Renewable and Sustainable Energy Reviews 171 (2023) 112989

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Benefits of pairing floating solar photovoltaics with hydropower reservoirs in Europe

G. Kakoulaki [a,*], R. Gonzalez Sanchez [a], A. Gracia Amillo [b], S. Szabo [a], M. De Felice [c], F. Farinosi [a], L. De Felice [a], B. Bisselink [a], R. Seliger [d], I. Kougias [e], A. Jaeger-Waldau [a]

[a] European Commission, Joint Research Centre (JRC), Ispra, Italy
[b] Fraunhofer Institute for Solar Energy Systems, ISE, Germany
[c] European Commission, Joint Research Centre (JRC), Petten, Netherlands
[d] Piksel S.R.L., Milan, Italy Working for the European Commission, Joint Research Centre (JRC), Ispra, Italy
[e] Regulatory & Business Development Division, Elpedison S.A., Greece

ARTICLE INFO

Keywords:
Floating solar photovoltaic
Hydropower
Water saving
Evaporation
Reservoir

ABSTRACT

Achieving carbon-neutrality is increasing the demand of renewable electricity which is raising the competition for land and associated acquisition costs. Installation of floating photovoltaic (FPV) on existing hydropower reservoirs offers one solution to limited land availability while providing solar electricity, leveraging water bodies, and reducing water evaporation losses. This work assesses the potential electricity output of FPVs at regional and national levels on 337 hydropower reservoirs in the EU27 considering four scenarios and two types of floaters. Evaporation, water losses and water savings due to FPVs installation are also estimated using climatic parameters for the year 2018. The reservoirs' total water losses are estimated at 9380 mcm. 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. In this case, up to 557 mcm could be saved by installing FPV. The FPVs' multiple benefits and the potential offered by existing hydropower reservoirs are compatible with the EU's goals for net zero emissions and more autonomy from imported fossil fuels and energy transformation.

1. Introduction

Floating photovoltaics (FPV) is an emerging technology in which solar photovoltaic systems are installed on water surfaces and provide a potential solution to increase PV deployment in land-constrained areas [1]. It provides an alternative solution for countries with high population density and/or shortage of available areas to expand conventional solar power installations while decarbonizing the energy supply and removing the pressure from urbanized areas or regions where land is required for other uses like agriculture [2–4]. In the last decade, FPV has attracted great interest thanks to the increased investment in renewable energies. However, much more deployment is needed to achieve global climate change mitigation targets. Under the Sustainable Development Scenario of the International Energy Agency's (IEA) World Energy Outlook (WEO) 2021, the electricity share of Renewable Energy Sources (RES) would increase from 28.4% in 2020 to 83.6% in 2050, globally. In 2050, electricity from hydropower and solar PV would account for 7921 TWh and 17,433 TWh respectively from the total available electricity production worldwide, compared to 4347 TWh and 833 TWh in 2020 [5]. This would require an increase of the installed PV capacity of 953 GW at the end of 2021–10,980 GW by 2050 – a tenfold increase in less than 30 years [6].

Floating solar photovoltaics could be combined with PV systems on reservoirs already used for hydropower introducing and promoting synergies on the integration into the energy system [7] by utilizing the existing grid-connections [8,9].

Globally, hydropower still represents the largest share of renewable electricity generation, with over 1330 GW (1360 GW in 2021) of capacity installed [10]. Out of this, 328 GW is produced from run-of-river hydropower plants, and the rest from hydropower reservoirs (160 GW of which is hydro pumped storage). These reservoirs have the potential to host 4444 GW of FPV power plants with only 25% surface coverage, generating approximately 6270 TWh of electricity [10]. [11] performed a study on the 128 largest hydropower reservoirs in the US, concluding that the same electricity generation obtained from hydropower could be obtained by covering 1.2% of the reservoirs surface area with FPV. Another study by Ref. [12] estimated the FPV power potential for the 20

* Corresponding author.
E-mail address: Georgia.Kakoulaki@ec.europa.eu (G. Kakoulaki).

https://doi.org/10.1016/j.rser.2022.112989
Received 29 March 2022; Received in revised form 23 August 2022; Accepted 7 October 2022
Available online 8 November 2022

Abbreviations

AOI	angle of incidence
AEP_{FPV}	annual electricity production FPV (MWh/yr)
A_{FPV}	total area of the reservoir covered by floating PV (m^2)
A_{res}	total area of the reservoir (m^2)
CAPEX	Capital Expenditure
CF	capacity factor
DNV	Det Norske Veritas
EMO-5	European Meteorological Observations whereas the 5 denotes the spatial resolution of 5 km
EU	European Union
EP	Electric power
FPV	floating photovoltaic
GRanD	Global Reservoir and Dam Database
GSW	Global Surface Water dataset
GWh	gigawatt-hour
HDAM	hydropower plant reservoir based
HE	hydroelectricity
HEIC	hydropower equal installed (power) capacity
HPP	hydropower plants
HROR	hydropower run of river
HPHS	hydropower plant pumped storage
ICOLD	International Commission on Large Dams
I_{opt}	annual PV energy yield at the reservoir's location (kWh/kWp)
JRC	Joint Research Center
LCOE	Levelised Cost of Electricity
LISFLOOD	hydrological rainfall-runoff and channel routing model
LISVAP	model developed to provide potential reference evapotranspiration
NUTS	Nomenclature of Territorial Units for Statistics
NUTS2	Nomenclature of Territorial Units for Statistics at regional level
OPEX	Operating Expenses
r_A	ratio of reservoir area covered by FPV (A_{FPV}/Ares)
$r_{AC/DC}$	ratio of alternating and direct current
RES	renewable energy sources
PRIMES	Price-Induced Market Equilibrium System
PV	photovoltaic
PVGIS	Photovoltaic Geographical Information System tool
STC	Standard Test Conditions
TWh	terawatt-hour
WS	water supply
y PV	area factor (kWp/m^2)

largest hydropower plants (HPP) in the world and it is shown that when covering 10% of the hydropower basin surfaces the HPP energy production is increased by 65% [13]. [14] estimated the technical potential of FPV deployed in hybrid systems with hydropower and identified 3 TW to 7.6 TW of worldwide potential (4251 TWh to 10,616 TWh annual generation). Additional work from Ref. [13] estimated the global potential for FPV paired with hydropower plants to range between 4.4 and 5.7 TW (6270–8039 TWh per year of generation) for installation on hydropower-only purposed reservoirs and all-purpose reservoirs, respectively.

FPV plants on waterbodies reduce the impact of the thermal coefficient [15] through the cooling effects of evaporation and wind ventilation. This can result in a slightly higher yield compared to land-based PV systems [15]. The temperature of FPV modules can be 5–10 °C lower than that in ground-based installations [16]. Hydroelectric dams operating in conjunction with FPV have been proven to optimize energy generation and increase system reliability compared to land-based PV systems due to the cooling effect of water [30–32]. Previous studies [20,33–37] suggested an average increase in efficiency from 5 to 12.5% compared to land-based PV systems, depending on the geographical location of the FPV installation.

In addition to improved yields, the shading effect [18] of the panels and the also decreased air flow [9,16–19] increase the hydropower effciency [3] as the PV module provides shading (depending on the module's design) and limits the evaporation from wind. Evaporation represents a significant loss factor of managed water resources worldwide, with reported values as high as 40% of the total volume of water storage [18,20,21]. Reducing water evaporation is critical, especially in countries where water is scarce. The annual water savings due to reduction of evaporation rate can range between 7000 and 10,000 m^3 per installed MWp of FPV [22]. Coupling FPV with hydropower could prevent up to 74 bcm of global water evaporation and support hydropower production—adding an estimated 142.5 TWh of generation from FPV systems on hydropower reservoirs [13].

The average land use for a ground-based PV power plant is 50–70 MWp/km2 [23,24] or to get 100 MWp it is necessary to cover roughly 1–1.5 km^2. However, with the competition of land for solar systems deployment and the associated costs derived from licensing and land preparation, the development of solar plants has become increasingly challenging, especially in densely populated countries [3,25], land-scarce countries or regions with high land prices [26,27]. [2] found that FPV installations offer the possibility to save on average 2.7 times the area of land-based PV projects for the same nominal capacity.

Coupling FPV and hydropower plants can share existing hydropower infrastructure such as transmission extensions, substations as well as easing time and siting constraints (such as land acquisition) [7,14].

Deployment of FPV is accelerating with global installed capacity raising from below 1 MW in 2007 to 1314 MW in 2018, over 2.4 GW (2400 MW) at the end of 2019 [28], and is expected to reach approximately !3 GW by 2022 [9,18]. By the end of 2022, floating solar will account for 2% of global annual solar installations as it is expected to reach 13 GW of installed capacity. The global technical advisory group Det Norske Veritas (DNV) has estimated that inland man-made water bodies alone have the potential to support up to 4 TW of new power capacity globally [29].

The world's largest FPV market is in China with 73% of the total capacity and the rest is credited to Japan and Korea, followed by Europe [18,24,30]. The total global estimated FPV installation capacity in hydropower reservoirs is around 7.6 TW. The FPV on freshwater artificial bodies holds an annual power generation potential of around 10,600 TWh, which represents 50% of the global electricity consumption in 2018 [29,31].

Europe has a high potential for floating PV and the demand for electricity. There are approximately 20,000 km^2 freshwater manmade reservoirs, corresponding to a market potential of 200 GWp if only 10% of that total surface area was used [32]. The countries in Europe with the largest number of reservoirs are Spain (ca. 1200), Turkey (ca. 610), Norway (ca. 364) and the UK (ca. 570), followed by Italy (ca. 570), France (ca. 550) and Sweden (ca. 190) (Seth Block et al., 2019).

The cumulative FPV installed capacity in Europe in 2020 was reported to be approximately 400 MWp of which 100 MWp are in the Netherlands alone [33]. The top 30 European floating solar projects based on installed capacity are in UK (65.5%), Netherlands (12.9%), Italy (7.7%), Spain (6.4%), Belgium (6.2%) and Portugal (1.4%) [34]. The world's first combined floating solar and hydroelectric plant was installed in Alto Rabagaor reservoir (Portugal), in 2017, with 840 panels covering an area of 2500 m^2 and an installed capacity of 22 MWp with an estimated electricity output of 300 MWh.

The largest floating solar plant in Europe is in the Bomhofsplas, Netherlands, with 27.4 MWp of installed capacity and 72,000 panels that produced 25 GWh in their first year of operation (2020). Recently, 70,000 floating solar panels were installed in another location with a total capacity of 29.9 MWp able to supply 9000 Dutch households [35].

1.1. Aim

This study aims to provide an estimate of the electricity output potential from FPV systems in existing hydropower reservoirs in EU27 and the associated water saving function under four different scenarios. Three scenarios consider different percentages of reservoir coverages (1%, 10% and 100%), while the fourth scenario considers the installation of an FPV plant of a total installed capacity equal to the installed capacity of the corresponding hydropower plants. The evaporation and the water savings of each reservoir were estimated using two alternate types of floating structures.

Our approach is based on a previous study assessing the floating solar photovoltaic potential on existing hydropower reservoirs in Africa [36].

The current study presents for the first time an estimate of the potential of installing FPV on hydropower reservoirs and also estimates the associated water savings after installing FPV systems (and the related water losses and evaporation). Our analysis also provides new insights into FPV potential in Europe, its capacity to cover the current electricity demand and where FPV systems could be better located to obtain higher electricity output. To the best of our knowledge, this is the first pan-European geospatial study assessing the electricity generation potential of FPV providing detailed estimates at reservoir, regional and national level, using open source data and high resolution data for specific location information on evaporation, water losses and water savings.

2. Data and methods

This study is developed both at regional and national level following the 2021 Nomenclature of Territorial Units for Statistics (NUTS) classification.[1] An analysis of the potential production of electricity from FPV with respect to the current total electricity consumption across all sectors was carried out.

We collated several existing datasets. The following sections describe the process in detail the data used to estimate the FPV energy output and the reduction of evaporation in specific reservoirs selected for four different scenarios of area coverage. For each scenario we evaluated electricity production at three inclination angles and water savings for two alterate floating structures. The workflow chart and databases used for the current assessment are presented in Fig. 1.

