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Assessing the Theoretical, Minimal Intervention Potential of Floating Solar in Greece: A Policy-Oriented Planning Exercise on Lentic Water Systems of the Greek Mainland

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Abstract: According to the recent revision of the Greek National Energy and Climate Plan, the country sets out to accomplish an ambitious target concerning the integration of renewables in the local electricity mix during the ongoing decade, at the levels of 80% by 2030. This implies the need to more than double the existing wind and PV capacity at the national level, which in turn introduces numerous challenges. Amongst them, spatial planning for new RES installations seems to be the most demanding, with the adoption of novel technological solutions in the field of RES potentially holding a key role. New technologies, like offshore wind and floating solar, are gradually gaining maturity and may offer such an alternative, challenged at the same time however by the need to entail minimum disruption for local ecosystems. To that end, we currently assess the theoretical potential of floating PVs for lentic water systems of the Greek mainland. We do so by looking into 53 different lentic water systems across the Greek territory that meet the constraint of 1 km^2 minimum surface area, and we proceed with the estimation of the relevant floating PV capacity per system under the application of a minimal intervention approach, assuming PV coverage of 1% over the total lentic water system area. In this context, our findings indicate a maximum, aggregate theoretical capacity that could exceed 2 GW_p at the national level, with the respective annual energy yield reaching approximately 4 TWh or, equivalently, >6% of the country's anticipated annual electricity consumption in 2030. Finally, our results extend further, offering a regional level analysis and a set of policy directions and considerations on the development of floating solar in Greece, while also designating the energy merits of floating PVs against similar, land-based installations.

Keywords: floating solar; lentic water systems; national energy planning; geographical analysis

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1. Introduction

According to the recent revision of the Greek National Energy and Climate Plan [1], the country sets out to accomplish an ambitious target concerning the integration of renewables in the local electricity mix during the ongoing decade, at the level of 80% by 2030. This implies the need to more than double the existing wind and PV capacity at the national level, which in turn introduces numerous challenges. Amongst them, spatial planning for new RES installations seems to be the most demanding, with the adoption of novel technological solutions in the field of RES potentially holding a key role. New technologies, like offshore wind [2] and floating solar [3], gradually gain maturity and may offer such an alternative, challenged at the same time however by the need to entail minimum disruption for local ecosystems [4,5].

Towards this direction, it is argued that distributed generation schemes could potentially serve the purpose of minimal intervention more effectively [6], as opposed to the promotion of industrial-scale RES plants, which also encourages the prospect of best practices for the energy–land–water nexus at the local level [7]. The former could also be in line with the emergence of local energy initiatives [8], allowing for the active engagement of local societies in the planning, development, and operation stages of similar projects, which may in turn ensure a more balanced view of costs and benefits in terms of generated value and impacts.

Meanwhile, on the technology front, progress made in the field of floating solar over the last decade is notable [9–14], with the global installed capacity currently standing in the order of 4 GW_p, and with medium-term predictions anticipating an accelerated increase by 2030, that shall lead to a cumulative capacity of 30 GW_p [15]. Early installations ranged in the scale of tens to hundreds of kWs [16], with latest ones exhibiting capacities reaching even hundreds of MWs, which is indicative of the span of applications that may be served by the given technology and of the associated techno-economic implications.

At the same time, in the recent body of literature, there is an increased interest in both technological advancements in the field [17] and the assessment of the relevant potential for the application of similar systems at the national and/or regional level. As far as the latter is concerned, the authors of [18] provided an estimation of the global theoretical potential regarding the installation of floating solar in water reservoirs. Using data from a total of 114,155 reservoirs across the globe, they estimated an annual energy yield of 9500 TWh and water savings of 106 km^3, also stressing the fact that such lentic water systems are found in the proximity of population centers, thus they can support the development of local-scale energy solutions, generating benefits for more than 6000 communities in 124 countries.

Moreover, there is an already significant number of similar studies looking at the assessment of national potential for floating solar in different countries. Indicatively, in [19], the authors estimated the national potential for floating solar in China, in the order of 705 GW_p–862 GW_p, with an annual energy yield between ~1165 TWh and ~1424 TWh, which could also lead to the conservation of more than 7100 km^2 of land attributed to terrestrial photovoltaics. Next, in [20], the authors estimated the exploitable potential offered by artificial water reservoirs in Turkey, which, they argue, could harvest an annual energy yield of ~125 TWh, equivalent to 40% of the country's electricity demand. In addition, in [21], the authors investigated the potential provided by more than 3000 irrigation ponds in the Spanish province of Jaén, with their results suggesting that under a significant coverage of 25%, a minimum of 490 MW_p of floating solar is possible. This, they argued, could cover 251% of the province's agricultural electricity consumption and 27% of the total electricity needs, avoiding the occupation of 12 km^2 of useable land and the evaporation of $8.8 \cdot 10^6$ m^3 of water per year.

In this context, despite the fact that in Greece preliminary steps have already been made regarding the relevant legislation on the one hand, aiming to promote the technology locally, and a strong investment interest may be witnessed over the recent period on the other (mainly for the development of large-scale floating PV plants), a similar analysis on the country's potential for the development of floating solar has not yet been conducted. Acknowledging the above, our study looks at the assessment of the theoretical, national-scale potential for floating solar in Greece, focusing on lentic water systems of the Greek mainland and putting forward a minimal-intervention approach. Aim of the latter is to both inform policy-making for the strategic development of the technology and support the protection of sensitive ecosystems locally.

To that end, in the following Section 2 of the paper, we provide the problem definition, present the relevant input data and analyze the methodological steps applied. Accordingly, in Section 3, we provide the main results of our research and proceed further with their analysis on the basis of a post-processing exercise, allowing for their representation and aggregation from the local, to the regional and the national level. Additionally, and with the aim to stimulate a policy-oriented discussion, we next elaborate a set of potential scenarios regarding the strategic development of the technology in Greece, while finally, a summary of main findings and key conclusions of the research are provided in Section 4.

2. Materials and Methods

2.1. Problem Definition

Following the introduction section of the paper, the problem definition, methodological steps, and assumptions of our research are provided here. As already mentioned, our work addresses the problem of assessing the theoretical potential of floating solar in lentic water systems of the Greek mainland. In support of the minimal intervention approach currently proposed so as to ensure the effective avoidance of impacts on the sensitive settings of similar ecosystems, our research focuses on lentic water systems, both natural and artificial (excluding lagoons), with a minimum area of 1 km^2. This results to a total of 53 lentic water systems, broadly distributed across the Greek mainland (see also Table 1), with the aggregate area exceeding 1.000 km^2.

Table 1. List of mainland lentic water systems with an area of ≥1 km^2 (sorted by latitude).

A/A	Lentic Water System	Category	Region	Area (km^2)	Lat.	Lon.
1	Platanovrisi	Artificial	Eastern Macedonia & Thrace	3.20	41.350	24.423
2	Thisavros	Artificial	Eastern Macedonia & Thrace	20.00	41.338	24.344
3	Doirani	Natural	Central Macedonia	28.00	41.211	22.744
4	Kerkini	Artificial	Central Macedonia	109.96	41.210	23.141
5	Gratini	Artificial	Eastern Macedonia & Thrace	1.00	41.163	25.520
6	Vistonida	Natural	Eastern Macedonia & Thrace	45.00	41.040	25.111
7	Arzani	Artificial	Central Macedonia	1.40	41.031	22.648
8	Chrysoupolis	Natural	Eastern Macedonia & Thrace	20.00	41.008	24.705
9	Ismarida	Natural	Eastern Macedonia & Thrace	3.40	40.984	25.317
10	Megali Prespa	Natural	Western Macedonia	37.60	40.871	21.028
11	Pikrolimni	Natural	Central Macedonia	3.70	40.833	22.814
12	Agra-Vriton	Artificial	Central Macedonia	6.00	40.804	21.948
13	Mikri Prespa	Natural	Western Macedonia	43.50	40.766	21.108
14	Nymfon	Natural	Eastern Macedonia & Thrace	2.40	40.761	26.078
15	Vegoritida	Natural	Central Macedonia	40.00	40.752	21.802
16	Petron	Natural	Western Macedonia	10.00	40.732	21.697
17	Volvi	Natural	Central Macedonia	68.60	40.678	23.435
18	Zazari	Natural	Western Macedonia	2.00	40.625	21.546
19	Chimaditida	Natural	Western Macedonia	10.80	40.601	21.560
20	Kastoria	Natural	Western Macedonia	28.00	40.525	21.298
21	Agias Varvaras	Artificial	Central Macedonia	2.60	40.491	22.260
22	Sfikia	Artificial	Central Macedonia	4.30	40.373	22.163
23	Polyfitos	Artificial	Western Macedonia	74.00	40.218	21.948
24	Agios Georgios	Artificial	Western Macedonia	7.00	40.182	21.435
25	Ilarionas	Artificial	Western Macedonia	21.90	40.090	21.787
26	Aoos	Artificial	Epirus	11.40	39.828	21.074
27	Pamvotida	Natural	Epirus	24.00	39.666	20.883
28	Karla	Artificial	Thessaly	37.37	39.494	22.829
29	Hotkova	Natural	Epirus	1.07	39.481	20.459
30	Plastira	Artificial	Thessaly	24.00	39.297	21.753
31	Pournari	Artificial	Epirus	18.23	39.235	21.016
32	Smokovo	Artificial	Thessaly	8.50	39.145	22.074
33	Kremaston	Artificial	Western Greece	81.00	38.951	21.498

