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Evaluating floating photovoltaics (FPVs) potential in providing clean energy and supporting agricultural growth in Vietnam

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ABSTRACT

Vietnam's promising economic growth has led to energy shortage, growing coal imports, and increasing carbon emissions. The country's electricity demand annual growth rate has been 12% in recent years and is projected to be 8–9% by 2030. In Vietnam 40% of the land is dedicated to agriculture and thousands of inland water bodies are used for agriculture/aquaculture. Utilising even a small portion of them for Floating Photovoltaics (FPVs) would mitigate land-use conflicts and benefits agriculture and aquaculture. To demonstrate FPVs' potential, we selected a hydropower dam reservoir in the North and six irrigation reservoirs in the South. System Advisor Model (SAM) software was used to simulate the electricity generated if we cover 1%, 5%, and 10% of surfaces of these reservoirs. The results show a potential capacity close to 1 GWp and annual potential generation of 1.4 TWh if 1% of these surfaces were covered by FPVs. We also evaluated FPVs potential for four different types of water bodies in Vietnam: Lake, Lagoon, River and Without Classification. The results showed that the potential capacity, considering use of only of 1% of these water surfaces for FPVs is 3.7 GWp, and provides 5385 GWh generation, which highlights the significant contribution that FPVs can make to the renewable energy sector in this country. However, FPVs face some socio-technical barriers, including regulatory ambiguity about water rights, uncertainty about economic policies and limited information about their environmental impacts that could hamper the expansion of this technology, and need to be addressed through further research.

1. Introduction

Vietnam's gross domestic product (GDP) has increased 55 times in the past 30 years, from 6.5 billion USD in 1990 to 362 billion USD in 2021 [1]. This growth has been accompanied by a high electricity demand annual growth rate. From 2012 year by year the electricity demand growth has been between 9 and 12% [2], except for 2020 which is attributed to COVID-19. This value has increased again to 9% in 2021, which is faster than any other comparable Asian economy, and is projected to be 8–9% annually till 2030 [3]. Since 2016, coal has become one of the most crucial energy sources in the country, and its use in 2013–2018 grew 75%, faster than any other country in the world, despite political resistance to coal due to local pollution concerns [4]. In addition, we have seen an increasing trend in investments in new coal-fired plants, which could result in a technological lock-in due to the long operational life of these plants.

The share of coal in electricity generation in Vietnam has increased 36.5 folds from 3.0 Terawatt hours (TWh) in 2000 to 109.5 TWh in 2021, which corresponds to an increase from 11.5% to 51.3%. The percentage shares of hydro and gas as the second and third sources of electricity generation in Vietnam between 2000 and 2021 has changed from 56.1% to 25.6% for hydro and from 15.9% to 11.6% for gas [2,3]. The share of Solar PV in Vietnam's electricity supply was about 0.01% in 2018 [5], which has increased to 2.3% in 2019 and 10.6% in 2021. Fig. 1 illustrates electricity generation by source in Vietnam in TWh and percentage share.

To maintain its economic growth and follow the Paris Agreement on Climate Change, the country has pledged to reduce its greenhouse gases emissions by 8% by 2030 [6]. Vietnam needs to have access to secure energy supply and sustainably shift its energy resources from fossil fuels to renewables. A process that has been initiated since 2018 with supporting policies for investment in Solar PV and has been reaffirmed in

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Vietnam's commitments to COP26, where the country announced its aim to stop deforestation by 2030, phase out coal fired power generation by 2040 and achieve net-zero carbon emission by 2050. This process also involves introducing stronger measures to reduce the country's greenhouse gases emissions.

Some studies suggest that the generous feed-in tariff (FIT) that the government announced in 2017 for solar projects has had an instrumental role in expanding solar PV in Vietnam [7]. The FIT stated that PV solar plants grid-connected before July 2019 would be able to sell their electricity to the state-owned Vietnam Electricity (EVN) at a FIT of US $93.5/MWh for 20 years. Such policy had a significant impact on increasing the installed capacity of solar PV, which changed from 0.02 TWh at the end of 2018 to 22.65 TWh by the of 2021 [3,7] In April 2020, the new purchase price for electricity generated by ground-mounted PV plants was announced as US $70.9/MWh for 20 years [8].

Nevertheless, Vietnam faces other challenges when it comes to solar energy, which cannot be merely addressed through providing financial incentives. High population density (310 people per km^2), land morphology, and geography make allocating land for renewable energies, particularly solar farms, quite challenging. As Fig. 2 suggests, the densely forested highlands in the central part and mountains in the far North and Northwest [9–11] has caused the highest population to cluster in two deltas in the North and South, where Hanoi with more than 8 million and Ho Chi Minh City with more than 9 million populations are located respectively. Such geographical characteristics make land conflicts a common issue in rural areas in Vietnam. These challenges sometimes go beyond the villagers and involve the government seizure of agricultural land for development and use of police force to evict farmers in rural districts [12]. The significant presence of inland waters (lakes, wetlands, and ponds) also adds to the land scarcity and makes land-use conflict a major concern in Vietnam.

Moreover, the crucial sector of agriculture exacerbates land shortage for solar farms and makes such installations against the interests of farmers and villagers. Vietnam has been transformed from a food-insecure nation to a world-leading exporter of food commodities [13]. About 40% of Vietnam's inhabitants are engaged in agriculture, making this sector the major employer before services and industries. Among all farmers nearly 90% are small family farmers, of which more than 65%

