricity, and*
e) *The additional hydro-electricity generation due to water savings after the installation of the solar photovoltaics in the water reservoirs.*

The paper is structured as follows: After the literature survey the technology of floating photovoltaic systems is presented followed by the characteristics of several hydropower plants in Greece. Next, the prediction of the Greek national energy and climate plan regarding the development of solar photovoltaics in the country is stated followed by estimations regarding the power, the generated electricity and the capacity factor of ten hydropower plants after the installation of FPV systems in their water reservoirs. In the next section the additional hydroelectricity generation due to installation of FPV systems in two hydropower plants is evaluated. The text ends with discussion of the findings, the conclusions drawn and the citation of the references used.

2. Literature survey

Reference [5] have studied the pairing of FPV systems with hydropower stations. The authors stated that the existing hydropower reservoirs worldwide, at 1,170 GW installed capacity, can host FPV systems at 4,400 GW_p 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 hydro-electricity during low irradiation hours. Additionally, more hydroelectricity can be generated due to water evaporation savings. Reference [10] have studied the integration of FPV systems with hydroelectric power plants mentioning their advantages. The authors have analyzed the 20 largest hydropower plants worldwide mentioning that by covering 10% of the water surface with FPV systems the energy generation is increased by 65%. They also stated that by covering 2.4% of the existing global hydropower water basins with FPV systems the energy generation is increased by 35.9%. Reference [11] have studied the pairing of FPV systems 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 many studies related with integration of FPV systems with hydropower plants in