Table 1. *Cont.*

A/A	Lentic Water System	Category	Region	Area (km^2)	Lat.	Lon.
34	Saltini	Natural	Western Greece	2.26	38.908	20.770
35	Voulkaria	Natural	Western Greece	9.40	38.864	20.842
36	Kastraki	Artificial	Western Greece	28.00	38.797	21.362
37	Orichion	Natural	Central Greece	1.00	38.771	23.483
38	Amvrakia	Natural	Western Greece	14.50	38.752	21.182
39	Stratos	Artificial	Western Greece	8.40	38.692	21.330
40	Evinos	Artificial	Western Greece	3.50	38.667	21.854
41	Ozeros	Natural	Western Greece	9.40	38.654	21.222
42	Trichonida	Natural	Western Greece	97.20	38.566	21.556
43	Lisimachia	Natural	Western Greece	13.00	38.561	21.374
44	Mornos	Artificial	Central Greece	15.00	38.540	22.153
45	Paralimni	Natural	Central Greece	15.00	38.462	23.348
46	Iliki	Natural	Central Greece	25.00	38.404	23.256
47	Distos	Natural	Central Greece	4.50	38.352	24.127
48	Marathonas	Artificial	Attica	2.45	38.168	23.895
49	Pinios	Artificial	Western Greece	19.89	37.906	21.466
50	Stimfalia	Natural	Peloponnesus	3.50	37.854	22.463
51	Ladonas	Artificial	Peloponnesus	4.00	37.762	22.007
52	Kaiafas	Natural	Western Greece	1.68	37.509	21.611
53	Taka	Natural	Peloponnesus	2.60	37.433	22.365

At the same time, to further support the notion of minimal intervention, our reference scenario assumes a coverage percentage for floating PV systems equal to 1% over the available area of each lentic water system examined. The adopted value is in line with, or lower than, the respective assumptions made in similar, recent research [21], and quite lower than the coverage coefficients proposed by local market associations, in the order of 5%.

Before introducing additional aspects of research assumptions, we proceed with the presentation of input data, methodological steps, and set of equations, considering a bottom-up approach of analysis, from individual lentic water systems, to the regional and accordingly, the national level. The latter is better represented in the flow chart of Figure 1, where the different levels of analysis are described, together with the sequence of methodological steps towards the estimation of key energy parameters and the formulation of different strategic planning scenarios.

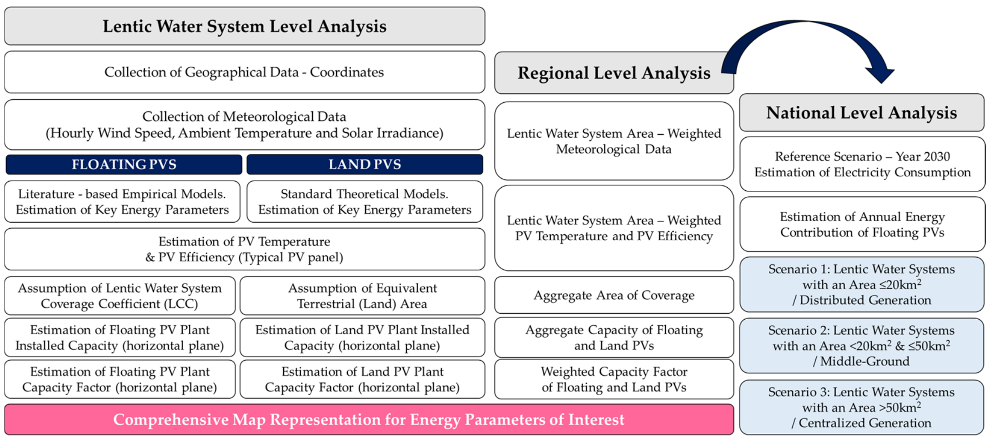

Figure 1. Schematic of the research methodological framework.

2.2. Input Data and Data Processing

For the application of the methodological framework, and by means of lentic water systems' coordinates, we made use of open-source meteorological data at a scale of 0.625° × 0.5°, available from the reanalysis MERRA 2 model [22]. The set of data refers to hourly time series for an entire year (2022), and captures the parameters of ambient temperature, ground level wind speed, and horizontal plane solar irradiance for each of the 53 lentic water systems.

Raw data were organized in a dedicated repository and further processed with the use of Visual Basic, in order to generate consolidated data files. The latter were accordingly used to enable the computation of both hourly time series and annual values of key energy parameters for the entire pool of lentic water systems examined. At the same time, consolidated data files were used to inform the development of relevant maps. The latter use the lentic water systems' area (Figure 2) as the backbone scaling parameter and illustrate annual averages of wind speed, annual solar potential values, and annual averages of ambient temperature (Figures 3–5). Moreover, clustering of lentic water systems per examined parameter assumes four different clusters (configured on the basis of percentiles p25, p50, and p75), applying to all four maps in Figures 2–5 and allowing for a higher-level of understanding concerning the spatial variation of key determinants for the assessment of floating PVs' theoretical potential.

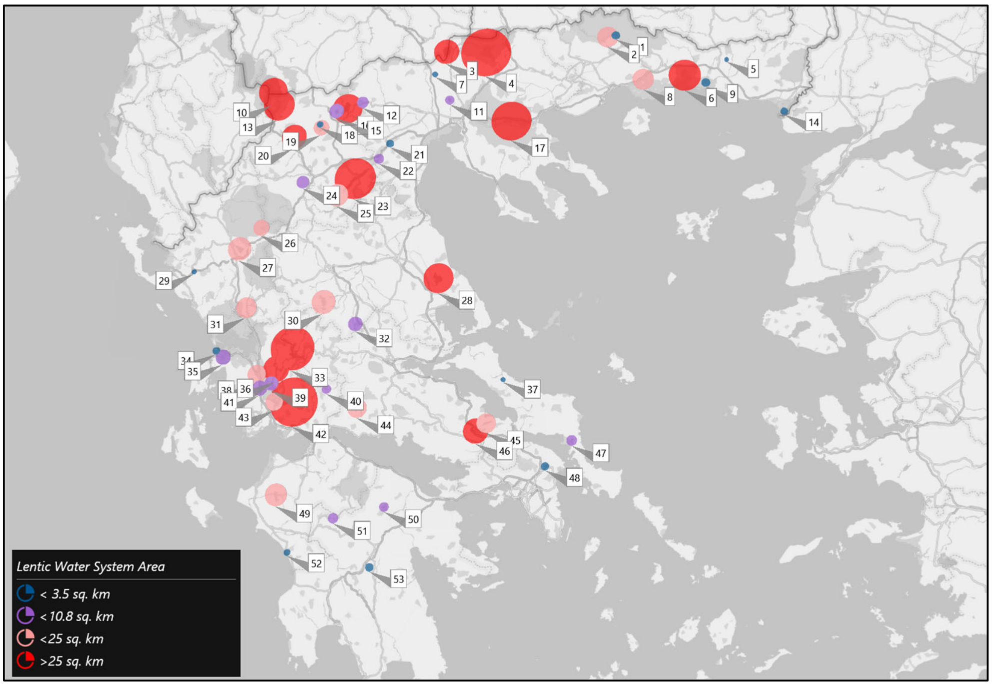

Figure 2. Map of lentic water systems' surface area.

In this context, as can be seen in Figure 2, the majority of larger-area lentic water systems can be found in the western and northern region of the Greek mainland, with medium and smaller scale ones located closer to sub-coastal areas and also in Peloponnese. Next, according to Figure 3, the majority of lentic water systems appreciate low-to-medium quality wind potential, with northern region systems featuring the lowest values of average wind speed. On the other hand, better quality wind potential may be encountered only in the case of a few, small-to-medium area lentic water systems, mainly on the eastern arc of the Greek mainland, in close proximity to the Aegean Sea.