2.1. Hydropower plants dataset

The JRC Hydropower database[2] (last access September 30, 2021) [37] was used as the main source of information for the hydropower plants. The plants are classified into three categories: run-of-river (HROR), reservoir based (HDAM) and pumped storage (HPHS). In total, there are 4186 plants in Europe with a total installed capacity of 195.2 GW. We have excluded from the analysis all the plants with less than 5 MW of installed capacity and all the plants classified as run-of-river, resulting in 1433 plants. Run-of-river plants do not normally include water bodies of notable size suitable for FPV systems. The JRC Hydropower database was linked spatially with the Global Energy observatory database[3] as the plant commissioning date was not provided in the JRC Hydro power database.

2.2. Reservoir dataset

Reservoir data was taken from the Global Reservoir and Dam Database (GRanD)[4] version 1.3 where reservoirs with area equal or above 0.1 km^2 are included, resulting in 1041 reservoirs in Europe. In the GRanD database the main use of each reservoir is reported and classified as: hydroelectricity, irrigation, water supply, flood control, recreation, navigation, fisheries, pollution control, livestock, or other. For the purposes of the current analysis, only reservoirs with hydroelectricity (HE) and reservoirs with water supply (WS) as main use were selected as the grid connection already exists thus avoiding the additional installation costs. Reservoirs that are used for flood control (main use) were excluded even if hydroelectricity was mentioned as secondary use. This excluded all reservoirs in Germany and the Netherlands for this study, despite the largest current FVP installations being located here. In the GRanD database, there are no reservoirs listed for Denmark.

Of the total 1041 remaining reservoirs, 337 are located within Natura2000[5] sites and 704 reservoirs outside. From the reservoirs falling outside Natura 2000, 424 reservoirs have HE or WS as main use. 174 of these reservoirs do not have a corresponding power plant based on our pre-mentioned criteria, therefore those reservoirs were eliminated from our final joined hydropower plants-reservoir database.

The final database created includes reservoirs data from iCOLD[6] and GRanD and corresponding hydro power plants from the JRC Hydro database, Global Energy Observatory. For some Balkan countries (Bulgaria, Croatia, Greece, Romania, Slovenia) the report (Stunjek et al., 2020) was utilized to supplement the existing data. In cases where the installed capacity was unavailable from the pre-mentioned sources, we consulted the reservoirs and/or hydropower plants company's websites for this information. For the results and conclusion sections we focused only on the EU countries, and the final selection resulted in 337 geolocated reservoirs-hydropower plants. In Fig. 2, the location, area, and installed capacity of the homogenized database with hydropower plants and reservoirs are presented.

2.3. Hydropower capacity factors per country

Annual average hydropower capacity factors (CF, see equation (1)) were estimated using EUROSTAT data of annual hydropower generation (Dataset code: NRG_IND_PEH [38]) and installed hydropower capacity (Dataset code: NRG_INF_EPCRW [39]) using equation (1) as follows:

$$CF = \frac{\text{Hydroelectricity generation}}{\text{Hydropower installed capacity*24*365}} \tag{1}$$

For the purposes of the present study, we used mixed hydro and pure hydro information combined to estimate the capacity factors for the reservoir based (HDAM) plants in each country. In addition, we processed the pumped hydro storage installed capacity with the corresponding generation to provide a general estimation of the CF or utilization rate (using Equation (1)) for the pumped hydropower storage fleet in each country. Summary table with the estimated capacity factors per country can be found in the Annex.

2.4. Scenarios

This study aims to provide a comprehensive assessment of the installation of FPV systems in the EU hydropower reservoirs and their benefits from different perspectives. We considered in total four scenarios:

[1] NUTS is a geocode standard for referencing the subdivisions of countries for statistical purposes.

[2] https://github.com/energy-modelling-toolkit/hydro-power-database.

[3] http://GlobalEnergyObservatory.org.

[4] http://globaldamwatch.org/grand/.

[5] Natura 2000 is a network of nature protection areas in the territory of the European Union.

[6] https://www.icold-cigb.org.

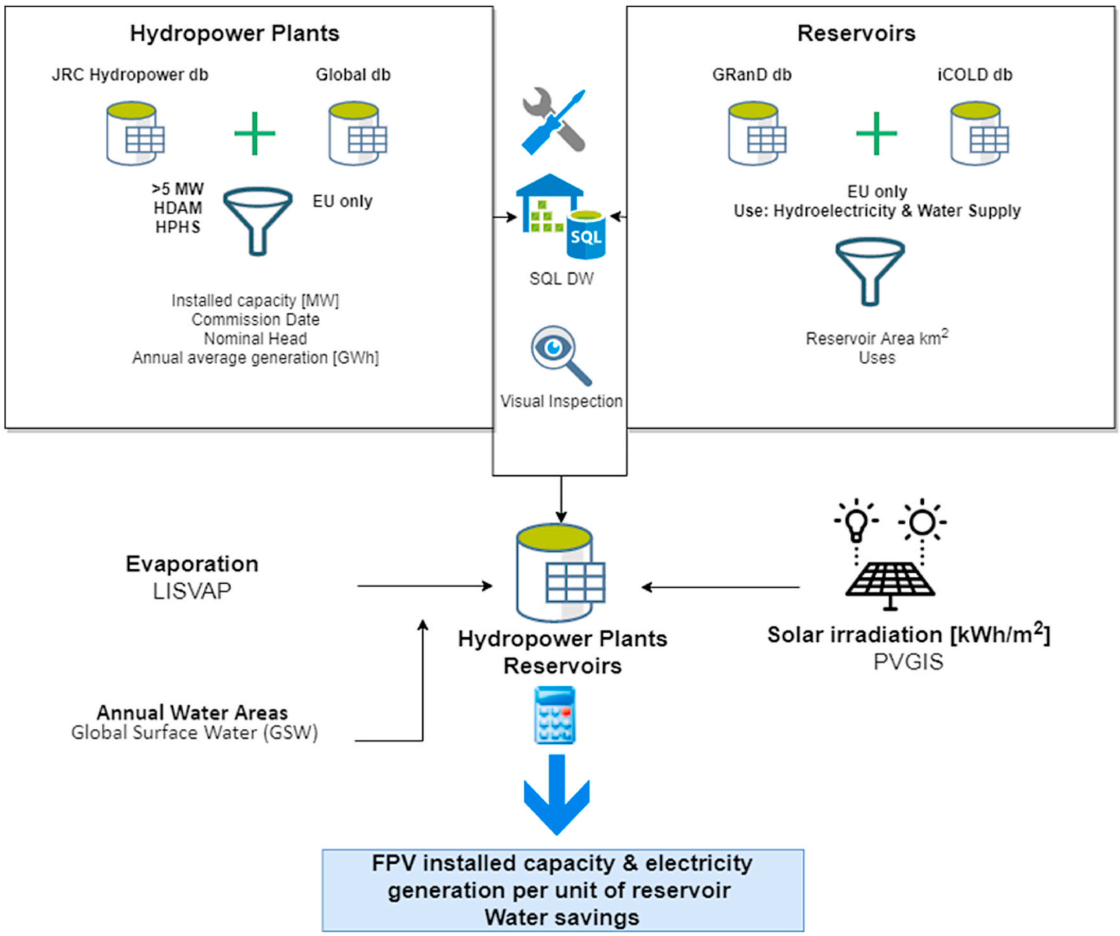

Fig. 1. Graphical representation of the methodology, databases and datasets used in the study and the final outputs.

- three area-based coverage scenarios: 1%, 10% and 100% of the area of the selected reservoirs.
- The hydropower equivalent installed capacity (HEIC) scenario: this assumes that in each reservoir the installed capacity of the FPV plant is equal to the installed capacity of the hydropower plant. This approach ensures that the hydropower will be able to compensate for the power deficiency in case needed [36]. In this scenario, reservoirs where the needed FPV area to match the installed capacity of the hydropower plant exceeds the total area of the reservoir are excluded.

2.5. FPV solar electricity output

The methodology used to assess the potential FPV generation builds on a previous geospatial analysis of the energy output and reliability of PV system, described in detail in Ref. [40]. We used the Photovoltaic Geographical Information System (PVGIS) online tool [41] to estimate the solar irradiance available at each reservoir and the potential PV output from the associated FPV system.

The methodology combines satellite based solar radiation data from CMSAF's SARAH-1 with approximately 5 km resolution [42], down-scaled temperature and wind speed data from reanalysis product ECMWF ERA-Interim with approximately 81 km resolution [43] and measured data on PV module performance.

To estimate the FPV potential output and chose the most suitable configuration, we examined three different inclination settings using PVGIS. The considered modules are crystalline silicon with an efficiency at Standard Test Conditions (STC) of 20%. This implies an area factor of 0.16 or 0.17 kWp/m^2; however, a final value of 0.1 kWp/m^2 has been considered in the calculations to account for separation between rows to avoid shadowing and to allow an adequate service area [36]. The three inclination configurations for the FPV systems are:

- horizontal modules
- modules south facing and optimally inclined for that location
- modules south facing and 10° inclination angle

The yearly average in-plane irradiation (kWh/m^2) and yearly average PV output (kWh) were estimated for each reservoir's specific geographic location based on the complete time series of hourly values between 2005 and 2016 and taking into consideration the surrounding horizon which may block the direct irradiance. As most of the FPV configurations are almost horizontal, there is minimum demand for spacing to avoid shadowing between arrays. The yearly PV output was used as input to estimate the annual electricity production (AEP) for each reservoir following [36] using equation (2),

$$AEP_{FPV} = A_{RES}{}^{*}r_{A}{}^{*}I_{OPT}{}^{*}y^{*}r_{\frac{AC}{DC}} \tag{2}$$

Where:

AEP_{FPV}: annual electricity production (MWh/yr)
A_{RES}: total area of the reservoir (m^2)
r_A: ratio of reservoir area covered by FPV (A_{FPV}/Ares), assigned according to different scenarios presented later.
I_{OPT}: annual PV energy yield (kWh/kWp)
y: PV area factor (kWp/m^2)
$r_{AC/DC}$: losses due to solar clipping. Inverter ratio assumed equal to 1.25 [36].

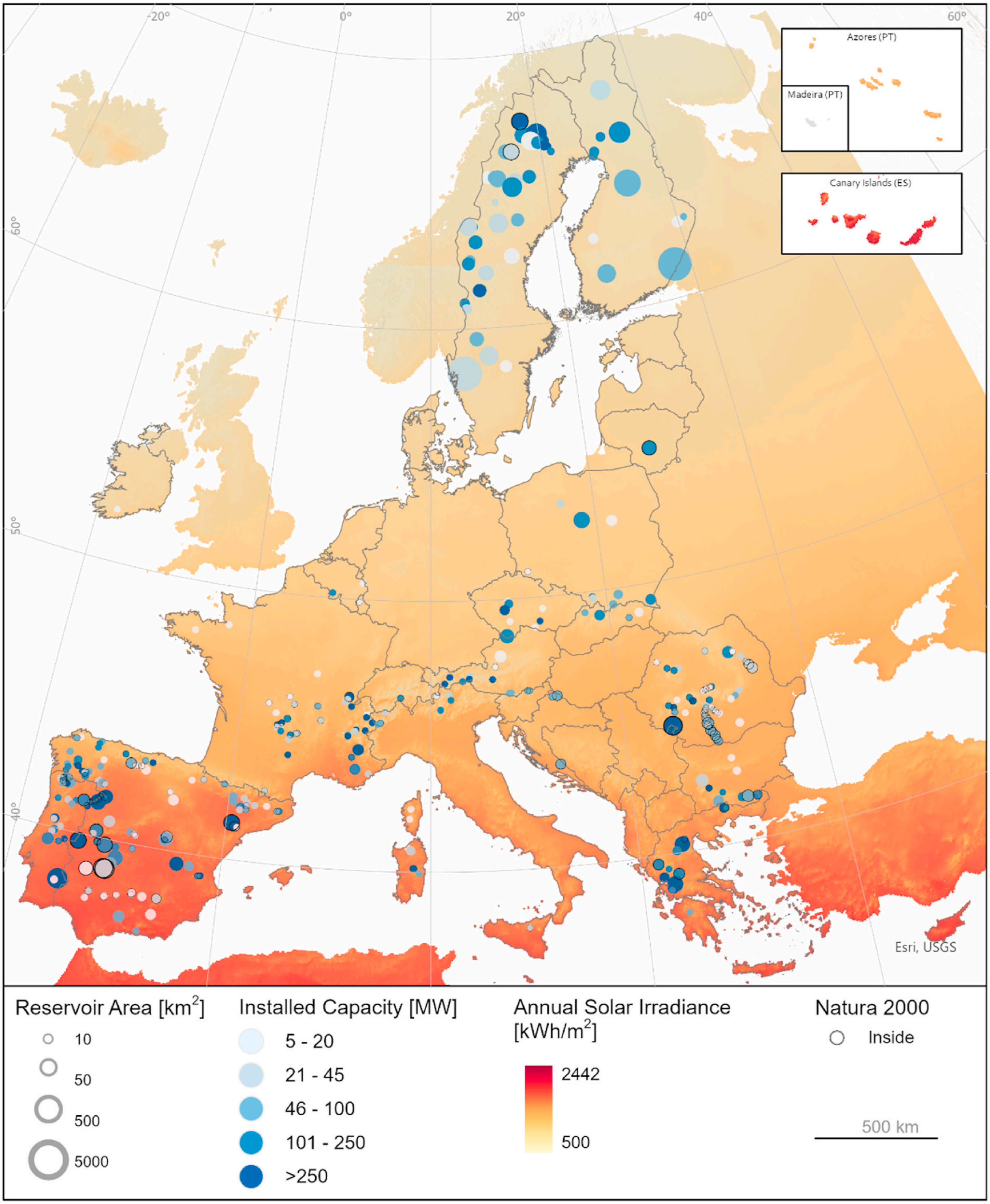

Fig. 2. Hydropower plants and corresponding reservoirs selected for the analysis are represented in circles. The assorted circles' colour indicates the installed hydropower capacity [MW] and the circles' size the corresponding reservoir area [km^2]. Points with a balck outline represent reservoirs inside the Natura 2000 sites. The background map represents the annual solar irradiation in [kWh/m^2], (source PVGIS JRC).