Australia so far. Reference [12] have investigated the integration of FPV systems with hydropower plants in Bangladesh. The authors stated the multiple benefits of hybrid solar-hydropower plants. They also studied the techno-economic feasibility of a floating photovoltaic system at 50 MW_p integrated with a hydropower plant mentioning that its payback period is at around nine years. Reference [13] have studied the integration of a FPV system with a hydropower plant in Pakistan. The authors analyzed the installation of the solar system at Taunsa Barrage, Pakistan where a low head hydropower plant has been designed. They stated that the hybrid energy system had multiple benefits. Reference [14] have studied the use of a floating photovoltaic system 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 initial capacity factor is increased by 17.3%. They also mentioned that solar electricity generation in hybrid hydropower plants compensates the lower hydro electricity produced due to climate change, the lower water precipitation and the increasing water droughts. Reference [15] 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 FPV systems can be installed in their water dams. They estimated that modernization of these old hydropower plants can increase the electricity generation by 8-10%. Reference [16] 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. Reference [6] have studied the installation of FPV systems in 128 hydropower reservoirs in USA. The authors estimated that FPV systems can generate up to 100% of the electricity generation in USA covering only a fraction of the water reservoirs' surface. They also mentioned that large amounts of water can be saved while in existing hydropower plants covering only 1.2% of the water reservoirs' surface with FPV panels similar amounts of hydro and solar electricity can be generated. Reference [17] have studied the complementarity of FPV systems and hydropower plants in the context of the water-food-energy nexus. The authors developed an algorithm with reference the Shihmen reservoir located in northern Taiwan. They estimated that integration of FPV systems with the 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%. Reference [18] have studied the criteria for integrating FPV systems 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_p and 458 GW_p depending on the surface coverage ratio of the water basins. They also mentioned that various parameters should be considered before the installation of FPV systems including the electricity generation, the levelized cost of electricity, the capacity factor, the elevation and the available area for the installation. Reference [19] have evaluated the hybrid FPV systems 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 of the FPV system 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%. Reference [20] has studied the integration of FPV systems with 22 hydropower plants in Brazil. The author stated that the installed capacity in these hydropower plants, which represent the 22% of the total hydropower capacity installed in Brazil, is at 31.5 GW. They mentioned that floating photovoltaic systems can be installed in the water dams of these hydropower plants having nominal power at 34 GW_p. They estimated that the generated solar electricity, at 53.3 TWh/year, corresponds at around 10% of the electricity demand in Brazil in 2018. Reference [21] have studied the possibility of installing FPV systems during retrofitting existing hydropower plants. The authors stated that integration of FPV systems with hydropower plants can improve their flexibility and increase the annual electricity generation. They also mentioned that additional hydro-electricity can be generated in these hybrid energy plants since the water volume is increased due to lower water evaporation while the capacity factor is increased by around 20%. Reference [22] have investigated the possibility of installing FPV systems 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 annual electricity generation from the installation of these two FPV systems in the water reservoirs is at 11.9 GWh and 11.3 GWh. Reference [7] 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 FPV plants 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. Reference [8] have analyzed the benefits of pairing FPV systems with hydropower plants in Europe. The authors studied 337 hydropower water reservoirs in the EU27. They stated that installation of FPV systems of equal installed capacity as the hydropower plants has the potential to generate 42.31 TWh/year covering 2.3% of the total reservoir area while large quantities of water could be saved by installing floating photovoltaic systems on water dams. Reference [9] have assessed the solar photovoltaics potential in existing hydropower reservoirs in Africa. The authors examined the installation of FPV systems in the largest 146 hydropower reservoirs in the continent. They estimated that by covering with floating photovoltaics less than 1% of the dams' water surface the existing hydropower capacity is doubled while the hydro-electricity generation is increased by 58%. Reference [1] have reviewed the floating photovoltaic systems worldwide. The authors stated that by covering 10% of the water surface in EU reservoirs with FPV systems the installed solar power capacity will be at 204 GW_p. They also mentioned that the main drawbacks of FPV systems are related with their higher installation cost, their unknown impacts on water quality and living organisms and the undesired humidity impacts on solar modules. Reference [2] has estimated the solar electricity generation from FPV systems in water reservoirs in Greece. The author evaluated that the nominal power of FPV systems that can be installed in the existing 128 water reservoirs in the country, covering 10% of the water surface, is at 4.77 GW_p while the annual solar electricity generation is at 6,435.2 GWh. Reference [23] has studied the integration of FPV systems in the existing 24 hydropower plants in Greece. The author stated that FPV systems can be installed in the existing hydropower plants covering 10% of their water surface having nominal power at 3,861 MW_p while they can generate 5,212.35 GWh/year corresponding at 10.04% of the annual electricity demand in the country. It is foreseen [4] that the nominal power of solar-PV systems in Greece will be increased at 14.1 GW_p in 2030 and at 34.5 GW_p in 2050 compared to the current installed power at 5 GW_p. It is also predicted that the power of the hydro-pumped-storage systems in Greece will be at 2.5 GW by 2030 and the power of electric batteries at 5.6 GW. Reference [24] has investigated the possibility of using FPV systems in the existing 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 FPV systems 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 and the characteristics of 128 water reservoirs in Greece has been published, [3]. Some data and parameters of the hydropower plants of Greece have been reported [25]. The main characteristics of the hydropower plants owned by P.P.C. in Greece have been also presented [26]. The published research so far globally indicates that: a) floating photovoltaic systems can be installed in water reservoirs including the water dams of hydropower plants without major difficulties, b) there are not major problems in the water quality when the covered surface does not exceed the 10% of the overall water surface, c) when the covered surface with FPVs is at around 10% of the total water surface the solar electricity generation is almost equal with the hydroelectricity generation, d) the potential of solar electricity generation from FPVs installed in the water dams of existing hydropower plants worldwide is very high, e) the installation cost of FPVs is higher at 10-15% compared to the cost of similar terrestrial solar-PVs, and f) the drawbacks of the FPVs installed in the reservoirs of hydropower plants are surpassed by their advantages.

3. Floating solar 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 water reservoirs. Water bodies include artificial or man-made lakes and irrigation ponds, water reservoirs of hydropower plants, water dams of hydro-pumped-storage systems et cetera. The solar modules are usually consisted of crystalline silicon placed on the surface of fresh water. The technology is growing rapidly during the last decade due to many advantages compared with similar technologies. Installation of FPV systems on the sea is not developed yet due to many reasons. The generated solar electricity is transmitted with underwater cables to an on-shore power sub-station. Installation of FPV systems on water bodies is often easier than their installation on the ground.

When the solar modules are placed on the surface of water bodies they are cooled and their energy efficiency is increased compared to ground-mounted solar-PVs. Floating photovoltaics installed on the surface of water bodies reduce the solar irradiance and the evaporation of water from them saving significant amounts of water resources which are valuable in regions with water shortages. 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 FPV systems 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 photovoltaic systems is usually higher at 10% to 20% than the installation cost of similar terrestrial solar-PVs but the higher cost is counterbalanced by their multiple advantages. The majority of floating photovoltaic systems have been installed in Asian countries so far. The distribution of floating photovoltaic systems in several countries is presented in table 1.

Table 1: Share of installed capacity of floating photovoltaic systems in various countries.