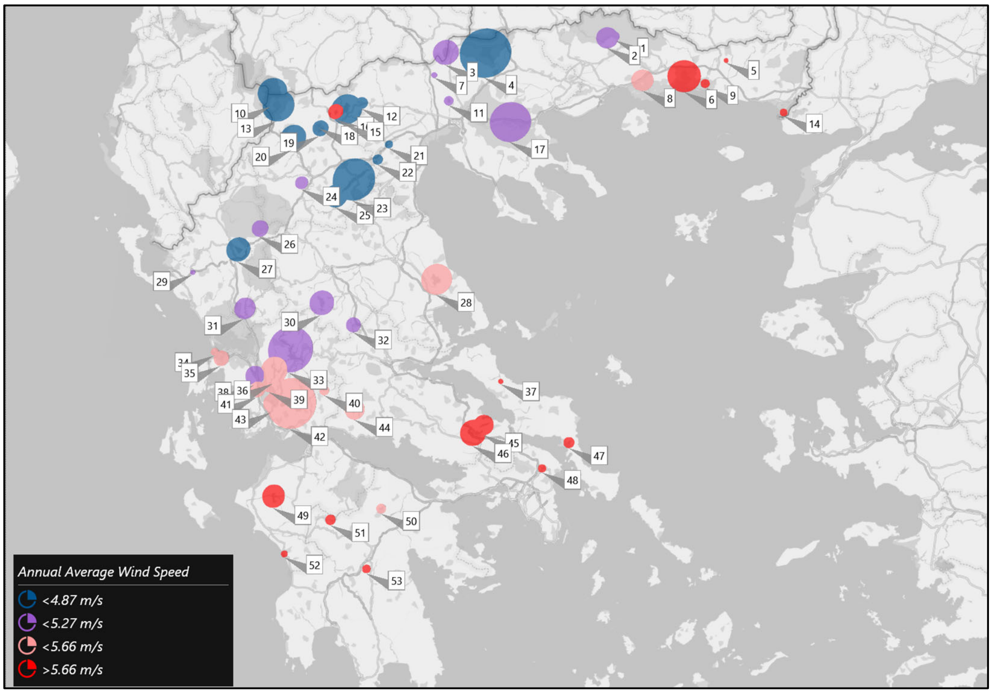

Figure 3. Map of lentic water systems' annual average wind speed.

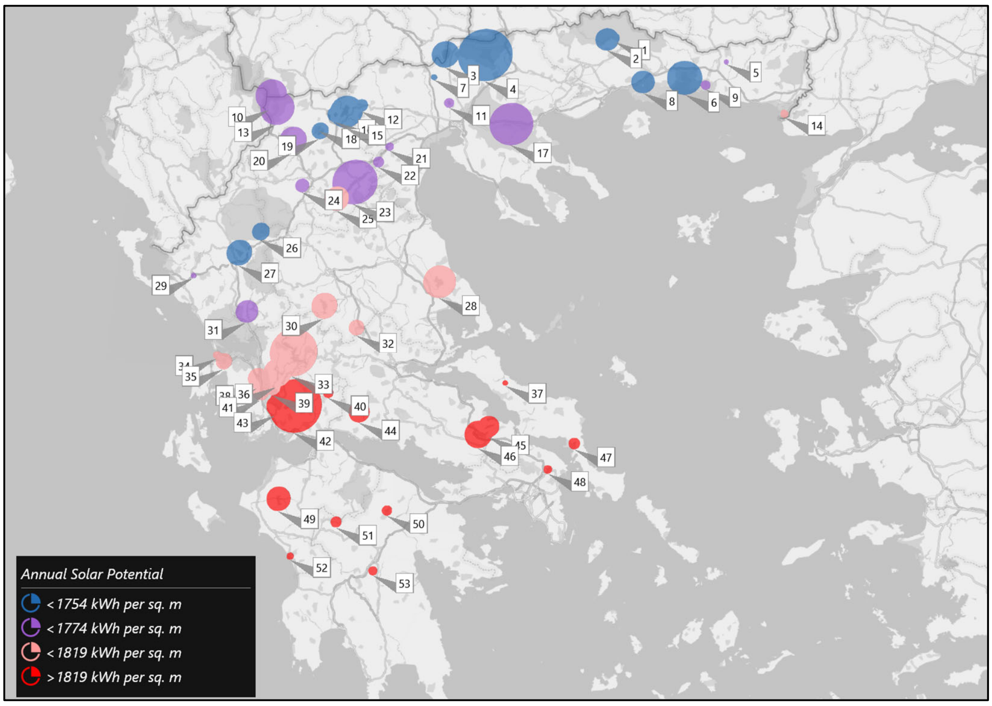

Figure 4. Map of lentic water systems' annual solar potential.

Moreover, as anticipated, the available solar potential (Figure 4) presents itself with higher values for lentic water systems in the south of the Greek mainland, gradually diminishing towards the northern regions. Besides, the same applies for ambient temperature averages, following an expected trend of decrease towards the north-western areas of the Greek mainland (Figure 5).

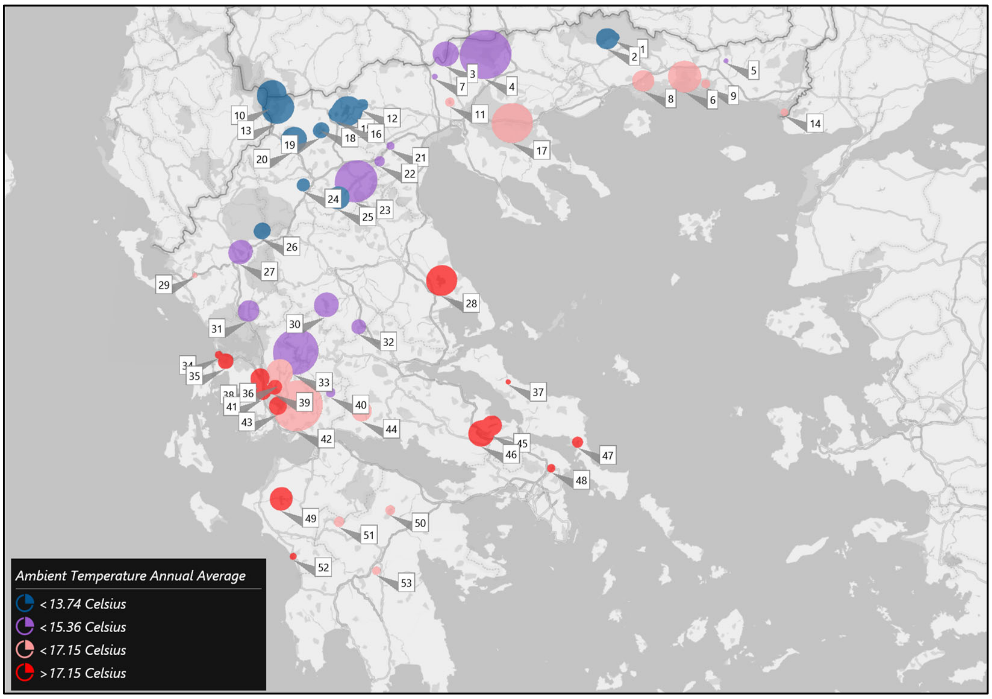

Figure 5. Map of lentic water systems' annual average ambient temperature.

2.3. Set of Equations and Assumptions

Having presented the input data of our research, presentation of the main equations used for the estimation of key energy indices follows. Initially, empirical models are drawn from the recent scientific literature [23], allowing for the estimation of floating PV panels' temperature "T_{fpv}" (the average values of Equations (1) and (2) are used, see also Equation (4)), based on the use of hourly data for the input parameters of ambient temperature "T_{α}", wind speed "WS", and solar irradiance "G", while accordingly, the respective parameter "T_{lpv}" is also determined for land-based PVs (see also Equation (5)).

$$T_{fpv-1} = 0.943 \cdot T_a + 0.0195 \cdot G - 1.528 \cdot WS + 0.3529 \tag{1}$$

$$T_{fpv-2} = 2.0458 + 0.9458 \cdot T_a + 0.0215 \cdot G - 1.2376 \cdot WS_w \tag{2}$$

$$WS_w = 1.62 + 1.17 \cdot WS \tag{3}$$

$$T_{fpv} = 0.5 \cdot \left(T_{fpv-1} + T_{fpv-2}\right) \tag{4}$$

$$T_{lpv} = 3.81 + 0.0282 \cdot G + 1.31 \cdot T_a - 1.65 \cdot WS \tag{5}$$

Next, by assuming the technical characteristics of a typical PV panel (Table 2), used also in [23], the respective hourly efficiency "η_{pv}" can be estimated (Equation (6)). The latter depends on the nominal panel efficiency "η_{STC}" (20.5%) under standard conditions of operation, i.e., panel temperature "T_{STC}", the respective actual panel temperature "T_{pv}" ("T_{fpv}" or "T_{lpv}"), and the power–temperature coefficient "γ" (−0.36%/°C), and is currently assumed to maintain the same value at the PV plant level as well.

$$\eta_{pv} = \eta_{STC} \cdot \left[1 - \gamma \cdot \left(T_{pv} - T_{STC}\right)\right] \tag{6}$$

By estimating the PV efficiency, the estimation of the hourly power output of the PV plant is possible (Equation (8)), after the determination of the relevant installed capacity (Equation (7)).

$$N_{pv} = \eta_{STC} \cdot A_l \cdot LCC \cdot G_{STC} \cdot AR \tag{7}$$

$$N_{pv(h)} = \eta_{pv} \cdot A_l \cdot LCC \cdot G_{(h)} \cdot AR \tag{8}$$

Table 2. Typical PV panel technical characteristics.