An inverter ratio of 1.25 (value typically used in commercial ground-based installations which accounts for around 1% losses of the total annual generation) have been considered in the study [36].

The PV output model considers the irradiance reflected at the module's surface at high incidence angles (angle of incidence effects, AOI) which is, therefore, not absorbed by the PV material, and the effect of the spectral content of the absorbed irradiance. The PV model also considers the working conditions of the module (received irradiance and temperature reached by the module) to estimate the efficiency of the module during the hourly simulations. The temperature of the module is estimated considering the received irradiance, the ambient temperature, and the cooling effect of the wind. In addition to these intrinsic losses due to AOI, spectral and thermal effects, we have assumed 14% system losses. These account for losses due to soiling, inverter's inefficiency, cables, and other balance-of-system losses as well as PV system degradation.

2.6. Evaporation and water savings

2.6.1. Water losses due to evaporation in the reservoirs

For each of the reservoirs, the time-series of annual water areas were estimated using the yearly water classification history of the Global Surface Water dataset (GSW),[7] for the period 1984 (or commissioning year)-2020 [44]. The Global Surface Water (GSW) dataset, developed by the JRC, provides consistent monthly water history and a yearly water classification history of surface inland water, at global scale and at 30 m of spatial resolution. The annual water areas were then used to estimate the annual open water evaporation in the reference period.

The open water evaporation was computed using LISVAP, the potential evapotranspiration pre-processor of the LISFLOOD model [45,46]. LISVAP uses the Penman-Monteith equation [47–49] to estimate the potential evapotranspiration for a standard crop. In case of open water evaporation, the crop coefficient is not considered, and the transpiration component is null. Potential and actual evaporation values from surface water are virtually identical. The EMO-5 dataset (European Meteorological Observations) is used for the input variables (wind speed, minimum and maximum temperature, water vapor pressure and radiation) for LISVAP at a daily scale from 1990 to 2018. EMO-5 is a pan-European regular 5 km resolution grid meteorological forcing dataset obtained by interpolating the spatially irregular observations from various sources throughout the continent [50]. Evaporation, precipitation, and average temperature data are then combined with the spatial extent of the water body obtained by the analysis of the reservoirs in the GSW dataset [44] for the period 1984–2020. This methodology was already successfully applied in previous works [51,52]. As the LISVAP data was limited until 2018, our analysis is based on this year to estimate the annual evaporation and water losses. It represents the most up-to date and complete data for the investigated reservoirs. To get an idea of the year-by-year variability of water extents and water losses considering the climate variability, year 2018 values are compared with its minimum and maximum values for the period 2000–2018 (Fig. 3). Notable is the case of Sweden where the largest reservoir extents and highest water losses are observed. While the reservoirs' extents are slightly varying for the period 2000–2018, the water losses showed significant variability due to local climate conditions. The year of 2000 had both lower shortwave radiation (more cloud cover) and wind speed which apparently resulted in lower evapotranspiration values compared to the year of 2018.

2.6.2. Floating PV and water savings

The main additional advantage of FPV arrays is the evaporation reduction in the water bodies. We estimate this analogously to the authors [36], analyzing the water savings for the most commonly used floaters in FPV applications, one that fully covers the water surface underneath (floater type A) and a second type consisting of a tubular structure (floater type B) in which the coverage is only partial [53]. The evaporation rates for the needed coverages are obtained applying a cubic spline interpolation function to the evaporation rates from [53].

2.7. Investment cost

Based on the literature, the greatest cost of the FPV derives from the higher installation costs of the FPV systems [54]. The floating platform and anchoring is more expensive compared to the mature ground mounting technologies. In the HEIC scenario, the substituted land value equals 450 million euro, but can reach 16.5 billion euro in the 100% scenario based on the product of the corresponding area and national average land value. In rental, it corresponds to 6 to 220-million-euro yearly savings (based on national land lease costs). To estimate the extent of the investment cost disadvantage (based on the HEIC scenario) we calculated the Levelized Cost of Electricity (LCEO) values for both the FPV and other (utility scale, commercial and residential) mounted PV systems. The Price-Induced Market Equilibrium System (PRIMES) modelling results were used for the installed PV capacities and average cost for 2020-30-40-50 in the EU and compared it to the FPV HEIC (Equal Capacity) scenario. The standard input parameters (30 years' lifetime, PRIMES Capital Expenditure (CAPEX) and Operating Expenses (OPEX) were used, assuming 40% higher FPV CAPEX cost at the beginning and using 5% discount rate (and ± 3,5% for the sensitivity cases) in the LCOE calculations.

3. Results

The range of FVP generation potential across the scenarios investigated is between 13.5 TWh and 1629.3 TWh. Coverage has a large linear effect on generation. The HEIC scenario where area coverage is defined reservoir specifically based on hydro power capacity has a total generation potential between the 1% and 10% scenario. The optimal and 10^o inclination angles provide a 25% and 2% improvement over the flat FVPs in the area based scenarios, while for the HEIC assessment flat FVPs are more effective than the 10^o inclination. Table 1 provides the specific FVP generation for each scenario.

A summary table with the total FPV output resulted from the three inclination configurations for all the reservoirs examined in the current study at EU level are presented Table 1. For the current analysis, the 10° inclination with south facing modules, was used even if the optimal inclination and south facing configuration resulted in higher total output. We use in the rest of this paper the 10° inclination with south facing modules as it is the most common configuration, and it allows cooling from the wind and uses a better inclination than the horizontal option. The optimal inclination with south facing modules was not taken into consideration as in high latitudes would imply extremely high inclination angles and high wind forces. The total electricity output for the selected configuration ranges from 13.9 TWh to 1387 TWh depending on the FPV scenario (described in section 2.6).

3.1. FPV potential output estimation in the EU

The scenarios depicted in Section 2.6 lead naturally to different values of used area (according to the % scenario) for FPV installations and generation potential (Table 2).

This study considers 337 reservoirs, with a total area estimated at 16,086 km^2. If we use only 1% of this area for floating solar arrays inclined at 10° (1% reservoir coverage scenario) we obtain a generation potential of 13.87 TWh/yr. With 10% and 100% this potential becomes 138.67 and 1386.7 TWh/yr, respectively. To put it in context, the total electricity generation in EU in 2019 was 2780 TWh (source EUROSTAT). Hence, the installation of FPV can potentially produce 5% and 50% of the total electricity genearation of the EU27 for the 10% and 100% area scenarios respectively. The produced potential electricity for the 10% scenario can be translated to 87% of the total power generation from solar photovoltaic in 2020 (156 TWh).

In the HEIC scenario, the produced electricity is 42.31 TWh with the total used area of 371 km^2, i.e., the 2.3% of the total available reservoir area (16014 km^2). The produced potential electricity from the HEIC coverage area scenario can be translated to 20% of the total power generation from solar photovoltaic in 2020 (156 TWh).

Note that the installed hydropower capacity for the HEIC scenario has decreased from 48.73 GW (total installed hydropower capacity) to 30.4 GW, as we excluded all the reservoirs for which the area coverage needed to equal the hydropower installed capacity was exceeding 100% (292 reservoirs remained).

3.2. Assessment of FPV potential at national level

Fig. 4 presents the FPV potential electricity production in each

[7] https://global-surface-water.appspot.com/.

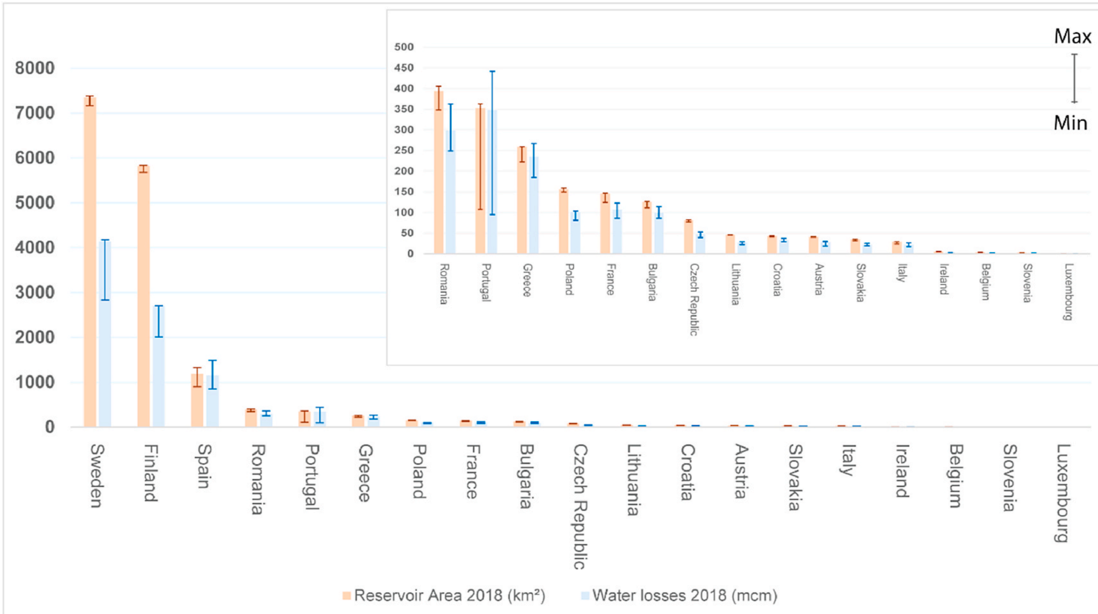

Fig. 3. Bar graph of the total reservoir areas and water losses of year 2018 and related minimum and maximum values for the period 2000–2018 aggregated at national level. Enlarged detailed view of the bar graphs for the countries with values of reservoir area and water losses less than 500 km^2 and mcm, respectively.

Table 1
Summary table with the different FPV electricity output (TWh) using different inclination angles for the selected reservoirs in the EU.

	100% area coverage	10% area coverage	1% area coverage	HEIC scenario
Horizontal	1356	133.56	13.5	56.41
Optimal inclination, south facing	1629.3	163	16.3	64.71
10° Inclination & South facing	1387	138.7	13.9	42.31

Table 2
Summary table of FPV output (TWh) and coverage area for each scenario used in EU with 10° inclination and south facing modules.

	100% Reservoir Coverage	10% Reservoir Coverage	1% Reservoir Coverage	HEIC
Number of reservoirs		337		292
Hydropower Electricity production (TWh)		94.4		61.9
Hydro Installed Capacity (GW)		48.73		30.04
Power of FPV modules (GWp)	16087	1609	160	30
Total area covered (km^2)	16086.86	1608.68	160.86	371.74 (≈2.3% total coverage)
Annual FPV electricity production (TWh)	1387 (49% of total EU27)	138.7(7% of total EU27)	13.9	42.31

scenario at national level. The countries are sorted based on the reservoirs' total area. In all the area scenarios, Sweden, Finland, and Spain are among the top 5 countries with higher potential of FPV output due to the extensive reservoir area available for installations. Due to the large available surface area Sweden could under the 100% coverage scenario produce 547.23 TWh (57.42 for the 10% scenario) roughly 4.6 times the annual electricity consumption (46% for the 10% scenario, 125.4 TWh of electricity consumption in 2020).