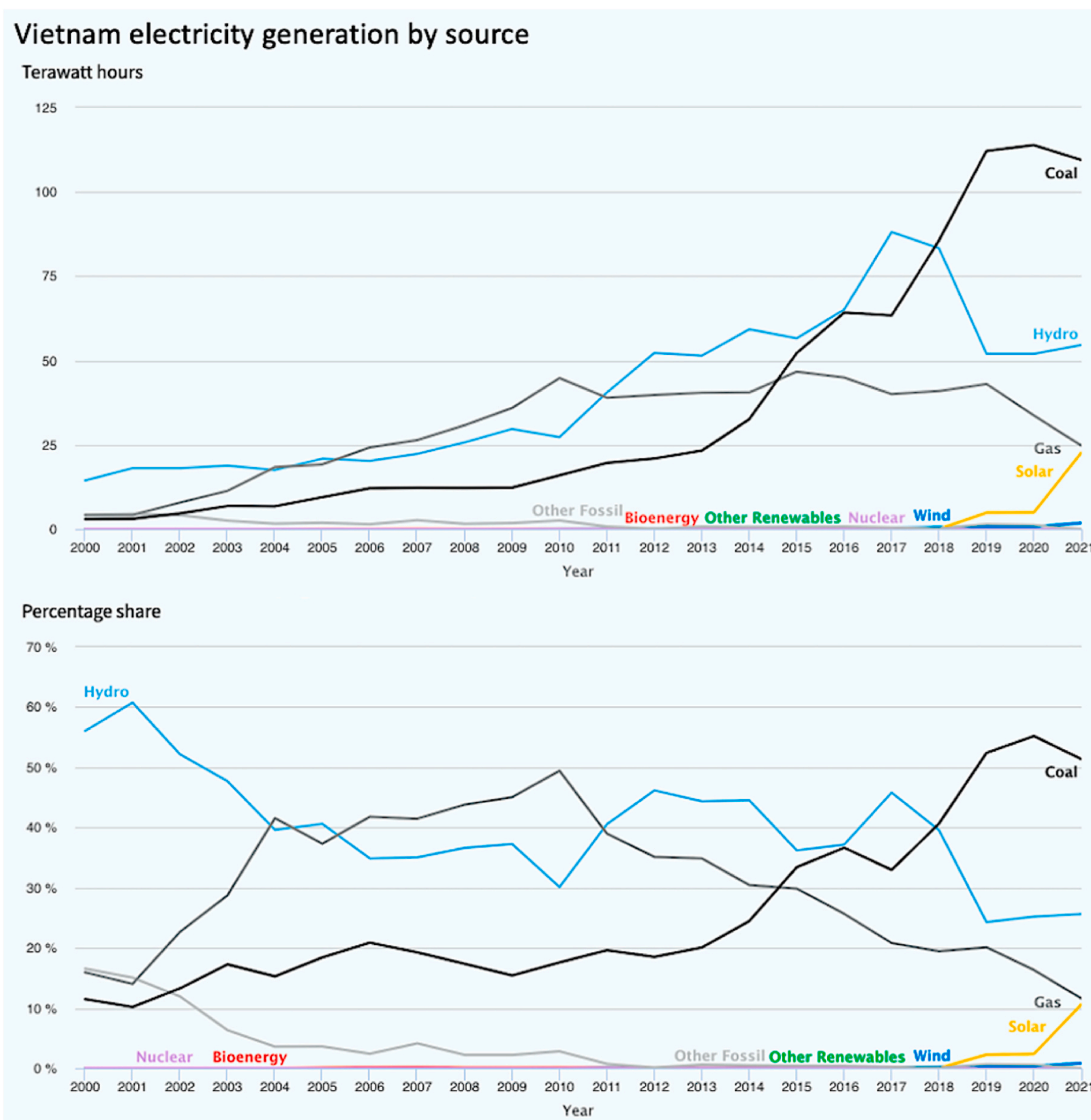

Fig. 1. Vietnam's electricity generation by source from 2000 to 2021 according Ember Climate and Energy Think Tank data [2].

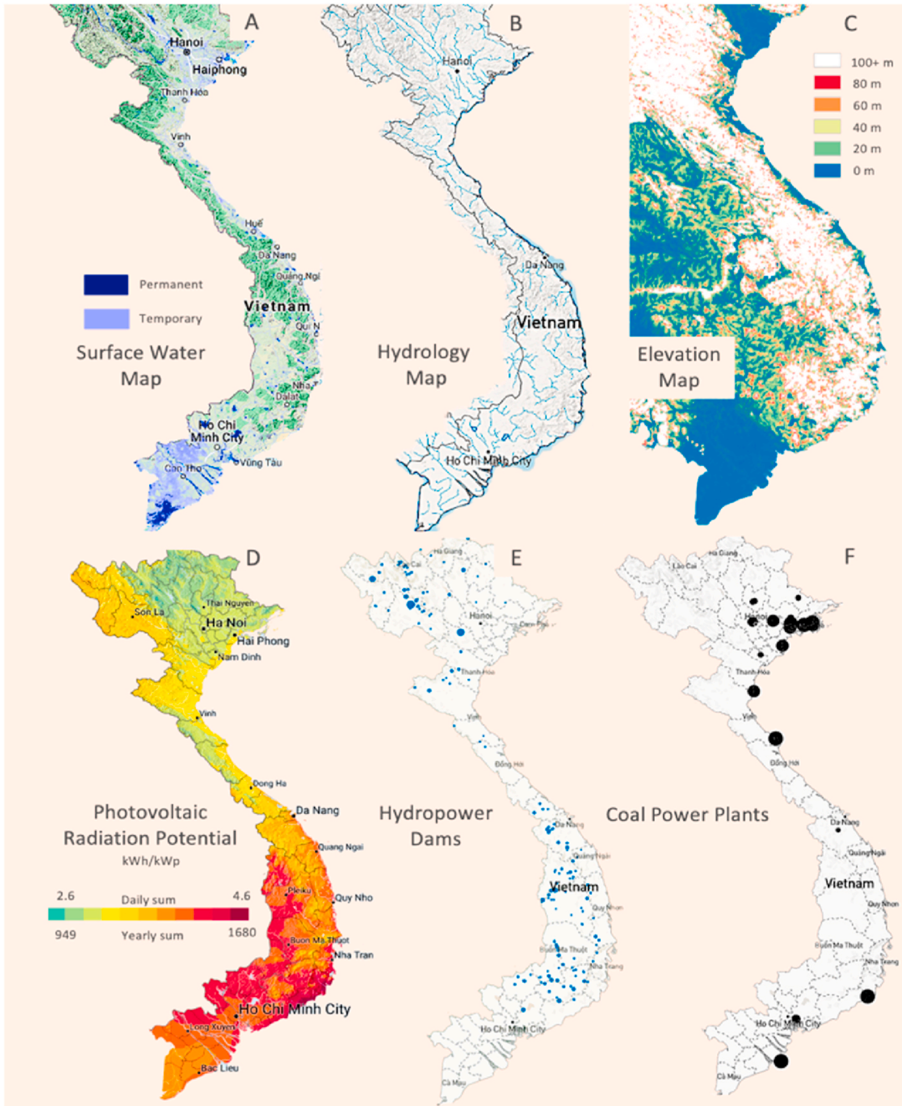

Fig. 2. Vietnam's surface water and elevation maps, hydrology map, hydropower dams and coal power plants and solar radiation potential.

are situated in rural areas. In addition to agriculture, aquaculture (the farming of aquatic organisms) is also a key sector in Vietnam that contributes to achieving food security, alleviation of poverty, sustainable livelihood creation, economic growth, and rural employment generation. Vietnam is the 4th major producer of fishery and aquaculture in the world with export of more than 9 billion USD per year [14]. In this country about 8.5 million people derive their main income directly or indirectly from fisheries, and around 30% of the dietary animal protein consumed by people is in from different aquatic products [15].

These numbers show the vital role that agriculture and aquaculture play in Vietnam's economy, development, and food security (which is increasingly important considering the population growth). However, the land areas dedicated to farming and the growing energy demands by this sector and other parts of the economy make it challenging for Vietnam to maintain its growth while reducing greenhouse gases emissions. Both agriculture and aquaculture sectors actively rely on different types of water bodies, which are extensively available across Vietnam. Fig. 3 illustrates the trends the we have seen in coal consumption, population, agriculture and aquaculture growth [16].

Vietnam's vast water surfaces could be used for deploying floating photovoltaics (FPVs) technology, which is an emerging and innovative approach in generating clean electricity. The country has successfully deployed local power generation through small and mini hydropower before, which has supported agricultural developments in Vietnam. Such small-scale hydropower plants have been widely used for rural electrification, where the operators require much lower training, and these generators could be locally managed. While some of small hydro powers haven't performed as expected, nevertheless, overall generated electricity through these systems has increased agricultural productivity in Vietnam and provided clean energy [17,18]. This experience shows the potential of small or even micro scales FPVs in Vietnam. Particularly now that Vietnam has completed various stages of electrification development and has achieved above 99% universal access to electricity across country the clean electricity generated by FPVs, can serve the entire nation regardless of the location of the power plant [19].