Panel Type	Multi-Crystalline
Max power	425 W
Max voltage	42.5 V
Max current	10.01 A
Open circuit voltage	49.8 V
Short circuit current	10.67 A
Nominal efficiency "η_{STC}"	20.5%
Power-temperature coefficient "γ"	−0.36%/°C

In more detail, by adopting a given coverage coefficient "LCC" in relation to the available area of the lentic water system examined "A_l", and by determining the ratio of the panels' area against the area of the PV installation "AR" (currently considered equal to one since assuming zero tilt angle in order to serve the purpose of minimal intervention through the minimization also of the panels' visual impact), the theoretical PV potential (installed capacity "N_{pv}") may be determined for standard solar irradiance of "G_{STC}" (1000 W/m^2).

Similarly, based on Equation (8), one may also estimate the hourly average of power output "$N_{pv(h)}$", also taking into account the hourly variation of solar irradiance "$G_{(h)}$" and PV efficiency "η_{pv}". At this point, it should be noted that the given value does not consider conversion and transmission–distribution losses. In addition, no shading effect is evaluated, assuming that, and owing also to the adopted value of relative size (LCC of 1%), floating PVs can be optimally sited within the boundaries of the lentic water system examined.

Furthermore, through the integration of hourly values of power output, the annual energy yield "$E_{pv(y)}$" and relevant capacity factor "$CF_{pv(y)}$" of the examined PV installation may be estimated using Equations (9) and (10). At the same time, through the aggregation of lentic water systems, the corresponding energy yield may be expressed at the regional and national level, as the sum of annual energy products "$TE_{pv(y)}$" for a number "n" of lentic water systems examined each time (Equation (11)). Finally, for other sets of parameters, the weighted average, in relation to the lentic water systems' area variation, can also be provided (e.g., the weighted average capacity factor "$WCF_{pv(y)}$" under Equation (12)).

$$E_{pv(y)} = \sum_{h=1}^{8760} N_{pv(h)} \tag{9}$$

$$CF_{pv(y)} = E_{pv(y)} \cdot \left(N_{pv} \cdot 8760\right)^{-1} \tag{10}$$

$$TE_{pv(y)} = \sum_{i=1}^{n} E_{pv(y),i} \tag{11}$$

$$WCF_{pv(y)} = \left(\sum_{i=1}^{n} CF_{pv(y),i} \cdot A_{l,i} \cdot LCC_i\right) \cdot \left(\sum_{i=1}^{n} A_{l,i} \cdot LCC_i\right)^{-1} \tag{12}$$

3. Results

Following the presentation of the methodology section, we proceed accordingly with the analysis of application results, first at the level of individual lentic water systems and next at the aggregate, regional level. Results obtained are analyzed with the support of informative maps, similar to input data of Section 2.2, facilitating spatial analysis and providing a lower (individual lentic water system) and a higher (regional) level of representation for strategic planning decisions.

3.1. Lentic Water System Level of Analysis

Applying Equations (7)–(10) under the assumption of 1% for the coverage coefficient (LCC), we estimate the theoretical, limited-intervention PV capacity per lentic water system, and reflect on the comparison between floating and land-based PVs in terms of anticipated annual CF values. At this point, it should also be noted that land-based systems refer to hypothetical installations of equivalent capacity to that of floating ones, and are assumed to encounter the same meteorological conditions (wind speed, ambient temperature, and solar irradiance profiles) met in the respective lentic water systems.

Estimated PV capacity results are provided in the map of Figure 6, with the designation of four capacity clusters, stretching from installations kept below ~7 MW to lentic water systems presenting a potential that goes beyond 50 MW. The driving parameter to that end is the area of the lentic water system "A_l", which may be confirmed by a comparison between the respective maps, given under Figures 2 and 6. To that end, the minimum capacity is given for lentic water system No. 5 (2.05 MW) and the respective maximum (~225 MW) for lentic water system No. 4.

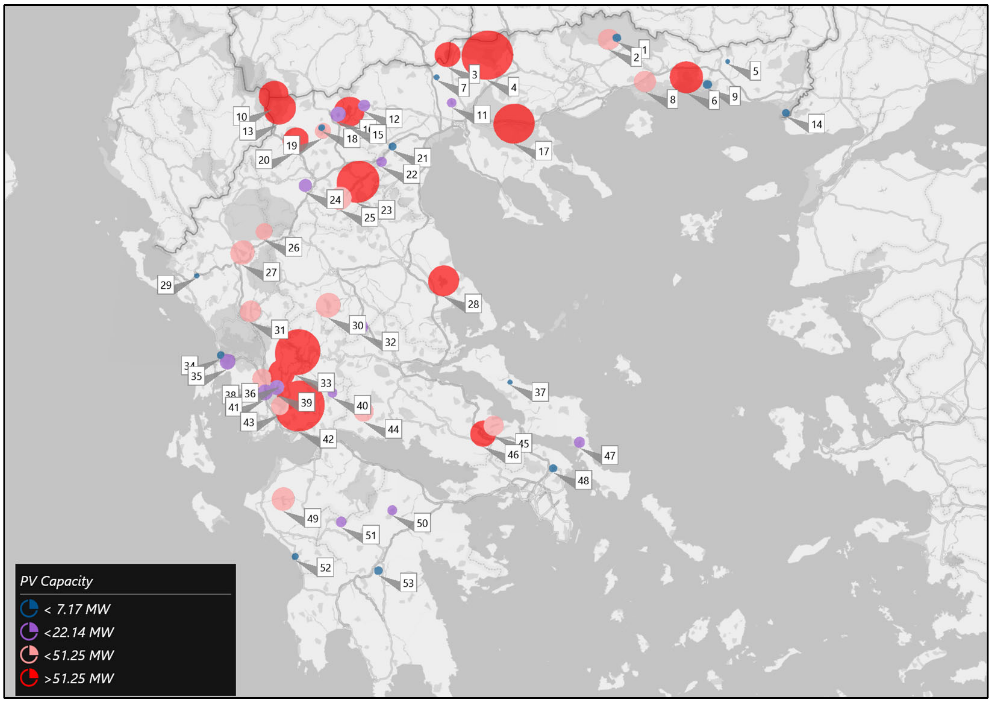

Figure 6. Map of lentic water systems' theoretical PV capacity.

At the same time, the theoretical, lentic water system floating PV capacity at the national level suggests a maximum, aggregate potential that could reach 2.2 GW_p, with the current, already existing capacity of land-based PVs in Greece presenting a total of ~7 GW_p [24]. This is indicative of the potential available even under the assumption of minimal intervention in terms of area coverage, with the geographical spread of floating PVs covering a large part of the northern and western Greece arc, while offering a wide spatial distribution that could serve the needs of numerous local communities.

Opposite to the results of theoretical capacity, clustering against the variation of the anticipated annual CF (Figure 7) is independent from the lentic water systems' available area, depending primarily on the quality of the local solar potential, and secondly on the rest of meteorological parameters, i.e., wind speed and ambient temperature. Given that, higher CF values are met in the southern and central parts of the Greek mainland, with numerous northern lentic water systems presenting values below 20% (e.g., lentic water systems No. 1, 2, 3, 7, 27, 4, 11, 8, and 12).

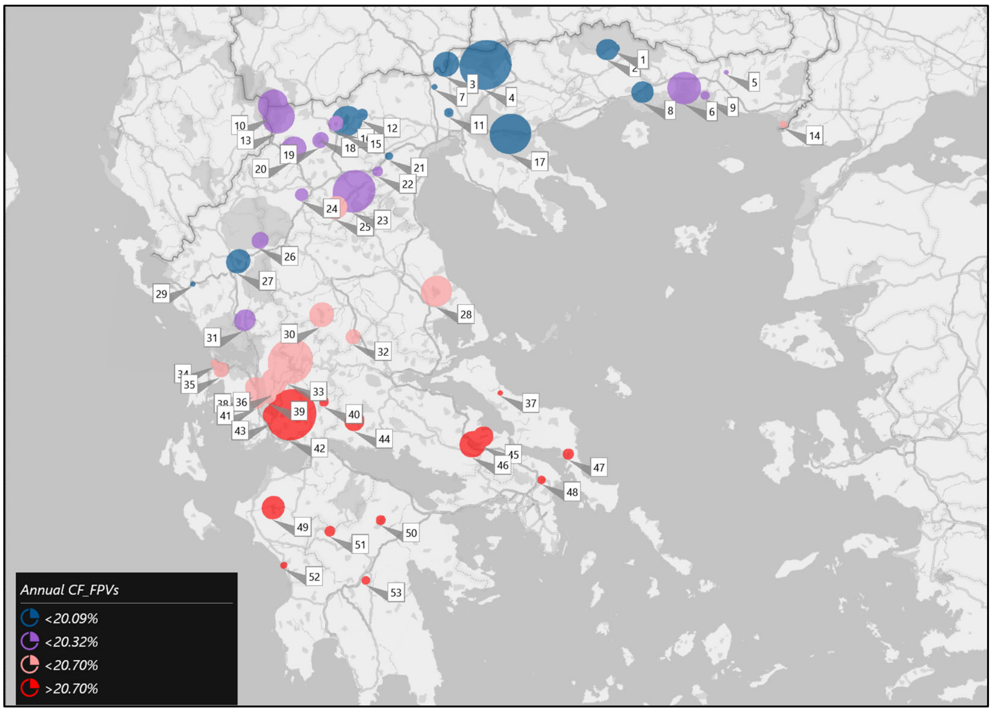

Figure 7. Map of lentic water systems' annual CF (floating PVs).