For the HEIC scenario, Spain may produce an extra 14.71 TWh if it uses only 9% of the total reservoirs' surface area. In addition, if Spain utilizes 10% of the total reservoir area available, it can produce up to 16.77 TWh from FPV. Thus, in this case the area coverage for the HEIC and the 10% area coverage scenarios are similar despite the reduced number of reservoirs in the HEIC scenario. Romania, Portugal, and Greece show a similar pattern. According to our data presented in Fig. 4, for the HEIC scenario most of the countries need less than the 15% of the total reservoirs' area available to be covered with floating solar panels to achieve 42.31 TWh production at EU level. Exceptions are Belgium and Slovenia as their total area of the reservoirs analysed is smaller than the rest of EU. Using only the 10% of the reservoirs' area the potential electricity output can reach values of 138.7 TWh, with the main production to be carried out in Sweden (57.42 TWh) and Finland (44.48 TWh) followed by Spain (16.77 TWh).

As expected, there is a strong positive linear relationship between the potential of FPV (TWh) and the used area (km^2) in the HEIC scenario (Fig. 5). This relationship would be with a coefficient of determination $r^2 = 1$ if we would have used the same solar irradiation across all the countries. In the HEIC scenario most of the countries can use the existing electricity grid capacity of the power plant to provide the grid with the possible maximum electricity created by the installed FPV modules. As an example, Spain is ranked 3rd in the classification for the total available reservoir area with suitable grid connection, after Sweden and Finland, but with higher number of reservoirs (85) compared to Sweden (35) and Finland (12). Note, that the reservoirs' number is only for the HEIC scenario here, as we have removed the reservoirs in which the area needed would be more than 100%. Thus, in the HEIC scenario Spain's hydro installed capacity (88.2 GWh) and utilized area (109 km^2) is bigger than Sweden's (44.06 GWh, 54.7 km^2) and Finland's (0.83 GWh, 10.38 km^2) resulting in 15.06 TWh of potential electricity output. As the annual average solar irradiation in Spain is higher than in Sweden or any northern countries, it can produce higher PV output with utilizing less reservoir area.

In the HEIC scenario, the general linear relationship between the potential FVP generation and area covered is retained within the

FPV technical potential in EU

	Total reservoir area (km^2)	HEIC % Area coverage	HEIC FPV output (TWh)	100% area scenario (TWh)	10% area scenario (TWh)	1% area scenario (TWh)
Sweden	7354.3	0.7	4.0	574.2	57.4	5.7
Finland	5821.1	0.2	0.8	444.9	44.5	4.5
Spain	1188.7	9.1	14.7	167.7	16.8	1.7
Romania	394.0	12.7	5.3	44.1	4.4	0.4
Portugal	352.8	10.6	4.9	49.8	5.0	0.5
Greece	258.8	13.2	4.3	32.6	3.3	0.3
Poland	155.7	4.8	0.7	14.1	1.4	0.1
France	145.9	27.6	3.9	16.3	1.6	0.2
Bulgaria	125.8	5.9	0.9	14.9	1.5	0.2
Czech Republic	81.2	10.9	0.8	7.7	0.8	0.1
Lithuania	46.5	2.7	0.1	4.0	0.4	0.0
Croatia	43.4	6.2	0.3	4.9	0.5	0.1
Austria	41.0	7.8	0.3	3.7	0.4	0.0
Slovakia	35.2	12.1	0.4	3.2	0.3	0.0
Italy	29.1	22.3	0.6	3.6	0.4	0.0
Ireland	5.7	6.1	0.0	0.5	0.1	0.0
Belgium	4.0	46.8	0.2	0.4	0.0	0.0
Slovenia	2.8	57.3	0.2	0.3	0.0	0.0
Luxembourg	0.8	24.4	0.0	0.1	0.0	0.0

Fig. 4. FPV technical potential for each scenario aggregated at the national level. The table is ordered by decreasing total available reservoir area per country. Note here, in the HEIC scenario we have excluded the reservoirs with surface coverage >100% (292 reservoirs). For the area scenarios the calculations are done for 337 reservoirs in total.

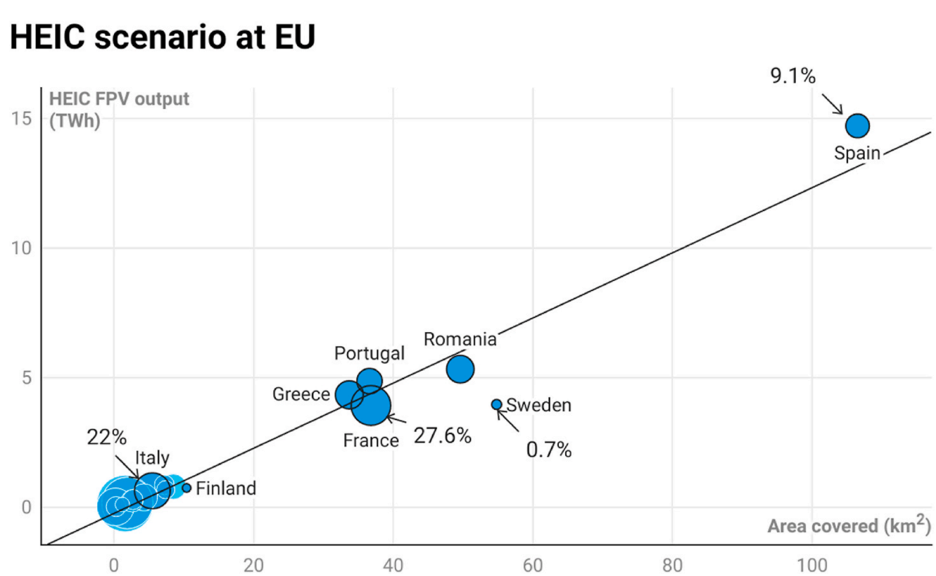

Fig. 5. Potential electricity output in TWh from installing FPV arrays for the HEIC scenario at EU level. The size of the circle indicates the percentage of area covered in HEIC scenario; some area covered percentages are indicated in labels.

country specific analysis (Fig. 5). Country specific deviations from the linear relationship are a result of regional differences in the solar irradiance.

In Fig. 6, the percentage of the area covered for the HEIC scenario and the ratio of FPV electricity output with the corresponding hydropower electricity production. Most of the analysed countries can produce at least half of the total electricity generated by the hydropower plant (and in many cases more than the total like in Spain, Portugal,

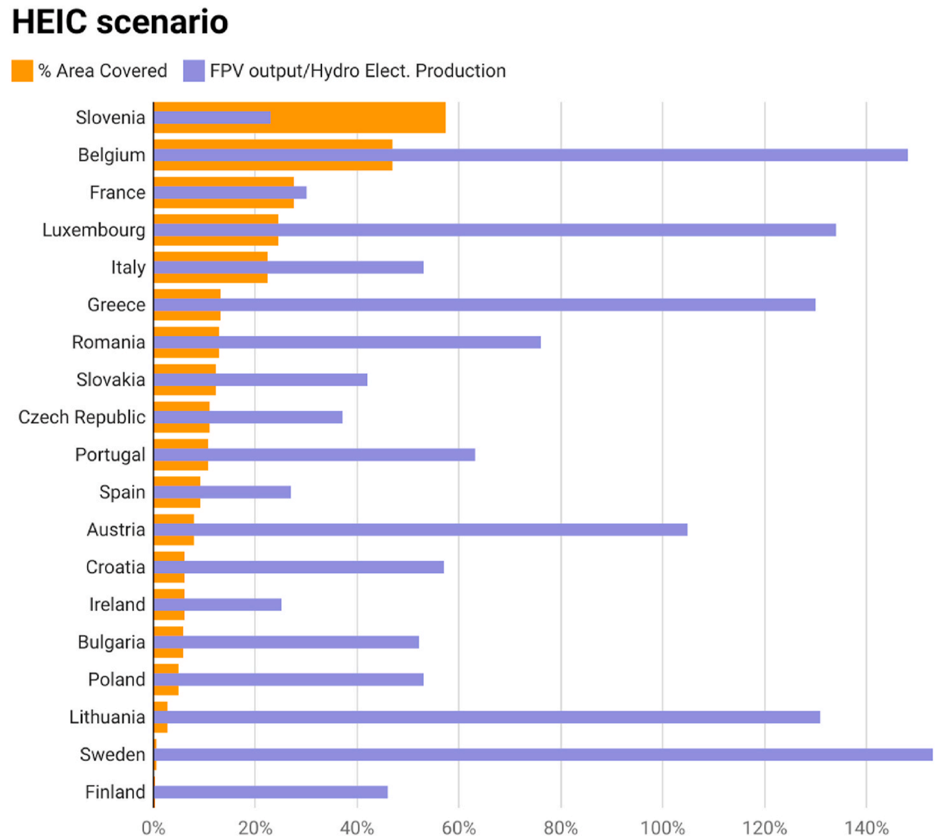

Fig. 6. Percentage of total area covered by FPV and the percentage of the total generated FPV output with the hydro electricity generation per EU27 country analysed for the HEIC scenario.

Greece, Belgium, and Slovakia), with the installation of FPV plants covering less than 15% percent of the total available reservoir area, as shown in Fig. 6. In the HEIC case, the total FPV potential electricity output is 68% of the hydropower generation, covering an area of 371.74 km^2, approximately 3% of the total available area in the reservoirs analysed.

3.3. Water losses and evaporation savings

3.3.1. Water losses due to evaporation in the reservoirs

The total water losses in the year 2018 for the 337 hydropower reservoirs analysed in this study is estimated at 9821 mcm, covering a total area of 16087 km^2. The three countries with the largest water losses are Sweden (4143 mcm, 35 reservoirs and a total area of 7354 km^2), Spain (1152 mcm, 85 reservoirs and a total area of 1188.74 km^2) and Finland (2791 mcm, 12 reservoirs and a total area of 5821.13 km^2). These three countries represent 84% of the total water losses with 142 reservoirs covering a total area of 14,326 km^2 (89% of the total). Table 3 presents county level aggregated data of the reservoirs analysed in this study, including information on the total area covered by the reservoirs, evaporation, water losses, installed capacity and electricity production. As mentioned, Sweden, Spain, Finland, are the countries with the largest water losses. Sweden presents the highest water losses due to the large surface area of their reservoirs and Spain presents the highest installed capacity, doubling the installed capacity in Sweden (13.08 GW vs 5.59 GW). At the same time, Spain presents much smaller water losses than Sweden despite the warmer climate. This is because the reservoirs in Spain are of smaller sizes compared to the ones in the Nordic country (35 reservoirs covering 7354.32 km^2 in Sweden vs 85 reservoirs covering 1188.74 km^2 in Spain) which has a clear effect on the total water loss. However, when looking at the electricity production, we can observe that in Sweden it is 1.6 times larger than in Spain despite the larger installed capacity in Spain, which is caused by a smaller hydropower capacity factor in Spain (0.45 vs 0.16). In Fig. 7, we can observe a large accumulation of small reservoirs in mountainous regions (e.g.: Alps, Carpathians, Pyrenees, etc.). These reservoirs present small water losses due to the local climate and relatively high hydroelectricity production due to the typically high hydraulic heads in these areas. Other countries such as Sweden and Finland, count with hydropower reservoirs of larger sizes with high water losses and high electricity production. In this case, despite the cold climate, the water losses are high due to the large surface of the reservoirs. On the other hand, in southern Spain and Portugal, we find a higher accumulation of small and middle size reservoirs with high water losses (due to the warm climate) and low electricity production, probably caused by less water available to run the turbines.

3.3.2. Floating PV and water savings

In the various scenarios the installation of floater type A has higher water savings reaching 1717 and 457 mcm for the year 2018 for the 10% coverage area scenario and HEIC, respectively. The water savings for each type of floater under the studied scenarios for the EU countries are presented in Table 4. In the scenario of 100% area coverage the water savings using the floater type A would save almost 9381 mcm and with floater type B a total of 5606 mcm. In the 10% area scenario, Sweden, Finland, and Spain have the highest water savings reaching annual values of 800 mcm. For the HEIC scenario the three top countries with highest water savings are Portugal, Spain and followed by Austria. Countries such as Belgium, Slovenia, Ireland, Lithuania have a minimum amount of water savings after installing FPV.