Country	Installed capacity (%)
China	75.04
Japan	15.98
Korea	6.01
UK	0.99
Others	1.98
Total	100

Source: [1]

The main advantages of FPV systems compared to ground-mounted PVs are related with less use of land which is important in land-scarce regions, in water evaporation savings which is important in regions with limited water resources and in higher electricity yields compared to terrestrial PVs due to lower temperature of the floating solar panels. Other benefits include less algae growth in the water reservoir, limiting soiling and less shading. Additionally, the hybrid energy plant will provide smoothly "green electricity" into the grid. Their main drawbacks include the higher installation cost, the not fully understood impacts on water quality and aquatic life and the undesired effect of humidity on the solar panels.

4. Hydropower plants in Greece

Several hydropower plants exist already in Greece located in different regions of the country. The installed power in these 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 hydropower plants. Almost half of these hydropower plants are located in the region of Macedonia, northern Greece while around one fifth of them are located in the region of Attiki-Sterea Ellada, southern Greece. The hydropower potential and the hydroelectricity generation are presented in table 2.

Table 2: 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: [25]

The mean annual capacity factor is estimated as the ratio of the total annual electricity generation divided by the electricity which could be generated if the hydropower plants were operating continuously at full capacity according to the following equation.

Capacity factor = (annual hydroelectricity generation)/(hydropower installed capacity x 24 x 365)

It has been estimated [8] that the capacity factor of hydropower plants in Greece is at 13% slightly lower than the value reported by [25] Public Power Company at 14.26%.

Ten hydropower plants of different scales located in four Greek territories have been selected and studied as follows:

a) Four large-scale plants with installed power higher than 150 MW,
b) Four medium-scale plants with installed power between 15 MW to 150 MW, and
c) Two small-scale plants with installed power up to 15 MW.
d) Five of the abovementioned plants have been constructed before 1970 while seven of them before 1990. The average capacity factor of these ten hydropower plants is estimated at 24.29%.

The characteristics of these ten hydropower plants are presented in table 3.

Table 3: Characteristics of ten hydropower plants in Greece.

Name of hydropower plant	Location of the plant/territory	Year of commercial operation	Installed hydropower (MW)	Surface of the water dam (Km^2)	Annual electricity generation (GWh/year)	Capacity factor (%)
Kastraki	Sterea Ellada	1969	320	24	598	21.33
Ilarion	Macedonia	2014	153	17	320	23.88
Pigai Aoos	Ipiros	1990	210	13	165	8.97
Agras	Macedonia	1954	50	6	35	7.99
Ladon	Pelopnnisos	1955	70	4	260	42.41
Macrochori	Macedonia	1992	10.8	1	30	31.71
Pournari II	Ipiros	1999	33.6	1	45	15.31
Louros	Ipiros	1964	10.3	0.37	50	55.43
Kremasta	Sterea Ellada	1967	437.2	81	848	22.14
Asomata	Macedonia	1985	108	3	130	13.74
Total			1,192.9	150.37	2,481	

Source: [3, 26]

5. The national energy and climate plan in Greece

The Greek national plan for climate and energy foresees an increase in solar-PV installations from 3 GW_p in 2020 to 7.7 GW_p in 2030 and an increase in solar-PV electricity generation from 4.5 GWh in 2020 to 11.8 GWh in 2030. The required surface for the installation of the additional solar-PV power of 4.7 GW_p is estimated at 47 Km^2.

It is also mentioned that the possibility of installing floating solar photovoltaic systems should be examined. It has been evaluated that FPV systems installed in 24 hydropower plants in Greece, covering 10% of their water reservoirs' surface at 38.62 Km^2, have nominal power at 3.86 GW_p [2].

The evolution of the installed renewable energy sources (RES) capacity in Greece during 2020-2030 is presented in table 4 while the electricity generation by RES in table 5.

Table 4: Evolution of installed RES capacity for power generation in Greece.

Power generation installed capacity [GW]	**2020**	**2022**	**2025**	**2027**	**2030**
Biomass & biogas	0.1	0.1	0.1	0.2	0.3
Hydro including mixed pumping	3.4	3.7	3.8	3.9	3.9
Wind farms	3.6	4.2	5.2	6.0	7.0
Photovoltaics	3.0	3.9	5.3	6.3	7.7
Solar Thermal	0.0	0.0	0.0	0.1	0.1
Geothermal	0.0	0.0	0.0	0.0	0.1
Total	10.1	11.9	14.6	16.4	19.0

Source: [4]

Table 5: Evolution of electricity generation by RES in Greece.