The purpose of this research is to show the significant role that FPVs technology can play in addressing Vietnam's energy needs, considering the challenges that this country faces including growing population, economy, electricity demand, land use conflict and commitments to Paris Agreement. Here we provide a case study and evaluate FPVs deployment potential on some of the important water reservoirs in Vietnam. We use System Advisor Model (SAM) for simulation.

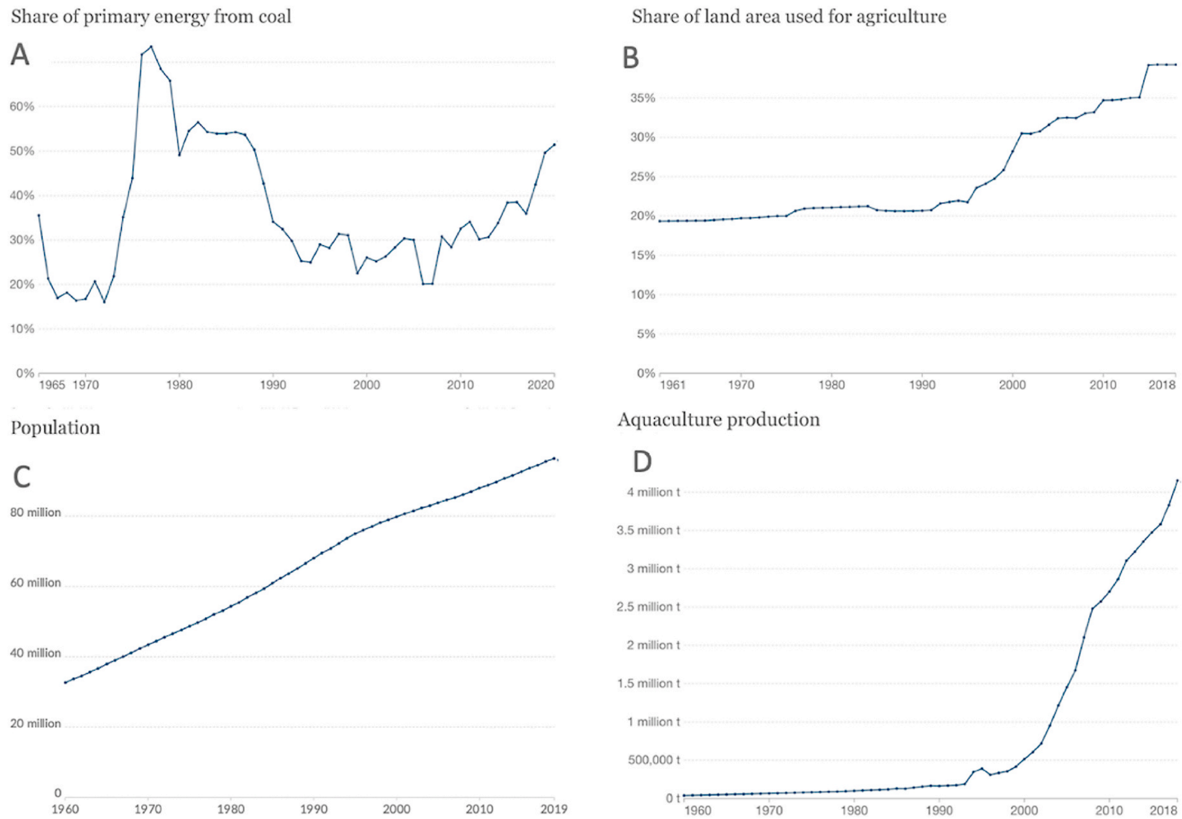

Fig. 3. Vietnam's information about energy, agriculture, population, and aquaculture [16].

2. FPVs role in providing a cost-effective, low carbon, and secure energy supply for Vietnam

2.1. What is floating PV technology?

Floating Photovoltaic (FPVs) systems provide a unique opportunity for Vietnam to address its growing energy demands and transition to a low carbon economy by utilising only a small portion of water surfaces available for this purpose. FPV is an innovative application of PV technology deployed on water surfaces from very small to large scales that can provide clean, cost-effective, reliable, and secure energy. The great potential of FPV technology lies in its flexibility and adaptability with different permanent and seasonal water bodies that allows deploying them even on drinking water reservoirs. In principle, FPVs are an array or combined arrays of photovoltaic panels placed on floating structures that keep them above the water surface [20]. In the long term, such floating infrastructures might be affected by the potential environmental risk that could damage their performance over the years, namely, severe earthquakes, tsunami, and destructive storms. Even considering such concerns, which are highly unlikely in non-marine environments, the strong performance and reliability of the existing floating solar farms have convinced many countries to express their interest in this system.

A study by US National Renewable Energy Lab (NREL) suggests that the floating solar technology could potentially provide about 10% of the US annual electricity needs. This evaluation is based on conservatives assumptions that consider only man-made reservoirs and those that do not face any legal or environmental barriers, which corresponds to about 24,000 water bodies [21]. The FPVs significant potential is not limited to the US, even 1% of the surface coverage of the existing hydropower reservoirs in Africa could produce an additional 171 GWh of electricity and increase the electricity output by 58% [22]. A report by the World Bank indicates that if 1% of the total surface area of man-made reservoirs is covered by floating solar, the FPV capacity would reach more than 400 GW globally [23]. Different scales of FPVs power plants have been installed globally, however, east, and southeast Asia are the regions with the highest number of floating solar projects, at various stages of development. China, South Korea, and India are of the biggest investors and operators of FPVs in the world.

2.2. What makes FPVs different from common PV solar

The latest figures regarding global deployments of FPVs belong to International energy agency (IEA) Photovoltaics Power Systems Programme (PVPS) report that suggests by 2021 the installed capacity of FPVs has surpassed 3GWp globally, which more than 20% of it has been achieved in 2020 alone [24]. This technology delivers several tangible socio-technical and environmental advantages that contribute to sustainable economic growth and achieving energy trilemma that often translates as affordability and access, energy security and resilience, and environmental sustainability [25]. Some of these benefits, like job creation, are similar to common ground-mounted PV farms; however, there are other advantages, which are unique to FPVs, and not occupying habitable or productive areas is one of them. These versatile systems can even be deployed on drinking water reservoirs and seasonal water bodies, including rainwater retention ponds, and reduce land-use conflicts, which is a concern for deploying renewables in Vietnam and many other countries. Moreover, the cost of land for renewables or the slopes and hilly areas that increase the challenges of installing PV solar farms can be eliminated using FPVs [26]. Preserving surface albedo is also another important advantage of FPVs [27].

Covering the water surface with PV panels and float structures reduces the water temperature and evaporation from the covered areas. Water scarcity is a major challenge, and even in countries like Vietnam, the impacts of climate change, including heatwaves and reduced annual precipitation, could affect water availability. Covering the water surface with FPVs can effectively reduce the evaporation of reservoirs and mitigate this problem [28]. The clean energy generated by these systems could also be used for water treatment and improving the quality of water.

Ground mounted PV solar farms require extensive land preparation that could add to deforestation, and loss of fauna and flora [29], while FPVs require minimum land preparation and land occupation is only limited to the energy transformer substations and cable ducts. The visual impacts of FPVs compared to more common PV are significantly less as they sit on the water surface, which is perfectly flat, does not require preparation, and reduces the effect of mutual shading of the rows of the modules.

