ASSESSING THE TECHNICAL, ECONOMIC, AND ENVIRONMENTAL FEASIBILITY OF FLOATING SOLAR POWER GENERATION ON WATER RESERVOIRS IN VIETNAM

By

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ABSTRACT

ASSESSING THE TECHNICAL, ECONOMIC, AND ENVIRONMENTAL FEASIBILITY OF FLOATING SOLAR POWER GENERATION ON WATER RESERVOIRS IN VIETNAM

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Vietnam has been developing an energy path involving increased renewable energy use. With over 7,000 existing water reservoirs, Vietnam has great potential to install floating solar photovoltaic (FPV) plants that will protect productive lands, reduce greenhouse gas emissions, and reduce water evaporation rates. This study investigates the technical, economic, and environmental feasibility of installing FPV in three reservoirs in Vietnam: Hoa Binh, Tri An, and Dau Tieng.

The capacities of the FPV plants assessed for three reservoirs range from 96 MW to 4,300 MW. The yearly solar generation from the three reservoirs ranges from 900 GWh to 13,700 GWh, and investment costs range from 690 to 10.3 billion USD, dependent on the reservoir size and FPV area coverage of 1%, 5%, 10%, and 15%. The payback period of the FPV systems at the three reservoirs could range from 6 to 14 years. The estimated Levelized Cost of Energy (LCOE) for Hoa Binh reservoir's FPV system ranges from \$50 to \$95/MWh, while the other two reservoirs' LCOEs range from \$40 to \$70/MWh.

These systems could supply 4% of Vietnam's predicted 2025 energy demand and would avoid approximately 11 million tons of CO_2e emissions per year. The shading provided by the FPV systems can save up to 136 million m^3 of water annually. If the water savings are coupled with hydropower on Hoa Binh and Tri An Reservoir, the whole facility could generate an additional 12 GWh per year. Future study should include more in-depth research into factors such as the impact of substation upgrade costs, variable interest rates, and economies of scale on project economics; environmental impacts such as changes in hydropower operation on aquatic life; and human social and economic displacement due to FPV infrastructure land and water occupation.

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INTRODUCTION

According to the National Renewable Energy Laboratory (NREL), Floating Solar Photovoltaic (FPV) technology is an emerging technology that has been shown to provide benefits in energy production and in land and water conservation (Spencer et al., 2018). FPV plants' feasibility has been studied, and many have been installed in various countries, with 80% of installations located in Japan. Globally, there are approximately 265.7 thousand square kilometers of hydropower reservoirs that, at 25% coverage, have the potential capacity to host 4,400 gigawatts (GW) of FPV plants, potentially generating 6,270 terawatt-hours (TWh) of electricity per year (Farfan & Breyer, 2018). This number can be extended to 8,000 TWh if all water reservoirs (for hydropower and for other purposes such as recreational and irrigation) have a 25% FPV coverage, serving approximately 30% of the 2018 global energy demand (Farfan & Breyer, 2018; International Energy Agency, 2018). The Energy Sector Management Assistance Program (ESMAP) of the World Bank and the Solar Energy Research Institute of Singapore (SERIS) estimated that at some hydropower reservoirs across the world, such as the 8,500 km^2 Volta Reseroir in Ghana, the 4,250 km^2 Guri Dam in Venzuela, and the 820 km^2 Attaturk Dam in Turkey, combining a hydropower plant with a solar plant that covers just 3-4% of the reservoirs could add enough solar generation capacity to match the hydroelectric generation capacity (2018). In addition to its electricity generation benefit, FPV does not compete with other land uses and possibly helps reduce water evaporation rates in specifically tropical climate due to its surface coverage, protecting the water from heat and wind. This is crucial when people's livelihood is dependent on land uses and water resources. Vietnam, a country in Southeast Asia, has excellent potential for FPV on 7,158 reservoirs that are currently used for flood control, energy storage, hydropower generation, daily water usage, fishing, and irrigation (Directorate of Water Resources, 2019). Hydropower in Vietnam is a significant component of the country's power resources. The government still plans to have 12.4% of total electricity production from hydropower and 10.7% from renewable energy in 2030 (The Socialist Republic of Vietnam, 2016). Thus, the use of reservoirs for FPV will help meet the renewable energy target of the country and take advantage of the already existing infrastructure of the hydropower plants (The Socialist Republic of Vietnam, 2016).

The goal of this study is to assess the technical, economic and environmental feasibility of installing FPV on the three water reservoirs in Vietnam, based on analysis of their PV output potential, the payback period and LCOE, and GHG emission reduction and evaporation savings. The cost of the FPV plant can be more expensive than the price of ground-mounted PV system due to the cost of equipment specifically designed for floating devices (ESMAP & SERIS, 2018). This study approaches an assessment of value through a cost comparison between future FPV projects in Vietnam by 2025 and the revenue from a feed-in-tariff (FIT). The first two sites for the study are the Hoa Binh and Tri An Reservoirs, which are components of existing hydropower power plants, while the third site is Dau Tieng Reservoir - the largest man-made reservoir in Vietnam and Southeast Asia. A discussion with the Director of the Directorate of Water Resource revealed that Dau Tieng Reservoir has excellent potential for an FPV installation due to the government’s interest (T. Nguyen, personal communication, April 4th, 2019).

LITERATURE REVIEW

The section gives an overview of Vietnam’s energy development and structure of the Vietnam’s electricity sector. It also includes more details on FPV structure, its benefits and potential in Vietnam, and literature gaps in FPV studies. The description of each of the study reservoirs was discussed last.

Vietnam Energy Outlook

For decades, Vietnam, a country with a population of approximately 95 million, has been one of the fastest-growing economies in the region and the world (World Bank, 2017). The energy sector has been playing an essential role in the country’s economic development. The Vietnam Ministry of Industry and Trade (MOIT) and the Danish Energy Agency (DEA) forecasted a 150% increase in national energy demand, from 54 million tons of oil equivalent (MTOE) in 2015 to 134 MTOE in 2035 under the business-as-usual (BAU) scenario, in which the average GDP growth reaches 6.7% per year (MOIT & DEA, 2017). In 2015, electricity consumption was 143,000 GWh. It was projected to be 348,000 GWh by 2025 and 663,000 GWh by 2035, increases of 143% and 364%, respectively (MOIT & DEA, 2017). In other words, the demand for electrical energy is projected to increase by more than twice as much as the increase in the total energy demand by 2035. To manage the expected demand growth, the Vietnamese government has laid out several policies and strategies to increase the use of domestic fossil fuel resources, renewable energy (hydropower regarded as a source of renewable energy), and energy efficiency (MOIT & DEA, 2017).

One of the most crucial policies for the power sector, the 2004 Electricity Law, which laid out the country’s power planning and development investment strategy for energy infrastructure, the structure of the electricity market, and the rights and obligations of electricity market participants, will be discussed in Vietnam Electricity Sector.The Socialist Republic of Vietnam, 2004). In 2007, the National Energy Development Strategy Up To 2020 with 2050 Vision was developed with specific objectives such as securing adequate energy supply to meet the demand of socio-economic development, increasing the reliability of the power supply, developing oil refinery plants, and ensuring the national strategic reserve of oil for 60 days by 2020 and 90 days by 2025. It emphasized the importance of 100% electrification of rural and mountain areas by 2020, the development of long-term environmental objectives and standards, and the formation of a competitive retail power market after 2022 (The Socialist Republic of Vietnam, 2007).

In 2011, the National Power Development Plan VII (PDP 7) was approved for the period 2011-2020 with a vision to 2030 (MOIT, 2011). The Prime Minister approved an adjustment to PDP 7 (now called PDP 7 revision) in 2016 that focused on the energy development from 2016 to 2030, with highlights on renewable energy development and liberalization of the power market. The strategy aims at the mitigation of GHG emissions, reduction of fuel imports, and an increase in total renewable energy generation to approximately 10.7% of total electricity production in 2030 (The Socialist Republic of

Vietnam, 2016). With more guidance from the government and incentives for renewable energy that will be later discussed, the electricity sector has tremendous potential in reducing emissions with investment in renewable technology.

Vietnam Electricity Sector

To understand how renewable generation, especially floating solar power generation, can contribute to Vietnam's electricity generation mix, knowledge of Vietnam's electricity sector, its structure, and financial model is crucial. This section provides an overview of Vietnam's electricity structure with crucial stakeholders, past and current development in the electricity market, and the advances and challenges in adopting renewable energy.

Overall structure

The primary national electricity buyer and supplier, Electricity of Vietnam (EVN), was established in 1994. EVN owns the entire national power transmission and distribution system and is responsible for all wholesale and retail energy sales countrywide (EVN, 2016). According to EVN, up to 99.97% of the communes and 98.69% of rural households had access to electricity in 2017 (2017).

Vietnam's Electricity Law of 2004 provided direction toward developing a competitive electricity market that involved unbundling the EVN monopoly, commencing a single-buyer for power scheme, establishing a competitive wholesale market and ultimately a competitive retail market. EVN has been restructuring to encourage private participation (The Socialist Republic of Vietnam, 2004; ADB, 2015). In 2008, the National Power Transmission Corporation (NPTC) was established. It is 100% owned by EVN and is responsible for managing the power transmission grid. The Electricity Power Trading Company (EPTC)and the National Load Dispatch Center (NLDC) established at the same time, were also part of EVN. However, the government's hope was that NLDC would soon separate from EVN at the start of the competitive wholesale market, which has not yet begun.

The single-buyer model was established in 2012 with generating companies (Gencos) and Independent Power Providers (IPPs) competing in a power pool to sell to EPTC. The three power Gencos (Genco 1, 2, and 3), also established in 2012, are operating within a holding company structure with EVN and allowing mixed ownership with private participation through equitization (EVN, 2017). In other word, EVN still owns the outstanding stock of Gencos, while the rest of the stocks can be owned by private companies. The structure of the power sector as of 2015 is shown in Figure A- 1. EVN has been working towards the creation of a competitive electricity market with the start of wholesale competitive market pilot in 2015, and a retail competitive market pilot in 2021 per Decision 63/2013/QD-TTG (The Socialist Republic of Vietnam, 2013).

Wholesale Electricity Market

The Vietnam Wholesale Electricity Market (VWEM) pilot project, initially planned to start in 2015, is Vietnam's effort in building a more integrated infrastructure, regulations, and operations of an electricity wholesale market. According to EVN (2017), the VWEM became fully in operation starting in 2019, instead of 2017 as planned (The Socialist Republic of Vietnam, 2013). As of 2015, 90% of sales in the generation and wholesale markets are negotiated through standard power purchase agreements (PPAs) between the generators and the single buyer. Foreign-owned build, operate, and transfer power plants (BOT) and independent power producers (IPPs) sell all output to a single buyer (in Vietnam's case, EVN) at long-term contract prices, dependent on the case. These contracts range from 10 to 20 years for a local IPP to 25 years for a BOT (ADB, 2015). Special tariffs apply to renewable generation, providing preferential pricing for renewable power (ADB, 2015), which will be discussed more in the next section.

The wholesale market price of Vietnam's electricity is shown below in Figure 1. To convert values into US dollars (USD), for example, the exchange rate in June 2017 was approximately 22,500 Vietnam Dong (VND) to 1 USD (International Monetary Fund, 2018). Thus, the wholesale market price for June 2017 was estimated at $0.026/kWh.

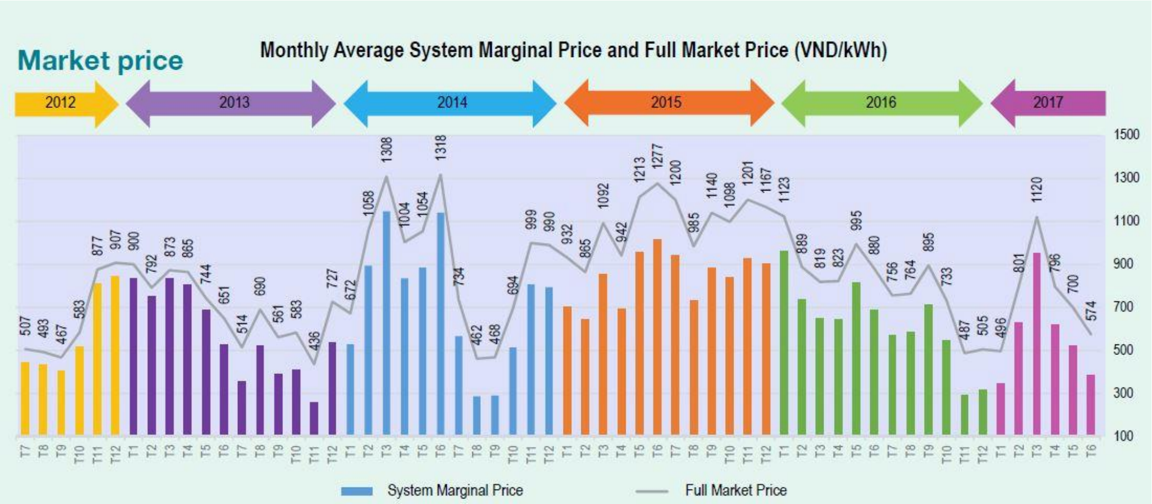

Figure 1. Average system marginal and full wholesale market price from July 2012 to Jun 2017 (EVN, 2017). The line is the full market price – the price that energy is sold into the wholesale market, while the bars are system marginal price or cost for the plants to run, which should be lower than the wholesale market price.

The installed capacity of all the generators that were eligible to participate in the wholesale market was 42,135 MW in 2015. The installed capacity is expected to be 60,000 MW in 2020, 96,500 MW in 2025, and 129,500 MW in 2030 (The Socialist Republic of Vietnam, 2016). At the end of 2016, the 142 MW of installed solar and wind energy generation capacity accounted for less than 0.4% of total energy supply, fourteen times lower than the PDP 7 revision target (EVN, 2017). Figure 2 presents the percentage of installed capacity by source for the years 2016, 2020, 2025, and 2030 as listed in PDP 7 revision.

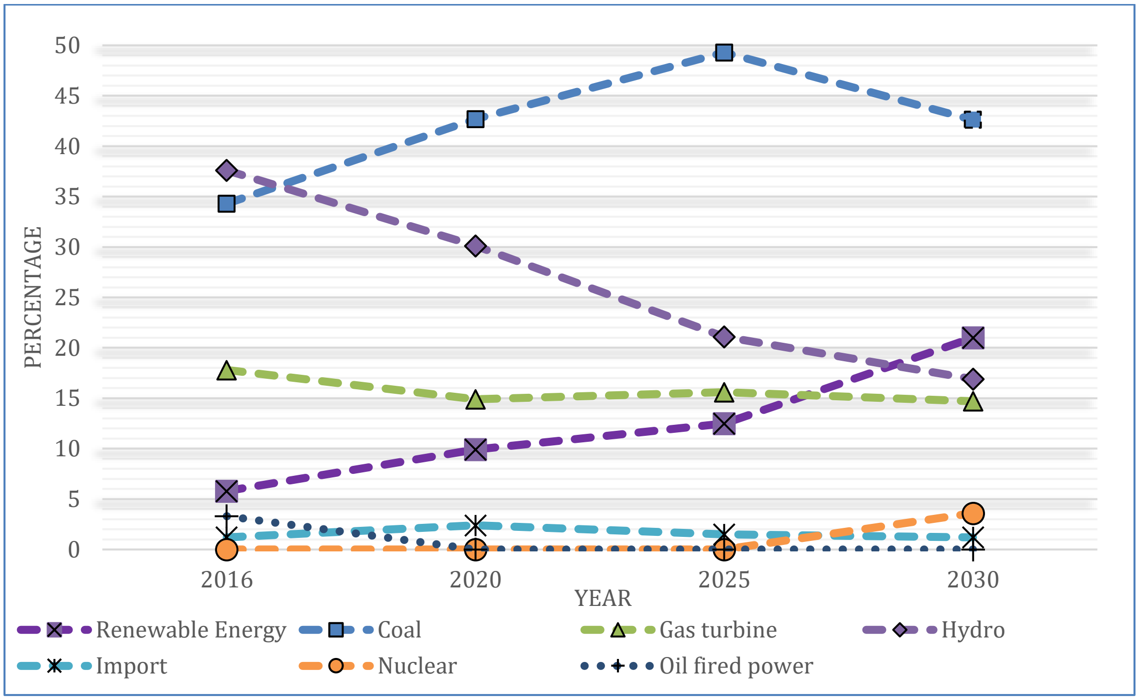

Figure 2. Percent of Vietnam power sources in total installed capacity from 2016 to 2030 (EVN, 2017; Government's Decision No. 428/QĐ-TTG). Renewable energy includes small-scaled hydro, wind, solar, and biomass power. It should be noted that even though the percentage contribution of coal and hydro in the power mix might decrease, it does not signal a decrease in the total amount of generation capacity. It means that hydropower, coal, and gas power will grow at a slower rate than renewables

By 2017, there were 12,900 MW of installed coal-fired power plants in operation in Vietnam, accounting for 33.5% of total electricity supply (EVN, 2016). The revised PDP 7 authorized the addition of another 42,000 MW of coal plants by 2030 to meet the fast-growing demand of the economy. Thus, 42.6% of the total power sources capacity and 53.2% of the country's total electricity production will come from coal by 2030 (The Socialist Republic of Vietnam, 2016). With more coal plants connecting to the grid, there will be an increase in greenhouse gas emissions within the energy sector (GHG emission). According to Rosa Luxemburg Stiftung (RLS), an NGO focusing on civic education, Vietnam's annual GHG emissions in 2010 were 250 million metric tons of carbon dioxide equivalent (tCO_2e), or approximately 2.8 tCO_2e per capita (2016). GHG emissions from the energy sector accounted for about 52% in 2013 compared to 30% in 1994 (The Socialist Republic of Vietnam Ministry of Natural Resources and Environment, 2019). In 2015, 2016, and 2017, it was estimated that GHG emissions from all Vietnam's power generation sources to be 0.795, 0.834, and 0.859 tCO_2e/MWh, respectively, or 0.830 tCO_2e/MWh average for the three-year period (The Socialist Republic of Vietnam Ministry of Natural Resources and Environment, 2019). According to the World Bank, the average grid emission factor in 2017 was 0.815 tCO_2e/MWh (World Bank, 2018). If the expansion goes as planned in PDP 7 revision, CO_2e emissions in the electricity generation sector are likely to increase ten-fold by 2030 compared to 2010 (RLS, 2016).

PDP 7 revision, however, also emphasized on the development of renewable energy, with a planned increase in its contribution to the power mix. At present, small-scale renewables, such as small hydropower, hold the largest share amongst all the renewable energy sources, followed by wind and biomass (StoxPlus, 2018). With high solar, wind, and biomass potential, renewable energy development is expected to play a significant role in the country's generation capacity growth.

Retail Electricity Market

Currently, retail electricity prices are capped and mostly only increased in accordance with inflation. Based on Figure 3, the average residential tariff was 1,660 VND/kWh in 2017 (~ \$0.074/kWh) (EVN, 2017). UNDP (2012) considered that the average electricity price needed to rise to $0.08-0.09/kWh to allow the sector to operate on a sustainable financial basis, which PDP7 is planning to achieve by 2020. In March 2019, the retail electricity price was increased by 8.36% to $0.08/kWh after two years of the unchanged rate (VNExpress, 2019). The retail tariff is set based on various factors, as shown in Figure A- 2. Average retail electricity tariffs are calculated based on generation costs (the most significant component), transmission and distribution costs, and sector administration costs. Tariffs are revised only if there are changes in fuel cost, exchange rate fluctuation, and generation capacity charges. Increases more than 5% would require approval from MOIT and the Prime Minister (ADB, 2015). The goal of the electricity market, in the end, is to have all generators sell on the competitive generating market, under PPA contracts based on benchmarked costs.