A summary figure plotting the water savings per floater, the reservoir's area covered (km^2), the hydropower installed capacity (GW) and the ratio of FPV output with the hydropower electricity production at national level is presented in Fig. 8. Countries such as Spain, Greece, Croatia, Lithuania, Ireland, Slovenia, and Luxemburg can produce FPV

Table 3
Summary table with total values for the EU all the reservoirs studied for reservoir surface area (km^2), evaporation (mm/yr.) for the year 2018, water losses (mcm), hydropower installed capacity in GW, energy production in GWh and the ratio of water losses (WL in mcm) and energy production (EP in mcm/GWh).

Country	Total surface area (km^2)	Total installed hydropower capacity (GW)	Total hydro electricity production (TWh)	Total evaporation (mm/yr)	Total water losses (mcm)	WL/EP (mcm/TWh)
Sweden	7354.3	5.6	22.2	15455.8	4142.5	186.8
Finland	5821.1	0.8	3.0	5268.9	2709.1	893.4
Spain	1188.7	13.1	13.2	79335.3	1151.5	87.5
Romania	394.0	4.6	11.5	35257.6	298.4	25.9
Portugal	352.8	5.5	8.0	21106.0	347.7	43.7
Greece	258.8	3.3	5.0	12350.7	234.9	46.6
Poland	155.7	1.1	0.9	6381.7	101.3	110.4
France	145.9	7.6	17.5	26238.0	107.0	6.1
Bulgaria	125.8	1.0	0.8	6804.5	99.0	119.9
Czech Republic	81.2	1.2	2.4	5480.3	48.0	19.8
Lithuania	46.5	0.1	0.3	585.1	27.2	93.2
Croatia	43.4	0.2	0.6	2260.6	33.3	58.4
Austria	41.0	2.5	5.9	4638.0	28.4	4.8
Slovakia	35.2	0.3	0.3	2647.8	22.4	77.3
Italy	29.1	1.5	2.0	8890.8	22.4	11.1
Ireland	5.7	0.0	0.1	1053.9	3.0	29.3
Belgium	4.0	0.2	0.1	1211.3	2.4	21.1
Slovenia	2.8	0.1	0.5	1112.6	1.5	3.1
Luxembourg	0.8	0.0	0.04	666.0	0.5	14.0
Total	**16087**	**48.73**	**94.4**	**236745**	**9380.7**	**1852.4**

electricity output higher than the electricity production from hydropower while only using 10% of the reservoirs' surface area. Countries such as Spain (most water-stressed industrialized countries in the world, water stress level more than 80%), could benefit from the FPV installation by achieving 210 mcm water savings annually.

3.3.3. Regional water saving assessment

A regional assessment on the potential electricity generation from FPVs can be carried out comparing the total potential generation with the total regional electricity demand. (Fig. 9 for the HEIC scenario). However, the output of hydropower plants can be adjusted to the solar generation and actual demand, resulting in a reduced need for additional storage. The annual regional electricity demand is based on the work by Ref. [56] which estimate the regional demand based on country demands for the year 2017 (only data publicly available) using the NUTS2 classification.

The map provides a first estimation of the potential impact of FPV in satisfying the regional demand of electricity at regional level.

The five regions with the highest share of electricity demand provided by the FPV in the HEIC scenario are the following:

- Extremadura, Spain (ES43): 76% (4167 GWh with a demand of 5482 GWh)
- Epirus, Greece (EL54): 61% (954 GWh with a demand of 1557 GWh)
- Western Macedonia, Greece (EL53): 58% (762 GWh and 1318 GWh of demand)
- Western Greece, Greece (EL63): 46% (1518 GWh and 3321 GWh of demand)
- Upper Norrland, Sweden (SE33): 46% (3676 GWh and 8070 TWh of demand)

3.4. Comparison of costs between land and FPV systems

As shown in Table 5, the initial 16 EUR/MWh LCOE cost difference (2020: 72.9–57.1 EUR/MWh) disappears at the end of the examined period. The cost difference calculated for the 42.1 TWh production projected in the HEIC scenario would already be compensated by the saving in land use changes. Therefore, we could consider the FPV as a low hanging cost option, for which scaling up the HEIC scenario to the higher percentage coverage would reach the economy of scale affects earlier.

However, this slow cost decrease scenario comparison would only be valid in the EU in case of slow deployment rates of FPV (i.e., in the case of 1% scenario, or slow HEIC, when each country would start their own FPV development without cross-country learning e.g., by international tenders, competitive auctions). In this case, technological learning would be realised slowly as it depends on the installed capacities. In case larger capacities would be installed in the potential locations, the technological learning can be realised in a much shorter time. The rapid cost decrease in the EU is realistic; according to Ref. [54] 45% cost reductions were realised within less than 5 years in India. However, the fast technological learning does not come automatically: if we take a closer look at the Indian and the other international project series, we see that in fact the technological learning (cost reduction) is more intricately linked to the size of the installation than to the year. However, robust statistical conclusions cannot be drawn from the small sample.

The lower costs in case of large capacity installations while this relation showed less connection with the time (see the R^2 0.24 to 0.12). It can be observed without exception that with development characterized by higher installed capacities, the cost per Watt are becoming lower. This is realised by the economy of scale through more standardised floating structures and lower unit costs. This means that the FPV can achieve cost parity with the land-mounted PV structures in a short time. If in the EU a similar development could take place like in India, the FPV could be cost competitive with the land mounted systems in 5 years if international procurement rules, tenders and competitive bidding processes would be applied.

4. Discussion

The estimates of FPV potential provide insight into the capacity of FPV to supplement renewable generation and that could significantly contribute to covering current and future energy demands. In this study, we have not considered the cooling effect of the water which could increase the efficiency of the modules, due to the lack of validated models for this purpose. Also, the additional water for the turbines, due to water losses reduction, was not considered, but in [57] it was estimated that could increase hydropower generation by 0.02% at the EU scale (and 0.05% at European scale). Therefore, the estimations of the PV output could be lower than the real performance of FPV systems. Losses due to wave and wind induced mismatch between the modules of the FPV system, which could reduce the PV output of the FPV system have not been considered. As a result, the estimated PV output could be higher than the real performance of FPV systems, especially in water reservoirs with high wave intensity [15].

Collocating FPV systems and hydropower can be beneficial in several terms, such as for example production, as hydropower can compensate for the intermittent output of solar PV, as solar resource is only available during certain periods of the day [9]. The power output of hydropower sold with its balancing capability could increase the revenues of the sector in addition to the new FPV development. This “double dividend” could lead to a more rapid scale up of RES shares in the European power generation portfolio without high pressure on the other land uses which is important in the near-term EU energy prospect.

Furthermore, coupling FPV and hydropower can offer energy storage opportunities, connection to existing grid transmission infrastructure and thus reducing additional costs related to grid extension and

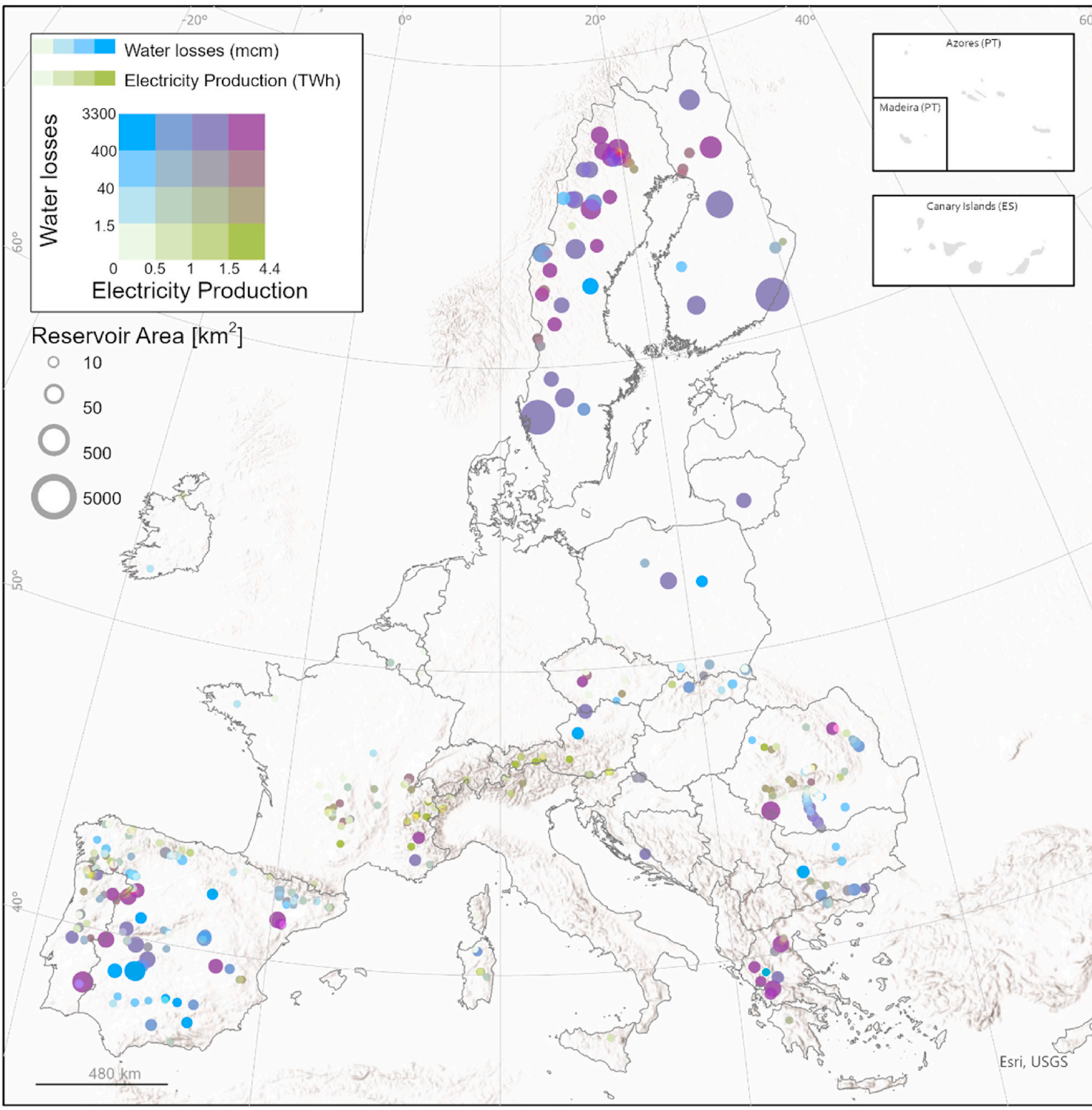

Fig. 7. Bivariate map for each reservoir in the analysed countries. The colours represent the water loss due to evaporation (mcm) and hydro electricity production (TWh). The circle’s size indicates the reservoir’s surface area in km^2.

Table 4
Total water savings (mcm) in EU under each scenario for the two studied floater types.

	100% area scenario	10% area scenario	1% area scenario	HEIC
Floater A	9381	1718	175	457
Floater B (suspended)	5606	560	56	557

infrastructure. Installing FPV systems at the surface of hydropower reservoirs has been proven to reduce water evaporation and support water conservation during dry-sunny periods.

Despite the FPVs' multiple benefits identified there are challenges that should be addressed. Data availability on reservoirs and hydropower plants was one of the limitation of this study. Several databases were combined spatially and visual checks were ultimately needed several occasions. A more accurate geo-located database would improve the results. This study also assumed that the total area of the reservoirs is available for FPV installation, however, further detailed reservoir data (e.g.: bathymetry, current uses, etc.) would be needed to provide more accurate results on the real useable area of each reservoir for FPV installation. Thus, further studies could focus on performing qualitative and quantitative local studies to assess the environmental conditions before the FPV installation. Furthermore, the impacts and disturbances of FPV on the local microclimate (flora and fauna), water quality are largely unknown as FPV is a new technology. The benefits of FPV installation on existing hydropower reservoirs are significant and can provide a solution to cover the current electricity demand and increase EU's resilience to climate change. We further investigated the inclination effect on the PV modules' performance by considering a south facing 10° tilted one axis tracking system, for the reservoirs selected in this study. The results showed an average gain of all stations of 26.4% in the irradiation and 27.7% on the energy yield. These gains depend on the locations, and ranges from around 6%–50% at high latitudes locations where the tracking system is extremely beneficial during summer months. In our simulations, the type of sky condition (diffuse fraction) was also considered, not only the amount of global irradiance. Hence, this could explain why in locations with similar latitude and even similar yearly horizontal irradiation levels, those with higher frequency of overcast situations, the tracking system is not as beneficial as for locations where clear skies are more common.