FPVs could also mitigate algal bloom. Algae, simple plants that live in the sea and freshwater, can grow out of control and cause algal bloom, with toxic or harmful effects on people and the environment [30,31]. These blooms occur through photosynthesis and receiving a high amount of sunlight is crucial for such growth [32]. Covering the water surface with FPVs reduces the sunlight penetration underwater, as well as the water temperature. The shading provided by the FPV can mitigate algae proliferation and improve the water quality [33–35]. The extent of the impact of FPVs on mitigating algal bloom depends on the different characteristics, including the nature and size of the water bodies, nutrients availability, the areas covered by the FPVs, and the design of FPVs.

The other FPVs advantage is reducing the PV panel temperature. When the photovoltaic panels receive sunlight, they generate heat as well as electricity. The increased temperature of the solar panel cells reduces the efficiency of the panel and, therefore, the energy output. Previous studies have shown that reducing the solar panel temperature and ambient heat would improve the energy outputs [36]. In FPVs, the cooling effect of water would result in a more efficient and cost-competitive system. A recent study in Indonesia on FPVs based on remote sensing analysis has shown that there is an 8 °C difference between the surface temperature of a lake and its surrounding environment (annual average) [37]. FPVs can also be integrated into future hydropower or the existing ones. When the high temperatures and evaporation reduce the reservoir's capacity, FPVs systems compensate for the hydropower reduced electricity generation while benefiting from the existing infrastructures and gridlines.

A slightly comparable technology to FPVs is installing PV panels on the top of water canals that could reduce water evaporation particularly in arid regions. However, in this method PV panels are not sitting on water surface and are ground mounted. A good example of this approach is the 10 MWp utility-scale grid-connected canal-top photovoltaic power plant in India [38]. Interestingly this canal-top system has shown to generate slightly lower electricity than a similar scale PV power plants, which has been attributed to the high humidity that the PV panels experience because of their ambient environment [39]. However, this could be case dependent scenario and variations depend on the design of these systems and environmental conditions. The key benefit of these canal-top systems beside generating electricity is saving water. A recent study that has simulated the benefits of canal-top PV installations in California shows that such system could potentially reduce annual water evaporation by an average of 39 ± 12 thousand cubic meter per km of canal [40].

Fig. 4 is a schematic presentation of an FPV plant.

2.3. Some of the challenges for FPV implementation

It is worth noting that FPVs are an emerging concept, and despite the unique opportunities that they provide, scarce information is available about their socio-technical and environmental impacts [20]. They cover only a small portion of the water surface, and it is unlikely that they affect the biodiversity as much as land-use intensive large-scale solar PV infrastructures that might cause habitat loss [42], however, further research on their impacts on ecosystem and water chemistry particularly in engineered reservoir and small lakes are required. Rare and unlikely events like overheating and fire due to man-made or natural phenomena (e.g., heavy storms similar to what happened in Japan in 2019) [43] are possible, and if the fire spreads on FPVs, the combination of electricity, fire and water makes tackling the blaze difficult. In early 2022, the 17 MW FPVs in Southern France experienced a fire accident, which has been attributed to the floating photovoltaics exposure to several days of strong winds and repeated frictions of cables. This minor incident shows the effects of wear and weather risks even in the short term [44]. The vulnerability of the floats to damage which could cause such floating structures to sink also adds to the risk.

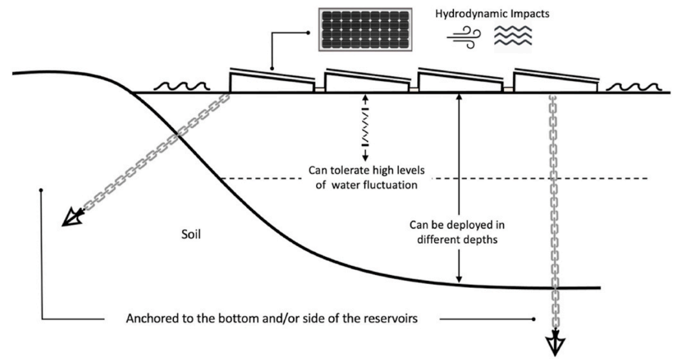

Fig. 4. Schematic representation of an installed floating solar power plant like those deployed for the Anhui project in China. Stability, flexibility, and adjustment with different environmental and hydrodynamic impacts, including water level fluctuations and heavy winds, are essential aspects of a floating solar system.

Public perception and acceptance of floating photovoltaics as a new technology is a topic that might hamper the expansion of FPVs. This is a largely unexplored topic and negligible or no published research that addresses the social or societal implications of FPVs is available [45]. The diverging use of waterbodies by different stakeholders affect the concerns that public has about the FPVs based on the perceived impact on their activities and interests. The uncertainties on possible impacts and the newness of FPVs could cause stakeholders' reluctance toward this technology [45]. Acceptability of FPVs deployment by public and different stakeholders particularly in rural areas is a concern that if not addressed could hinder successful expansion of this technology despite the government's supportive policies.

In terms of maintenance, complex anchoring might be required as well as diving. The electrical safety of the equipment and potential environmental impacts of the reduced sunlight on the aquatic life in small reservoirs or possible release of chemicals from the panels or floats also need to be considered. The current focus of FPV technology is mainly on onshore floating photovoltaics as being exposed to harsh marine environments for such systems could jeopardise their stability and long-term performance.

3. Methodology

Vietnam has truly extensive water surfaces, which includes thousands of hectares of large lakes, wetlands, ponds, and more than 2360 rivers with a length greater than 10 km and 16 major river basins with an average catchment area over 2500 km^2 each [41]. Water is of primary importance as a major resource for economic activities, including agriculture, forestry, fisheries, and energy production in this country.

In the following sections first, we provide a case study to demonstrate the potential impacts of FPV technology in Vietnam based on seven selected reservoirs and then using the same methodology we calculate potential FPV capacity installations and generations for different types of water bodies in this country. The estimated electricity generated by FPVs for each of the above scenarios have been presented in the 4. Results section.

3.1. Reservoirs selection for demonstrating the FPVs potential as part of Vietnam clean energy supply

To demonstrate the potential impacts of FPV technology in clean energy production in Vietnam we have selected seven reservoirs (Fig. 5) to carry out a case study. The one in the North is one of the largest hydropower plants in the country, located close to capital Hanoi. The other reservoirs are in the South and are usually used for irrigation. This region receives the highest irradiance in the country, as seen in Fig. 1. We used System Advisor Model (SAM) software [46] to simulate the electricity generated under three different scenarios; if we cover 1%, 5%, and 10% of the water surface of these seven reservoirs.

Because of the latitude and longitude proximity of some of these reservoirs, the solar resources of these places are similar, and they could be grouped in the same weather data information:

- Group 1: Hoa Da Den, Ho Song Ray, Ho Bau Can, Ho Cau Moi
- Group 2: Ho Da Ton, Ho Tri Na
- Hydropower Plant: Ho Binh Hydropower

The selected reservoirs, as shown in Figure, as well as their respective location and areas can be seen in Table 1.

To calculate the potential installed capacity and estimate electricity generation, we need to know the composition and size of the FPV plants. For our calculations, we used the FPV systems based on the Sungrow company designs [47]. The floats' characteristics are as follow: material composed of high-density polyethylene (HDPE), resistant to UV-radiation, temperature tolerance from −40 °C to 85 °C, anti-fatigue and wave resistance, 25-year lifespan, and an adjustable area for different panel angles. The FPV system design is shown in Fig. 6.