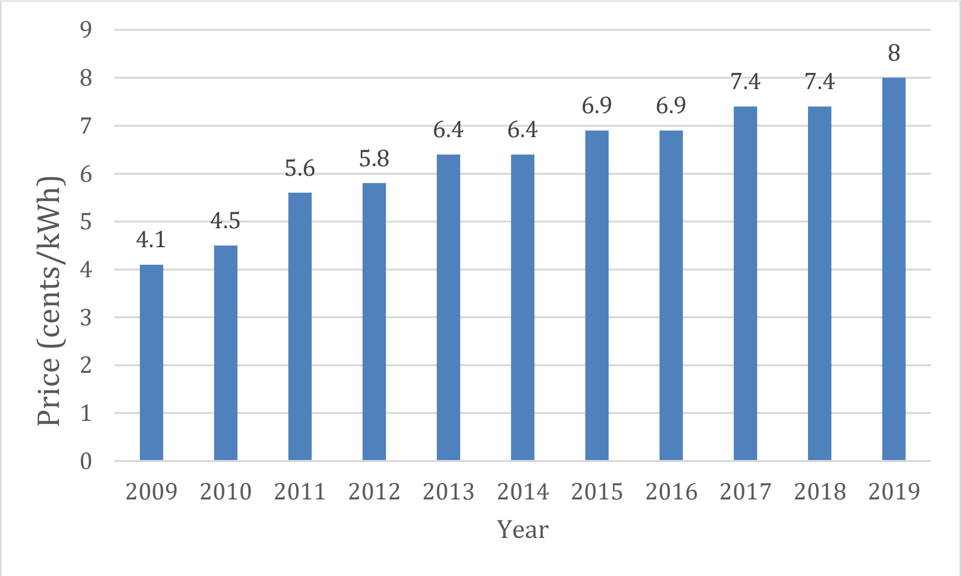

Figure 3. Vietnam retail electricity price from 2009 to 2019 (VNExpress, 2019). The price increased in the range of 4 to 7% gradually every year, from 4.1 cents/kWh in 2009 to 8 cents/kWh in 2019

The Vietnam Retail Electricity market (VREM) was planned to be introduced in 2021 as a pilot and in full operation by 2023. In this phase, the distribution company will work on network management and operation, retail, and give end-users the option to choose their supplier (ADB, 2015). The future final Vietnam electricity market is shown in Figure 4, with the System & Market Operator (SMO) regulating the bidding and dispatching of generators, similar to an Independent System Operator (ISO) in the United States that coordinates, controls, monitors the electric grid, and act as a marketplace operator in a wholesale power (Federal Energy Regulatory Commission, 1996). The end users will pay the Transmission Network Owners (TNO), who then pay SMO. SMO pays the generators, who then continuously deliver energy to the customers through TNO.

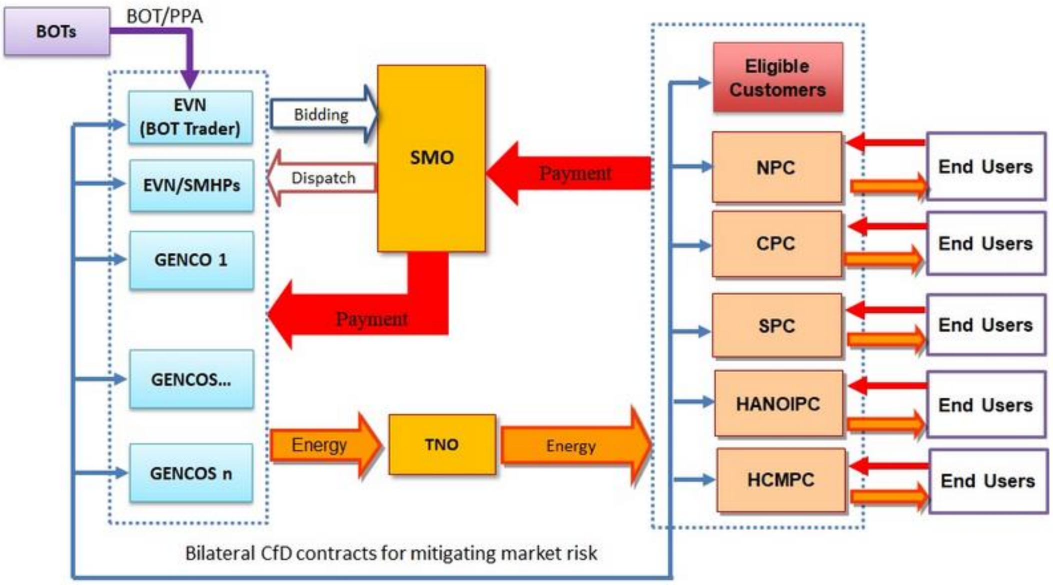

Figure 4. Vietnam near future model for power market structure. BOTs are the organization that build, operate and transfer power plants, SMHPs is the Strategic Multi-purpose Hydro power plants, GENCO are the Generating Companies, SMO is the system market operator, TNOs are the Transmission Network Owners. NPC, CPC, SPC, HANOIPC, HCMPC are the transmission owners subset of TNOs (Pranadi, 2018)

Transmission Networks

In 2011, the transmission and distribution networks or the transmission network owners (TNO) were split into five corporations: Northern Power Corporation (EVNNPC), Central Power Corporation (EVNCPC), Southern Power Corporation (EVNSPC), Hanoi City Power Corporation (EVNHANOI), and Ho Chi Minh City Power Corporation (EVNHCNC) (EVN, 2017). These companies will work with end-users to collect payments and return them to the SMO, who will then pay the generators. As of December 2016, the national power transmission system has approximately 26,100 MVA of 500 kV substations, 7,446 km of 500 kV lines, 41,538 MVA of 220 kV substations, and 16,071 km of 220 kV lines. From 2020 to 2030, EVN is planning to expand the transmission system with another 50,000 MVA of 500 kV substations and 65,000 MVA of 200 kV substations (Figure A- 3). By the end of 2019, thirteen solar power plants with a combined capacity of 630 MW are scheduled to be connected to the grid, raising the total number of solar power plants in the country to 95 (Power Technology, 2019). With all this new generation connected to the grid, not mentioning other technology, transmission network upgrade planning is crucial in accommodating these new power sources.

Vietnam Renewable Energy development

As highlighted in the PDP 7 revision, electricity production from renewable energy planned to be roughly 6.9% in 2025 and 10.7% in 2030. Specific renewable generation targets include 1.2% and 2.1% from biomass, 1% and 2.1% from wind with total capacity of 2,000 MW and 6,000 MW, 1.6% and 3.3% from solar with total capacity of 4,000MW and 12,000 MW, and the rest are from small scale technologies by 2025 and 2030, respectively (The Socialist Republic of Vietnam, 2016).

Solar Projects Potential

Of all the renewable energy technologies, solar photovoltaic (solar PV) is one of the most rapidly developing that could potentially surpass the cheapest fossil fuel alternative by 2020 (IRENA, 2018b). Even though currently the weighted average LCOE of solar PV in Southeast Asia is still one of the most expensive worldwide, recent declines in costs are rapidly bringing the cost down to the range of fossil-fuel technology, which has strengthened the economic case for the adoption of this technology (IRENA, 2018a). Vietnam has potential for solar PV with annual average daily global horizontal irradiance (GHI) at 3.4 kWh/m^2/day in northern parts of the country, 3.8 kWh/m^2/day on the north-central coast (Polo et al., 2015). These number are considered low compared to areas at the same latitude globally (World Bank Group, 2019). Annual average daily GHI for the south-central coast, central highlands, and southern regions are around 4.8 kWh/m^2/day (Polo et al., 2015). With the realized potential, solar development by 2025 and 2030 will comprise most of the renewable energy generation mix (The Socialist Republic of Vietnam, 2016). However, as of 2016, installed solar and wind energy generation capacity (which comprised of mostly wind) accounted for less than 0.4% of the total annual energy supply in Vietnam (EVN, 2016).

In April 2017, the Prime Minister issued a decision on FIT for solar energy called the “Decision on the Support mechanisms for the Development of Solar Power Projects in Vietnam" valid until 30 June 2019 (The Socialist Republic of Vietnam, 2017a). EVN has the obligation to purchase all on-grid solar power generated for 20-year period from the beginning of operation (Campbell et al., 2018). The electricity price is set at 9.35 US cents per kWh ($0.0935/kWh) or 2,086 Viet Nam Dong (2,086 VND), excluding value added tax, and is subject to fluctuations of VND-USD exchange rate. This rate applies to on-grid projects that had solar cell efficiency of more than 16%, or if the projects have a variety of solar cell types, the cumulative efficiency must be 15% or higher at Standard Testing Condition (STC) (The Social Republic of Vietnam, 2017). This FIT rate for renewable energy was higher than the electricity retail price of 2017 ($0.074/kWh).

Currently, there are various incentives issued by the Government to support renewable energy development to reach the ambitious target. According to Campbell et al. (2018), under the Law of Investment, renewable energy projects are eligible for investment incentives, such as corporate income tax preferences, import duty preferences, and land related incentives. Under corporate income tax preferences, renewable energy production will be subject to corporate income tax at 10% for the first 15 years. For raw materials and manufactured materials that will be imported to construct fixed assets such as solar farms, there is an exemption from import duty. According to the Law on Land, investors can be exempted from land rents and water surface rents. All land lease and land allocation projects will be handled by the relevant provincial People's Committees (Campbell et al., 2018). This information was further confirmed through conversation with Mr. Gabisch – the ADB project officer and investment specialist on the Da Mi project FPV plant, located in Binh Thuan Province, south Vietnam (M. Gabisch, personal communication, April 23rd, 2019). Land leases and allocation for the transmission infrastructure for the Da Mi FPV project were in EVN and Binh Thuan province People's Committee scope of work. What this meant was the financers, ADB, Canadian Climate Fund for the Private Sector in Asia, and Leading Asia's Private Infrastructure Fund (LEAP) did not finance the land leases and the bulk transmission facilities (M. Gabisch, personal communication, April 23rd, 2019). The Binh Thuan province People's Committee worked with EVN to ensure the construction of the bulk transmission facilities did not significantly alter the livelihood of the people and the ecosystems in the region (M.Gabischm personal communication, April 23rd, 2019).

In February 2019, MOIT proposed a new feed-in tariff (FIT) rate that would be applied after the current FIT expires on 30 June 2019. For FPV in four regions of Vietnam, the tariff will range from 6.85 cent per kWh to 9.44 cent per kWh, which are 0.18 to 0.24 cents per kWh higher than ground-mounted solar projects and approximately 1.04 to 1.43 cents per kWh lower than rooftop solar projects. Higher tariffs are proposed for regions with lower solar irradiance (primarily the northern and north central provinces of Vietnam). The reverse is true for the regions with higher solar irradiance, so there are lower feed-in tariffs for the central highlands and southern provinces of Vietnam (Baker McKenzie, 2019). The tariffs illustrate the Government's policy to develop energy security across different regions and diversify the geographic distribution of investment (Baker McKenzie, 2019). Despite the incentives and favorable tariffs, there are still various questions and challenges associated with financing and developing renewable projects in Vietnam that deter investors in this sector.

Development challenges

According to the Asian Development Bank (ADB), there are significant challenges in financing renewable energy, namely high subsidies for fossil fuels and low electricity prices that prevent investment from the private sector (ADB, 2018a). In addition, Vietnam still has an immature financial system incapable of sustaining long-term loans and innovation effectively, with a preference for short-maturity bonds, and inadequate capacity to assess risk and evaluate new technologies. Vietnam still relies on public institutions, such as traditional donors and development banks, to fund the infrastructure investment (IRENA, 2018a). Some of these energy development institutions that are active in Vietnam are GIZ and ADB. There are also concerns that the giant state-owned enterprise Vietnam Electricity (EVN) is operating at a loss due to its low energy prices, thus affecting its creditworthiness (ADB, 2018a). As of 2017, wholesale electricity prices are higher than retail prices, as shown in Figure 1 and Figure 3(MOIT & DEA, 2017; EVN, 2017; VNExpress, 2019).

Currently, there are many concerns about solar PPA in Vietnam. Circular 16/2017/TT-BCT issued in September 2017 includes templates of model PPAs for grid-connected projects such as residential/commercial/industrial rooftop projects (The Socialist Republic of Vietnam, 2017b). In the Circular, it was mentioned that VND/USD currency fluctuation will be applied in tariff adjustment. However, there is no clear tariff adjustment mechanism in this respect, such as Consumer Price Index (CPI) to address inflation risks. The PPAs do not specifically state in which currency payment shall be made by EVN. Per Vietnamese law, the tariff must be payable in VND and then converted to be repayments of shareholder loans in the case of foreign investor. It is also unclear how power distribution prices are calculated as sellers are responsible to pay EVN this price. Thus, the sellers bear the risk of transmission and distribution interruption, and there is no provision on any compensation in cases of such interruption (Campbell et al., 2018).

Cumulatively, EVN has been maintaining a retail price below cost-recovery levels. This has a significant impact on the sector's cash flow, leaving EVN no option but to increase the debt to meet capital needs (Maweni & Bisbey, 2016). Thus, the debt-to-equity ratio for renewable projects in Vietnam is one of the highest in the Southeast Asia region (Lee et al., 2019; M. Gabisch, personal communication, April 23rd, 2019). There are also problems in EVN's planning and upgrading the transmission infrastructure. Recent news showed that electricity transmission lines were overloaded in Ninh Thuan and Binh Thuan provinces, which currently have 38 solar power plants with a capacity of 2,027 MW. This was due to the increased power production from renewable power projects without increasing the capacity of the transmission system and substations. Mr. Lam, deputy director of the Southern Corporation, affirmed that they were working on its 16 110 kV lines at a total cost of $52.1 million (Viet Nam News, 2019).

Despite these challenges, the investment in renewable projects in Vietnam is still increasing, especially in FPV (Bellini, 2018). The advance in technology, favorable economics, and beneficial environmental impacts all contribute significantly to this rise.

Floating Photovoltaic Solar Generation

This section focuses on the trends in floating solar technology, the advantages, the challenges, and its current development and potential in Vietnam.

Technology

FPV has only received significant attention in the last ten years (Nguyen, 2017). The first FPV came online in 2007, but the majority of the current 198 MW FPV systems started operation around 2014 and 2016 (Spencer et al., 2018). From 2016 to 2018, about 100 MW of FPV systems were installed globally (Cazzaniga et al., 2017). There have been more than 100 projects around the world where FPV is installed on reservoirs for hydroelectric dams, mostly in Japan. Some key floating solar players, compiled as of 2019, are shown in Figure 5.

Figure 5. Major FPV players. Noted that some floating structure vendors produce their own mooring and anchoring solutions. However, the mooring and anchoring vendors as listed only produce these products (Cox, 2019).

Sujay et al. (2017) gave examples of various installed FPV plants, ranging from the small system (up to 500 kWp) to medium size plants (500 to 1500 kWp), and large size power plants (above 1500 kWp). There are also many projects being studied and assessed for feasibility. A potential 1 MW FPV system in Korea assessed using the System Advisor Model (SAM) software showed the production of 972 MWh/year, covering 87,650 m^2 of water surface (Song & Choi, 2016). A grid-tied 2 MW FPV and electric transportation facility that covered 4,000 square meters (m^2) of a reservoir that would generate 2,685 MWh annually, cost around 1.6 million USD with a payback period of 6 years in Pondicherry, India (Singh et al., 2017). Overall, feasibility studies for FPV have been done in various continents, showing high potential in energy generation and competitive payback periods with other generation technologies.

Coupling FPV with a hydropower plant can lead to an increase in the plant's overall installed generation capacity (ESMAP & SERIS, 2018). According to the International Hydropower Association (IHA), this hybrid model was proven successful at the Longyangxia hydro-ground-mounted solar farm plant in China and at the world’s first hybrid pumped hydro- FPV plant, built in Portugal at the Alto Rabagao reservoir (2017). Under a complimentary control system, the variation in solar output was smoothed by hydropower generation. The hydropower plant can reduce its production when the solar output is high and increase its production when solar output is low. Overall, there is an increase in total energy generation and improvement in the reliability of the power output to meet the grid need due to the smoothing of output variation (Farfan & Breyer, 2018; IHA, 2017). Another benefit of the hybrid model is the increased utilization of the transmission lines. Due to low water flow during the dry season, the turbines and transmission lines are often underutilized. The co-location will help solve the problem partially by linking the FPV to the hydropower plant's existing high-voltage grid connection, saving additional costs of transmission infrastructure typically faced by new generation projects. In addition, the water saved from evaporation due to FPV coverage can also be used for hydroelectricity generation (IHA, 2017). To match with reservoirs' capacity, FPV does not need to cover a lot of reservoir area (Table 1), showing that the technology has the potential to scale up and provide more auxiliary benefits. There are approximately 265.7 thousand square kilometers of hydropower reservoirs globally, that, at 25% coverage, have the potential capacity to host 4,400 gigawatts (GW) of FPV plants, potentially generating 6,270 terawatt-hours (TWh) of electricity per year, meeting 30% of the global energy demand in 2018 (Farfan & Breyer, 2018; International Energy Agency, 2018).

Table 1. Reservoir areas required to match dam's hydropower capacity (ESMAP & SERIS, 2018)

Dam/Reservoir	Country	Reservoir size (km^2)	Hydropower (GW)	Percentage of reservoir area required for floating solar to match dam's hydropower capacity (%)
Bakun Dam	Malaysia	690	2.4	3
Lake Volta	Ghana	8,500	1.0	<1
Guri Dam	Venezuela	4,250	10.2	2
Sobradinho "Lake"	Brazil	4,220	1.0	<1
Aswan Dam	Egypt	5,000	2.0	<1
Attaturk Lake and Dam	Turkey	820	2.4	3
Narmada Dam	India	375	1.5	4

FPV systems are usually comprised of a racking assembly mounted on floating structures on an enclosed water body (Cazzaniga et al., 2017). The components included are floating structures, a mooring system that can adjust to water level fluctuations, and cables, as shown in Figure 6 (Nguyen, 2017). The mooring system is a permanent structure that the system can be secured to, such as quays, wharves, piers, anchor buoys, and mooring buoys. Due to the strong winds and big waves common on large hydropower reservoirs, FPV faces more challenges in those locations than on small scale irrigation reservoirs. Under these conditions, the mooring design often gets tested and usually is the highest BOS component cost (IHA, 2017).

Most of the projects commissioned so far have not used underwater cables, with most wiring being above water. Properly rated cables and waterproof junction boxes are crucial above water, while transformers and any associated batteries remain on land. From there, high-voltage transmission lines are used to connect the power to the substation, then to the grid (Sahu et al., 2016). The power producing components of FPV are almost the same as any ground-mounted PV system.

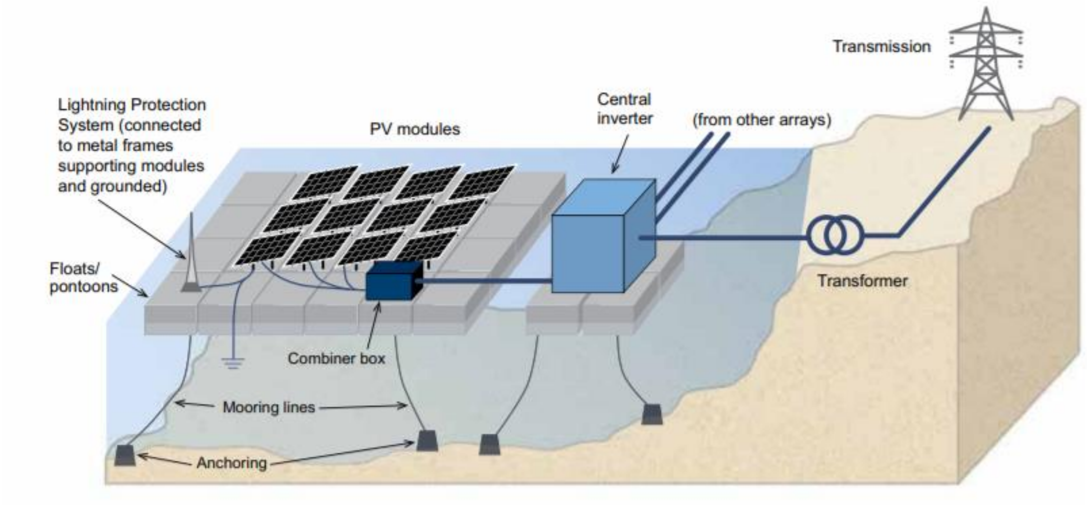

Figure 6. The layout of a typical floating PV system (ESMAP & SERIS, 2018). The PV module is attached on top of the floats/pontoon. There is a lighting protecting system (connected to metal frames supporting modules and grounded). The floats is anchored to the reservoir floor with mooring lines and anchors. All the electrical wires go to a combiner box, which is then connected to a central inverter on a float. The inverter is then connected a transformer on land. A transmission line runs the electricity from the transformer to the grid.