The lowest CF value to that end is presented for lentic water system No. 1, while the highest one is for lentic water system No. 48. As such, lentic water systems appreciating high-quality solar potential and favorable wind speed and/or temperature conditions may refer to a higher CF cluster, compared to the respective area cluster and vice versa. One similar example corresponds to lentic water system No. 49, belonging to the third area cluster, i.e., <25 km^2 (Figure 2). The given system features a solar potential of 1882.5 kWh/m^2.a and annual average wind speed of 5.82 m/s, leading to an annual CF value of 21.39% which matches the fourth CF cluster (>20.70%).

Accordingly, by attempting a comparison with the respective CF values for similar capacity land-based PV stations, while maintaining the same range of variation for CF cluster values (Figure 8), energy benefits from the exploitation of floating PVs become apparent. On average, the corresponding CF values anticipated in the case of land-based PVs suggest a relative reduction of approximately 5.5%, while it is only for the areas corresponding to lentic water systems No. 45–53 that we meet values exceeding the lower CF cluster of <20.09%.

3.2. Regional Level of Analysis

Following the presentation of results at the individual lentic water system level, representation at the regional level is provided (Figures 9–11 and Table 3). In this context, in Figure 9 we present the aggregate, theoretical PV capacity for the different mainland regions of Greece, followed by the respective CF maps for both floating and land-based PVs. In each of the maps, the estimated range of values adapts to a grey scale variation, with the higher and lower values among regions highlighted with different colors (dark blue and pink, respectively). In more detail, Figure 9 suggests that half of the maximum, national theoretical capacity of ~2.2 GW$_p$ is concentrated in western Greece and central Macedonia (591 MW and 542 MW, respectively), with the southern territory (Peloponnese and Attica) holding a quite limited potential in the order of ~26 MW, i.e., ~1.2% of the respective national capacity. At the same time, the northern arc, extending from Epirus to eastern Macedonia and Thrace, presents a theoretical potential that exceeds 1.2 GW$_p$, with Thessaly and central Greece holding a share of ~12% over the respective national capacity.

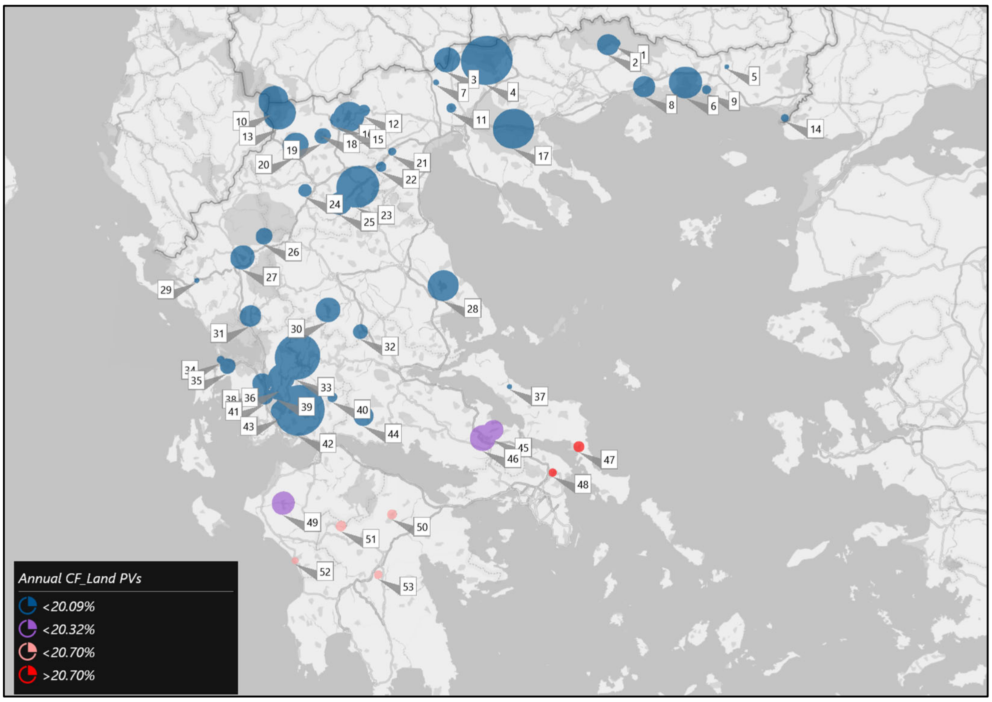

Figure 8. Map of annual CF for equivalent, land-based PVs.

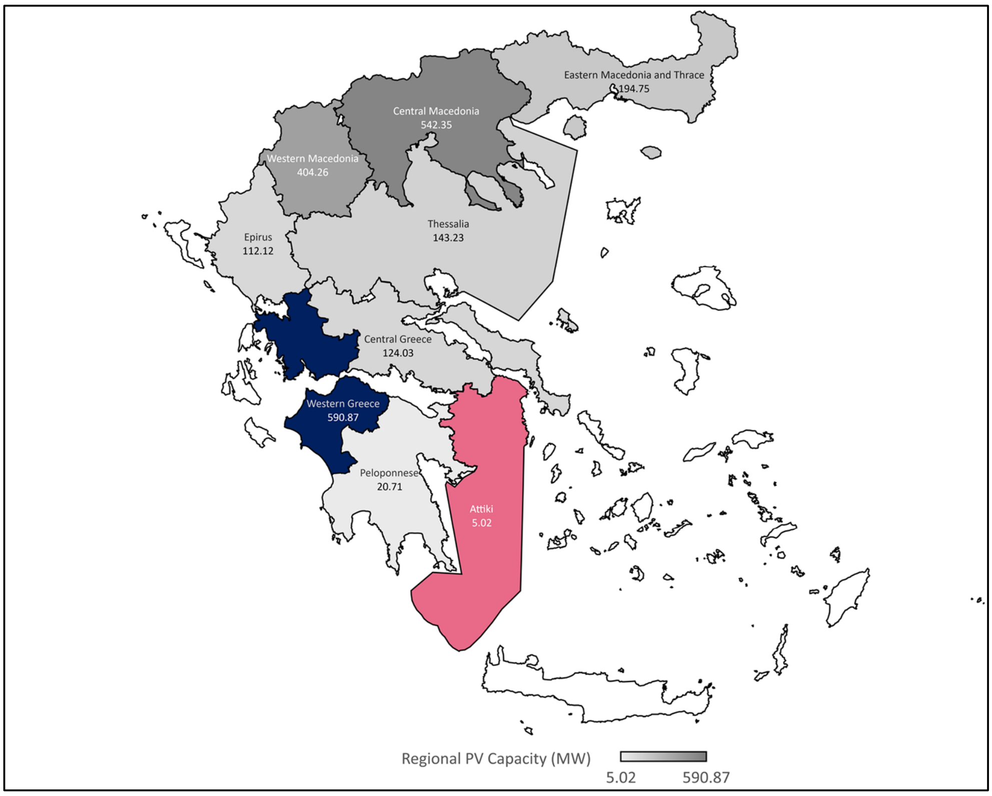

Figure 9. Map of lentic water systems' theoretical PV capacity at the regional level.

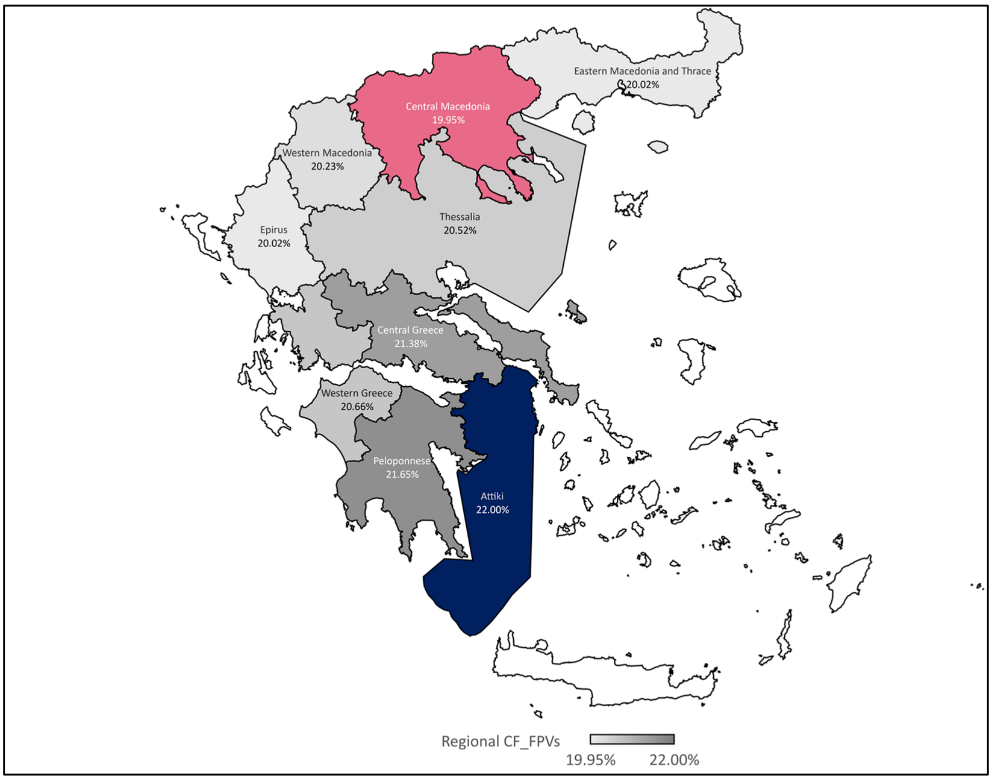

Figure 10. Map of lentic water systems' annual CF at the regional level (floating PVs).