The floating system parts, applications, dimensions, quantities of 1 MW system, and the surface area occupied are shown in Table 2. From the size and composition data of the FPV system, it is possible to calculate the area covered by 1 MWp installed.

A_{total} is the sum of base areas (*BA*) of a quantity (*Q*) of each type of floating piece "*i*" that make up the floating PV system of 1 MWp. For this

Table 1
Location and areas of selected reservoirs in Vietnam for the case study.

Group	Water Body	Location		Total Area (km^2)
		Latitude	Longitude	
1	Ho Da Den	10.6253	107.1752	3.53
	Ho Song Ray	10.6740	107.3583	7.38
	Ho Bau Can	10.7463	107.1364	1.95
	Ho Cau Moi	10.7677	107.1175	1
2	Ho Da Ton	11.3258	107.4753	2.95
	Ho Tri An	11.1397	107.1414	218
Hydropower Plant	Hoa Binh Hydropower	20.8083	105.3238	208
	Total	–	–	442.81

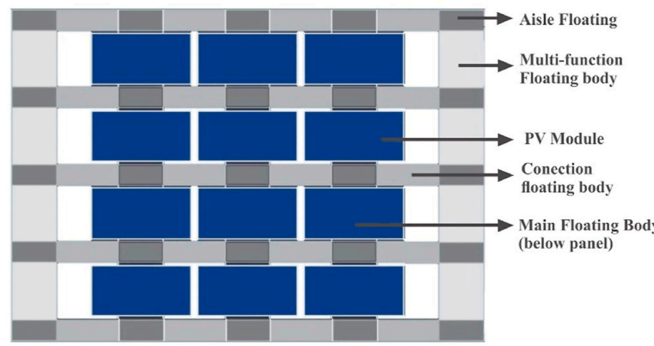

Fig. 6. Schematic representation of the floating photovoltaic system [48].

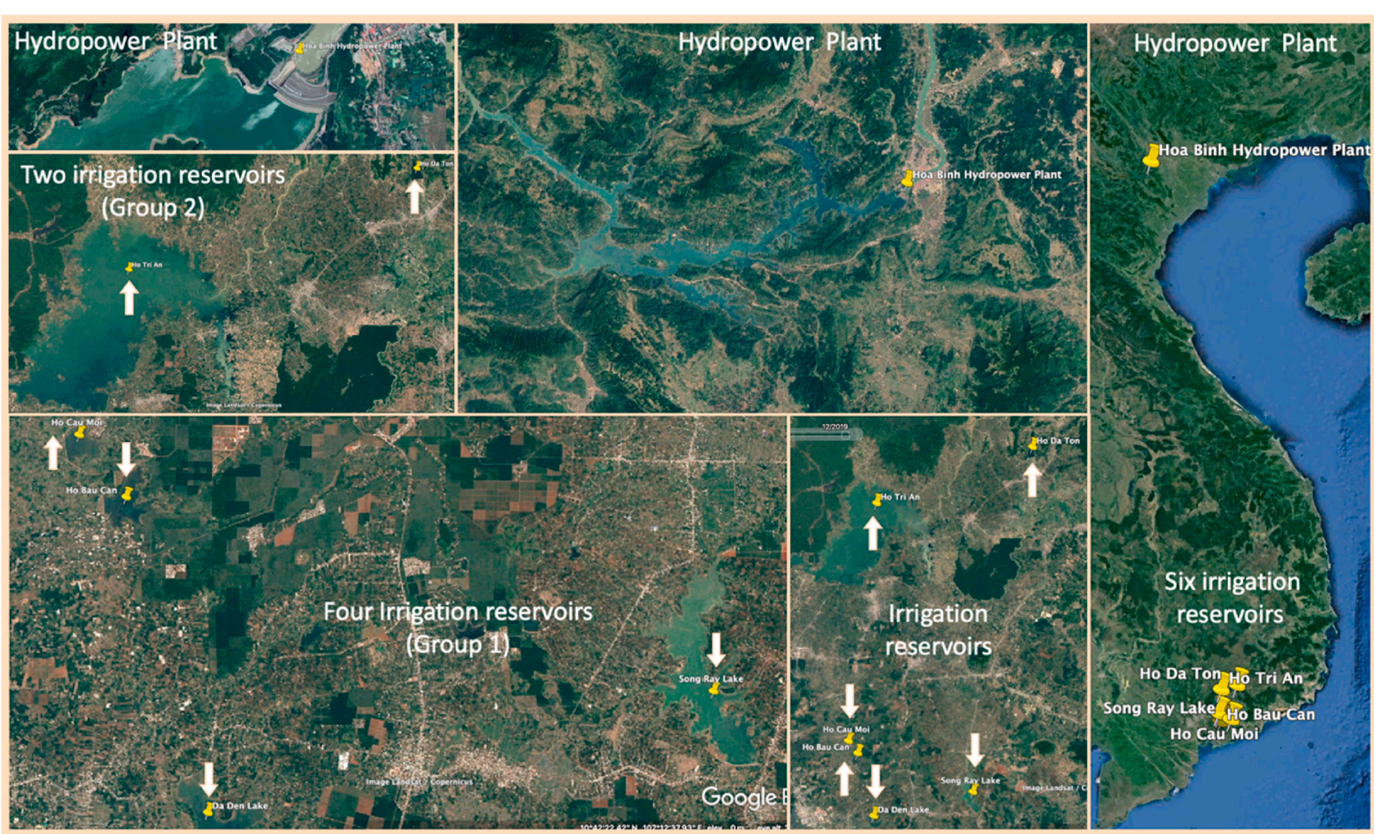

Fig. 5. Selected reservoirs in this study. A hydropower reservoir in the north and six irrigation reservoirs in the south have been selected (Credit Google Maps, 2021).

Table 2
Parts, functions, dimensions, and quantity for composing 1 MWp of the FPV system [48].

$$A_{total} = \sum (Q_i \times BA_i) \quad (1)$$

Parts	Function	Quantity for 1 MW	Unit Size	Occupied area for 1 MW (m^2)
 Main floating body SF-M	Support PV modules	2436	1110 × 880 × 190 mm (base area = 0.9768 m^2)	2379.5
 connection floating body SF-C	Connection of support floats	2520	1212 × 410 × 205 mm (base area = 0.4969 m^2)	1252.2
 aisle floating body SF-A	O&M technician pathway	2604	880 × 410 × 205 mm (base area = 0.3608 m^2)	939.5
 mutli-function floating body SF-H	Multi-function floats	84	1110 × 880 × 205 mm (base area = 0.9768 m^2)	82.1
	PV module 410 Wp, monocrystalline Boviet Solar Technology	2436	2008 × 1002 mm	4901.3
inverter-booster floating platform SF-P 	Inverter support	1	4003 × 2470 × 2912 mm (base area = 9.9 m^2) Estimated dimensions*	9.9

1 MWp floating PV system, modules of 410 Wp arranged in 84 parallel strings of 29 modules per string, 2436 modules in total covering an area of 4663.2 m^2 or 4.663 × 10^{-3} km^2. This potential installation design of FPVs was considered for the above reservoirs, and three scenarios of surface coverage were evaluated. These scenarios were: 1%, 5%, and 10% of the covered surface with FPVs. The details for surface area for each of the reservoirs were obtained from the Google Earth Pro. The capacity potentials for each reservoir under different scenarios were calculated using Equation (2).

$$P_{FPV} = \frac{A_{RES} \times \%C_{RES}}{A_{1MWp}} \times 1\ MWp \quad (2)$$

P_{FPV} is expressed in MWp and represents the potential capacity of floating PV considering the reservoir area (A_{RES}), generally expressed in km^2, m^2 or ha; $\%C_{RES}$ is the percentage of reservoir covered, and A_{1MWp} is the area occupied for 1 MWp installation, generally expressed in km^2, m^2 or ha.