Figure 7 demonstrates a typical floating structure, developed by Ciel & Terre, one of the leading FPV floating structure developers.

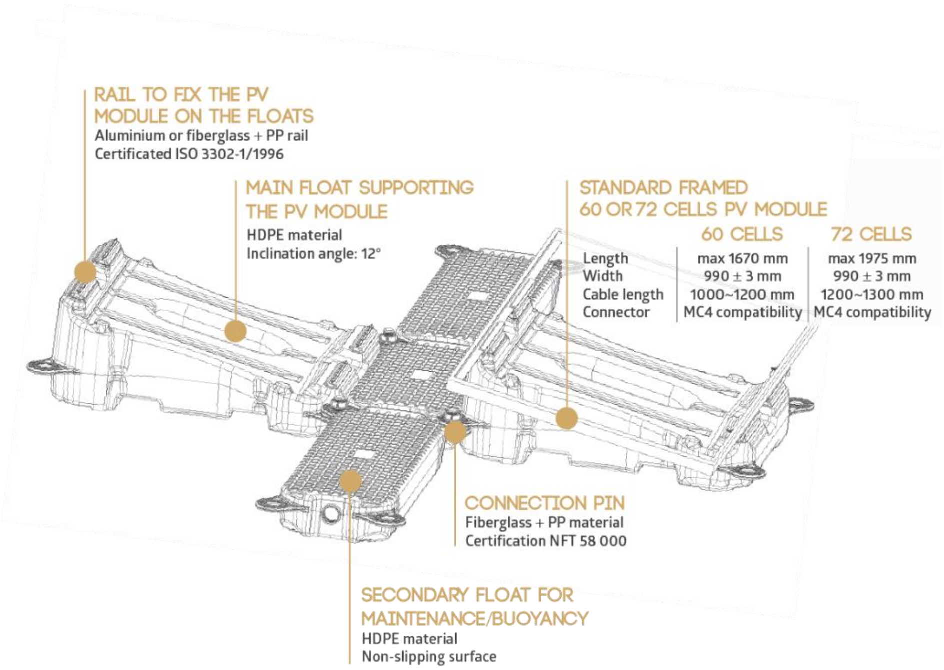

Figure 7. Ciel & Terre main float structure supporting solar module. (Ciel & Terre, n.d).

The position of the sun in the sky at the location is crucial in planning a PV system. The availability of incident solar energy is a key criterion in determining solar energy and consists of three forms: Direct Normal Irradiance (DNI), Diffuse Horizontal Irradiance (DHI), and Global Horizontal Irradiance (GHI). While DNI is the amount of solar irradiation received at a surface that is always held perpendicular to the direct solar beam, DHI is the radiation reflected from the sky (NREL, n.d(a)). GHI is the total amount of DHI and DNI in which:

$$GHI = DHI + DNI * \cos(Z) \tag{1}$$

where Z is the solar zenith angle which is the angle between the direction of the sun and the zenith (directly overhead) (NREL, n.d.(a)). However, GHI is not the only determinant of PV output. Other factors needed to be considered include, especially in this study: solar panels materials (crystalline silicon, thin-film, cadmium telluride, etc. with different panel efficiencies), total solar panel areas, inverter efficiency, and performance losses due to soiling, shading, module temperature, and other factors (PVGIS, 2017a).

The transmission connection with the power grid is another crucial component of the entire FPV system. The new transmission required can be divided into three main parts: spur transmission, Point of Interconnection (POI), and bulk transmission(The University of Texas at Austin Energy Institute, 2017). The POI is the facility that allows the connection between the spur line and the bulk grid. There are several options for connecting POI with the grid through bulk transmission, as shown in Figure 8 (The University of Texas at Austin Energy Institute, 2017).

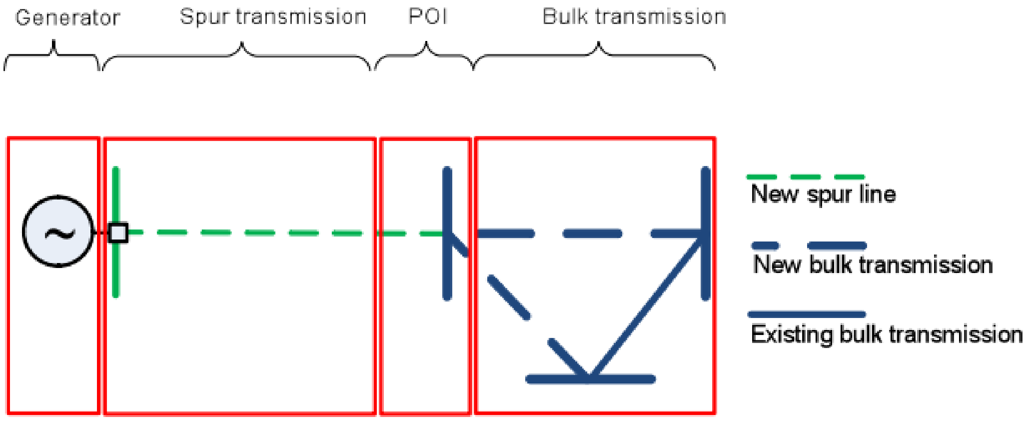

Figure 8. Transmission network scheme for new generator. (The University of Texas Energy Institute, 2017)

In the case of Da Mi, the project includes a 22-kV spur transmission line, a 22/110kV boosting voltage transformer near the shoreline, and a 110-kV spur line connected to the national grid (ADB, 2018c). These aforementioned substations and transmission lines are expected to be constructed and upgraded by EVN, and are usually not considered in the financing of Vietnam's new renewable projects (ADB, 2018c).

Economics of FPV

All-in costs for FPV applications are typically more expensive than ground-mounted applications due to the high structural balance of system costs (BOS), including the floating structure and mooring and anchoring system, while the cost of the solar modules and inverters are comparable. Compared to convential ground-mounted solar PV systems, a new set of risks is involved, in which the BOS equipment must be engineered and designed based on the water-level variation, extreme weather conditions, and many other factors (Cox, 2019).

Floating structure costs usually account for 25% to 34% of the total building cost for the plant, but these are still less than the cost of acquiring equivalent land area (M. Gasbich, personal communication, May 23rd, 2019; Cox, 2019). According to Ranjbaran et al. (2019) and Sahu et al. (2016), operational and maintenance costs for FPV systems are lower than for ground-mounted systems, partially due to the readily available water needed for cleaning. Due to the lower ambient temperature on the reservoir, the system components are cooler, leading to lower maintenance costs. However, Cox (2019) found that soft costs, including labor, design & engineering, and supply chain logistics, contribute to the higher cost of FPV and vary across projects. The uncertainty around these costs can deter developers and investors (Cox, 2019).

Most FPV projects are financed with local currencies with local or regional banks, mostly in China, Japan, and Taiwan (ESMAP & SERIS, 2018). However, the involvement of large international commercial banks and multilateral development finance institutions such as the Asian Development Bank and the World Bank is already happening. ADB has allocated $3 million of technical assistant to Azerbaijan, Kyrgyzstan, and Afghanistan, based on the approval of the Floating Solar Energy Development project in August 2018 (ADB, 2018d).

Most of the economic analysis did not consider required upgrades of the transmission network (Song & Choi, 2016; Singh et al., 2017, Rosa-Clot et al., 2017). The cost of spur transmission is generally a small expenditure, roughly 5% of the overall plant capital expenditure (CAPEX) (The University of Texas at Austin Energy Institute, 2017). In Vietnam, the average cost of the bulk transmission line is in the range of $300,000 to $500,000 per km of the 500-kV line and $150,000 to $250,000 per km of the 220-kV with the average cost shown in Table 2 (Maweni & Bisbey, 2016). Based on data from the Western Electricity Coordinating Council in the United States, a single-circuit 230-kV line would cost approximately $600,000/km, while a 500-kV line would cost $1.2 million/km (2014). Table 2 demonstrate that the transmission and substation cost in Vietnam is relatively low compared to the U.S. The amounts nonetheless represent large investments for the local economy, although they are not unreasonable given that many projects in Vietnam involve areas that are difficult to access.

Table 2. Unit cost for transmission and substation assets in Vietnam and the U.S. (Maweni & Bisbey, 2016; WECC, 2014a; WECC, 2014b)

Asset	Vietnam	U.S	Units
500 kV lines	356,300	1,200,000	$/km
230 kV lines	N/A	600,000	$/km
220 kV lines	173,500	N/A	$/km
500 kV substations	35,500	105,700*	$/MVA
230 kV substations	N/A	56,500*	$/MVA
220 kV substations	33,100	N/A	$/MVA

* the cost of the U.S substations was assumed based on WECC transmission capital cost calculator (2014b). The cost of the 230 kV substation was calculated for a 138/230 kV transformer with a 200 MVA rating, and the cost of the 500 kV substation was calculated for a 230/500 kV transformer with a 200 MVA rating.

Details on the existing and planned transmission lines and substations could be found on The World Bank's Vietnam – Electricity Transmission Network website (2016). The investment needed for Vietnam's transmission network upgrade and expansion for 2011-2020 was estimated at $8 billion (ADB, 2012). However, the development of new transmission lines or upgrading of substations potentially can pose as an economic challenge for EVN, whose financial structure has not yet stabilized and is wholly reliant on debt to fund many of its ambitious capital programs (Maweni & Bisbey, 2016). In order to ensure the grid capacity to accommodate new generation, especially renewable generation, more economic analysis should be done to understand the current and future investment scenarios for transmission infrastructure.

Environmental

One of the major benefits of FPV on reservoirs is the conservation of land that can be used for other purposes, such as cropland and pastureland, alleviating the land demand of traditional ground-mounted systems (Spencer et al., 2018). The shading provided by the PV panels can also significantly reduce water evaporation, conserving water for other purposes, along with reducing algae growth in the reservoir, thus improving water quality (Farfan & Breyer, 2018). Santafe et al. (2014) studied an irrigation reservoir in Agost, Spain with an area of 4490 m^2 which was 100% covered by FPV. They estimated a water evaporation reduction of 5000 m^3/yr or 25% of the reservoir's storage capacity annually, and a carbon savings of 1,450 tCO_2 from renewable electricity generation in its 20-year lifetime. Mittal et al. (2017a) estimated a savings of 64 to 496 million liters (or 64,000 to 496,000 m^3) annually for four different reservoirs with sizes ranging from 0.1 km^2 to 1.5 km^2 with different degrees of coverage (5%, 10%, 15%, and 20%) that produce between 3 MW – 27 MW. A 1 MW FPV plant at Kishore Sagar reservoir in Rajasthan, India (one of the reservoirs studied by Mittal et al. 2017a) could in one year produce up to 18.5 GWh, save 37 million liters of water, and reduce 1,700 tCO_2 of emissions (Mittal et al., 2017b). An assessment of water evaporation in South Australia's four wastewater basins concluded that FPV can reduce evaporation by 90%, such that a surface covering roughly 69,000 m^2 or 0.069 km^2 could save up to 124,000 m^3/year (Rosa-Clot et al., 2017). In addition, in coupling FPV with existing hydropower plants or pumped storage, solar power can be generated during the day for consumption and the output from the hydropower plant could be curtailed during that time. Water, thus, could remain stored in the reservoirs and be released during peak demand periods. The FPV system can take advantage of existing transmission infrastructure at the hydropower plant, resulting in additional savings for investors

(International Hydropower Association, 2017). As mentioned earlier, Vietnam has great reservoir resources that can be utilized for FPV power generation.

Additional benefits and disadvantages

As an additional benefit, water cooling of the FPV array has been used as a method to increase PV module efficiency. In a no-shading-or-faults condition, a high operating temperature and reduced incoming irradiance due to soiling can affect the panels' efficiency. The body of water can be passively (let the panels float on top of the water), or actively used to cool the panels. As water bodies provide an area free of trees and shading and contribute to a lower ambient temperature, PV deployment benefits (Sahu et al., 2016). The water taken from the water body supporting FPV can be actively sprayed or used to create a water veil onto the module when the temperature is too high, or irradiance is too low due to soiling (Cazzaniga et al., 2017). However, this method can reduce the water available for other benefits such as irrigation, drinking water, or hydropower. Choi (2014) showed that relative to ground-mounted systems FPV could have an average efficiency of 11% higher and a capacity factor that is 7.6% to 13.5% higher. Capacity factor (CF) was calculated in Choi (2014) by:

$$CF = \frac{Generation\ during\ Analysis\ period\ (kWh)}{Installed\ Capacity\ (kW) \times Analysis\ period\ (hr)} \tag{2}$$

A Vietnam-Japan Joint Evaluation Team reported that the existing hydropower plant on Da Mi Reservoir has the capacity of 175MW with two 87.5MW generating units and a dam height of 72m (2008). They also reported that from 2001 to 2007, the average yearly volume of water used to run the generators were 1,528 million cubic meters, ran for average 6,780 hours, generating on average 590 GWh per year (2008)[1]. Based on this data and Equation 2, the capacity factor of the Da Mi power plant averaged 37% in the period 2001 to 2008. According to ABD, this number is 46% (2018b). Due to low rainfall to support the hydroelectric facilities, in 2011, EVN incurred a significant financial loss (World Bank Group, 2016). Thus, co-generation with solar PV will enable better utilization of the already existing transmission network at the hydropower plant, save water from evaporation that can also be utilized for hydropower generation, and potentially increase the capacity factor of the facility.

FPV, however, has some disadvantages. The system is prone to threats such as storms and corrosion of the metallic structure which can reduce the system's life. On September 9th, 2019, Japan's largest FPV plan, a 13.7 MW project at Yamakura Dam, caught fire in the aftermath of Typhoon Faxai (Bellini, 2019). There are some environmental concerns such as the reduction of light penetration that can affect the growth of aquatic life (Sahu, et al., 2016).

Literature Gaps

Due to the novelty of FPV system, there are still gaps in research on the productivity, economics, and environmental impact of the system.

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[1] These numbers are inconsistent. The theoretical power available at Da Mi reservoir based on dam height, the water flow and operating hours to calculate flow, is 44.2 MW, suggesting the plant's efficiency at 25%, which are low for hydropower plants (The Engineering Toolbox, 2008). However, using the energy generation and operating hours, the theoretical power avaliable is 87MW, suggesting the plant's efficiency at 50% (The Engineering Toolbox, 2008).

The maintenance schedule and cost of FPV are not readily available for research and comparison. Besides the standard PV site maintenance such as module cleaning, general site maintenance such as road management, security equipment maintenance, equipment and perimeter fencing repair, on-site measurement such as weekly or monthly meter reading, string measurements, thermal inspections, I-V curve tracing, FPV possibly requires more maintenance than a ground-mounted or rooftop system (SolarPower Europe, 2018).

The economy of scale for FPV system is not yet clearly observed and studied, but was assumed in various studies (IHA, 2017; Cox, 2019; ESMAP & SERIS, 2018). However, according to Bollinger & Seel (2018), there was weak evidence on the economy of scale of solar PV based on their sample size studied. This statement was supported by the Institute for Local Self-Reliance (ILSR), which stated that the cost of transmission and distribution of large-scale solar projects largely undermined gains from scale (ILSR, 2016).

Ecosystem impacts of FPV on reservoirs are also not yet addressed, namely effects of water retention in reservoirs on river hydrology and ecosystems due to the use of FPV during the day, instead of hydroelectricity. There is no current research addressing possible algal growth on FPV panels, which can potentially increase maintenance cost and reduce PV output, when lake water is sprayed on the surface of the modules for cooling.

FPV is a rising market, still early in its deployment and needs more attention in the upcoming years. Despite some challenges and gaps in knowledge, the rapid development of FPV will provide researchers more data to investigate the system benefits and disadvantages and also address other questions.

Vietnam Floating Solar Generation Potential

Construction for the 47.5 Megawatt peak (MWp) FPV power plant on Da Mi Reservoir, Vietnam was finished in late May 2019, as seen in Figure B- 1 (M. Gabisch, personal communication, September 9th). M.Gabisch noted that the loan was signed after the construction due to the rush to meet the FIT deadline of June 30th, 2019. On Oct. 2nd, the loan was signed. This was first FPV project in Vietnam and in Southeast Asia, paving the paths for many future projects (ADB, 2018c). ADB is loaning 20 million USD to Da Nhim - Ham Thuan - Da Mi Hydropower Joint Stock Company (DHD), a dependent accounting unity of EVN to develop the FPV project on the 175 MW Da Mi hydropower plant (Asian Development Bank, 2018b). DHD is entering into a 20-year PPA with EVN under the solar power feed-in tariff (FIT) regime.

A floating central inverter, a land-based substation, and a new 3.5-kilometer, 110-kilovolt (kV) transmission line are the additional facilities at Da Mi Reservoir to support the FPV plant. The total footprint of the project is 51.55 hectares (ha), both on land and water. This project has been estimated to reduce greenhouse gas emissions in carbon dioxide equivalent (CO_2e) units by 30,302 metric tons annually due to the renewable energy generation (ADB, 2018c). According to ADB, the land acquisition for the lines and access road will result in the economic displacement of 42 households, including three households that will lose more than 10% of their agricultural land permanently due to access restrictions and 25 households that will lose land access temporarily due to transmission line construction. There will be no physical displacement in which households have to move completely from their lands. During the planning process, ADB mentioned the development of Livelihood Restoration Plan and the Community Development Plan to mitigate and measure the economic impact within the local community (ADB, 2018c). The plans, suggested by ADB, included small-scale agricultural support for economically impacted families, linked job opportunities from the project, and various support programs for the community (ADB, 2018e). However, it is unclear whether any program was yet implemented.

FPV has promise as a renewable energy technology with widespread adoption potential in Asia (ESMAP, & SERIS, 2018). There are currently more approved and registered FPV projects in Vietnam since Da Mi project approval, according to Mr. Stelter from Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) Vietnam (see APPENDIX B). The biggest project has the rated capacity of 530 MW, while the smallest is at 5 MW, mostly located in the southern part of Vietnam.

Study Reservoirs

The reservoirs that are the focus for analysis in this study were located in two main regions of Vietnam: Hoa Binh Reservoir located in Hoa Binh Province, northern part of Vietnam, while Tri An Reservoir and Dau Tieng Reservoir both located in the southern part of Vietnam, in Dong Nai Province and Tay Ninh Province, respectively (Figure 9).