As we discussed earlier, hydropower provides many benefits to local communities given the multi-purpose role that reservoirs often have (electricity generation and tourism, irrigation, flood management, etc.). This "local" dimension of hydropower plants, which are often located in mountainous regions, will be enhanced with FPVs which provide both green electricity (that can be injected to the grid or used locally and support the decarbonisation and electrification) and environmental benefits [55]. Although this analysis is based on an estimation of the regional electricity demand and it does not include any information on electricity grid, it might suggest that many regions may have an easier access to low-carbon electricity to decarbonise the local economy and increase the electrification rate.

In Alpine environment, where HPPs are characterized by high heads and low flows (i.e., high power density per unit of reservoir surface), this would require a FPV surface much larger than the HPP reservoir surface. In HPPs characterized by large flows and small heads a small percentage is instead enough to obtain the same power. The optimal percentage is hence site specific [22]. However, it still offers room for further and investigations are necessary to validate this kind of conclusions.

Regardless of these potential benefits, coupling FPV with hydropower is a relevant innovative technology and knowledge gaps of the potential negative impacts and challenges exist (reliability and expected lifetime of systems, environmental impact, waves and wind effects, aesthetic concerns) that could obstruct further investment and deployment.

Although, making double use of the available areas of hydroelectric reservoirs and their surface would lead to manifold synergies in a direct complementary mode with the installed FPV production, so their ancillary services in the power grid could be reinforced.

5. Conclusions

Water reservoirs offer an extra surface on which floating PV could be installed presenting an investment opportunity. In this study, we estimated the technical potential for FPV installation on 337 hydropower reservoirs in the EU (1/3 of the total number in the EU).

To the best of the authors knowledge this is the first study in the EU that provides detailed estimates of annual FPV electricity output, evaporation, water losses and water savings at reservoir, regional and national level. Moreover, the high resolution GSW data used to derive the reservoir areas allows to provide a consistent and accurate estimation of water losses from the hydropower reservoirs.

The main findings of this study are summarized as follows:

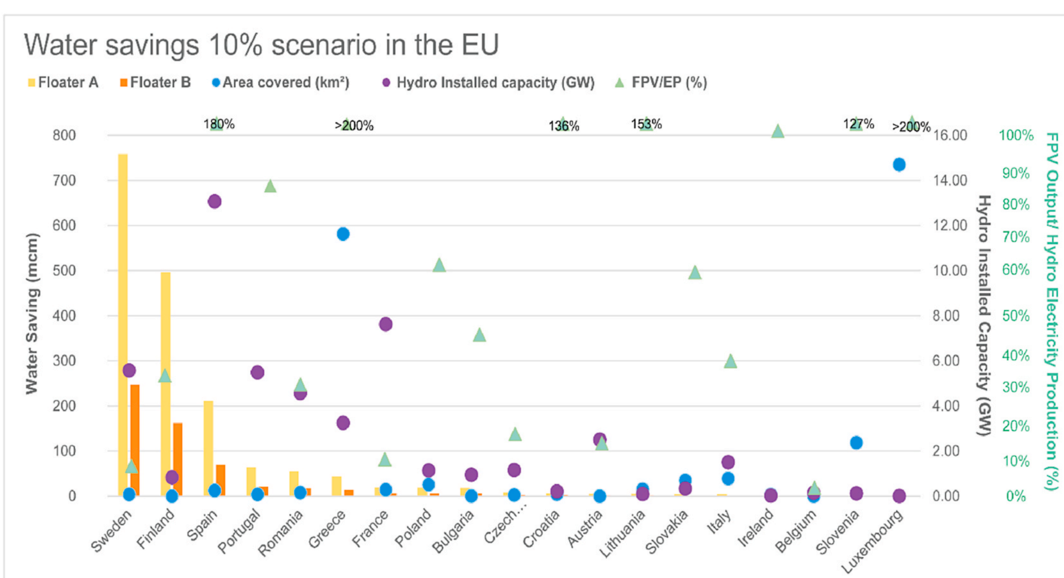

Fig. 8. Water saving after the installation either of floater A or floater B (suspended) in the EU for the 10% area scenario. The countries are sorted based on the water savings (larger to smaller).

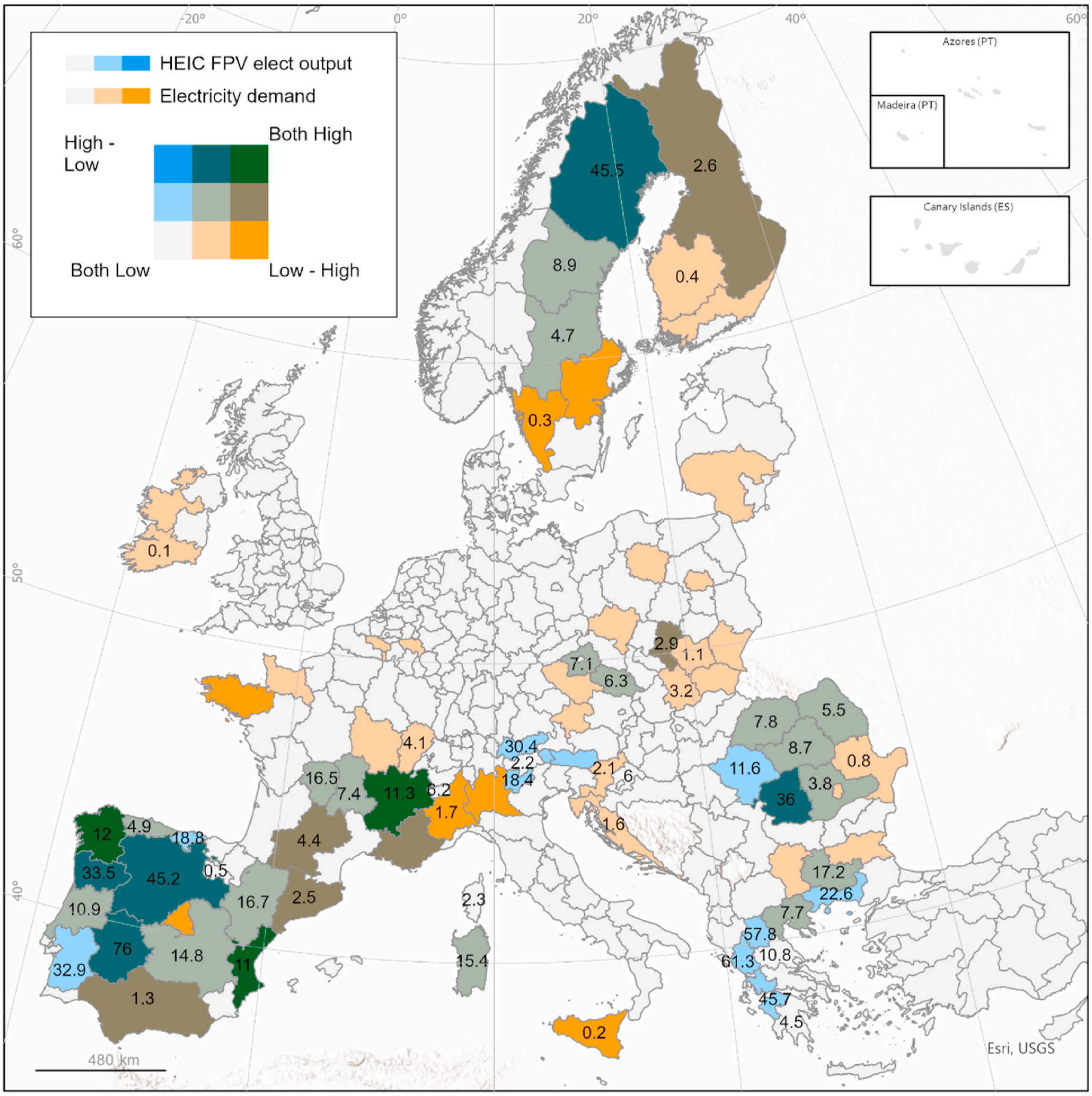

Fig. 9. Bivariate map with the FPV electricity output in the HEIC scenario and the electricity demand at NUTS2 level. The numbers represent the percentage between annual FPV potential generation with the HEIC scenario and regional total electricity demand.

Table 5
Summary table with the LCOE cost projections for the years 2020–2050.

Year	LCOE Eur/MWh FPV			LCOE Eur/MWh PV ground-mounted		
Discount rate sensitivity (WACC)	1.50%	5%	8.50%	1.50%	5%	8.50%
2020	53.5	**72.9**	96.1	38.9	**57.1**	73.5
2030	42.0	**56.7**	74.3	32.2	**47.2**	60.8
2040	34.0	**46.5**	61.5	26.8	**40.8**	53.4
2050	28.4	**38.7**	51.1	24.6	**38.1**	50.1

- The total annual potential electricity generation of FPV covering 100% of the reservoirs' area is estimated at 1386.7 TWh (49% of total EU electricity generation).
- 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 (371.74 km^2, 292 reservoirs). The total FPV electricity output in this scenario is 68% of the hydropower generation.
- The total water losses of the analysed reservoirs are estimated at 9380 mcm. In the HEIC scenario annual water savings up to 557 mcm can be obtained by installing FPV.
- A 10% FPV coverage increases electricity output by 1.5 times and saving up to 1718 mcm of water annually (117 times the water consumption of Italian population in 2018, 0.2 m^3 per capita).

Future work, can focus on collecting information about the hydraulic head of hydropower stations to estimate the productivity of a station and the additional hydroelectricity generation utilizing the water savings from the FPV installation.

Countries such as Spain, Greece, Italy and Portugal will specially benefit from the water savings after installing FPV due to high water scarcity. These water saving will become more important to the climate adaption scenarios as the population living in the pre-mentioned countries are threatened by an acute water shortage and the water stress level is extremely high, >80%.

In conclusion, coupling FPV with hydropower offers a unique energy aid with reducing simultaneously the evaporation and providing water savings especially in areas suffering water stress. Moreover, the current findings show that countries could benefit from the use of FPV and support investments in coupling hydropower and solar energy to meet the ambitious energy target set by the European Commission to tackle climate change and reach climate neutrality.

Disclaimer

The views expressed are based on the current information available to the authors and may not in any circumstances be regarded as stating an official or policy position of the European Commission.

Authors

Dr Kakoulaki conceived the presented idea, contributed to this work with data curation and analysis, investigation, methodology, visualization, writing – original draft. Dr. Gonzalez Sanchez R., contributed to this work with taking part in the analysis, investigation, methodology, editing-writing. Dr. Gracia Amillo A., implemented the solar irradiation and PV output analysis, editing-writing. Szabo S., contributed with the cost analysis, editing-writing. Dr. Farinosi F., Dr. De Felice L., Dr. Bisselink B., Dr. Seliger R., contributed to this study with data processing and editing, Dr. De Felice M., performed the regional assessment, editing, Dr. Kougias I., estimated the hydropower coefficient, editing, and Dr. Jaeger-Waldau A., supervised the findings of this work. All the pre-mentioned authors contributed in discussing the results and the final writing of the manuscript.

Suplementary data

The detailed dataset for the 337 reservoirs and the estimated values can be downlaoded from https://doi.org/10.6084/m9.figshare.21345660

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: All the authors working for the JRC reports financial support was provided by European Commission Joint Research Centre Ispra.

Data availability

Data will be made available on request.

Acknowledgments

The authors gratefully acknowledge the valuable comments and suggestions of Nigel Taylor, Christian Thiel, Tony Sample, Sven Kupschus, Emanuele Quaranta. Tim Tröndle for providing electricity demand data. Giovanni Caudullo for the visualization and python scripting. Fernado Fahl for his support and fruitful discussions. This study was performed under the European Commission Joint Research Center Annual Work Program 2021.