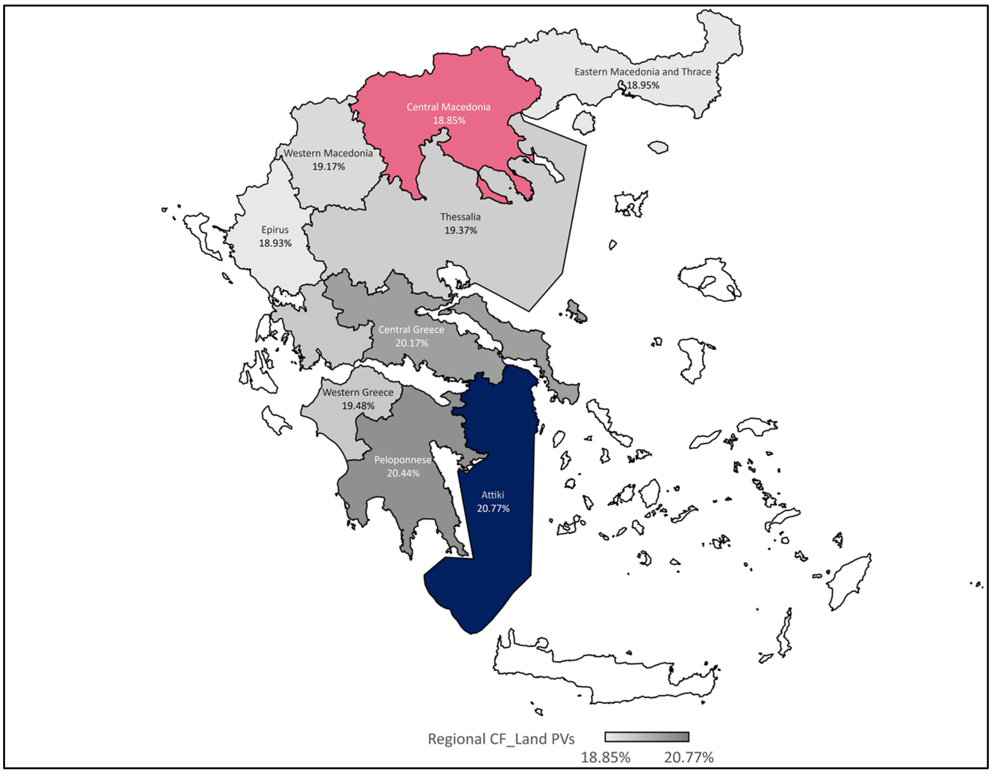

Figure 11. Map of annual CF for equivalent, land-based PVs at the regional level.

Table 3. Synopsis of regional analysis results.

Mainland Region	Theoretical PV Capacity (MW)	Floating Solar Annual CF	Land-Based Solar Annual CF
Eastern Macedonia & Thrace	194.75	20.02%	18.95%
Central Macedonia	542.35	19.95%	18.85%
Western Macedonia	404.26	20.23%	19.17%
Epirus	112.12	20.02%	18.93%
Thessaly	143.23	20.52%	19.37%
Central Greece	124.03	21.38%	20.17%
Western Greece	590.87	20.66%	19.48%
Attica	5.02	22.00%	20.77%
Peloponnese	20.71	21.65%	20.44%

Given the above, it can be seen that the greatest shares of floating PV capacity are met in the peripheral, western–northern arc of the Greek mainland, where almost 1/3 (~3.3 M people) of the mainland population resides and where the local solar potential is the least favorable across the Greek territory. On the other hand, the interior, east side of the mainland, including the regions of Thessaly, central Greece, Attica, and Peloponnese, carrying ~2/3 of the mainland population, introduces an aggregate capacity of less than 300 MW_p. At this point, it should be mentioned that the already existing capacity of land-based PVs in the Greek mainland is relatively balanced between these two broader geographical regions, with the interior east-side arc holding a share of ~55% [25], owing also to the more favourable solar potential conditions met in the area.

This is further supported by the presentation of weighted average CFs (see also Equation (12)) at the regional level (Figure 10), with the highest of values noted in the case of the interior, east-oriented arc of the Greek mainland. To that end, the Attica region, which is in essence referring to a single lentic water system, i.e., No. 48, presents the highest CF of 22%, while the lowest one is given for the region of central Macedonia (18.85%). At the same time, the advantage of floating against land-based PVs is again reflected through the presentation of relevant results in Figure 11. The respective range of variation reduces in the span between 18.85% and 20.77%, which, as already seen, compares unfavorably with the corresponding of floating PVs, i.e., 19.95–22%.

On the other hand, as expected, regional variation follows the same pattern, as in floating PVs, with Attica presenting the highest CF and central Macedonia the lowest. Finally, by applying Equation (11) for both floating and land-based PVs at the national level, the estimated annual energy yield reaches approximately 3.95 TWh and 3.73 TWh, respectively, with the Greek mainland's overall electricity consumption currently found to exceed 50 TWh.

3.3. Strategic Planning Scenarios

Based on the assessment of the theoretical floating PV potential in lentic water systems of the Greek mainland, in the current section we proceed with the elaboration of three different strategic planning scenarios concerning the development of floating PVs at the national level. In doing so, we categorize lentic water systems of Table 1 into three different groups, i.e., small-scale systems with an area less than or equal to 20 km^2, medium-scale systems with an area between 20 km^2 and 50 km^2, and large-scale systems with an area exceeding 50 km^2.

To that end, we argue that the selected groups reflect on scenarios supporting distributed generation patterns on the one hand and a centralized generation model on the other, with the intermediate group of medium-scale lentic water systems offering a middle-ground alternative.

On that note, under the first group, one may find a total of 36 lentic water systems with an aggregate area of 267.07 km^2, while under the second group, the total number of medium-scale lentic water systems reaches 12, with an aggregate area of 382.37 km^2. Finally, the number of large-scale lentic water systems is limited to five, with the respective aggregate area stretching to 430.76 km^2.

By adopting the above categorization, we next provide an estimation of the equivalent area coverage coefficient required per different group of lentic water systems, in order to achieve the annual energy yield of ~4 TWh, corresponding to all 53 lentic water systems and the minimal-intervention approach (assumed area coverage coefficient of 1%). The relevant results are gathered in the following Table 4.

Table 4. List of strategic planning scenarios.

Scenario	Category	No. of Lentic Water Systems	Annual En. Yield (1% Coverage)	Revised Area Coverage
Distributed Generation	$\leq$20 km^2	36	~0.98 TWh	~4%
Middle-Ground	>20 km^2 and $\leq$50 km^2	12	~1.39 TWh	~2.8%
Centralized Generation	>50 km^2	5	~1.57 TWh	~2.5%

As one may obtain, adoption of the distributed generation scenario introduces an increase in the required coverage area to the level of 4%, with the middle-ground and centralized generation scenarios moving to lower numbers, i.e., 2.8% and 2.5%, respectively. This is indicative of the trade-off between the dimensions of lentic water systems' number, available area, and floating PV coverage coefficient, with the results obtained presenting mild sensitivity while coping with the principle of limited intervention, even in the case of the distributed generation scenario.

At the same time, by maintaining the minimal intervention coverage coefficient of 1%, a relatively balanced distribution of the aggregate energy yield may be witnessed amongst the three scenarios, from ~0.98 TWh in the case of the distributed generation model, to 1.57 TWh in the case of the centralized model.

The given figures imply a potential contribution of ~1.5–2.5% over the predicted Greek mainland electricity consumption in 2030 (~60 TWh) [1] for each different group of lentic water systems, which is arguably considerable and at the same time provides sufficient flexibility for the elaboration of different planning and policy-making exercises towards the development of a strategic roadmap for the application of floating PVs in the Greek territory.