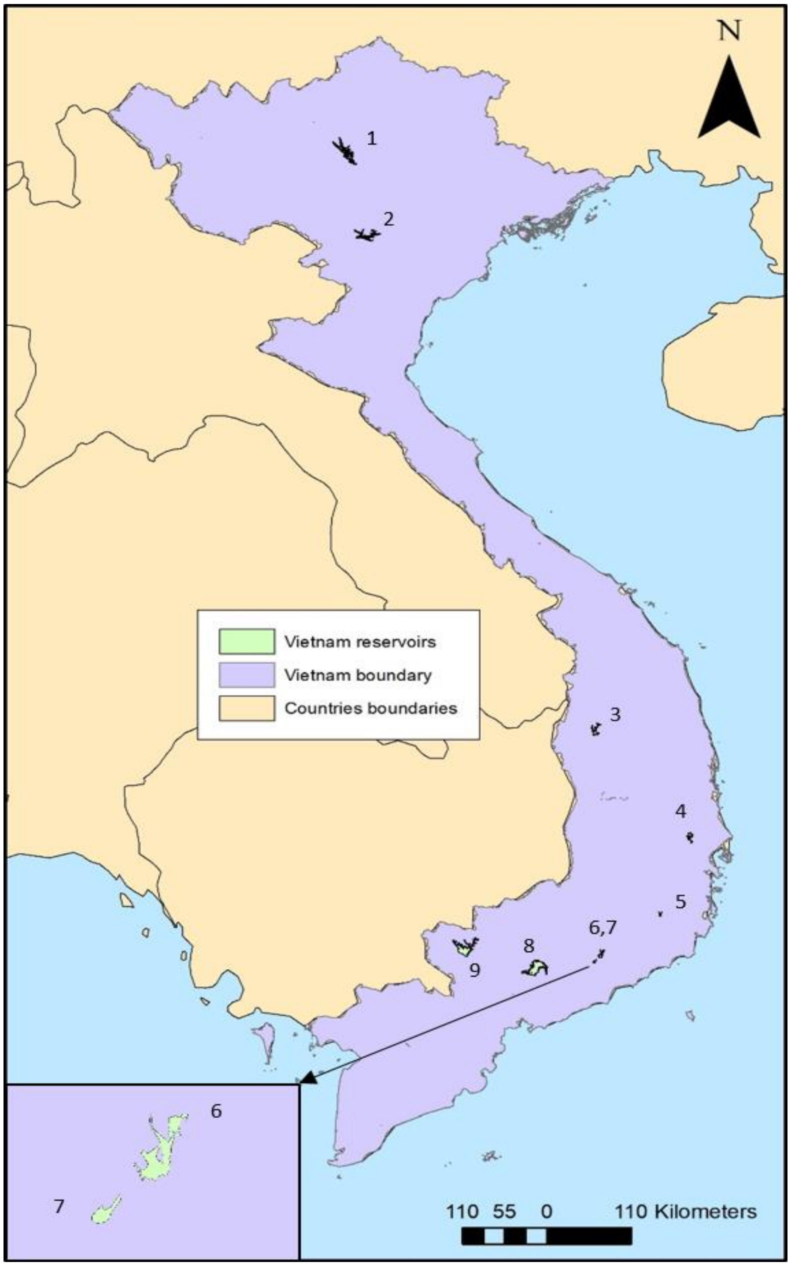

Figure 9. Locations of reservoirs acquired from GRanD database and additional Dau Tieng Reservoir. Da Mi Reservoir is number 7. The ones in studied are number 2 - Hoa Binh Reservoir, 8 - Tri An Reservoir, and 9 -Dau Tieng Reservoir.

At Hoa Binh Reservoir, Hoa Binh Dam has been in operation since 1994 and is the largest hydroelectric dam in Vietnam, with power generated by eight turbines with a capacity of 240 MW for a total installed capacity of 1,920 MW. The maximum discharge through all the turbines are 2,400 cubic meter per second (m^3/s) (Ngo, 2007). The effective head of the plant is 109 meters (EVN & Japan International Cooperation Agency or JICO, 2004). The efficiency of the system, therefore, is approximately 75%. From 2010 onwards, the power output of the Hoa Binh hydropower plant averaged at 10.1 TWh per year. In 2017, the output set a record high of 11.25 TWh (EVN, 2018). The operation and regulation of the reservoir with a capacity of 9 billion m^3 has tremendously aided in controlling flooding in Red River Delta. In addition, the water discharged from the reservoir provided 65-70% of the irrigation for agricultural production of Red River Delta provinces (EVN, 2018).

At Tri An Reservoir, Tri An Dam has been in operation since 1988 and has 400 MW of hydropower installed capacity, utilizing four 100 MW turbines. As of 2012, the average electricity production at the facility was 1.74 TWh per year with the maximum discharge through all the turbines at 880 m^3/s with an effective head of 52 meter (EVN & JICO, 2004). The efficiency of the system, is similar to the Hoa Binh Dam, at 75%. Tri An Reservoir's richness in biodiversity constitutes a great portion to people's livelihood with various economic activities such as tourism, agricultural crops, and fishing (VTV3 Vui Song Moi Ngay, 2014).

Dau Tieng Reservoir was a man-made effort meant to increase rice production by providing irrigation for a large area from its 26,000 hectares or 260 km^2 reservoir that can store up to 1,050 cubic meter (m^3) of water (The World Bank, 1991). Thus, it does not have the key features of flowing water to create a hydropower reservoir. However, based on conversation with Mr. Nguyen, Director of Vietnam Directorate of Water Resource (personal communication, March 15th, 2019), Dau Tieng Reservoir has high potential for FPV project approval.

The three study reservoirs, each has its distinctive features, including solar radiation, FIT rate, and environmental functionality, are proven as potential homes for new FPV projects.

METHODS

This study assessed the technical, economic, and environmental feasibility of FPV projects at each of the three case study sites. Tasks included analysis of a) PV generation potential at each of the three case study sites (Hoa Binh, Tri An, and Dau Tieng Reservoir), using PVGIS software and Geographical Information System (GIS)-based solar data, b) the associated payback period and levelized cost of electricity (LCOE) for each system based on the economics of solar projects in general and specifically informed by the first FPV project in Vietnam on Da Mi reservoir, and c) some of the resulting environmental benefits from operating the system, focusing mainly on the reductions in GHG emissions and reservoir water evaporation, and on the additional electricity generated from water saved from evaporation.

Technical feasibility

Technical feasibility was assessed based on the estimated power generation from the FPV plant and the requirements for transmission structures. The area of the reservoir that is covered by FPV is the main variable for determining the overall scale of a project. In order to accurately assess the scale of the system, the reservoirs' area was first calculated through acquiring the shapefiles of the reservoirs. The shapefiles of the two hydropower reservoirs, Hoa Binh and Tri An, were acquired through the National Aeronautics and Space Administration (NASA)'s Global Reservoir and Dam (GRanD) database (NASA, 2011). Since the GRanD database did not have the shapefile for Dau

Tieng reservoir, the shape of the reservoir was digitized from Google Earth Pro and converted from a Keyhole Markup Language Zipped (.kmz) file format to an ESRI shapefile (.shp). For consistency, the shapes of all the reservoirs in this study were also manually digitized at five-kilometer granularity in Google Earth Pro to confirm the value with the GRanD database values.

To assess the geographical condition at each reservoir and possible impact of transmission lines passing through the surrounding areas, land cover data and substation location data were used. Land cover data in raster form for the southern region of Vietnam were downloaded at a 10-meter (Northern Vietnam) and 15-meter (Southern Vietnam) resolution from Japan’s Advanced Land Observing Satellite 2 (ALOS 2), also called Daichi 2. Rasters are matrix of cells (or pixels) organized in a grid, where each cell contains values representing information, in this case, types of land (ArcMap, 2016). Rasters for the reservoirs’ associated regions within at least 10 km were combined into a new raster and the land cover type was reclassified into nine categories: water, urban and built, rice paddy, crops, grasslands, orchards, bare land, forest, and mangrove. The rasters use a series of cells to represent locations on the earth and give the properties of each cell. The electrical substation coordinates were extracted from Google Maps to show their locations. These data was then used to choose the possible geographical coordinates of the FPV installation that are closest to the substation infrastructure, which will further reduce cost for transmission lines and other necessary land acquisition (The University of Texas at Austin Energy Institute, 2016).

Yearly GHI and PV output maps were created based on yearly output from SolarGIS solar resources GEOTIFF data at a spatial resolution of 250 meters (SolarGIS, n.d). SolarGIS PV output potential was calculated based on average yearly electricity energy production from a 1 kWp grid-connected solar plant from 2005 to 2016. The PV system for SolarGIS calculations consisted of ground-based free-standing structures of crystalline-silicon PV modules. Each system was mounted at a fixed position with a tilt ranging from 5° to 24° towards the equator to maximize the energy yield. The cumulative losses from dirt, cables, inverters and transformers were assumed to be 9% (SolarGIS, n.d). The plant's availability is considered to be at 100% (SolarGIS, n.d).

The peak power and potential annual energy generation in Gigawatt-hours (GWh/yr) was determined for each of the three study locations and Da Mi reservoir, using the European Commission Institute for Energy and Transport (IET)'s Photovoltaic Geographical Information System version 5 (PVGIS 5) (European Commission, 2012). As the main variable for determining the overall scale of a project, the water surface coverage of 1, 5, 10, and 15% was assumed in this study. NREL's study on floating solar potential in the United States used a coverage of 27% based on the median coverage value of FPV projects internationally (Spencer et al., 2018). Our study's coverage assumption was kept conservative but had potential to scale. These reservoir coverages were also used to calculate evaporation savings.

Using those coverage percentages, the panels areas were calculated following these next steps. First, the floating structure for solar panels alone was calculated as a percentage of lake coverage, accounting for the walkways and spacing between modules.

Then, the actual panels areas were calculated based on the floating structure for solar panels and the tilt of the panels. Finally, the peak power of each system was found based on the panel's area and panel's efficiency. Using the peak power as an input variable in PVGIS, the potential energy generation at each study site was generated.

Using Da Mi project's system size as an example, the area of floating structure was found based on the tilt of the panels. The Da Mi project used 143,940 PV panels with dimensions of 1956 mm length and 992 mm width, which would cover 27.9 ha or 6.5% of the reservoir surface if they were in a horizontal position. All the panels at Da Mi project are south-facing panels with 11° tilt (M.Gabisch, personal communication, Oct. 27, 2019). The typical mounting angle for floating solar system is 11° (Mow, 2018). The actual panels area or floating structure of the solar panels alone will be:

$$Area\ of\ floating\ structure\ panels = panels\ area\ \times \cos\,(tilt\ angle) \qquad (3)$$

The percentage of lake coverage of the floating structure for the panels for all the projects in this study was found based on Da Mi's project dimensions. Based on Equation 3, the actual area of Da Mi Lake's floating structure for panels is 27.4 ha. However, the actual coverage of the total floating infrastructure came to approximately 44.9 ha or 164% of the panel areas alone (ADB, 2018b). Thus, the actual areas of modules alone were calculated by using only the inverse of 164%, or 61%, of each of the four coverage percentages :

$$Area\ of\ floating\ structure\ for\ panels\ only = 61\%\ \times lake\ coverage \qquad (4)$$

Using Equation 4, then Equation 3 again, the panels area for each project in this study was calculated. The calculation for peak power of each FPV plant was based on the panels area, panel efficiency and assumption on peak GHI. Nominal power or peak power of the PV modules was measured under Standard Test Conditions (STC) in the laboratory or at the factory. The peak power is the power claimed by manufacturer of the module measured at 1000W/m^2 solar irradiance, 25˚C, and an air mass of 1.5. This means that if the module were 100% efficient, the system size only needs to be 1m^2 to achieve peak power of 1kW at STC. Since the modules are not 100% efficient, for example, a 10% efficient module would need 10m^2 to achieve a 1kWp system (PVGIS, 2017b). Hayter & Kandt (2011) found that the STC efficiency for polycrystalline is roughly 13%–17%, and for monocrystalline 14%–19%. The efficiency of the panel in the field for this study was assumed to be 17% at STC before all other losses, same as the Da Mi project panels as shown in Table B- 3. The value of 17% is an average efficiency for crystalline silicon technology (Hayter & Kandt, 2011).

The installed peak PV power (kWp) for each reservoir was calculated based on a PVGIS simplified equation, assuming average irradiance or peak GHI of 1kW/m^2 on a 100% efficient panel on horizontal plane (2017b):

$$\textit{power (kWp)} = \textit{peak GHI } (1\ kW_p/m^2) \times \textit{panels area } (m^2) \times \textit{efficiency at STC } (\%) \qquad (5)$$

The mounting position was set to free-standing (the other option in PVGIS is building-integrated which was not in the scope of work). 11° tilt and 0° azimuth was chosen for PVGIS to calculate the PV module positioning that correlates with typical FPV tilt, and current Da Mi FPV plant’s azimuth. When PV modules are mounted outdoors, the conditions will be very different than the standard conditions. Thus, there are also other losses associated with the system, called system losses. The calculations in

PVGIS only showed the power delivered at the connectors of the array (PVGIS, 2017a). However, there are also power losses associated with AC current by the inverters, cables, and the transmission lines (PVGIS, 2017a). In addition, the power of PV modules tends to decrease slowly with age (Jordan & Kurtz, 2013). It was found that PV modules typically have approximately 0.5% decrease in power per year of operation. With an expected lifetime of 20 years, this means that the power on average over 20 years would be 95% of the original power, with 90% of original power at the end of 20 years (Jordan & Kurtz, 2013). PVGIS took these into consideration as system losses for its yearly average production output. The suggested system loss by PVGIS was 14%, including losses from cables, inverters, transmission lines, degradation, temperature variation, and excluding snow, dust and dirt, and partial shadowing (PVGIS, 2017a). This number is comparable to PVWatts, another PV generation model created by NREL (NREL, n.d (b)). The default system loss values in NREL for Hanoi, Vietnam were 15%, including 2% for soiling, 3% for shading, 0% snow, 2% mismatch, 2% wiring, 0.5% connection, 1.5% light-induced degradation, 1% nameplate rating, 0% age, 3% availability (NREL, n.d (b)). This study used the PVGIS 14% system loss for all three reservoirs' FPV plants.

Since the study sites are in Vietnam, PVGIS automatically chose the PVGIS-SARAH solar radiation database which covers Europe, Africa, most of Asia, and parts of South America. The time period for the data is 2005-2016. The data has hourly time resolution and a spatial resolution of 3 arcminutes or approximately 6-km grid resolution (PVGIS, 2017a). The PV technology chosen for the study was crystalline silicon. Based on all input data, PVGIS calculated the average yearly output of the system (see

APPENDIX C). These data were then compared with Vietnam’s 2025 forecasted energy demand to estimate the contributions of FPV in meeting the national energy demand. The land cover and nearby substation maps are shown in APPENDIX D.

Economic feasibility

The project also included an economic analysis, using a payback period model. A payback analysis of FPV was conducted for each of the study sites to determine the economic feasibility, based on the new proposed FIT rate as described in Literature Review and trend in solar PV and FPV cost in Vietnam. The analysis excluded the costs of substation upgrades to accommodate the new voltage and currents. These upgrades are under EVN jurisdiction, not the project developers (Mr. Gabisch, personal communication, May 25th, 2019). EVN currently already has plans to upgrade the substations across the country. However, the project developers or sellers are responsible for the spur transmission lines, according to the PPA (The Socialist Republic of Vietnam, 2016). The costs of the spur lines generally comprise a small portion of the overall project cost (Mr. Gabisch, personal communication, May 25th, 2019). The spur line cost at Dau Tieng Reservoir was included in its payback model due to the lack of hydropower substation nearby and the extension needed to reach the closest substation. The installation cost of the system was validated based on the contract cost of the Da Mi project and the global utility-scale solar PV cost projection from the International Renewable Energy Agency (IRENA, 2016; IRENA, 2017)

The three reservoirs are in three different regions in Vietnam, and each, therefore, has a different economic payback. While Hoa Binh reservoir is in the northern region that has higher FIT based on the new MOIT's proposal, Tri An and Dau Tieng reservoirs are both in the southern provinces that have a lower proposed FIT.

The simple payback period was calculated using the Equation 6, including the 10% corporate tax on production:

$$Payback\ (years) = \frac{Initial\ Cost\ (\$)}{(100\% - Tax(\%)) \times Annual\ production\ \left(\frac{kWh}{year}\right) \times Value\ \left(\frac{\$}{kWh}\right) - O\&M\ \left(\frac{\$}{year}\right)} \qquad (6)$$

According to Mr. Gabisch, Da Mi project has a 15-year loan tenor (i.e., the period to repay the loan), with a loan payment period of 14 years (year one is for construction). The payback period calculated for Da Mi was compared to Da Mi project's eight-year-payback estimation to validate the result (M.Gabisch, personal communication, July 4th, 2019).

The simple payback period is an attractive calculation because it is straightforward and easy to understand and explain. However, there are limitations since the calculation ignores the time value of money, changes in energy price, variable rate electricity pricing, etc. In the case of Vietnam, the energy price paid to developers for the project should remain the same for the lifetime of the project under the PPA (The Socialist Republic of Vietnam, 2017b). However, the time value of money based on inflation, opportunity cost, and risk are not factored in (Hay, 2016).

The levelized cost of energy (LCOE) of the system, which is the minimum price at which energy must be sold for the project to breakeven, is usually calculated to understand the value of the technology at a bigger economic scale. This helps developers and policymakers understand the economic viability of these projects, given market prices and trend. Thus, the LCOE of the FPV projects at the reservoirs in the study was calculated based on the simplified LCOE equation (7):

$$LCOE = \frac{sum\ of\ discounted\ costs\ over\ lifetime}{sum\ of\ discounted\ energy\ produced\ over\ lifetime}$$

$$= \frac{\sum_{t=0}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{E_t}{(1+r)^t}} \tag{7}$$

where
I_t: investment expenditures in the year t (\$)
M_t: O&M expenditures in year t (\$)
F_t: fuel expenditures in year t (\$)
E_t: energy produced in year t (MWh)
r: discount rate (%)
t: expected lifetime of the system (years)

There are several assumptions used in this model. The expected lifetime of the system or number of annuities received, t, in this case, assumed to be the same as the Da Mi’s PPA – 20 years. The discount rate reflects the project’s risk profile. Mr. Gabisch suggested that the discount rate r would be close to the spread of Vietnamese government bond yield, averaging 5.5-6%. The project is not able to have a lower risk than the country in which it is located, thus the sovereign risk rating is a good benchmark (M. Gabisch, personal communication, Jun 4th, 2019). Discount rates for projects can be based on various factors. According to Professor Fisher at Humboldt State University, sometimes discount rates will be based on government bond rates, but often they are higher than the government bond interest rate due to the riskiness of the project. However, if experts use the government bond rate, that rate should be adequately reliable to assume (W. Fisher, personal communication, June 30th, 2019). Thus, the analysis in this study assumed the higher end of the interest rate or discount rate suggested by Mr. Gabisch, 6%. Different discount rates were discussed and analyzed in the Results section. There are presumably no fuel costs and variable O&M associated with renewable projects. This study also assumed a scalable fixed O&M cost for each of the three FPV systems, at $24.6/kW/year[2], which was the input provided by ASEAN Centre for Energy to NREL for solar PV installation in Vietnam (Lee et al., 2019). This number is high compared to the O&M cost in the United States, at $13/kW/year (Fu et al., 2018). The high solar PV O&M cost was acknowledged by Lee et al., 2019, but the reasons for the high cost was not explained. The fixed O&M cost for FPV might be potentially higher due to the limited knowledge on system functioning after installation in Southeast Asia (Da Mi FPV project was the first FPV project in Southeast Asia). For this study, the $24.6/kW/year for fixed O&M cost was assumed. Sensitivity analysis by changing PV output, fixed O&M cost that results in changes in the LCOE was performed to investigate the range of variability in this study. More details of economic analysis are shown in APPENDIX E.

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[2] In the report, the O&M unit is cited as $/kW/year. However, in Table A-5 of the report, the number possibly mistaken put in as $/MW/year.

Environmental feasibility

The environmental impacts of the FPV plants also played an important role in determining the feasibility of the projects. The environmental factors that this study focused on were GHG emission, water resource conservation, and potential ecological impacts. During its feasibility study, ADB found that there were no critical negative environmental impacts on the fish habitat, water quality, or biodiversity associated with the Da Mi FPV plant installation (2018b). Nonetheless, a literature review and calculation about the various potential FPV environmental impacts was completed.