Electricity generation [TWh]	**2020**	**2022**	**2025**	**2027**	**2030**
Biomass & biogas	0.4	0.5	0.8	1.0	1.6
Hydro	5.5	6.4	6.5	6.6	6.6
Wind farms	7.3	10.1	12.6	14.4	17.2
Photovoltaics	4.5	6.0	8.2	9.7	11.8
Solar Thermal	0.0	0.0	0.0	0.3	0.3
Geothermal	0.0	0.0	0.0	0.3	0.6
Total	17.7	23.0	28.4	32.2	38.1

Source: [4]

6. Installation of floating solar photovoltaic systems in several hydropower plants in Greece

Floating solar photovoltaic systems can be installed in water dams of the existing hydropower plants in Greece. They can cover a small percentage of their water surface without causing undesired problems in water quality and to water living organisms. The abovementioned ten Greek hydropower plants have been selected and estimations have been made assuming that FPV systems could be installed covering 10% of the water reservoirs' surface. The evaluated parameters of the hybrid hydro-solar energy systems include: nominal power of the FPV systems, the ratio of the FPV power to hydro power, the annual solar electricity generation, the ratio of FPV electricity to hydro electricity generation, the capacity factor after the installation of the FPV systems. The results are presented in table 6. The overall capacity factor after the installation of floating photovoltaics in these ten hydropower plants is estimated as [hydroelectricity +solar electricity generation]/[installed hydropower X 24 X 365] X 100, at 34.57%. The surface of FPV systems installed on the water dams with equal solar capacity to hydropower capacity and the surface of FPV systems generating the same amount of solar electricity as hydroelectricity have been also evaluated and presented in table 7.

Table 6: Electricity generation from floating photovoltaics installed in ten hydropower's dams covering 10% of their water surface.

Name of hydropower plant	Water surface for the installation of FPVs (km^2)	Nominal power of FPVs (MW_p)	(FPV power / hydro power) (%)	Solar electricity generation (GWh/year)	(FPV-electricity/hydro - electricity) (%)	Capacity factor after the installation of FPVs based on the installed hydropower (%)
Kastraki	2.4	240	75	324	54.18	32.89
Ilarion	1.7	170	111	229.5	71.92	41.01
Pigai Aoos	1.3	130	61.90	175.5	106.36	18.51
Agras	0.6	60	120	81	231.43	26.48
Ladon	0.4	40	57.14	54	20.77	51.22
Macrochori	0.1	10	92.59	13.5	45	45.98
Pournari II	0.1	10	29.76	13.5	30	19.90
Louros	0.037	3.7	35.92	5	10	60.98
Kremasta	8.1	810	185.27	1093.5	128.95	50.69
Asomata	0.3	30	27.77	40.5	31.15	18.02
Total	15.04	1,503.70		2,030		

Source: [3, 26], Annual electricity generation = 1,350 KWh/KW$_p$

Table 7: Characteristics of floating photovoltaics installed in several hydropower's reservoirs in Greece.

Name of hydropower plant	Surface of FPVs with equal nominal power as the installed hydropower (km^2)	Surface of FPVs with equal nominal power as the installed hydropower to water reservoir surface (%)	Surface of FPVs generating the same amount of solar electricity as hydroelectricity (Km^2)	Surface of FPVs generating the same amount of solar electricity and hydroelectricity to water reservoir surface (%)
Kastraki	3.20	13.33	4.43	18.46
Ilarion	1.53	9.00	2.37	13.94
Pigai Aoos	2.10	16.15	1.22	9.38
Agras	0.50	8.33	0.26	4.33
Ladon	0.70	17.50	1.93	48.25
Macrochori	0.108	10.80	0.22	22.00
Pournari II	0.336	3.60	0.33	33.00
Louros	0.103	27.84	0.37	100.00
Kremasta	4.372	5.40	6.28	7.75
Asomata	1.08	36.00	0.96	32.00
Total	14.03		18.37	

Source: [3, 26]

The average coverage ratio of the total surface of ten water dams installing FPV systems with the same power as the installed hydropower is at 9.39% of the total surface of the water reservoirs.

The average coverage ratio of the total surface of the ten hydro dams installing FPV systems generating annually the same electricity as the hydroelectricity is at 12.22% of the total surface of the water reservoirs.