3.4. Regional Planning Results and Strategic Roadmaps' Directions

Our analysis concludes with the elaboration of implications concerning the application of the three strategic scenarios at the regional level. In support of that, the following set of maps (Figures 12–14) demonstrates the distribution of envisaged floating PV capacity per different scenario and each Greek mainland region, while additional aspects of the results obtained are given in Figure 15. In Figure 15a, the number of lentic water systems and the share of artificial lentic water system per different region is provided in more detail and in Figure 15b, the variation of floating system size per different strategic scenario, for all regions examined, is illustrated.

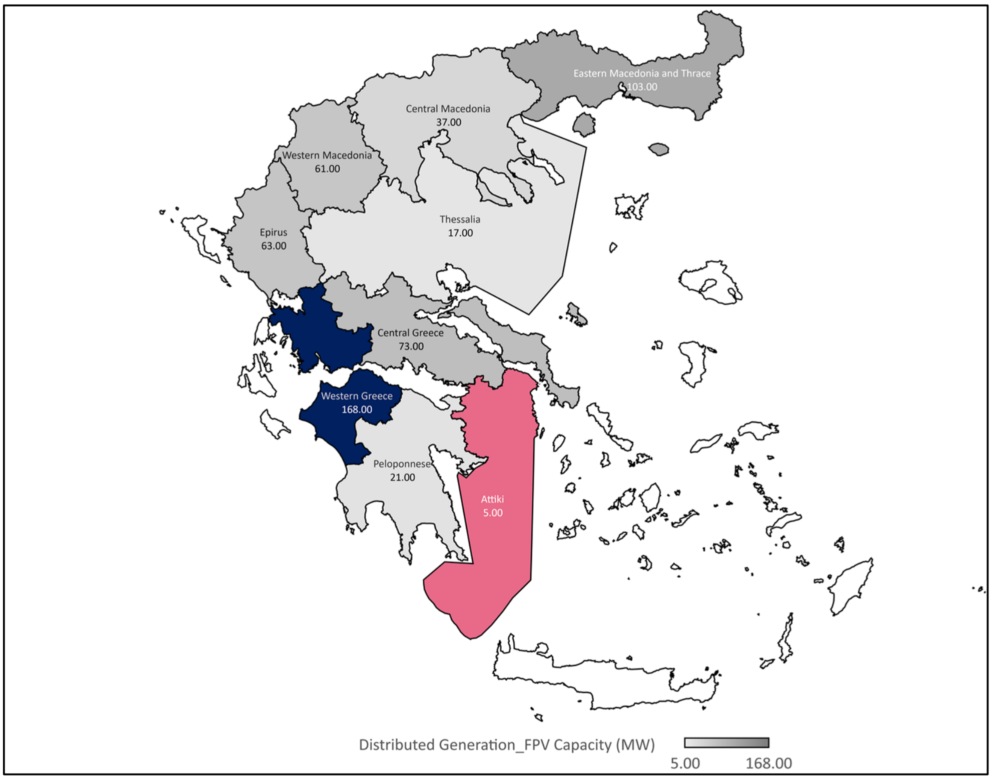

Figure 12. Map of theoretical PV capacity at the regional level (distributed scenario).

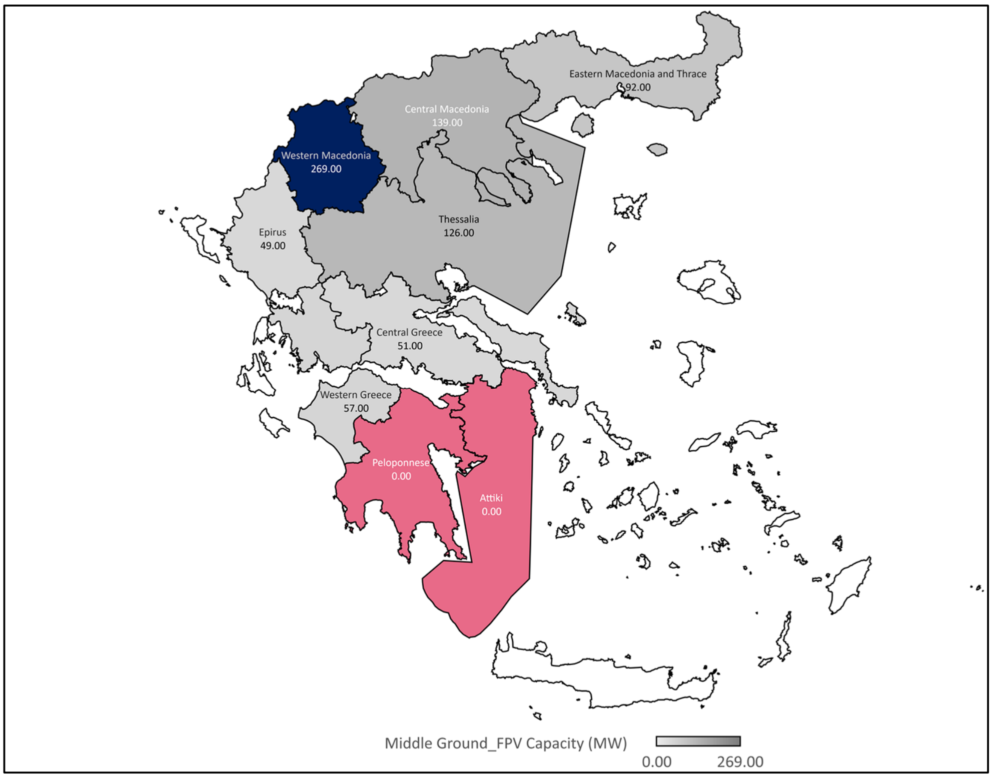

Figure 13. Map of theoretical PV capacity at the regional level (middle-ground scenario).

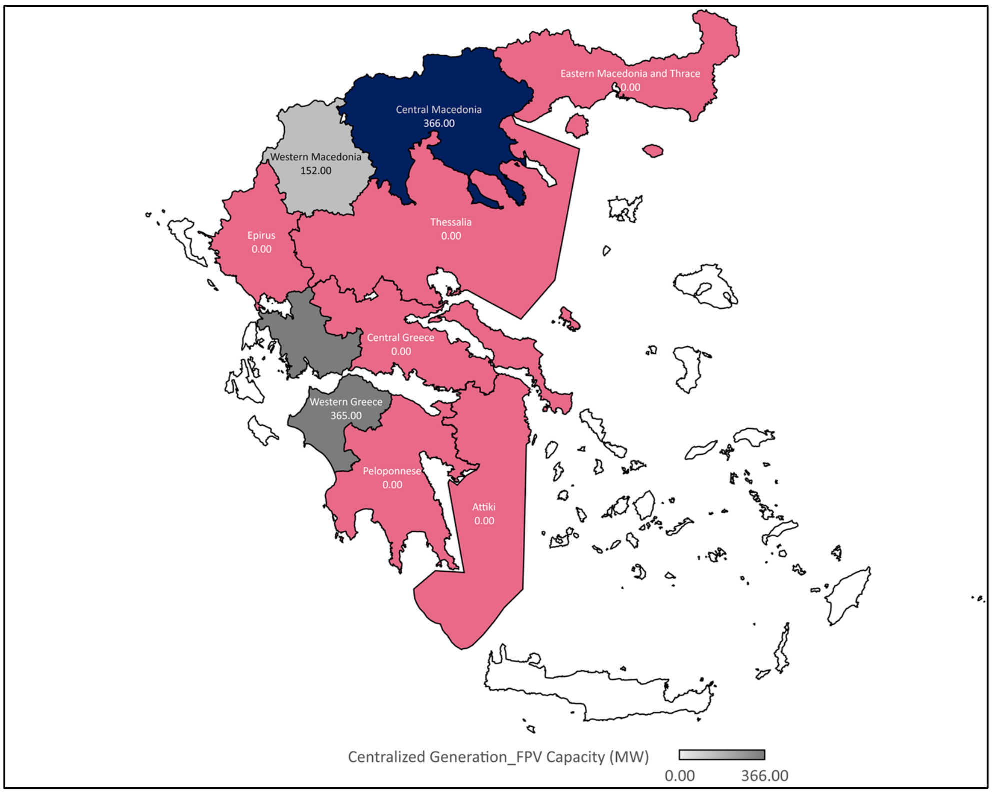

Figure 14. Map of theoretical PV capacity at the regional level (centralized scenario).