An assessment of potential GHG emission reductions compared to the current grid mix was conducted based on the potential PV generation over the FPV's projected lifetime and the emissions that would have occurred from producing an equivalent amount of electricity from the current grid mix. The grid power emission factor (EF) was calculated in more details in APPENDIX F, based on data retrieved from The Socialist Republic of Vietnam Ministry of Natural Resources and Environment Equation (8):

$$EF_{grid}\left(\frac{tCO_2}{MWh}\right) = \frac{Emission\ (tCO_2/yr)}{Electricity\ Generation\ (MWh/yr)} \tag{8}$$

Another likely environmental benefit of FPV to the reservoir is the reduction in water evaporation from the reservoir. The conservation of water is critical to meeting the demands of irrigation and daily domestic water usage and can sometimes be overlooked in environmental impact assessments. The evaporation rate (E) in millimeter per day (mm/day) was calculated using the variation of Penman formula developed by Valiantzas (2006) that requires relative humidity, mean air temperature, wind speed, and solar radiation data:

$$E \approx 0.051(1-\alpha)R_s\sqrt{T+9.5} - 0.188(T+13)\left(\frac{Rs}{Ra} - 0.194\right)(1 - 0.00014(0.7Tmax + 0.3Tmin + 46)^2\sqrt{\frac{RH}{100}} + 0.049(Tmax + 16.3)\left(1 - \frac{RH}{100}\right)(a_u + 0.536u) \qquad (9)$$

where
α: water albedo or reflectivity - 0.08
T: the mean air temperature (°C)
Tmax: the maximum air temperature (°C)
Tmin: the minimum air temperature (°C)
RH: the relative humidity (%)
Rs: the global horizontal solar radiation (MJ/m^2/day)
Ra: extraterrestrial radiation (MJ/m^2/day).
u: wind speed at 2 m above the water surface (m/s)
a_u: 0 if using Linacre (1993) and 1 if using Penman (1948)

The mean temperature was derived from the average of the maximum and the minimum temperature instead of an average daily (Valiantzas, 2006). The temperatures were acquired from TerraClimate – a dataset consists of different climate variables and climatic water balance for global terrestrial surfaces with a 4-km or 1/24th degree spatial resolution (Abatzoglou et al., 2018).

Daily total sunshine hours (n) were estimated based on the monthly sunshine duration at the General Statistics Office of Vietnam station closest to the reservoirs divided by the number of days in that month (General Statistics Office of Vietnam ,2017a). For Hoa Binh reservoir, the Ha Noi station was used; for Tri An and Dau Tieng reservoirs, Vung Tau station. Monthly R_s was calculated based on monthly R_a, daylight hours (N), and daily total sunshine hours (n) by Valiantzas, 2016:

$$R_s = R_a \times \left(0.5 + 0.25 * \frac{n}{N}\right) \tag{10}$$

Extraterrestrial radiation R_a or the radiation received at the top of the earth's atmosphere on a horizontal surface at different latitudes relative to the reservoirs are provided by Food and Agriculture Organization of the United Nations (FAO, 1998). N was calculated for each month based on the following equations by Valiantzas, 2016:

$$N = 4\emptyset \sin(0.53i - 1.65) + 12 \tag{11}$$

where:

i: rank of the month (e.g. January has rank 1)

$\emptyset$:latitude of the site (radians), positive for the Northern hemisphere.

Relative humidity was calculated based on the water vapor pressure, using the formula:

$$RH = \frac{actual\ vapor\ pressure}{saturation\ vapor\ pressure} \times 100\% \tag{12}$$

Saturation vapor pressure for water was shown in APPENDIX G. It is important to note that Penman (1963), Linacre (1993), and Cohen et al. (2002) suggested the incorporation of wind function to estimate potential evaporation from open water, which appears in equation 8 as :

$$f_u = a_u + 0.536u \tag{13}$$

The wind speed at 2 m above the water surface was found based on the equation for windspeed at different height, provided by FAO (1998):

$$u = u_z \frac{4.87}{\ln(67.8z - 5.42)} \tag{14}$$

where:

u_z : measured wind speed at z meter above ground surface (m/s).

For each of the three reservoirs, the windspeed at 50 meters was acquired from Global Wind Atlas (DTU Wind Energy & The World Bank Group, n.d). The average speed shown was assumed to be the wind speed at each reservoir (see APPENDIX G).

The evaporation volume E (m^3/year) was calculated based on the equation:

$$E = Project\ area\ (m^2) \times Yearly\ evaporation\ \left(\frac{mm}{year}\right) \times \frac{1m}{1000\ mm} \tag{15}$$

The potential annual energy that could be generated via hydropower using the water saved from evaporation W (kWh) was calculated to quantify the theoretical power available (J) of the combined hydropower-FPV facility and coverted into GWh (The Engineering Toolbox, 2008):

$$W = \rho \times V \times g \times h \times \eta \frac{2.7 * 10^{-13}\ GWh}{J} \tag{16}$$

Where

W: energy (GWh)

ρ : water density (1000 kg/m^3)

V: volume of water (m^3/s)

g : acceleration of gravity (9.81 m/s^2)

h : effective head (m)

ɳ : efficiency of the turbine, assuming similar to Hoa Binh and Tri An Dam, at 75 %

RESULTS

This chapter includes the results for the technical, economic, and environmental feasibility of floating solar power generation on the three water reservoirs in Vietnam. The topics covered are the potential energy production, the LCOE, the potential GHG emission, and evaporation reduction of each project.

Technical feasibility

Table 3 shows the average yearly electricity production (kWh/kWp) of FPV for three study reservoirs along with Da Mi reservoir that has already had a FPV plant installed, using PVGIS. APPENDIX B shows the current location and specifications of the Da Mi project. The reservoir coordinates, PVGIS configuration examples at 15% reservoir surface coverage[3], and the PV output of all four reservoirs FPV system are shown in Table C- 1.

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[3] PVGIS gave out a warning when the system size input was greater than 20 kW_p in PVGIS version 4. It recommended consultation from more data providers and professional assistant from PV performance experts. In PVGIS 5, this warning did not appear, and the layout of the results was different between the two versions. However, the results were comparable between the two PVGIS versions.

Table 3. Comparison of yearly solar resources (kWh/m2) and production (kWh/kWp) from FPV installation at three study reservoirs and Da Mi reservoir, using two solar data sources PVGIS and SolarGIS.

Reservoirs	Area (km^2)*	Annual solar resources GHI based on SolarGIS (kWh/m^2)	Annual SolarGIS average production (kWh/kWp)	Annual solar resources GHI based on PVGIS (kWh/m^2)	Annual PVGIS average electricity production (kWh/kWp)
Hoa Binh	91.1	1,340	1,055	1,490	1,125
Tri An	277.4	1,873	1,478	1,960	1,471
Dau Tieng	235	1,914	1,505	2,000	1,486
Đa Mi	7	1,844	1,444	1,900	1,425

***** Reservoir's area for the three study reservoirs were taken from GRanD reservoirs, while for Da Mi was from Binh Thuan government website (2012)

In the case of Da Mi project, 47.5 MW of FPV panels and the inverter system take up 45.25 ha or 0.4525 km^2, which is approximately 6.5% of the reservoir area (ADB, 2018c; Binh Thuan government, 2012). The areas of Hoa Binh reservoir, Tri An reservoir, and Dau Tieng reservoir were estimated to be 91.1 (GRanD), 277.4 (GRanD) and 235 km^2 (Google Earth polygon measurement), respectively. However, there was some discrepancy on the reservoir surface areas. The Vietnam Directorate of Water Resources database has data from 7,168 reservoirs in Vietnam, but only has a measurement of the watershed area and not the surface area of the reservoirs. It should be noted that a reservoir's surface area and volume fluctuation are dependent on seasonal variation in inflow and outflow characteristics such as precipitation, inflow river discharge, discharge from riparian communities, evaporation, reservoir outflow and water percolation, etc. (Geraldes & Boavida, 2005; Ratnayaka, Brandt, & Johnson, 2009;

Busker et al., 2019). Dao et al.(2010) mentioned Tri An reservoir surface area to be 323 km^2 without citing sources. In addition, there is currently no extensive research on these reservoir areas. The water levels and reservoirs areas should vary, dependent on seasons and hydropower operation. On August 19th, Da Mi reservoir's area measured in Google Earth Pro was 6.12 km^2, close to Binh Thuan's government claim. Tri An's reservoir area measured on Google Earth Pro was 276 km^2, close to the measurement in the GranD reservoir database (277.4 km^2). Hoa Binh's reservoir area was 80 km^2 (not considered the length of the wide tributary which is Da River). For simplification, this study assumed the reservoir areas as shown in GRanD database for Hoa Binh and Tri An reservoir, and Google Earth polygon measurement for Dau Tieng Reservoir.

The land cover map and the locations and the voltages of the existing substations within 5 to 10 kilometers of the three reservoirs are given in APPENDIX D, showing the existing electricity infrastructure that FPV can connect to. For Hoa Binh and Tri An FPV projects, there are currently substation located at the reservoirs due to the hydroelectric facilities. These substations can be updated, or a new substation can be constructed as in the case of Da Mi project (ADB, 2015a). For Dau Tieng Reservoir, additional transmission lines to the nearest substation (110-kV Dau Tieng substation) was considered for economic analysis (Figure D- 3).

Figure 9, Figure 10, and Figure 11 demonstrate the locations of study reservoirs, GHI and expected yearly PV generation across Vietnam based on the SolarGIS map. Table 3 shows data on electricity production and the difference in electricity production (kWh/kWh) between two data sources (PVGIS results and SolarGIS), along with the annual GHI resources from SolarGIS. There is a small 2-5% difference in electricity production between the two sources. For this study, PVGIS software data, instead of SolarGIS, was used to calculate the total electricity production.

The average yearly production of Da Mi plant as predicted by PVGIS, using the current tilt and azimuth, is 67,400 MWh/year with year-to-year variability of 2,190 MWh, relatively close to the production amount stated in the Initial Environmental and Social Examination Report prepared by ADB at 69,990 MWh/year (ADB, 2018c). The number provided by ADB is 4% higher than the PVGIS output. If the variability is taken into consideration, the difference can be as low as 0.6%, and as high as 6%. Even though there is some discrepancy, the PVGIS method shows high validity due to its precision to the predicted output by ADB.

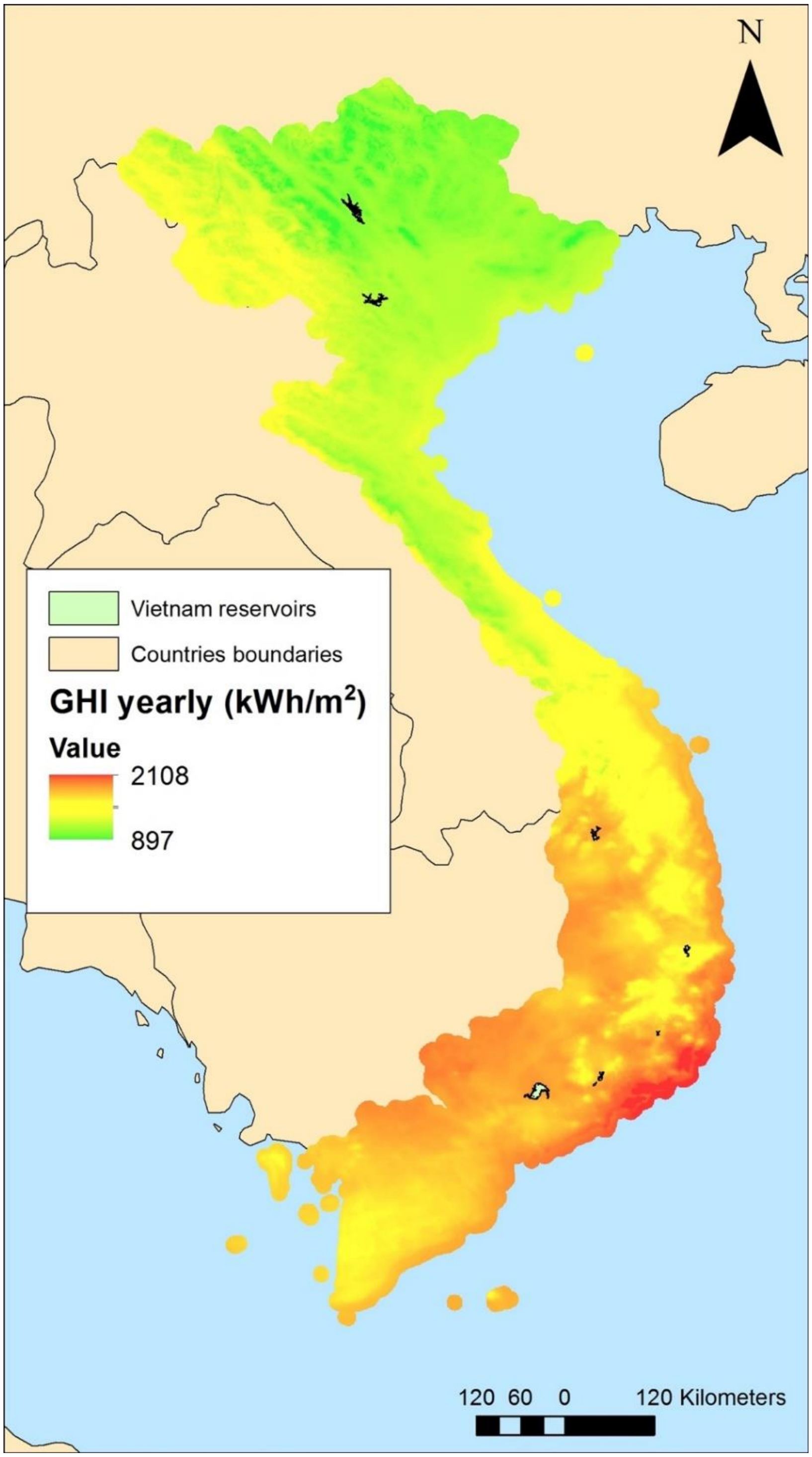

Figure 10. Global Horizontal Irradiance (GHI) yearly (kWh/m2) across Vietnam and the locations of the GRanD reservoirs (SolarGIS, n.d)

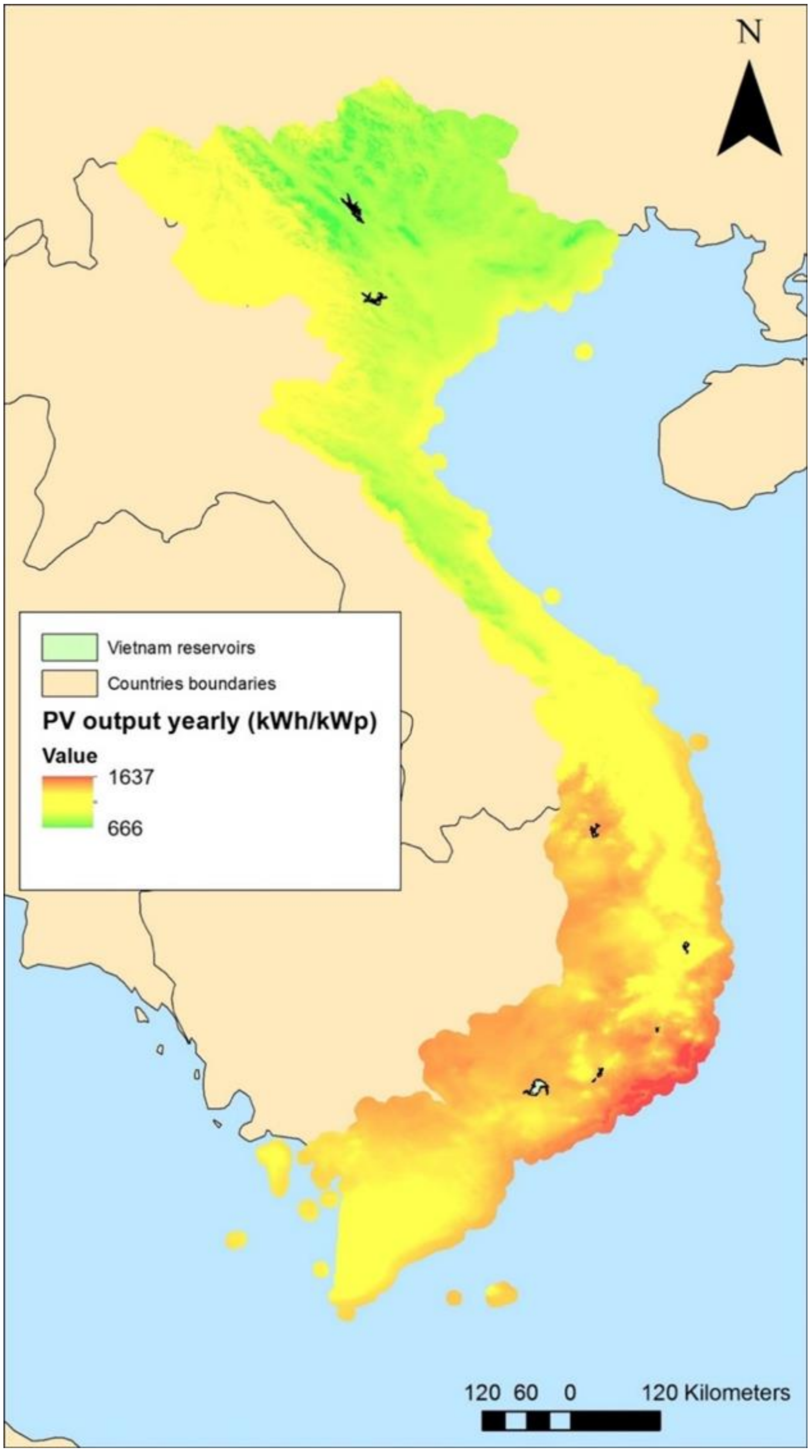

Figure 11. PV potential output (kWh/kWp) across Vietnam and the locations of the GRanD reservoirs (SolarGIS, n.d).

Table C- 2, Table C- 3, and Table C- 4 summarize the PV output from the three study reservoirs. The tilt and azimuth angle for all the panels at the three reservoirs were assumed to be the same at 11° and 0°, respectively. It is interesting to note that the monthly output in Hoa Binh (the northern reservoir) during the summer months (May to October) was higher than during the winter months (November to April). At the other two reserervoirs (Tri An and Dau Tieng), the summer month outputs were generally lower than the winter month outputs.

Tri An's FPV system would have the largest area coverage out of the three systems. Hoa Binh system has the smallest area coverage and the lowest yearly production potential (kWh/kWp) as shown in Table 4 due to its northern location. Table 4 shows that dependent on the reservoir coverage, if all the FPV plants in all three study reservoirs are developed by 2025, they will cover from 0.26% to 3.94% the 2025 forecasted national electricity demand which is 347,527 GWh (MOIT& DEA, 2017).

Table 4. Percent 2025 energy demand coverage from all three reservoirs. Forecaseted national energy demand cover in 2025 is 347,537 GWh (MOIT & DEA, 2017)

Percent coverage (%)	Sum of expected annual production from all three reservoirs (GWh)	Percent of 2025 forecasted national energy demand cover (%)
1%	914	0.26
5%	4571	1.32
10%	9140	2.63
15%	13700	3.94

Economic feasibility

The project installation cost of the 47.5 MW Da Mi plant in 2017 as projected in contract was $62 million USD, which translated into $1.3/W (ADB, 2018b). According to Mr. Gabisch, the revenue from the hydropower plant will serve as the collateral for the project (personal communication, April 23rd, 2019). The price for the floating structure would substitute for the land acquisition payment; thus in the long run, the finance of land and floating project will ultimately be comparable. Mr. Gabisch believed the $62 million was largely overpriced as a budget contingency. He suggested that the total project cost for the current FPV plant in Vietnam would be approximately USD $750,000 to $1 million per MW installed (inverters and land acquisition included), or $0.75/W to $1/W. This would bring the cost of the Da Mi plant to approximately $35.6 to $47.5 million. The FPV plant construction was finished by June, 2019. However, on October 2nd, 2019, ADB signed the loan with DHD for $37 million. Mr. Gabisch noted that this was an equity risk to sign after the construction. However, a lot of renewable projects in Vietnam began construction before the loan was signed to reach completion by June 30, 2019 – the FIT deadline (M.Gabisch, personal communication, October 27th, 2019).