We estimated the potential electricity produced in one year for each water body using the System Advisor Model (SAM) program based on ground-mounted systems. Several studies have compared the efficiency of ground-mounted (GM) PV and FPV systems and described a higher efficiency of the latter one suggesting an increased efficiency ranging between 0.79% and 15.5% [49–53] In this study, we considered a 10% higher efficiency for FPV compared to ground-mounted PV systems.

The weather data used in SAM to calculate the potential energy generation are obtained from National Solar Radiation Database (NSRD) from National Renewable Energy Laboratory (NREL) [54]. The technical data inputs in SAM consist of location data, module and inverter chosen, system design, shading and layout considerations, energy losses, and grid limits set up. The module characteristics for the potential electricity generation in the chosen reservoirs can be seen in Fig. 7.

The inverter technical characteristics for the proposed 1 MWp FPV system are shown in Fig. 8. The ratio of total inverter DC to total AC capacity is an important factor in solar PV projects. Traditionally, projects have sized the DC to AC ratio around 1.25, not representing a significant clipping loss, the loss of energy in a solar PV system because of the inverter derating its output to meet either its maximum power rating or the maximum allowable power at the grid connection, which is often less than 1% of power output. The nominal capacity of PV array is only reached under standard testing conditions (STC); solar radiation of 1000 W/m^2, cell temperature 25 °C, and Air Mass 1.5, when the array produces above 80%–90% of modules nominal capacity [55]. Meeting STC rarely happens in a real environment. In this analysis, an inverter with a maximum DC capacity of 838 kW, i.e., a DC to AC rating of 1.23 was considered.

An electrical configuration of 29 modules per string and 84 strings in parallel, in total 2436 modules for each MW installed, was adopted in this system. The PV modules' tilt adopted was equal to latitude local,

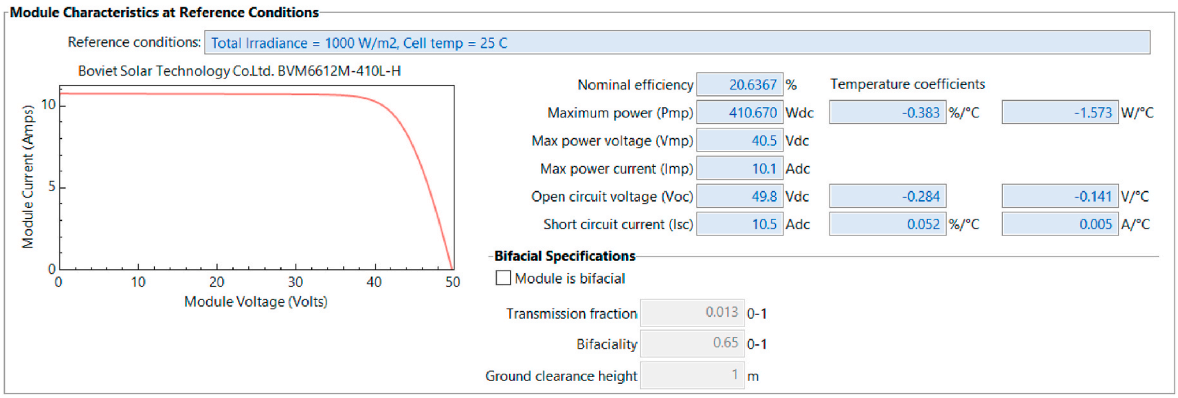

Fig. 7. Technical characteristics of the modules that were considered for deployment in this analysis (Image obtained in SAM simulation).

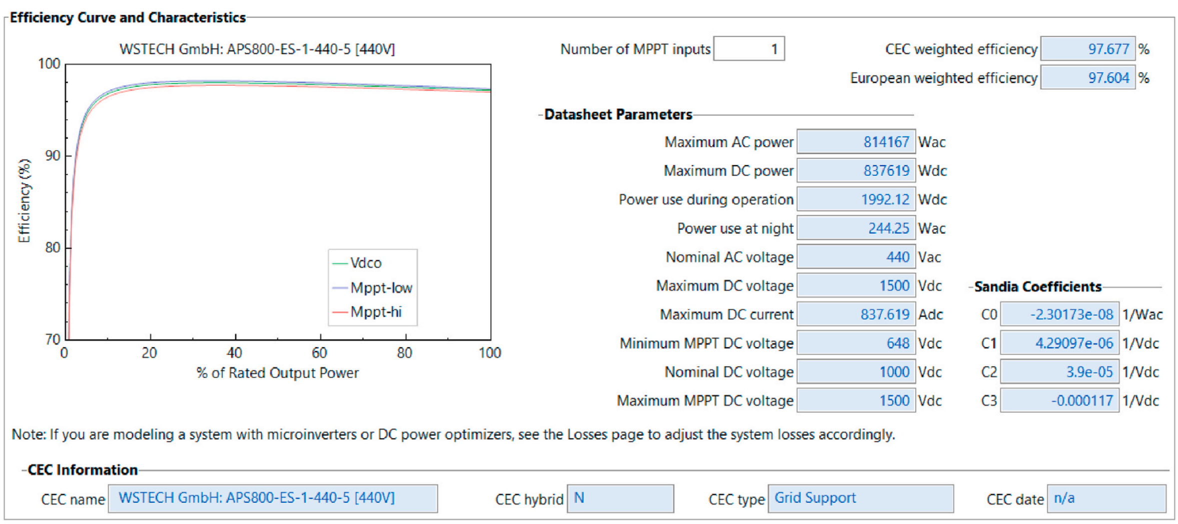

Fig. 8. Technical characteristics of the inverter that was considered in this analysis for 1 MWp FPV (Image obtained in SAM simulation).

and the azimuth used was 180° facing south. This FPV system design has no tracking system.

The following equations [56] were used to estimate reduced evaporation in the studied reservoirs. These equations aim to show the reduced evaporation because of the surface water coverage.

$$\varepsilon = 1 - (1 - \alpha)^{2/3} \tag{3}$$

$$\alpha = \frac{A_{SC}}{A_{res}} \times 100\% \tag{4}$$

In Equation (3), ε is the efficiency of evaporation reduction, given in % and α is the percentage of the covered area calculated by the surface covered area (A_{SC}) concerning the total area of the reservoir (A_{res}). As mentioned before, we have considered three scenarios for surface coverage of the reservoirs: 1%, 5%, and 10%. Considering the above equations would achieve an evaporation reduction of 0.7%; 3.4% and 6.8%, respectively. It is worth noting that this is an estimate and an accurate evaluation of the reduced water evaporation can only be achieved through field studies that involve considering a range of variables, e.g., temperature, humidity, wind speed, and air pressure.