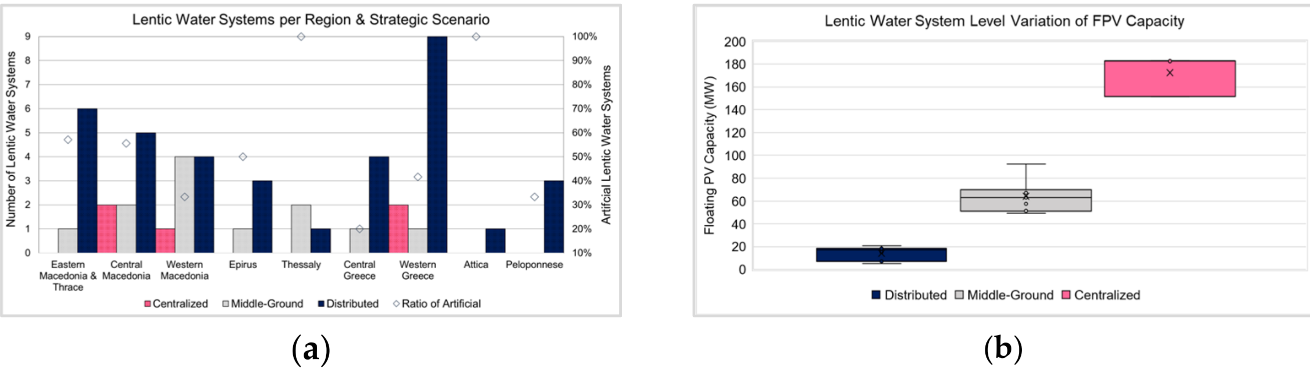

Figure 15. Region-based number of lentic water systems and share of artificial lentic water systems per strategic scenario (**a**) and lentic water system level floating PV capacity variation (**b**).

Starting with the distributed generation scenario, the number of involved lentic water systems varies from one to nine (Figure 15a), with the respective aggregate regional capacity ranging between ~5 MW and 168 MW, with an average of 61 MW (Figure 12). Moreover, the capacity per lentic water system presents a variation between 5 MW and 21 MW, and an average of ~14 MW, with the distributed generation scenario spanning across all examined regions (Figure 15b).

Accordingly, under the middle-ground scenario, the number of involved regions narrows down, excluding Attica and Peloponnese, with the lentic water systems for the rest of the regions varying from one to a maximum of four in the case of western Macedonia (Figure 15a). At the same time, the aggregate regional level capacity is found to be between ~49 MW and ~269 MW, with an average of 112 MW (Figure 13), while the lentic water system capacity presents a minimum of 49 MW, a maximum of ~92 MW, and an average of ~64 MW (Figure 15b).

Next, the centralized generation scenario is supported by a limited number of regions, i.e., three, with either one or two lentic water systems per region (Figure 15a). The aggregate regional level capacity lies between 152 MW and 365 MW, with an average of 294 MW (Figure 14), and the lentic water system capacity suggests the development of installations spanning from 152 MW to 182 MW, with an average of 172 MW (Figure 15b).

Finally, another aspect of the results obtained is given in Figure 16, where the overall variation in lentic water system size for all three scenarios per different region is presented. According to the latter, the average lentic water system varies between ~25 MW and 60 MW, with the exception of Attica and Peloponnese, capturing distributed generation systems alone.

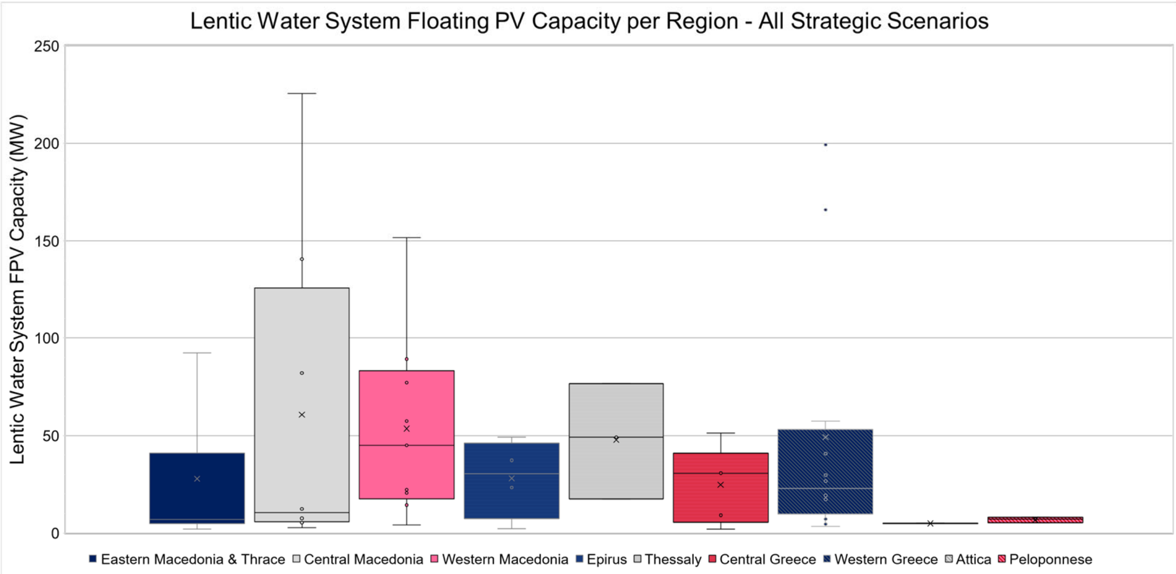

Figure 16. Variation of lentic water system level floating PV capacity per region.

Acknowledging the above, the development of different strategic roadmaps for the exploitation of the identified potential may be informed. These may refer to the adoption of regional and/or national scale planning directions, putting forward different sets of criteria. Similar, indicative strategic directions may refer to the following:

- Prioritization of installations in regions with the highest potential of floating solar capacity and/or number of available lentic water systems, and/or proportional development per region under a potential-driven approach per different strategic scenario;
- Prioritization of small-scale, pilot installations for demonstration purposes under the adoption of a bottom-up transition approach, i.e., from the distributed to the centralized generation scenario;
- Prioritization of centralized installations implying a greater impact that may accordingly trigger a roll-out effect under a top-down transition approach;
- Prioritization of cooperative schemes (e.g., district-level cooperatives) for the exploitation of the available potential through the provision of relevant state incentives;
- Prioritization of artificial lentic water systems over natural ones in order to gain a better understanding of system environmental impacts, starting from ecosystems of comparably lower vulnerability, offering also the opportunity for the exploitation of already existing infrastructure (e.g., in the case of lentic water systems where hydropower plants are operated).

To conclude our analysis, Table 5 attempts a comparison between the three strategic scenarios considered, listing different challenges and opportunities that may rise in the prospect of implementing each of the former.

Table 5. Strategic scenarios challenges and opportunities.

Scenario	Challenges and Opportunities
Distributed Generation	✓ Higher specific costs anticipated ✓ Pilot stations' development ✓ Mainland-wide application ✓ Balanced mix of artificial and natural lentic water systems (17/19) ✓ Local-scale industry development ✓ Encouragement of cooperative schemes' development ✓ Potential generation of benefits for local communities ✓ Market power decentralization ✓ Limited understanding of broad-scale environmental impacts
Middle-Ground	✓ Moderate economies of scale ✓ Territorial-wide application (except for two regions) ✓ Positive, territorial-scale impact ✓ Risk of negative, territorial-scale impact ✓ Non-balanced mix of artificial vs natural lentic water systems (4/8) ✓ Territorial-scale industry development ✓ Development of broader cooperative schemes ✓ Development of public-private schemes ✓ Deeper understanding of potential environmental impacts
Centralized Generation	✓ Economies of scale benefits ✓ Limited number of regions involved ✓ Positive, national-scale impact ✓ Risk of negative, national-scale impact ✓ Balanced mix of artificial and natural lentic water systems (3/2) ✓ Reduced opportunities for cooperative schemes ✓ Increased risk of market oligopolies ✓ Large-scale industry development ✓ Sufficient appreciation of environmental impacts at the large scale

4. Conclusions

In the present study, we assessed the theoretical potential of floating PVs for lentic water systems of the Greek mainland. We did so by looking into 53 different lentic water systems across the Greek territory, meeting the constraint of 1 km^2 of minimum surface area. Based on the given pool of lentic water systems, we proceeded with the estimation of the relevant floating PV capacity per system, and also at the regional level, under the application of a minimal intervention approach, assuming PV coverage of 1% over the total area of each lentic water system.

In this context, our findings indicated a maximum, aggregate theoretical capacity which could exceed 2 GW_p at the national level, with the respective annual energy yield reaching approximately 4 TWh or, equivalently, over 6% of the country's anticipated annual electricity consumption in 2030. Moreover, our results extended further, identifying the energy merits of floating PVs against the development of similar, land-based installations, with the respective annual energy yield presenting, on average, a difference of approximately 5.5% in favour of floating solar.

Finally, our work concluded with the elaboration of strategic planning scenarios that offer a set of different roadmap alternatives concerning the development of the floating solar technology locally, addressing both distributed and centralized generation policy directions.

In closing, it goes without saying that for a more thorough evaluation of the potential for floating solar development, especially at the local, lentic water system level, a more meticulous, multi-criteria analysis is required, capturing environmental, economic, biodiversity, and social aspects, as foreseen by the authors in the context of further research work in the given subject area.

In the same direction, investigation of alternative planning objectives could also be considered for future research, such as with the assessment of the maximum energy yield theoretical potential under the application of optimum panel tilt angles for the examined lentic water systems and the conduction of a more targeted energy analysis on the introduction of floating solar in hydroelectric reservoirs of the Greek mainland, aiming to a coordinated operation with local hydropower plants.

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