According to engineering firm RETTEW's national market lead, Jason Wert, in the U.S, while FPV projects are still more expensive than ground-mounted projects, the costs were estimated to decline to approximately $1.5/W by mid-2019 (Trabish, 2019). However, data are not yet available to confirm the actual price of FPV in the U.S by mid-2019. In the case of Da Mi project in Vietnam, Mr. Gabisch confirmed the floating infrastructure, panels, and inverters for the Da Mi project were manufactured in China. This was considered one of the lowest prices on the market, factoring in transportation and a Vietnam tax exemption for manufactured materials that are imported to construct solar farms. In the future, the costs of FPV are expected to decrease even further (M.Gabisch, personal communication, May 25th, 2019).

Between 2010 and 2017, the global average installed cost for utility-scale PV projects (inverters not included) decreased by 68% (Figure 12). From 2015 to 2025, the installed cost for utility-scale ground-mounted PV system was forecasted to drop 59% from $1.75 to $0.75/W (IRENA, 2016). From 2015 to 2017, the price already dropped approximately 20%, from $1.75/W to $1.39/W (Figure 12) (IRENA, 2017). If this trend continues, the 2025 forecasted price for utility-scale projects by IRENA will ultimately reach $0.75/W.[4]

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[4] These cost estimations by IRENA were analyzed from the perspective of private investors, excluding government incentives or subsidies or any merit order effect system-wide cost-savings (IRENA, 2017).

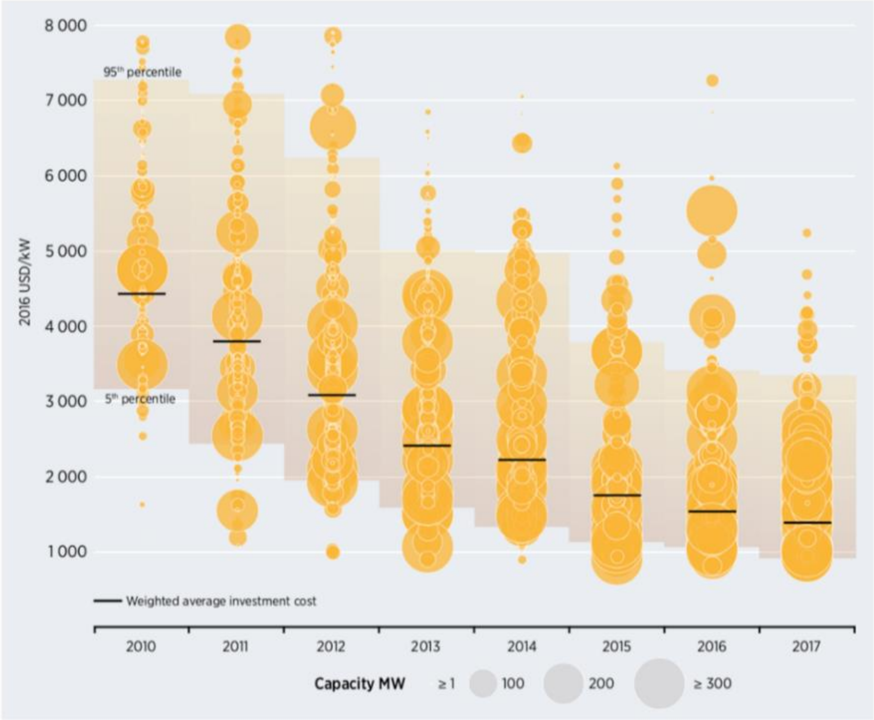

Figure 12. Total installed costs for utility-scale solar PV projects and global weighted average 2010-2017 (inverter cost not included). The 5th and 95th percentile range of the LCOE declined from $0.18/kWh and $0.60/kWh in 2010, to between $0.07/kWh to $0.31/kWh. (IRENA, 2017)

Based on IRENA (2017), the cost of utility ground-mounted solar PV is $1.39/W, higher than the range of ESMAP & SERIS (2018) data on the FPV investment cost, which is in the range of $0.8 to $1.2/Wp, dependent on location, depth of the water body and the size of the FPV system. This is due to the fact that IRENA data were based on global average values, while ESMAP & SERIS data only focused on Asia. Calculated on a pretax basis, the LCOE of a 50 MW FPV was found to not differ significantly from a ground-mounted system due to the higher energy yield (ESMAP & SERIS, 2018). The

LCOE comparison between a 50 MWp ground-mounted system and a FPV system at different discount rates is shown in Table 5.

Table 5. Levelized cost of electricity comparison between a 50 MWp ground-mounted PV system and floating PV system (ESMAP & SERIS, 2018)

Dam/Reservoir	Ground-mounted PV (fixed tilt)	Floating PV (fixed tilt)
Electricity produced first year (GWh)	75.8	79.6*
Increase in performance from ground-mounted fixed tilt		5%*
LCOE ($/MWh)		
At 7% discount rate (base case)	50	56
At 8% discount rate	52	57
At 10% discount rate	54	60

* These numbers were taken from ESMAP & SERIS's compilation of 50 MWp system, both ground-mounted and floating solar.

Assuming the Da Mi proposed project cost was the price in 2017 and the cost trend predicted from IRENA for utility-ground-mounted PV (IRENA, 2016; IRENA, 2017), the cost of the FPV system by 2025 is forecasted to be $0.70/W, which is approximately 90% of the 2017 contract cost ($37 million) of the Da Mi project and closely matched the IRENA PV projects forecast (without inverters) of $0.75/W.

The price for each component is calculated individually and combined to compare with Mr. Gabisch's suggested system cost. Figure E-1 shows the global average selling prices for Chinese Tier 1 crystalline silicon modules. By 2022, the high case scenario shows the cost for modules to be $0.28/Wp, while the average case cost is $0.22/Wp. The balance of system (BOS) costs and installation cost comprises of the remaining costs of a PV system, including the inverter, mounting and racking of PV system, combiner boxes and miscellaneous electrical component, site preparation and installation, system design, management, permit fees, supply chain, any up-front financing costs and other overhead. The representative module cost of a standard utility-scale ground-mounted system is roughly 40-50% of the entire system cost between 2016 and mid-2019 in the United States (Solar Energy Industries Association, 2019). As shown in Figure E-2, central standalone inverters are projected to cost roughly \$0.05/Wac, and three-phase string inverters are projected to cost \$0.12/Wac in 2022. Combining all the necessary hardware of a solar PV system (the panels and the BOS), the 2022 total system cost to install Chinese Tier-1 crystalline-silicon modules (using the higher end of the panel cost, \$0.28/W, and assuming this makes up the 40% of the project cost) can be up to \$0.70/W, exactly matching IRENA delineated cost of \$0.70/W. This study used \$0.70/W as the capital cost to assess the economic feasibility of the three FPV projects. It should be noted that this cost is still half of the cost in the United States, predicted by RETTEW (Trabish, 2019).

This study also assumed a scalable fixed operation and maintenance (O&M) cost for each of the three FPV systems, at \$24.6/kW/year, which was the input provided by ASEAN Centre for Energy to NREL for solar PV installations in Vietnam (Lee et al., 2019). The 20-year period O&M cost for each system was scaled based on its associated peak power. The transmission cost was assumed to be zero for the case of the Hoa Binh and Tri An reservoirs, at which the hydropower substations were located at shore, near the Hoa Binh and Tri An dams (APPENDIX D). For Dau Tieng Reservoir, the cost of the transmission line was estimated based on the closest 110-kV substation’s distance to the closest shoreline, which was approximately 7 km away. Since there were no available cost data for a 110-kV transmission line in Vietnam in the literature (Table 2), the study assumed a conservative cost estimate for the line based on data for a 220-kV transmission line, at $173,500/km (Maweni & Bisbey, 2016).. The cost was scaled up based on the percentage reservoir coverage. For example, at 1% coverage, the cost of the transmission line is approximately $1.2 million, while at 5% coverage, the cost is $6 million. If the new proposed FIT rate mentioned in Solar Projects Potential is accepted, the rate for Hoa Binh Reservoir will be $0.0944 /kWh. For Tri An Reservoir and Dau Tieng Reservoir, the rate is $0.0728/kWh (Baker Mckenzie, 2019). Payback period results are shown in APPENDIX E. Table 6 is an example of payback period for each reservoir at 1% coverage.

Table 6. Payback period of each reservoir at 1% coverage

	Output (GWh/year)	Variability (GWh/year)	Payback period (years)
Hoa Binh	108	5	9.9
Tri An	430	16	9.8
Dau Tieng	376	11	9.7

An example of the payback period (years), calculated based on Equation (6) for the Hoa Binh Reservoir FPV system that covers 1% of the reservoir with 96,240 kWp and generates yearly average 108,000,000 kWh, is shown below:

$$Payback = \frac{\frac{\$0.7}{W} * \frac{1000W}{kW} * 96{,}240\ kW}{90\% \times 108{,}000{,}000 \frac{kWh}{year} * \frac{\$0.09444}{kWh} - \frac{\$24.6}{kW} \times 96{,}240\ kWp}$$

$$= 9.9\ years$$

The simple payback periods for all the systems are roughly 10 years, regardless of the percentage of area cover. Dau Tieng project has a slightly lower payback period, 2 months earlier than Hoa Binh Reservoir, which has the highest payback period. Tri An Reservoir has the highest yearly revenue due to the bigger system peak power (kWp) and the high solar potential (kWh/kWp).

The capital cost result can be compared to various economic feasibility study as shown in Table 7. The capital cost of the project is low, compared to other projects, partially because of the delineated FPV capital cost in Vietnam in 2025, instead of using data from the current year.

Table 7. Capital cost of 1MW floating solar PV projects globally, retrieved from feasibility study

Study	Location	Capital cost ($)
1MW of Hoa Binh Reservoir	Hoa Binh, Vietnam	$ 700,000
Singh et al. (2017)	Pondicherry, India	$ 800,000
Song & Choi (2016)	Gangwon Province, South Korea	$ 900,000
Rosa-Clot, et al. (2017)	Adelaide, Australia	$ 990,000

Using Equation 7, the LCOE for all FPV systems in 2025 were calculated to be approximately $73.3/MWh for Hoa Binh Reservoir (Table E- 4), $56.0/MWh for Tri An reservoir (Table E- 5), and $55.7/MWh for Dau Tieng reservoir (Table E- 6). According to NREL, the lowest LCOE value for the Southeast Asia region, also the minimum for Vietnam, is $64/MWh (Lee et al., 2019). However, this study’s LCOEs are still approximately 35% lower than the results from the Renewable Energy Data Explorer, an NREL interactive software package, under the Moderate Technical Potential Scenario, at

6% interest and 82.5% debt-to-equity ratio (NREL, 2019). For Hoa Binh Province, in which Hoa Binh Reservoir is located, the LCOE for the system is $119/MWh. In the Dong Nai and Binh Duong provinces where the Tri An and Dau Tieng reservoirs are located, respectively, the LCOE is $88.4/MW (NREL, 2019). The LCOEs of FPV systems in this study are comparable with those used by ESMAP & SERIS (2018). At a 7% annual discount rate, the global average of LCOE of FPV was $56/MWh (ESMAP & SERIS, 2018). However, this number only indicated the global average, not the values for specific locations as in the NREL analysis. The total PV output (kWh), the total installed cost ($), and the payback period (years) for each scenario were calculated and shown in APPENDIX E.

Overall, the economic viability analysis demonstrates that FPV has the potential to be expanded in the next five to ten years as a leading renewable technology in Vietnam.

Environmental feasibility

The environmental impact of renewable energy infrastructure is being studied more intensively to quantify the holistic benefits of such systems. One of the most pronounced benefits of solar PV system is the avoided emission compared to the emission from fossil fuel plants. In addition, in regions that facing land scarcity and water, FPV proves as a prominent solution as it utilizes the water surface and reduces evaporation due to heat. With the government’s PDP 7 plan of continuing the construction of coal-fired power plant, FPV poses as an alternative that not only will help the country meets its national energy demand, but also provides more water for other purposes.

In 2016, the total capacity of 14.5 GW of coal-fired power plants in Vietnam provided roughly 34.3% of total electricity supply, or 61,000 GWh of electrical energy. In 2020, 131,000 GWh of electricity is expected to be produced from 26 GW of coal-fired power plants, 4,400 GWh from 9 GW of natural gas plant (The Socialist Republic of Vietnam, 2016). By displacing new fossil fuel connecting the grid, FPV will help reduce the emissions of the Vietnam electricity grid. Assuming the grid mix in 2025 is almost the same as 2017 emission, the emission factor (thousand tCO_2e/MWh) of the 2025 grid were calculated following Equation 7. The grid emissions avoided by FPV at each reservoir for different coverage scenarios are shown in Table F- 2. If all the reservoirs in this study are all 15% covered with FPV, they will produce 13,700 GWh per year, or 8.6% of all the planned additional coal-powered plant productions and help avoided 11 million metric tons CO_2e. To put this number into perspective, using the Rosenfield number as “the electricity savings of 3,000 GWh per year, the amount needed to replace the annual generation of a 500 MW coal-fired power plant”, the coal-fired power plant avoided capacity is 2.3 GW (Chao, 2010).

The evaporation reduction benefits are shown in Table G- 4, Table G- 6, and Table G- 8 with variables calculated based on equations (9) through (15). Tri An Reservoir FPV has twice the reduction potential in cubic meters of water (m^3) per year than Hoa Binh Reservoir due to its three-times-larger area. However, the evaporation savings (m^3) per FPV area (m^2) of Hoa Binh Reservoir is 20% higher than Tri An Reservoir. Dau Tieng Reservoir has a slightly lower evaporation quantity than Tri An Reservoir. The water saved from evaporation can be utilized for various purposes such as drinking and irrigating. The estimated evaporation rate in artificial reservoirs in Vietnam in 2011 totalled 1.36 km^3/ year (United Nations Food and Agriculture Organization - UNFAO, 2011). The evaporation reduction from the three reservoirs with FPV projects (assuming that 15% coverage or 91.28 km^2 of FPV area) will be approximately 119 million m^3/year, 0.119 km^3 per year, or 8.7% of the estimated total 2011 evaporation losses. Comparison with different literature is shown in Table 8. If the amount suggested by Santafe et al. (2014) for a reservoir in Spain was scaled up, Hoa Binh amount of evaporation is 56% higher than Santafe et al. (2014). Compared with the reservoirs studied in South Australia (Rosa-Clot, Tina, & Nizetic, 2017), the result of the study is 3% lower. According to project WATCH (Water and Global Change) with more than 25 institutions in European countries taking part in, the 15-year evaporation average for Vietnam from 1985 to 1999 for each month is in the range of 40 to 130 mm (Centre for Ecology & Hydrology, n.d). This range is compatible with the result of the study which is in the range of 75 to 170 mm per month.

Table 8. Evaporation savings comparison among study

Study	Location	FPV areas (m^2)	Evaporation savings (m^3/year)	Evaporation savings (m^3) per unit area (m^2) per year
Hoa Binh Reservoir 1% cover	Vietnam	910,000	1,587,000	1.74
Tri An Reservoir 1% cover	Vietnam	2,770,000	3,981,000	1.44
Dau Tieng Reservoir 1% cover	Vietnam	2,400,000	3,536,000	1.47
Santafe, et al. (2014)	Spain	4,500	5,000	1.11
Rosa-Clot et al. (2017)	Australia	69,000	124,000	1.80

To put the savings into perspective, in Asia, according to United Nations Population Fund, a household use 95 liters per person per day (2002). Binh Duong province, in which Dau Tieng Reservoir belongs to, has a population of 2 million people in 2017 (General Statistics Office of Vietnam, 2017b). The water saved from Dau Tieng's evaporation per year at 15% reservoir coverage can be used to provide drinking water for this population for approximately 9 months. The water withdrawal rates for agriculture purposes is between 15,000 and 35,000 m^3/ha/year (UNFAO, 2011). Using an average of 25,000 m^3/ha/year, if use for irrigation, the evaporation savings from all three reservoirs at 15% cover can provide water up to 5,440 ha of land in a year. According to The World Bank, in 2016, Vietnam had 12 million ha of agricultural land (The World Bank, 2016). To put this into perspective, the water saved from evaporation can irrigate 0.05% of Vietnam's agricultural land per year.

In addition, based on each dam's effective head, the water saved can increase the energy output of the hydropower-FPV combined facility. Using Equation 15, the theoretical additional output associated with water saving for Hoa Binh Reservoir ranges from 0.4 to 5.3 GWh or 0.33% of Hoa Binh's total PV output, and for Tri An Reservoir range from 0.4 to 6.4 GWh or 0.11% of Tri An's total PV output.

The environmental effect of the FPV on wildlife currently has not received system-wide assessment. Literatures on wildlife activities along with floating structures in tropical reservoirs are scarce. According to Mr. Nguyen Huu Phuoc, deputy manager of forest service department at Dong Nai National Reserve, there are various aquatic life on Tri An Reservoir and 72 different islands used as agriculture land and tourism (VTV3 Vui Song Moi Ngay, 2014). The Reservoir is home for a variety of fish species, including marble goby (*Oxyeleotris marmorata* Bleeker), silver carp (*Hypophthalmichthys molitrix*), bighead carp (*Aristichthys nobilis*), common carp (*Cyprinus carpio*) and grass carp (*Ctenopharyngodon idella*). There is an abundant of food resources for the fish such as phytoplankton, benthos, detritus, small wild fish and prawns (Luong, Yi, & Lin, 2005). On Hoa Binh reservoir, in 2018, 4,000 fish cages were reported. The reservoir produced approximately 1 thousand tons of captured fish and 3 thousand tons of cultured fish (The Socialist Republic of Vietnam Ministry of Agriculture and Rural Development, 2018). There are studies that compared the difference between artificial structures and natural habitat, with contradictory results. However, currently, there are limited studies on the effects of artificial shading, especially from novel structures such as FPV, on tropical freshwater fish species. Helfman (1982) pointed out that fish are attracted to floating or hanging structures because they give the fish advantages over predators, mostly seen in pelagic species. More studies needed to be done in each individual reservoir in the study to ensure the species natural habitat are not threatened by the installation of a floating structures.

Sensitivity analysis

The feasibility of FPV depends on a range of factors that were studied in this work. There is uncertainty in assumptions for these that ultimately affect the analyses of PV output, economic feasibility, GHG emissions, and evaporation savings. Sensitivity analyses were conducted to assess the influence of the main factors: variation in PV output, project capital cost cost, O&M cost, and discount rate**,** on each of the reservoirs' FPV system associated payback period and LCOE. I first assessed the variation and uncetainties in PV output. Then, I assessed the changes in payback period and LCOE based on the main factors, gathered from Vietnam's historical, current and forecasted data. The uncertainties in evaporation savings were addressed last.

Payback period and LCOE assumption, and sensititivity analysis

In technical analysis of this study, the output was determined based on PVGIS 5 assumptions. The lake coverage was assumed at 1%, 5%, 10%, and 15%. The coverage percentage was conservative. Projects by Ciel & Terre, a leading floating solar developer in the world, usually cover 30% to 60% of the water surface (n.d). The solar panels had the same technical specification as the panels from the Da Mi's project, the lake coverage was 164% of the area of the panels, and system loss was 14%. There was number of effects that would influence the estimated energy output but were not considered in the calculation, including dust and dirt in the area and partial shadowing. The solar radiation data used in the study was available in 6-km resolution. The shapes of the reservoirs were digitized or traced at the zoomed-out 5-km resolution, using Google Earth Pro. The granularity of PV output data is at monthly average and yearly variation. These model assumptions, containing uncertainties and inaccuracies ultimately affect the actual output of solar panels.