3.2. *Floating PV potential of different types of water bodies in Vietnam*

To estimate the FPV technical potential across Vietnam we could use geoprocessing tools. For this purpose, we have taken three main steps, similar to our previous publications [57]. These steps include evaluating meteorological data of the area of interest, determining the priority areas of installation, and considering the system generation characteristic and technical limitations. The estimated long-term PV power generation in Vietnam, considering average solar radiation, and air temperature has been provided by Solargis and published by the World Bank [11]. This evaluation considers systems of 1 kWp, grid connected, ground based and free-standing structures with losses in the PV crystalline-silicon modules with dirt and soiling about 3,5% added to 7, 5% of losses of mismatch, inverters, inter-row shading, cables, and transformers. This map which shows PV power potential in kWh/kWp in Vietnam can be seen in Fig. 9 [11].

After obtaining the data of PV potential power generation across Vietnam, it was necessary to cross compare the data with the location of Vietnam water bodies. The information about inland water bodies in Vietnam was obtained from Stanford University EarthWoks that provides a search tool for geographic information systems (GIS) and datasets [58]. According to this dataset the water bodies are divided into four categories: Lake, Lagoon, River and Without Classification. While deploying FPVs in rivers is challenging and adds to the complexity of anchoring systems and further adjustments, nevertheless we have included rivers in our calculations. We used QGIS software for geoprocessing. In QGIS the intersections of the waterbody layers and PV potential power generation were obtained for each water body. The generated data through this approach was exported and the technical potential of FPV systems in Vietnam water bodies were calculated. The following assumptions were considered as part of calculating FPVs potential:

Fig. 9. Photovoltaic electricity potential in Vietnam [11].

- If the area of a water body e.g., lake was large enough to receive different levels of solar radiation, the average FPV potential of that water body was calculated. Then all FPV potentials of that category across Vietnam were added to represent the total FPV potential for that type of water body.
- A 10% gain was added to the energy yield values as they represent floating photovoltaic systems and the electricity generation estimated by Solargis [11] is based on ground-mounted systems. This is because of higher efficiency of FPVs due to the cooling effect of water [20].
- The estimated FPVs potential is based on covering only 1% of the surface of each type of the water bodies mentioned above.
- The quantity of kWp installed depends on the size of each water surface and the size of floating PV system. This paper considers the same FPV system proposed by Lopes et al. (2022) [28], were 1 MWp of PV system contains 3125 PV modules of 320 Wp, one central

inverter and the system are on Sungrow floating model that occupies 10,512 m^2/MWp installed.

The potential of FPV capacity for each waterbody was calculated based on Equation (2) that was mentioned in the previous section.

4. Results

4.1. Potential FPVs electricity outputs for the selected reservoirs

Table 3 shows the potential FPV capacity for the chosen reservoirs considering the three scenarios of water surface coverages. The simulation of the electricity generation by the FPVs was performed using SAM.

Fig. 10 indicates monthly electricity generation for a 1 MWp FPV in each of the selected reservoirs' locations. In other words, it demonstrates the impact of geographical location on the energy output of an FPV for the selected regions.

The annual average energy generation for 20 years was calculated considering the degradation of PV panels of 2.5% in the first year and 0.6% in subsequent years. Table 4 indicates the energy production for the first year (based on the results from SAM) and the average energy production for 20 years expected lifespan of the FPV project for a 1 MWp installed (see Table 5).

The potential capacity installation for each of the reservoir surface coverage scenarios was obtained based on SAM simulations. An additional 10% efficiency was added to each output, because of the expected increase in efficiency of FPVs due to the cooling effect of water [20,28].

4.2. Electricity generation potential by FPVs for different types of water bodies in Vietnam

As described in the previous section, methodology, we calculated the technical potential of FPVs deployment capacity and electricity generation for four different categories of water bodies in Vietnam: Lake, Lagoon, River and Without Classification. The results are presented in Table 6.

According [59], Vietnam has 149 water bodies catalogued, with a total area of 3889 km^2. The total potential capacity, considering use of only of 1% of available water surface areas by FPVs is 3.7 GWp, and provides a generation of 5385 GWh. Considering annual per capita electricity consumption in Vietnam of 2218 kWh [2,4] the energy generated by 1% of water bodies cover could supply more than 2.4 million people. If the potential of installation in River were removed due to the likely technical difficulty for installing FPVs in water bodies with current, the estimated generation could still provide electricity for more than 1 million people.

In such large-scale projects, the floats can be manufactured locally, which reduces the logistic costs. Also, considering the low depths of the water bodies, which lowers the anchoring costs and relies on the local labour force, achieving close to 1 USD/Wp for FPV costs is realistic. This estimate is based on a compatible technology that has been used for the 70 MW Anhui project in China [20] and consulting with industry leaders in FPV technology.

In May 2019, the Electricity of Vietnam announced the grid-connection of 20.5 MW solar power capacity as phase one of an envisaged 47.5 MW FPV plant [60]. Limited information is available about the challenges faced by this first FPV project in Vietnam; however, a report published by The Asian Development Bank (ADB), which has invested in this project, considers understanding the power purchase agreement (PPA) and the differences that it may have with those in other more developed markets as one of the challenges of investing in FPVs in Vietnam. At the same time, there seem to be no major technological challenges in terms of deploying FPVs [61].

In 2020 to encourage private sector investment, the Vietnamese government introduced 7.69 US cent FPVs FIT, which is 8.5% higher than ground-mounted PV solar [8], and it seems to have had positive impacts on FPV development as two large-scale floating PV systems were grid-connected at the end of 2020 on two irrigation lakes in the South of Vietnam as seen in Fig. 11 [62].

By the end of 2021 Sungrow stated that the company has deployed approximately 125 MW in Vietnam [63]. The country also aims to build a new major FPV project, which is likely to be commenced in 2022. This 500 MW floating PV known as Tri An floating PV solar park, is currently in permitting stage and when pass this step it will be deployed in Dong Nai near Ho Chi Minh City in the south [64].

Table 3
Potential capacity of FPV installation in the selected reservoirs considering different water surface coverage scenarios.

Group	Water Body	Total Area (km^2)	Potential FPV installation (MWp) for various surface coverages (SC)		
			1% SC	5% SC	10% SC
1	Ho Da Den	3.53	8	38	76
	Ho Song Ray	7.38	16	79	158
	Ho Bau Can	1.95	4	21	42
	Ho Cau Moi	1.00	2	11	21
2	Ho Da Ton	2.95	6	32	63
	Ho Tri An	218	467	2337	4675
Hydropower Plant	Hoa Binh Hydropower	208	446	2230	4460
	Total	442.81	949	4748	9495

4.3. How FPVs can help agricultural growth in Vietnam

About 90% of all farms in Vietnam are small family farmers, of which more than 65% are in rural areas. Small scale FPVs on water surfaces used in agriculture/aquaculture would enable smallholders as producers and consumers (prosumers), and the electricity generated can be used by the owner/operator or sold to the grid. Also, according to FAO, one-third of the farms in Vietnam are headed by women [13]. In the long term, the benefit of deploying FPVs on energy supply and security, rising income, and living standards in the rural areas will have a bigger impact on alleviating the poverty and inequality for women, especially because the primary beneficiaries of this project will be communities involved in farming in the rural areas. Electricity generated by FPVs would provide more opportunities for the farmers to modernise and mechanising their farming; for example, it could be used for the irrigation of the farmlands and help to shift reliance on rain-fed agriculture to managed and efficient agricultural practices.