7. Evaluation of changes in the capacity factor of the hydropower plants after the installation of floating solar photovoltaic systems

Integration of solar photovoltaics with existing hydropower plants results in solar electricity generation complementary to hydroelectricity produced in the hybrid energy plant. The hybrid energy plant can operate flexibly generating solar electricity when the solar irradiance is high and hydro-electricity when it is low. The initial capacity factor of the hydropower plants will be increased after the installation of the FPV systems. The initial capacity factor, the new capacity factor after the installation of FPV systems and their increase in the ten abovementioned hydropower plants studied are presented in table 8.

Table 8: Increase of the capacity factor in ten hydropower plants in Greece after the installation of floating photovoltaic systems covering 10% of their reservoirs surface.

Name of hydropower plant	Nominal power of FPV systems (MW_p)	Solar electricity generation (GWh/year)	Initial capacity factor of hydropower plan (%)	Capacity factor after the installation of FPV systems based on the installed hydropower (%)	Increase of the capacity factor after the installation of FPV systems (%)
Kastraki	240	324	21.33	32.89	54.19
Ilarion	170	229.5	23.88	41.01	71.73
Pigai Aoos	130	175.5	8.97	18.51	106.35
Agras	60	81	7.99	26.48	231.41
Ladon	40	54	42.41	51.22	20.77
Macrochori	10	13.5	31.71	45.98	45.00
Pournari II	10	13.5	15.31	19.90	29.98
Louros	3.7	5	55.43	60.98	10.01
Kremasta	810	1093.5	22.14	50.69	128.95
Asomata	30	40.5	13.74	18.02	31.14
Total	1,503.70	2,030			

Source: Own estimations

The % increase of the capacity factor is estimated from the following equation:

[Increase of the capacity factor after the installation of FPV systems, %] = (Capacity factor after the installation of FPV systems, %) – (initial capacity factor, %)/(initial capacity factor, %)

The average capacity factor in these ten hydropower plants, at 34.57%, has been increased after the installation of floating photovoltaics by 42.32% compared to the initial capacity factor, at 24.29%.

The change in the capacity factor of the hydropower plants after the installation of FPV systems is presented in table 9.

Table 9: Change in the capacity factor of ten hydropower plants after the installation of FPV systems covering 10% of their reservoirs' surface.

Capacity factor	Value (%)
Average value of the existing hydropower plants in Greece [25]	14.26
Average value of the existing hydropower plants in Greece [8]	13.00
Average value of the ten hydropower plants studied before the installation of FPV systems	24.29
Average value of the ten hydropower plants studied after the installation of FPV systems covering 10% of the reservoirs' surface	34.57
Increase of the average initial capacity factor in the ten hydropower plants studied after the installation of FPV systems covering 10% of the reservoirs' surface	42.32

Source: own estimations

8. Additional hydro-electricity generation due to water savings after the installation of solar photovoltaic systems

Installation of FPV systems in the hydro-reservoirs results in water evaporation savings which are estimated at around 15,000 M^3/year per installed MW_p [27]. The water saved in the reservoir has the potential to generate additional hydroelectricity. The hydroelectricity generation due to water savings is estimated by the following equation:

Hydroelectricity (MWh/year) = water volume (m^3/year) X 9.81 X height (m) X efficiency (unitless) (8)

The additional hydroelectricity generation is estimated for two hydroelectricity plants, Kremasta and Ladon.

8.1 Hydropower plant in Kremasta

The characteristics of Kremasta hydropower plant are [3]:

Surface of the water reservoir = 81 km^2

Hight of water fall = 132 m

Installed hydropower = 437.2 MW_{el}

Hydroelectricity generation = 848 GWh/year

Efficiency of the hydropower plant = 0.85

The installed power of FPV system covering 10% of the water surface has been estimated at 810 MW_p while the solar electricity generation at 3,710 GWh/year (*table 6*).

Water evaporation savings due to installation of the FPV system at 810 MW_p = 12,150,000 M^3/year

The additional hydroelectricity generation from equation (8) is evaluated at 3,710 MWh/year which corresponds at 0.43% of the initial annual hydroelectricity generation and at 0.33% of the annual solar electricity generation from the FPV system.

8.2 Hydropower plant in Ladon

The characteristics of Ladon hydropower plant are [3]:

Surface of the water reservoir = 4 km^2

Hight of water fall = 56 m

Installed hydropower = 70 MW_{el}

Hydroelectricity generation = 54 GWh/year

The installed power of FPV system covering 10% of the water surface has been estimated at 40 MW_p while the solar electricity generation at 77.8 MWh/year (*table 6*).