A comparison between output of the reservoirs using the same system peak power, 96,000 kWp (Hoa Binh reservoir’s peak power at 1%), showed that production at Tri An and Dau Tieng reservoir are 31% higher than Hoa Binh reservoir’s production. The higher FIT in draft was supposed to incentivize solar investment in less sunny parts of the country, however as seen in Table 9, the payback period of the southern reservoirs (Tri An and Dau Tieng) have almost two years less simple payback period than Hoa Binh. This is because Tri An and Dau Tieng Reservoir are geographically close together or have a small difference in latitude, thus sharing more commonality in solar radiation and temperature characteristic (see APPENDIX C). The annual GHI solar resources at these two southern reservoirs are approximately 50% higher than Hoa Binh Reservoir (Table 3). Table 9 demonstrates the production, output variation or standard deviation, and payback period of each project, using the same peak power at appoximately 96,000 kWp.

Table 9. Output using the same 96,240 kWp FPV system capacity between three study reservoirs. Variability is the standard deviation of energy generation

	Output (GWh/year)	Variability (GWh/year)	Payback period (years)
Hoa Binh	108	5.0	9.9
Tri An	141	5.4	7.0
Dau Tieng	143	4.2	7.0

Other sensitivity analysis for the payback period and LCOE was conducted based on the historical solar output, PVGIS5 variability, and project's capital cost to assess different possible economic outcomes. Scenario 1 is the output from the broad 30% addition to the PVGIS 5 output based on the actual output difference of the Solar Park farm in California. The Solar Park farm has a capacity of 747.3 MWp and 579 MW_{AC}, with system losses of 22% that produced an average 1,685 GWh per year in 2017-2018 (SunPower, 2016; EIA (US Energy Information & Administration), 2019a; EIA, 2019b). This output was approximately 30% higher than the prediction from PVGIS 5 tool, using the same location. Scenario 2 is the output from adding PVGIS 5 variability for each reservoir, as shown in Table C- 2,Table C- 3, and Table C- 4. Scenario 3 is the output from subtracting PVGIS 5 variability. The next two scenarios, Scenario 4 and Scenario 5, show changes in the project cost, instead of PV output. Scenario 4 shows the 43% decrease in project price to $0.4/W, which aligned with Figure E- 1 delineated costs in 2022 for the medium scenario for a Chinese Tier 1 crystalline silicon modules and inverters. Scenario 5 shows an increase in project price, from $0.7/W to $1/W, a 43% increase. Scenario 6 demonstrates the increase of system losses to 20% from the 14%

baseline. Scenario 7 has a system loss of 8%. APPENDIX E shows the PV output variability (standard deviation of the energy generation) between the Scenarios 1, 2 and 3. Scenario 8 uses a lower 5% discount rate, projected by Trading Economics by 2020 (Trading Economics, n.d (a)). Scenario 9 shows the increase to 7% discount rate, based on Vietnam's average discount rate from 2000 to 2019 (ESMAP & SERIS, 2018; Trading Economics, n.d (a)). Scenario 10 uses an O&M cost at $12/kW, approximately half of the cost used in this study and close to the O&M cost for utility ground-mounted solar in the United States at 13/kW/year (Fu et al., 2018). Scenario 11 demonstrates the O&M cost at $6/kW/year, based on the cost suggested by M.Gabisch for Da Mi project, $300,000 per year, or $6.3/kW/year (M.Gabisch, personal communication, May 25th, 2019). Table 10 provides a summary of all the sensitivity scenarios. Figure 13 shows the simple payback period and LCOE for all the scenarios.

Table 10. Summary of the sensitivity scenarios

	Scenario description
Scenario 1	Increases the PV output by 30%
Scenario 2	Adds the PVGIS5 output variability (standard deviation)
Scenario 3	Subtracts the PVGIS5 output variability (standard deviation)
Scenario 4	Decreases the project price to \$0.4/W
Scenario 5	Increases the project price to \$1/W
Scenario 6	Increases the system losses to 20%
Scenario 7	Decreases the system losses to 8%
Scenario 8	Decreases the discount rate to 5%
Scenario 9	Increases the discount rate to 6%
Scenario 10	Decreases the O&M cost to \$12/kW/year
Scenario 11	Decreases the O&M cost to \$6/kW/year

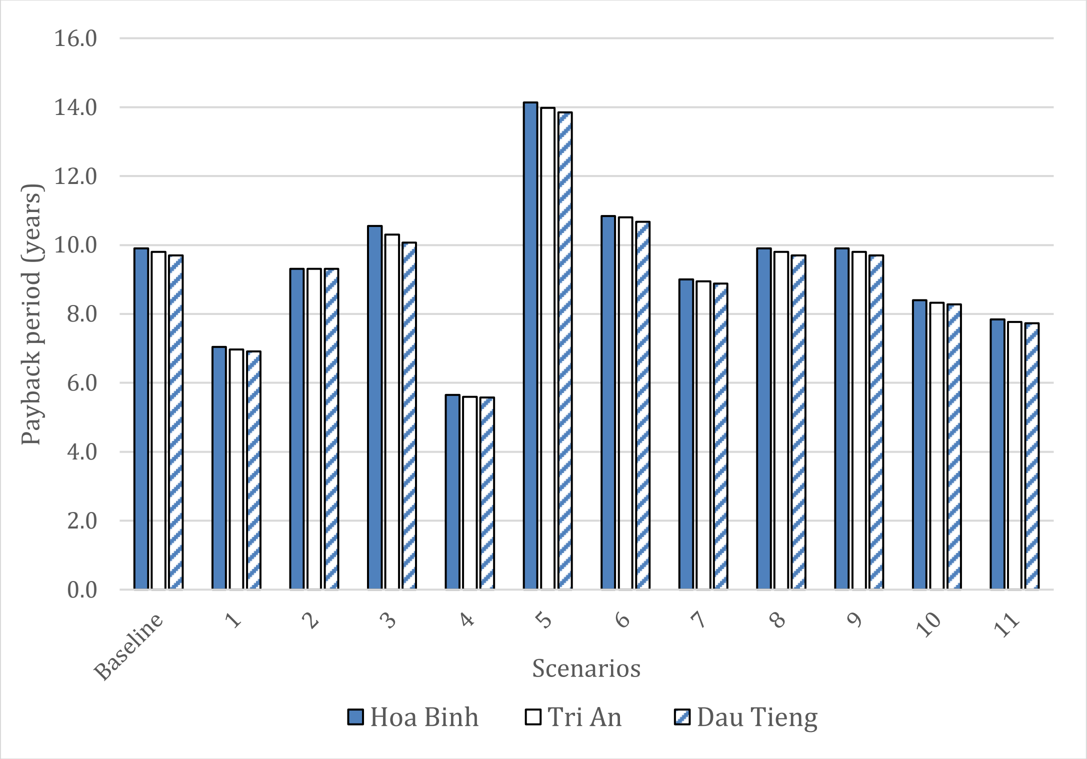

Figure 13. Payback period with sensitivity analysis. The baseline is the model this study used. Scenario 1 is the result from adding 30% to the PVGIS 5 output. Scenario 2 is the result of adding PVGIS 5 variability to each reservoir's listed PV output. Scenario 3 is the result of subtracting PVGIS 5 variability. Scenario 4 has a project cost of $0.4/W. Scenario 5 shows the increase of project cost to $1/W. Scenarios 6 and 7 have system losses of 20% and 8%, respectively. Scenario 8 and 9 shows the payback period at 5% and 7% discount rate that is the same as the baseline scenario. Scenario 10 and 11 demonstrate the lower O&M cost, $12/kW/year and $6/kW/year, respectively

The simple payback period ranges from 6 to 14 years for all the projects. The factors that introduce the most sensitivity are the capital cost, followed by additional 30% yearly output, and the O&M cost. The payback period for Scenario 1, in which the result contained the additional 30% PVGIS 5 original PV output, was approximately two years shorter than the baseline. For Scenario 2, where PVGIS variability was added, the payback period was close to the base case, ± half a year. The payback periods for

Scenario 2 for three reservoirs were close together, instead of a distinguished different among the reservoirs. However, in Scenario 3, when the PV output decreases, the payback period slope among the reservoirs gets bigger, showing more discrepancy between their payback periods. This is because of the southern projects' bigger system size with higher PV output variability or standard deviation in energy generation. Even though the FIT for the two southern reservoirs is 30% lower than Hoa Binh, the northern reservoir, the increase in PV output of the southern reservoirs make them an economic match for the northern FPV project. The system losses did not change the payback period significantly. The changes in project cost significantly alter the payback period, which is the same as saying that the payback period is highly sensitive to the project cost assumptions (Scenario 4 and 5). The payback period of all projects increases to 14 years with 43% higher cost, while the it decreases to approximately 6 years with 43% lower cost, showing the payback period is influenced tremendously by the project capital cost. In other words, the payback period is most sensitive to changes in capital costs in this study.

In LCOE analysis, the study used a constant interest rate of 6%, with the O&M cost assumed unchanged throughout the lifetime of the system. The LCOE was calculated under the assumption that there is no economy of scale. Due to the recent investment in FPV, there are not yet credible data on the CAPEX of the systems. However, as more FPV systems are installed across the globe, these data would potentially become available (World Bank Group, ESMAP & SERIS, 2018). Figure 14 demonsrates the LCOE for all the scenarios previously used for payback period calculations.

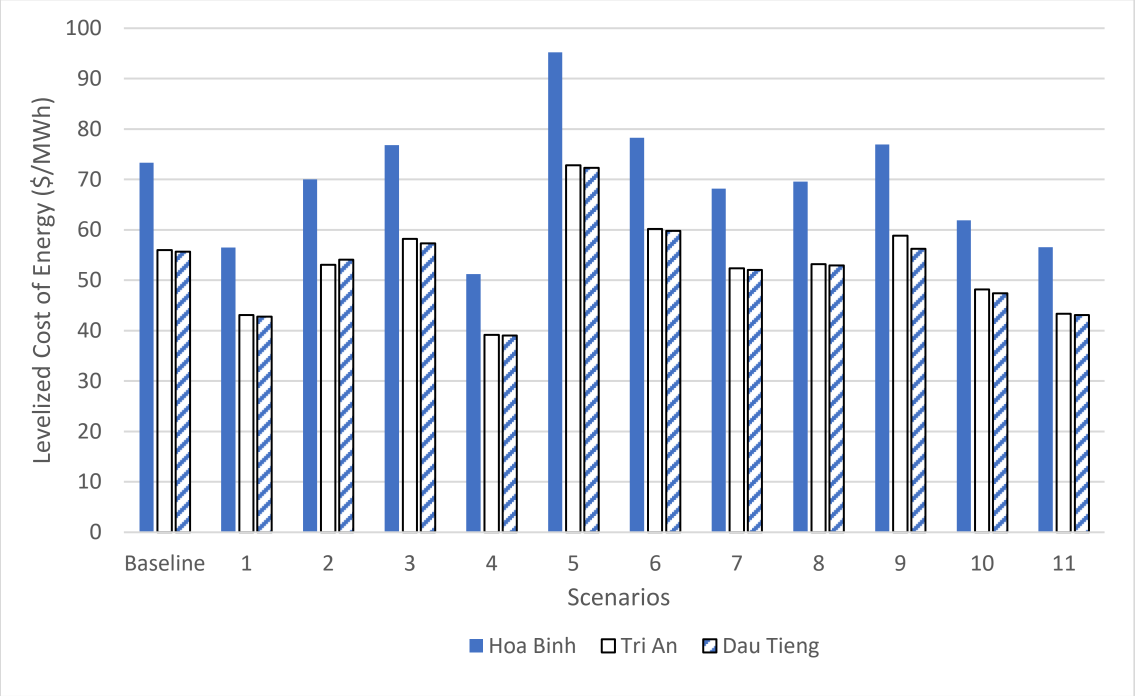

Figure 14. Levelized cost of energy (LCOE) with sensitivity analysis. The baseline is the model this study used. Scenario 1 is the result from adding 30% to the PVGIS 5 output. Scenario 2 is the result from adding PVGIS 5 variability for each reservoir. Scenario 3 is the result from subtracting PVGIS 5 variability. All these three scenarios have the same LCOE as the baseline because the PV output does not affect the system cost. This is also the case for Scenarios 6 and 7 that have system losses of 20% and 8%, respectively. Scenario 4 has the project cost of $0.4/W. Scenario 5 shows the increase of project cost to $1/W. Scenario 8 and 9 shows the payback period at 5% and 7% discount rate that is the same as the baseline scenario. Scenario 10 and 11 demonstrate the lower O&M cost, $12/kW/year and $6/kW/year, respectively.

The LCOE for the Hoa Binh Reservoir FPV system ranges from $50 to $95/MWh, while the LCOE for the Tri An and Dau Tieng reservoir FPV systems ranges from $40 to $70/MWh. Even though the payback periods of all the FPV systems are within proximity, there is at least a $10/MWh discrepancy between the northern reservoir Hoa Binh, and the southern reservoirs, Tri An and Dau Tieng. This study’s smaller system size for the Hoa Binh FPV compared to the other two FPV systems and its higher

FIT tariff rate compensated for its lower output in the payback period analysis. As shown in Table 9, if the FPV system size is the same among all the three reservoirs, the payback period of Tri An and Dau Tieng reservoirs are approximately two years less than the payback period for the Hoa Binh Reservoir. As seen in Figure 14, LCOE is the most sensitive to the capital cost of the system, similar to the payback period sensitivity result. Scenario 4, in which the capital cost is reduced to $0.4/W, has the lowest LCOE, while Scenario 5, with the capital cost of $1/W, has the highest LCOE. LCOE is also sensitive to O&M cost, with a cost reduction of 15 to 20% compared to the baseline case, if the O&M cost declines by half to one-fourth of the baseline cost. If the PV output of all projects improves or declines by 1%, the LCOE is also changed approximately 0.8%, accordingly.

The FIT rate was kept static in all the scenarios. However, it can play an important role in project developers' investment choice. With every $0.10/kWh change in FIT rate for each location, the simple payback period changes by approximately one and a half years. The higher FIT in the Northern region of Vietnam helps compensate for the higher LCOE cost or lower energy production of the Hoa Binh project, shown in the almost similar payback periods between the reservoirs. As of 2014, the LCOE of other renewable projects, such as hydropower at $44/MWh and biomass at $88/MWh, were one-fourth and half-lower than the solar LCOE, at average $220/MWh in Southeast Asia (ASEAN Center for Energy, 2016). With lower O&M costs (Scenario 10 and 11), projects at Tri An and Dau Tieng can be comparable with the cost of hydropower projects that are already installed. The projected LCOEs in all the scenarios and Da Mi project's

$50/MWh (using $37 million capital investment, $6/kW/year, and 5% discount rate) surpass the average LCOE of combined cycle power plants in Southeast Asia, at $113/MWh in 2014 (ASEAN Center for Energy, 2016). Even though there is uncertainty in the future cost of fossil fuel, FPV has already shown the potential to replace future fossil fuel plants with a low future cost.

Environmental analysis assumption and sensitivity analysis

For environmental assessment, there are various assumptions made to calculate GHG emission and evaporation savings.

First, the GHG emission avoided was based on the national grid mix emission. Currently, there is no available data at the level of regional emission to compare with the national emission. In addition, the grid mix emission factor is not yet quantified for 2035.

Secondly, the equation used to quantify evaporation was a simplified model of Penman-Monteith equation, leading to some discrepancy in model output. However, Valiantzas (2006) stated that the difference between Penman-Monteith models was negligible when tested on other case studies. Windspeed data was assumed based on the mean wind data from DTU Wind Energy and The World Bank Group’s Global Wind Atlas at 50 meters above ground and extrapolated to 2 meters for the total year. However, this yearly windspeed was used to calculate evaporation for each month, thus leading to monthly inaccuracies. The evaporation losses underneath the solar panels were also not factored in in the study.

Sensitivity analysis with regards to the effect of wind on evaporation was conducted. According to DTU Wind Energy & The World Bank Group (n.d (b)), there are uncertainties associated with the windspeed. The validation between Global Wind Atlas and wind flow modeling software WAsP, currently performed in Vietnam, showed an approximate 20% higher mean wind speed value in Global Wind Atlas. Decreasing the mean windpeed by 20% shows a 2 to 3% decrease in evaporation savings. It should be noted that the temperature and relative humidity used were historical weather data in the region, not direct reservoir's measurements. These data do not necessarily reflect the accuracy of the current and future data. This level of analysis is currently out of the scope of this study and should be addressed through actual data collection.

DISCUSSION

South Vietnam has 50% higher solar resource (and PV potential) than the North. Even with the proposed higher FIT at $0.0944/kWh for reservoirs in the North, compared to $0.078/kWh for reservoirs in the Central and Southern Vietnam, the payback period and LCOE analyses demonstrate that Dau Tieng and Tri An project is a better investment. If the Vietnamese government is interested in incentivizing more investment in the north, one possible mechanism is to increase the northern FIT rate. If the government's interest aligns more with meeting the energy demand in the future, another alternative is to build more FPV in the southern part of Vietnam and raise the transmission capacity of the grid that connects to the north.

The simple payback period of the projects are in the range of 6 to 14 years, which is still lower than the possible 20 year lifetime of the system. The LCOE of the projects in 2025 are in the range of $40 to $95/MWh, which is 50% lower than NREL's 2019 analysis of PV LCOE in Vietnam for the three provinces that the reservoirs are located in, with the range from $90 to $120/MWh (Lee et al., 2019). If solar project cost continues to decrease (e.g., by 43% by 2025, extrapolated from 2016 analysis of IRENA (2016)), the projected LCOE of the projects in 2025, based on current 2019 NREL data, will be comparable with the predicted cost in this study. The average global FPV cost range of $50 to $60/MWh in 2018, compiled by ESMAP & SERIS (2018), already demonstrated potential of this floating solar system across the globe, and now in Vietnam.

The O&M cost of the system has potential for reduction. If the cost is as low as $6/kW/year as projected by Mr. Gabisch, the simple payback period of each system can be as low as 8 years, similar to the predicted payback period of the Da Mi FPV project (M. Gabisch, personal communication, May 25th, 2019). As more FPV projects are awaiting approval or are already approved by the government (see APPENDIX B), there will be opportunities to learn and potential to reduce O&M along with other costs.

CONCLUSIONS AND RECOMMENDATIONS

All three reservoirs studied, Hoa Binh, Tri An, and Dau Tieng have good PV potential. Dependent on the coverage, the total PV potential of the three systems range from 900 GWh/yr to 13,700 GWh/yr, and capital costs range from $690 to $10,300 million USD and O&M cost from $15 to $240 million USD . Out of all the reservoirs, Tri An reservoir has the highest PV potential but also the highest installed cost if project developers consider using reservoir area coverage from this FPV feasibility study. For all levels of coverage, the payback period of all the reservoirs are approximately 10 years, with Dau Tieng reservoir being the fastest payback. The payback period can be as fast as 6 years, and as slow as 14 years. The LCOE of Hoa Binh, Tri An, and Dau Tieng projects are $73.3/MWh, $56/MWh, and $55.7/MWh, respectively. However, sensitivity analysis shows that LCOE for Hoa Binh Reservoir's FPV system can range from $50 to $95/MWh, while the other two reservoirs' LCOE ranges from $40 to $70/MWh. The LCOE of FPV project on Hoa Binh Reservoir are generally 25% higher than those on Tri An and Dau Tieng reservoirs. Even with the added cost of transmission lines, Dau Tieng FPV project still proves as having the fastest payback period, and lowest LCOE. Payback period and LCOE are the most sensitive to the capital cost, then the PV output and the O&M cost.

If 15% of all the three reservoirs are covered with FPV, these systems would be able to supply about 4% of Vietnam's 2025 energy demand. At 15% total coverage, the avoided emissions would total approximately 11 million metric tons of CO_2e per year.

This coverage can save 136 million m^3 of water annually that can be used for irrigation for up to 0.04% of Vietnam’s total agricultural land. The water saved from evaporation at Dau Tieng can provide Binh Duong Province drinking water for 9 months. The additional hydropower output associated with water saving for the each hydropower reservoir, Hoa Binh and Tri An, can range from 0.4 to 6.4 GWh, dependent on coverage. Future work should explore more the cost of FPV in Asia after more deployment of FPV in order to predict the cost of FPV projects in Vietnam more accurately.