ANNEX

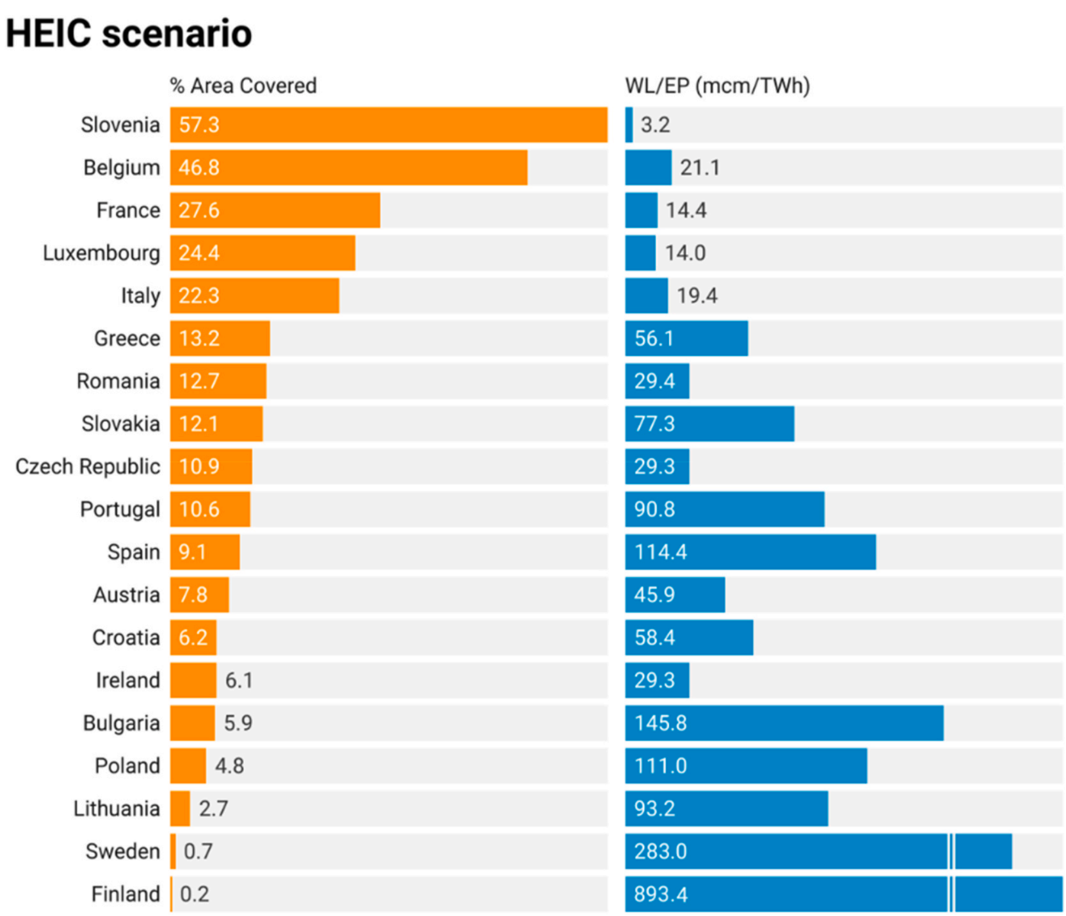

Fig. 1. ANNEX 1% of area covered and the WL/EP ratio for the HEIC scenario

Table 1
ANNEX 1 Table with the capacity and utility factors estimated for each country.

Country	for HDAM	for PHS
	CF HYDRO	CF Pure PHS
Austria	0.30	no data
Belgium	0.33	0.07
Bulgaria	0.13	0.05
Croatia	0.30	no data
Czechia	0.21	0.11
Denmark	0.27	no data
Estonia	0.36	no data
Finland	0.43	no data
France	0.27	0.30
Germany	0.42	0.13
Greece	0.13	no data
Hungary	0.42	no data
Iceland	0.72	no data
Ireland	0.42	0.09
Italy	0.28	0.05
Latvia	0.15	no data
Lithuania	0.33	0.09
Luxembourg	0.34	0.07
Netherlands	0.23	no data
Poland	0.23	0.06
Portugal	0.14	0.3
Romania	0.27	0.53
Slovakia	0.30	0.03
Slovenia	0.43	0.13
Spain	0.16	0.08
Sweden	0.45	0.45

Table 2
ANNEX 1 Summary table at national level of the reservoir number used in the HEIC and area scenarios

Country	Number of reservoirs HEIC	Number of reservoirs area scenarios
Austria	5	10
Belgium	2	2
Bulgaria	8	9
Croatia	3	3
Czech Republic	7	8
Finland	12	12
France	31	39
Greece	12	14
Ireland	2	2
Italy	9	14
Lithuania	1	1
Luxembourg	1	1
Poland	9	10
Portugal	19	25
Romania	47	50
Slovakia	4	4
Slovenia	2	2
Spain	83	94
Sweden	35	37
Total	**292**	**337**

Table 3
ANNEX 1 Summary table of the largest 20 hydropower reservoirs (sorted based on installed capacity) with information on FPV output, evaporation, water losses, water extent for the year 2018.

Reservoir Name	Country	Reservor Area (km^2) 2018	IC (MW)	EP (GWh)	Irradiation (kwh/kwp)	Max Water Area (km^2)	Min Water Area (km^2)	Range min-max (km^2)	Avg. Water Area (km^2)	Evaporation (mm) 2018	Water Losses (mcm) 2018	FPV output 100% scenario (TWh)	FPV output 10% scenario (TWh)	HEIC output (TWh)	Area covered HEIC (km^2)	%_area covered HEIC
Maison	France	1.842471	1800	4441.32	955.09	1.847535	1.701789	0.197009	1.802309	403.4023	0.743257	0.174213	0.017421	2.127463	22.275	12.08974
Cortes de Pallas	Spain	3.288082	1516	398.0544	1362.7	3.291556	3.0885	0.211401	3.256232	1039.807	3.418972	0.443586	0.044359	2.556493	18.7605	5.705606
Iron Gate 1	Romania	106	1165.8	2936.067	1159.5	106	98.6	7.4	105.3619	776.5002	82.30902	12.16779	1.216779	1.672785	14.42678	0.136102
Aldeadavila	Spain	2.25794	1142	1135.296	957.45	2.25794	2.038424	0.219516	2.184354	1103.816	2.49235	0.214025	0.021402	1.353092	14.13225	6.258914
Venda Nova	Portugal	3.009791	1038	2049.84	1288.7	3.02187	2.363978	0.657892	2.927995	680.9972	2.049659	0.383993	0.038399	1.655367	12.84525	4.267821
Koelnbrein	Austria	2.161252	1028	1909.768	823.14	2.161865	1.984746	0.177119	2.05693	329.5924	0.712332	0.176122	0.017612	1.047158	12.7215	5.88617
Alcantara 2	Spain	66	934	1309.094	1466.8	66	47.6	18.4	61.67619	1143.155	75.44823	9.584071	0.958407	1.695364	11.55825	0.175125
Almendra	Spain	50.7	851	596.3808	1434.4	68.8	35.8	34.9	56.20952	985.6237	49.97112	7.199684	0.719968	1.510585	10.53113	0.207714
Bissorte	France	1.000528	825	2168.1	983.13	1.000528	0.959318	0.069072	0.987367	455.6285	0.455869	0.097381	0.009738	1.003714	10.20938	10.20399
Harspranget	Sweden	2.063329	818	3433.482	690.09	2.08176	1.625119	0.469754	1.955094	388.2352	0.801057	0.140964	0.014096	0.698561	10.12275	4.906028
Alto Lindoso	Portugal	7.953334	630	772.632	1214.3	7.959351	6.685106	1.291633	7.547463	724.6253	5.763187	0.956116	0.095612	0.946699	7.79625	0.980249
Porabka	Poland	2.864812	551	22.1628	886.17	2.874122	2.829949	0.054063	2.849645	642.9252	1.84186	0.251332	0.025133	0.604246	6.818625	2.38013
Roselend	France	2.671639	546	1291.399	991	2.672896	2.440391	0.289692	2.608284	471.956	1.260896	0.262112	0.026211	0.669594	6.75675	2.529066
Alqueva	Portugal	198	518.4	363.2947	1489.3	207	6.035355	200.9646	159.5969	1078.387	213.5206	29.19326	2.919326	0.955416	6.4152	0.0324
Vidra	Romania	8.660259	510	1284.435	978.71	8.660896	3.665984	5.100863	7.851417	418.3402	3.622934	0.839112	0.083911	0.617688	6.31125	0.72876
Cedillo	Spain	6.645331	500	662.9568	1449.2	6.701344	6.099003	0.602341	6.506709	1062.24	7.058934	0.953411	0.095341	0.896693	6.1875	0.931105
Letsi	Sweden	17	483	1714.77	706.09	17	15.3	1.7	16.51053	384.8186	6.541916	1.188349	0.118835	0.422039	5.977125	0.351596
Dalesice	Czech Republic	3.52954	480	883.008	987.87	3.622553	2.90183	0.720723	3.488876	785.5498	2.772629	0.345186	0.034519	0.586795	5.94	1.682939
Messaure	Sweden	22.6	463	1773.9	692.73	22.6	21.1	1.5	22.28	404.3382	9.138043	1.549914	0.154991	0.396908	5.729625	0.253523
Picote	Portugal	0.583319	441	543.2952	1237.1	0.59074	0.490338	0.100402	0.566126	984.0696	0.574026	0.071441	0.007144	0.675132	5.457375	9.355736
San Esteban	Spain	3.532362	438	613.9008	1188.3	3.532362	3.231825	0.309194	3.437359	717.0413	2.532849	0.415553	0.041555	0.644088	5.42025	1.534455
Kremasta	Greece	68.8	437.2	733.0375	1338	68.9	59.1	9.8	67.22857	943.2616	64.8964	9.113386	0.911339	0.723905	5.41035	0.078639
Bemposta	Portugal	2.795273	431	528.5784	1407.1	2.819553	2.617226	0.202327	2.758991	1071.912	2.996286	0.38939	0.038939	0.750494	5.333625	1.908087
Total		**583.9593**	**17546.4**	**31564.77**	**25686.87**	**611.3969**	**328.2589**	**285.3376**	**541.6488**	**16996.22**	**540.9224**	**76.11039**	**7.611039**	**24.21028**	**217.1367**	**72.5839**

References

[1] Spencer RS, Macknick J, Aznar A, Warren A, Reese MO. Floating photovoltaic systems: assessing the technical potential of photovoltaic systems on man-made water bodies in the continental United States [cited 2022 Feb 4] Environ Sci Technol [Internet]. 2019 Feb 5;53(3):1680. –9. Available from: https://pubs.acs.org/doi/full/10.1021/acs.est.8b04735.

[2] Cagle AE, Armstrong A, Exley G, Grodsky SM, Macknick J, Sherwin J, et al. The land sparing, water surface use efficiency, and water surface transformation of floating photovoltaic solar energy installations. Sustain Times 2020;12:8154 [Internet]. 2020 Oct 2 [cited 2022 Feb 4];12(19):8154. Available from: https://www.mdpi.com/2071-1050/12/19/8154/htm.

[3] Exley G, Armstrong A, Page T, Jones ID. Floating photovoltaics could mitigate climate change impacts on water body temperature and stratification. Sol Energy 2021 May 1;219:24–33.

[4] Floating solar photovoltaics gaining ground | state, local, and tribal governments | NREL [internet] [cited 2022 Feb 4]. Available from: https://www.nrel.gov/state-local-tribal/blog/posts/floating-solar-photovoltaics-gaining-ground.html.

[5] World energy Outlook 2021 – analysis - IEA [internet] [cited 2022 Feb 4]. Available from: https://www.iea.org/reports/world-energy-outlook-2021.

[6] Jäger-Waldau A. Snapshot of photovoltaics – February 2022. EPJ Photovolt 2022; 13:9. https://doi.org/10.1051/epjpv/2022010. In press.

[7] Kougias I, Bódis K, Jäger-Waldau A, Monforti-Ferrario F, Szabõ S. Exploiting existing dams for solar PV system installations. Prog Photovolt Res Appl [Internet] 2016 Feb 1;24:229–39 [cited 2022 Feb 7]; Available from: https://onlinelibrary.wiley.com/doi/full/10.1002/pip.2640.

[8] Marian W. Floating PV's watershed moment – pv magazine International. PV magazine, issue 6 [Internet] [cited 2022 Feb 4]; Available from: https://www.pv-magazine.com/magazine-archive/floating-pvs-watershed-moment/; 2019 Jun.

[9] Lee N, Grunwald U, Rosenlieb E, Mirletz H, Aznar A, Spencer R, et al. Hybrid floating solar photovoltaics-hydropower systems: benefits and global assessment of technical potential. Renew Energy 2020 Dec 1;162:1415–27.