Water evaporation savings due to installation of the FPV system at 40 MW_p = 600,000 M^3/year

The additional hydroelectricity generation from equation (8) is evaluated at 77.8 MWh/year which corresponds at 0.035% of the annual initial hydroelectricity generation and at 0.14% of the annual solar electricity generation from the FPV system.

9. Discussion

It should be noted that the absence of similar studies in Greece and the absence of funding limit our study which could be more extensive. The size of the sample which we used was consisted of ten hydropower plants and the accuracy of our results depends on the accuracy of the data that we have used. The results indicate that the water reservoirs of the hydropower plants in Greece can be used for the installation of FPV systems covering part of the surface in their water dams producing significant amounts of solar electricity complementing the hydro-electricity produced improving the operation of the hydropower plants. Although the energy efficiency of the floating solar photovoltaic systems, at around 16-19%, is lower than the energy efficiency of hydroelectric plants, at around 80-90%, they can complement each other and achieve mutual benefits. Their installation increases significantly the initial capacity factor in these plants. With reference the ten hydropower plants studied the FPV systems installed on their water reservoirs covering slightly less than 10% of their surface have the same power as the installed hydropower while when covering slightly more than 10% of the water surface they will generate annually equal solar electricity as the hydroelectricity generated. Other studies [8] have estimated that in 337 hydropower plants in EU27 the nominal power of FPV systems installed at 2.3% of the water dams' surface is equal to the hydropower installed. It has been evaluated [9] that in the largest 146 hydropower plants in Africa by covering with floating photovoltaics less than 1% of the dams' water surface the existing hydropower capacity will double while the hydroelectricity generation will increase by 58%. Studies in the 20 largest hydropower plants worldwide [10] have indicated that by covering 10% of the water surface with FPV systems the energy generation will increase by 65%. The estimated additional hydroelectricity generation due to water evaporation savings in two hydropower plants in Greece is rather small compared to the initial hydroelectricity generation and the solar electricity generation while it has not been considered in our estimations. If the additional generated hydroelectricity was taken into account the increase of the initial capacity factor would be slightly higher. In areas with water shortages, like many Greek regions, installation of floating photovoltaic systems in the reservoirs of existing hydroelectric plants will result in saving of valuable water resources as well as in solar and additional hydroelectricity generation which are necessary in these regions. The most of hydropower plants studied in the present work are old and their retrofitting can be combined with the installation of solar photovoltaic systems on their water dams. Taking into account that, according to forecasts, climate change will result in lower precipitation in Greece and lower capacity for hydroelectricity generation the solar electricity generated in the existing hydropower plants can compensate the lower hydroelectricity generation due to climate change. Our study does not indicate which hydropower plants in Greece are appropriate for the installation of FPV systems neither the profitability of these energy investments. Further work should be focused in the implementation of techno-economic studies regarding the installation of FPV systems in various hydropower plants in Greece evaluating also the co-produced benefits. It is also recommended that a pilot floating solar-PV system should be installed in a small water reservoir in order to investigate the impacts of the crystalline silicon solar panels on the quality of the water and on the living organisms.

10. Conclusions

The installation of floating photovoltaic systems in water reservoirs in ten hydropower plants in Greece, transforming them to hybrid energy systems, has been studied. Solar photovoltaics are expected to grow rapidly in Greece during the coming decades due to high solar irradiance in the country contributing in the elimination of fossil fuels use for electricity generation by 2050. It has been found that the initial capacity factor of these hydroelectric plants has been increased after the installation of FPV systems, on average, by 42.32% varying in the range of 18.02% to 60.98%.

It has been estimated that, on average, by covering 9.39% of the reservoirs' surface with FPV systems the installed hydropower is doubled while by covering 12.22% their surface with FPV systems the solar electricity generation is equal to hydro-electricity generation. The additional hydroelectricity generation due to installation of the floating photovoltaic systems in two hydropower plants varies in the range of 0.035% to 0.43% of the initial hydroelectricity generation and in the range of 0.14% to 0.33% of solar electricity generation. Our results indicate that the water reservoirs of the existing hydropower plants in Greece can be used for the installation of floating photovoltaic systems which when installed, on average, at around 10% of their water surface can generate significant amounts of solar electricity doubling the hydroelectricity generation.

Therefore, the water reservoirs in the existing hydropower plants in Greece can be used for installation of FPV systems additionally to their terrestrial installation assisting in the achievement of the ambitious target of carbon neutrality by 2050.

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