5. Conclusions & policy implications

Population density, geography, resources, nature of the economy, and land use make the energy challenges faced by Vietnam unique and complex that can be addressed only through relying on innovative technologies. Floating photovoltaics (FPVs) is a technology that can significantly contribute to the renewable energy sector in Vietnam. Also, Decentralisation of energy supply through the integration of small scale FPVs make the entire energy supply more resilient, when faced natural hazard e.g., extreme weather events. FPVs could contribute to sustainable management of Vietnam's vast water resources, particularly through diversifying investments in infrastructure for the water sector, deepening public participation and involvement, and improving compliance and enforcement.

FPV is a promising technology yet its socio-technical impacts and key economic, regulatory, technical, and environmental barriers that it faces are largely unknown or have not been fully addressed yet. For example, uncertainty about water rights is one of the issues that may add to the costs and make investors reluctant about such projects. Cautiousness

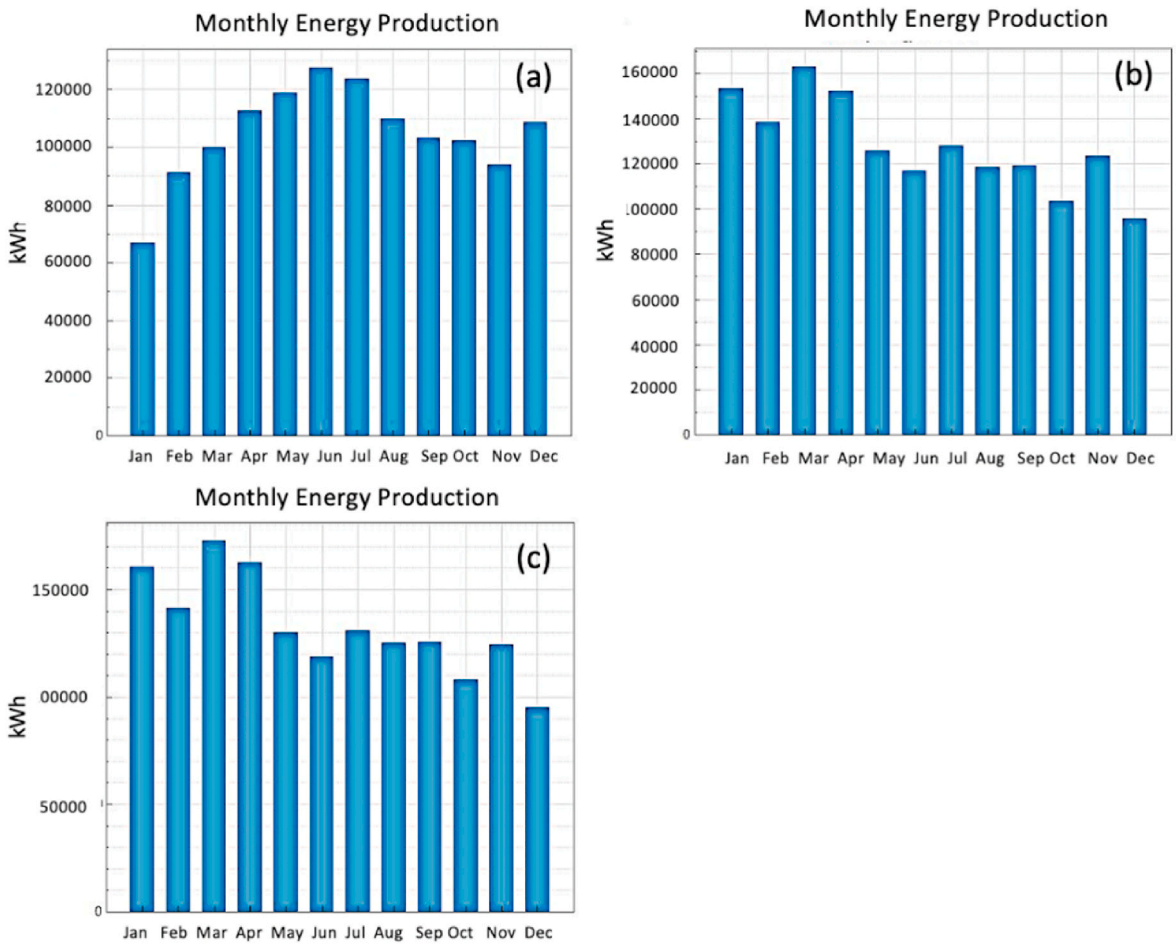

Fig. 10. Monthly electricity output generated by 1 MWp FPV in different regions across Vietnam. In this Figure (a) is Group 1 (b) Group 2 and (c) hydropower plant reservoirs.

Table 4
Annual energy production and energy yield for the first year and an average of 20 years for a 1 MWp FPV installed.

Group	Electricity output in year one		Annual average electricity generation over 20 years		Annual average electricity generation over 20 years considering 10% more efficiency	
	Annual energy (kWh)	Energy yield (MWh/MW)	Annual energy (kWh)	Energy yield (MWh/MW)	Annual energy (kWh)	Energy yield (MWh/MW)
1	1,595,222	1595	1,480,195	1480	1,628,215	1628
2	1,538,301	1538	1,427,379	1446	1,570,117	1591
Hydropower Plant	1,259,032	1259	1,168,247	1168	1,285,072	1285

Table 5
Potential electricity generation based on different FPVs surface coverage scenarios in selected reservoirs.

Group	Water Body	Total area (km^2)	Potential FPV generation (GWh) under different surface coverage scenarios		
			1%	5%	10%
1	Ho Da Den	3.53	13.0	61.9	123.7
	Ho Song Ray	7.38	26.0	128.6	257.2
	Ho Bau Can	1.95	6.5	34.2	68.4
	Ho Cau Moi	1	3.3	17.9	34.2
2	Ho Da Ton	2.95	9.5	50.9	100.2
	Ho Tri An	218	742.6	3716.4	7434.3
Hydropower plant	Hoa Binh Hydropower	208	573.1	2865.6	5731.3
	Total	442.81	1374	6875	13,749

about economic policies, lengthy/costly approval processes, and the hybrid hydropower FPVs ambiguity of ownership and operation are potential challenges that could hamper FPVs development. Such barriers are not unique to Vietnam and are common among many other countries [65]. Addressing these issues would also strengthen the policy and institutional frameworks for integrated water resources management, which is a crucial aspect of sustainable development and has been reflected in different UN sustainable development goals.

To improve the share of FPVs in Vietnam energy mix the government needs considering complementary policies beyond the existing drivers and the electricity demand growth. The Vietnamese government should also investigate and support investigations for better understanding of the economic, regulatory, technical, and environmental barriers that could potentially prevent FPVs deployment. Different policy setting sectors at government level – including energy, agriculture and water managements – need to collaboratively address investors and users concerns about potential uncertainties. Incentivizing the electricity

Table 6
Quantity, areas and technical potential of installation and generation of FPV in Vietnam.

Classification	Quantity	Area (km^2)	1% Waterbody Area (m^2)	Potential Capacity (MWp)	Estimated FPV Generation (GWh/year)
Lake	13	992	9,921,353	944	1401
Lagoon	2	203	2,029,274	193	268
River	37	2156	21,557,748	2051	2996
Without Classification	97	538	5,383,311	512	720
Total	149	3889	38,891,686	3700	5385

Fig. 11. One of the two large-scale 35 MW floating solar farms that were connected to the grid at the end of 2020. Both are placed on irrigation lakes (Credit Google Earth Pro, 2021).

generated by FPVs for modernizing the farming process and equipment is also needed to encourage smallholders to invest in small scale FPVs.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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