[10] IHA. Hydropower status report [internet]. 2021 [cited 2022 Feb 18]. Available from: https://assets-global.website-files.com/5f749e4b9399c80b5e421384/60c37321987070812596e26a_IHA20212405-status-report-02_LR.pdf; 2021.

[11] Perez M, Perez R, Ferguson CR, Schlemmer J. Deploying effectively dispatchable PV on reservoirs: comparing floating PV to other renewable technologies. 2018. https://doi.org/10.1016/j.solener.2018.08.088 [cited 2022 Feb 4]; Available from:.

[12] Cazzaniga R, Rosa-Clot M, Rosa-Clot P, Tina GM. Integration of PV floating with hydroelectric power plants. Heliyon [Internet]. 2019. https://doi.org/10.1016/j.heliyon.2019.e01918 [cited 2022 Feb 4];e01918. Available from:.

[13] Farfan J, Breyer C. Combining floating solar photovoltaic power plants and hydropower reservoirs: a virtual battery of great global potential. Energy Proc 2018 Nov 1;155:403–11.

[14] Lee N, Grunwald U, Rosenlieb E, Mirletz H, Aznar A, Spencer R, et al. Hybrid floating solar photovoltaics-hydropower systems: benefits and global assessment of technical potential. Renew Energy 2020 Dec 1;162:1415–27.

[15] Dörenkämper M, Wahed A, Kumar A, de Jong M, Kroon J, Reindl T. The cooling effect of floating PV in two different climate zones: a comparison of field test data from The Netherlands and Singapore. Sol Energy 2021 May 1;219:15–23.

[16] Liu H, Krishna V, Lun Leung J, Reindl T, Zhao L. Field experience and performance analysis of floating PV technologies in the tropics. Prog Photovolt Res Appl [Internet] 2018 Dec 1;26:957–67 [cited 2022 Feb 4];Available from: https://onlinelibrary.wiley.com/doi/full/10.1002/pip.3039.

[17] Taboada ME, Cáceres L, Graber TA, Galleguillos HR, Cabeza LF, Rojas R. Solar water heating system and photovoltaic floating cover to reduce evaporation: experimental results and modeling. Renew Energy 2017;105:601–15.

[18] World Bank Group. ESMAP, SERIS. Where sun meets water: floating solar handbook for practitioners [internet] [cited 2022 Feb 4]. Available from: www.worldbank.org; 2019.

[19] Ziar H, Prudon B, Lin FY, Roeffen B, Heijkoop D, Stark T, et al. Innovative floating bifacial photovoltaic solutions for inland water areas. Prog Photovolt Res Appl [Internet] 2021 Jul 1;29:725–43 [cited 2022 Mar 11]; Available from: https://onlinelibrary.wiley.com/doi/full/10.1002/pip.3367.

[20] Helfer F, Lemckert C, Zhang H. Impacts of climate change on temperature and evaporation from a large reservoir in Australia. J Hydrol 2012 Dec 19;475:365–78.

[21] Santafé MR, Ferrer Gisbert PS, Sánchez Romero FJ, Torregrosa Soler JB, Ferrán Gozálvez JJ, Ferrer Gisbert CM. Implementation of a photovoltaic floating cover for irrigation reservoirs. J Clean Prod 2014 Mar 1;66:568–70.

[22] Quaranta Emanuele R-CM, Alberto Pistocchi. The role of floating PV in the retrofitting of existing hydropower plants and evaporation reduction. In: Solar hydro [internet]; 2021 [cited 2022 Feb 4]. Available from: https://www.researchgate.net/publication/353043174_The_role_of_floating_PV_in_the_retrofitting_of_existing_hydropower_plants_and_evaporation_reduction.

[23] Ong S, Campbell C, Denholm P, Margolis R, Heath G. Land-use requirements for solar power plants in the United States. 2013 [cited 2022 Feb 7]; Available from: www.nrel.gov/publications.

[24] Aznar AY, Lee N, Booth SS. International applications for floating solar photovoltaics. 2019 Jun 12 [cited 2022 Feb 7]; Available from: http://www.osti.gov/servlets/purl/1526906/.

[25] Solomin E, Sirotkin E, Cuce E, Selvanathan SP, Kumarasamy S. Hybrid floating solar plant designs: a review. Energies 2021;14:2751 [Internet]. 2021 May 11 [cited 2022 Feb 4];14(10):2751. Available from: https://www.mdpi.com/1996-1073/14/10/2751/htm.

[26] Abid M, Abid Z, Sagin J, Murtaza R, Sarbassov D, Shabbir M. Prospects of floating photovoltaic technology and its implementation in central and south Asian countries. Int J Environ Sci Technol [Internet] 2019 Mar 14;16:1755–62 [cited 2022 Feb 4]; Available from: https://research.nu.edu.kz/en/publications/prospects-of-floating-photovoltaic-technology-and-its-implementat.

[27] Campana PE, Wästhage L, Nookuea W, Tan Y, Yan J. Optimization and assessment of floating and floating-tracking PV systems integrated in on- and off-grid hybrid energy systems. Sol Energy 2019 Jan 1;177:782–95.

[28] Wood Mackenzie, Cox M. Floating solar landscape 2019 [internet]. 2019 [cited 2022 Feb 4]. pp. 1–200. Available from: https://www.woodmac.com/reports/power-markets-floating-solar-landscape-2019-347469.

[29] Hopson C. Floating solar going global with 10GW more by 2025: fitch [Internet]. Recharge News 2020 [cited 2022 Feb 4]. Available from: https://www.rechargenews.com/transition/floating-solar-going-global-with-10gw-more-by-2025-fitch/2-1-894336.

[30] Floating solar PV gains global momentum – pv magazine International [Internet] [cited 2022 Feb 7]. Available from: https://www.pv-magazine.com/2020/09/22/floating-solar-pv-gains-global-momentum/.

[31] Renewable Energy Agency I. Offshore renewables: an action agenda for deployment (A contribution to the G20 Presidency). 2021 [cited 2022 Feb 4]; Available from: www.irena.org.

[32] Floating PV - potentials and challenges in Germany | Rödl & partner [internet] [cited 2022 Feb 7]. Available from: https://www.roedl.com/insights/renewable-energy/2020-11/floating-pv-potential-challenges-in-germany.

[33] ETIP PV the European technology and innovation platform for photovoltaics - ETIP PV [internet] [cited 2022 Mar 8]. Available from: https://etip-pv.eu/.

[34] Solarplaza | the global platform for solar resources [internet] [cited 2022 Feb 7]. Available from: https://www.solarplaza.com/channels/future-grid/11954/top-30-floating-solar-pv-plants-europe/.

[35] Netherlands. Hotspot for floating PV - pv Europe [internet] [cited 2022 Feb 7]. Available from: https://www.pveurope.eu/installation/floating-solar-parks-netherlands-hotspot-floating-pv.

[36] Gonzalez Sanchez R, Kougias I, Moner-Girona M, Fahl F, Jäger-Waldau A. Assessment of floating solar photovoltaics potential in existing hydropower reservoirs in Africa. Renew Energy 2021 May 1;169:687–99.

[37] GitHub - energy-modelling-toolkit/hydro-power-database: JRC Hydro-power plants database [Internet] [cited 2022 Mar 11]. Available from: https://github.com/energy-modelling-toolkit/hydro-power-database.

[38] Eurostat - data explorer [internet] [cited 2022 Mar 11]. Available from: https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_ind_peh&lang=en.

[39] Eurostat - data explorer [internet] [cited 2022 Mar 11]. Available from: https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_inf_epcrw&lang=en.

[40] Huld T, Gracia Amillo AM. Estimating PV module performance over large geographical regions: the role of irradiance, air temperature, wind speed and solar spectrum. Energies 2015;8(6):5159–81.

[41] Photovoltaic geographical information system (PVGIS) | EU science hub [internet] [cited 2022 Feb 7]. Available from: https://ec.europa.eu/jrc/en/pvgis.

[42] Müller R, Pfeifroth U, Träger-Chatterjee C, Trentmann J, Hollmann R. Surface solar radiation data set - heliosat (SARAH) - edition 1 [internet]. Satell Appl Facil Climate Monitor 2015 [cited 2022 Mar 11]. Available from: https://climatedataguide.ucar.edu/climate-data/surface-solar-radiation-data-set-heliosat-sarah-edition-1. https://wui.cmsaf.eu/safira/action/viewDoiDetails?acronym=SARAH_V001.

[43] Dee DP, Uppala SM, Simmons AJ, Berrisford P, Poli P, Kobayashi S, et al. The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Q J R Meteorol Soc [Internet 2011 Apr 1;137:553–97 [cited 2022 Mar 14]; Available from: https://onlinelibrary.wiley.com/doi/full/10.1002/qj.828.

[44] Pekel JF, Cottam A, Gorelick N, Belward AS. High-resolution mapping of global surface water and its long-term changes. Nature 2016;540:418–22. 5407633 [Internet]. 2016 Dec 7 [cited 2022 Feb 7]; Available from: https://www.nature.com/articles/nature20584.

[45] Van Der Knijff J, De Roo A. JRC publications repository - LISFLOOD - distributed water balance and flood simulation model - revised user manual [internet]. 2008 [cited 2022 Feb 7]. Available from: https://publications.jrc.ec.europa.eu/repository/handle/JRC44410.

[46] Peter Andreas Burek, Johan Van Der Knijff, Victor Nyakatura Ntegeka. JRC publications repository - LISVAP evaporation pre-processor for the LISFLOOD water balance and flood simulation model [internet]. 2013 [cited 2022 Feb 7]. Available from: https://publications.jrc.ec.europa.eu/repository/handle/JRC84451.

[47] Supit I, European Commission B, Hooijer AA, Van Diepen CA. System description of the WOFOST 6.0 crop simulation model implemente in CGMS. 1994 [cited 2022 Feb 7]; Available from: https://agris.fao.org/agris-search/search.do?recordID=XF2015031404.

[48] Kohli A, Frenken Aquastat Programme K. Evaporation from artificial lakes and reservoirs. 2015.

[49] de Wit A, Boogaard H, Fumagalli D, Janssen S, Knapen R, van Kraalingen D, et al. 25 years of the WOFOST cropping systems model. Agric Syst 2019 Jan 1;168:154–67.

[50] Thiemig V, Gomes GN, Skøien JO, Ziese M, Rauthe-schöch A, Rehfeldt K, et al. EMO-5: a high-resolution multi-variable gridded meteorological data set for Europe [cited 2022 Feb 7] Earth Syst Sci Data Discuss [Internet] 2021;26 (November):1–35. Available from: https://essd.copernicus.org/preprints/essd-2021-339/.

[51] Gonzalez Sanchez R, Seliger R, Fahl F, De Felice L, Ouarda TBMJ, Farinosi F. Freshwater use of the energy sector in Africa. Appl Energy 2020 Jul 15;270:115171.

[52] Hughes DA, Farinosi F. Assessing development and climate variability impacts on water resources in the Zambezi River basin. Simulating future scenarios of climate and development. J Hydrol Reg Stud 2020 Dec 1;32:100763.

[53] Bontempo Scavo F, Tina GM, Gagliano A, Nižetić S. An assessment study of evaporation rate models on a water basin with floating photovoltaic plants [cited 2022 Feb 7] Int J Energy Res [Internet] 2021 Jan 1;45(1). 167–88. Available from: https://onlinelibrary.wiley.com/doi/full/10.1002/er.5170.

[54] Seth Block D, Kumar Senior Director A, Kumar A, Director S. Floating solar photovoltaic (FSPV): a third pillar to solar PV sector2 floating solar photovoltaic (FSPV): a third pillar to solar PV sector. www.teriin.org; 2019.

[55] Pimentel Da Silva GD, Branco DAC. Is floating photovoltaic better than conventional photovoltaic Assessing environmental impacts. https://doi.org/101080/1461551720181477498 [Internet]. 2018 Sep 3 [cited 2022 Feb 7];36(5): 390-400. Available from: https://www.tandfonline.com/doi/abs/10.1080/14615517.2018.1477498.

[56] Tröndle T, Pfenninger S, Lilliestam J. Home-made or imported: on the possibility for renewable electricity autarky on all scales in Europe. Energy Strategy Rev 2019 Nov 1;26:100388.

[57] Quaranta Emanuele, et al. Assessing the energy potential of modernizing the European hydropower fleet. Energy Convers Manag 2021;246:114655. https://doi.org/10.1016/j.enconman.2021.114655. In press.