Several assumptions were used to calculate the output, such as generation assumption from the software that used 14% system losses and solar radiation data from 2005 to 2016, static interest rate of 6%, high O&M costs, and static weather data such as temperature and windspeed based on historical trend. Each assumption should be further studied with field data collection and conversation with experts to get more accurate data. There are also various literature gaps, mostly the environmental impact of FPV on the ecosystems and human physical and social activities, that needed more attention, more survey and field study.

With all the benefits analyzed in this study and more than 7,000 reservoirs potential that is not yet explored, FPV is a great solution for displacing fossil fuel resources and utilizing the existing water body. It is also an attractive investment for Vietnam and the world to propel towards an sustainable path.

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APPENDIX A. ELECTRICITY VIETNAM (EVN) STRUCTURE

Appendix A shows the structure of Electricity Vietnam (EVN) (Figure A- 1), the tariff determination structure (Figure A- 2), and the power and transmission distribution lines that EVN owns (Figure A- 3).

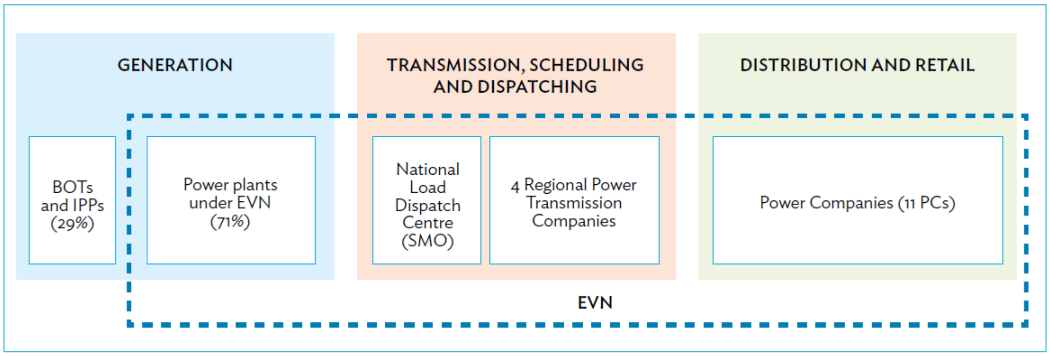


Figure A- 1. Vietnam Electricity structure as of 2015 (ADB,2015). BOTs are Build, Operate and Transfer power plant, and IPPs are Individual Power Producers

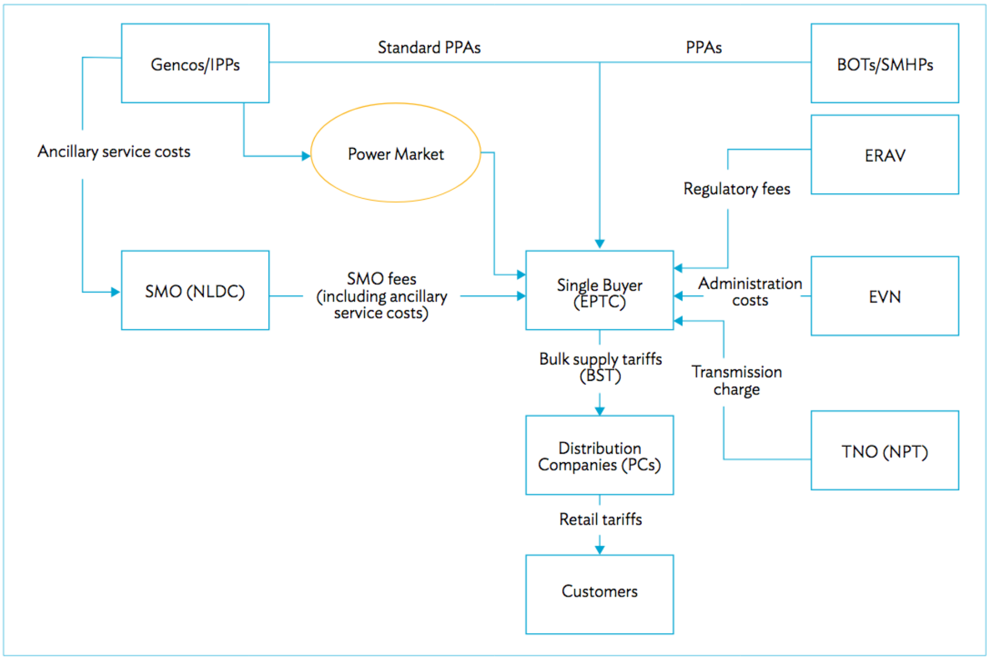
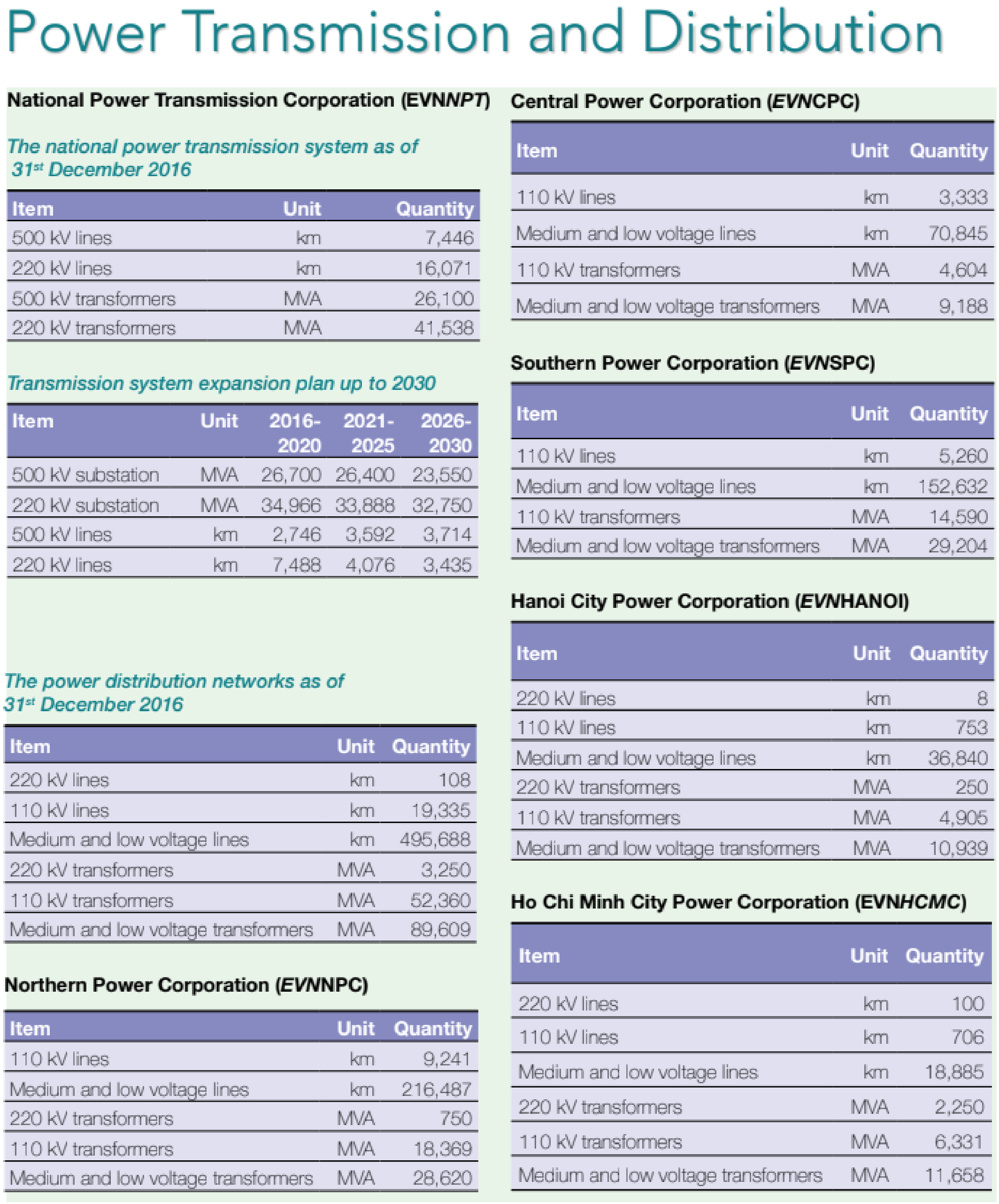


Figure A- 2. Electricity Tariffs determination structure (ADB, 2015). BOT is the Build, Operate and Transfer power plant, EPTC is the Electricity Power Tranding Company, ERAV is the Electricity Regulatory Authority fo Vietnam, GENCO is the generating company, IPP is the independent power producer, NLDC is the National Load Dispatch Center, NPT is the National Power Transmission Corpotation, PPAs is the power purchase agreements, SB is the single buyer, SMHP is the strategic multipurpose hydropower plant, SMO is the System Market Operator, and TNO is the Transmission Network Owner. The Single Buyer currently is EVN who purchases power and other ancillary services through PPAs with BOTs and GENCOs. Other costs such as regulatory fees from ERAV, admistration and transmission costs are then passed down to customers through retail tariffs.



Power Transmission and Distribution

National Power Transmission Corporation (EVN*NPT*)

The national power transmission system as of 31st December 2016

Item	Unit	Quantity
500 kV lines	km	7,446
220 kV lines	km	16,071
500 kV transformers	MVA	26,100
220 kV transformers	MVA	41,538

Transmission system expansion plan up to 2030

Item	Unit	2016-2020	2021-2025	2026-2030
500 kV substation	MVA	26,700	26,400	23,550
220 kV substation	MVA	34,966	33,888	32,750
500 kV lines	km	2,746	3,592	3,714
220 kV lines	km	7,488	4,076	3,435

The power distribution networks as of 31st December 2016

Item	Unit	Quantity
220 kV lines	km	108
110 kV lines	km	19,335
Medium and low voltage lines	km	495,688
220 kV transformers	MVA	3,250
110 kV transformers	MVA	52,360
Medium and low voltage transformers	MVA	89,609

Northern Power Corporation (*EVN*NPC)

Item	Unit	Quantity
110 kV lines	km	9,241
Medium and low voltage lines	km	216,487
220 kV transformers	MVA	750
110 kV transformers	MVA	18,369
Medium and low voltage transformers	MVA	28,620

Central Power Corporation (*EVN*CPC)

Item	Unit	Quantity
110 kV lines	km	3,333
Medium and low voltage lines	km	70,845
110 kV transformers	MVA	4,604
Medium and low voltage transformers	MVA	9,188

Southern Power Corporation (*EVN*SPC)

Item	Unit	Quantity
110 kV lines	km	5,260
Medium and low voltage lines	km	152,632
110 kV transformers	MVA	14,590
Medium and low voltage transformers	MVA	29,204

Hanoi City Power Corporation (*EVN*HANOI)

Item	Unit	Quantity
220 kV lines	km	8
110 kV lines	km	753
Medium and low voltage lines	km	36,840
220 kV transformers	MVA	250
110 kV transformers	MVA	4,905
Medium and low voltage transformers	MVA	10,939

Ho Chi Minh City Power Corporation (EVN*HCMC*)

Item	Unit	Quantity
220 kV lines	km	100
110 kV lines	km	706
Medium and low voltage lines	km	18,885
220 kV transformers	MVA	2,250
110 kV transformers	MVA	6,331
Medium and low voltage transformers	MVA	11,658

Figure A- 3. EVN's transmission and distribution current state and expansion plan (EVN, 2017)

APPENDIX B. VIETNAM FPV DEVELOPMENT

Appendix B shows the approved and registered floating solar photovoltaic (FPV) projects in Vietnam (Table B- 1 and Table B- 2), a picture of Da Mi FPV project from Google Earth (Figure B- 1), and the Da Mi FPV projects' panels specification (Table B- 3).

Table B- 1. Approved FPV projects in Vietnam (I. Stelter, personal communication, April 23rd)

Project name	Registered DC capacity (MWp)	Province	Commune	Project developer
Da Mi	47.5	Binh Thuan	La Ngau	Da Nhim-Ham Thuan-Da Mi Hydropower JSC
Se San 4	49	Kon Tum	Ia Toi	EVN
Bau Ngu	50	Ninh Thuan	Phuoc Hai	Truong Thanh Investment Development JCS

Table B- 2. Other registered FPV projects in Vietnam (Stelter, personal communication, April 23rd)

Project Name	Registered DC capacity (MWp)	Province	Project Developer
Buon Kuop hydropower reservoir	50	Dak Lak	GENCO 3 (EVN)
Srepok 3 hydropower reservoir	50	Dak Lak	GENCO 3 (EVN)
Vinh Tan	5	Binh Thuan	GENCO 3 (EVN)
Buon Kuop	80	Dak Nong	GENCO 3 (EVN)
Buon Tua Srah	530	Dak Lak	GENCO 3 (EVN)
Dong Nai 4	50	Dak Nong	GENCO 1 (EVN)
Hieu Thien	135	Ninh Thuan	GENCO 3 (EVN)
Ca Ron	150	Ninh Thuan	GENCO 3 (EVN)
Phuoc Huu	131	Ninh Thuan	GENCO 3 (EVN)
Cong Hai	40	Ninh Thuan	GENCO 2 (EVN)
Thac Mo	50	Binh Phuoc	Thac Mo Hydropower JSC.
Quang Tri	30	Quang Tri	GENCO 1 (EVN)
Buon Jong	20	Dak Lak	Tam Duc one-member Ltd. Company
An Khe wetland SPP	43	Quang Ngai	System Technology Ltd. Company
Nuoc Man wetland SPP	43	Quang Ngai	System Technology Ltd. Company

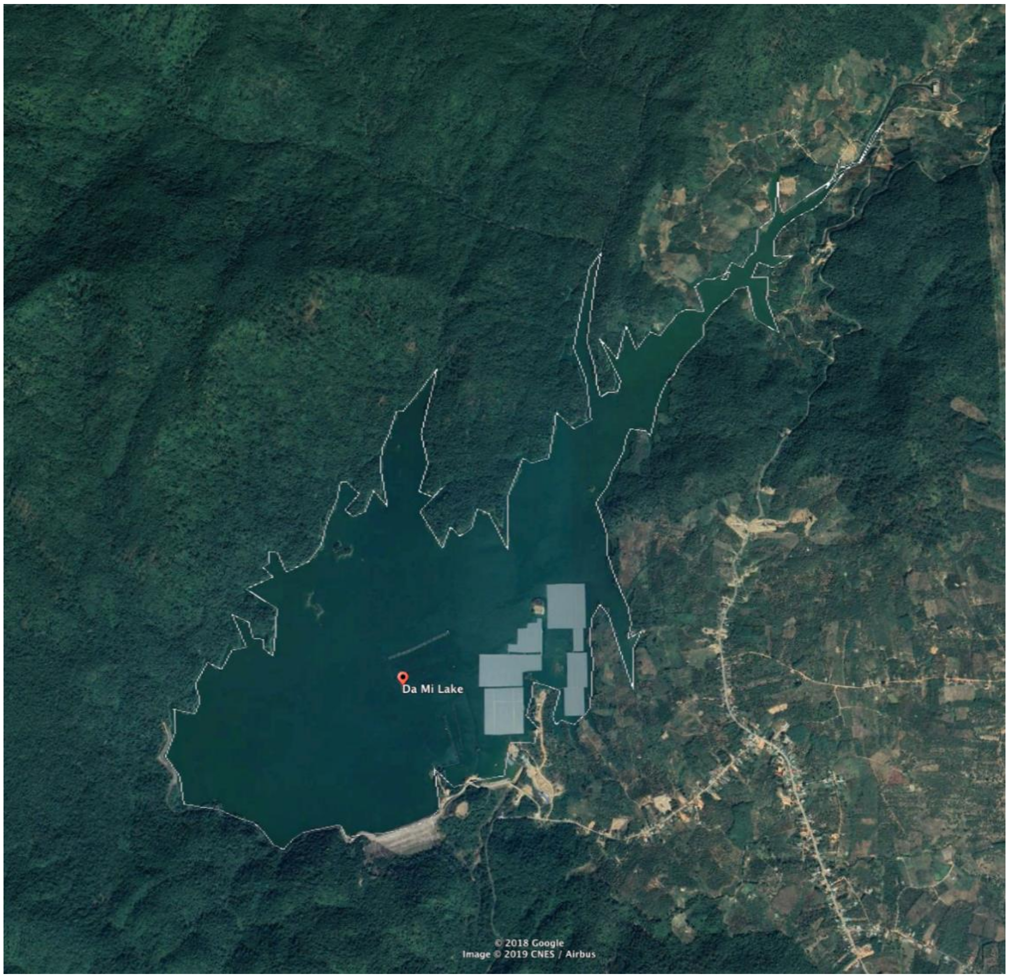


Figure B- 1. Da Mi reservoir area measurement using Google Earth Pro as of August 27th, 2019. (Google Earth, 2019)

Table B- 3. Da Mi project FPV panel specification. (ADB, 2018b)

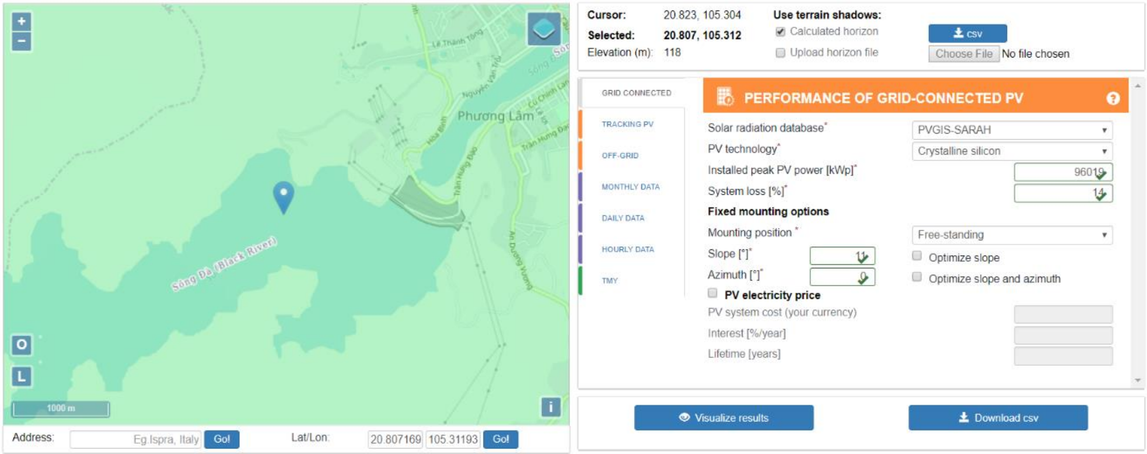
Specification	Value
Type	Single or multi-crystal silicon
Rated capacity (Pmpp)	>330 Wp
Rated voltage (Vmpp)	37.8V
Nominal current (Impp)	8.74A
Open-circuit voltage (Uoc)	46.9V
Short-circuit current (Isc)	9.15A
Conversion efficiency	17%
Range of operating temperature	- 40 °C to 85 °C
Rated current of fuse	15A
Measurement uncertainty of capacity	0-3%
NOCT	45 ± 2°C
Temperature coefficient Pmax	- 0.4%/°C
Temperature coefficient Voc	- 0.3%/°C
Temperature coefficient Isc	- 0.06%/°C
Number of cells	76
Size	1956 x 992 x 40 mm
Weight	26.5 kg
The thickness level of glass cover	4.0 mm, heat resistant
Bracket	Alluminum alloy
Wire box	IP67 Standard
Connecting wire	MC4, 0.9-1.1 mm of length

APPENDIX C. TECHNICAL ANALYSIS – PV OUTPUT

Appendix C shows the geographical location and technical analysis of all the study reservoirs (Table C- 1), an example of PVGIS5 settings (Figure C- 1), examples of PVGIS layout for each of the reservoir at 1% lake coverage (Figure C- 2, Figure C- 3, and Figure C- 4). Figure C- 5 shows Da Mi output at its peak power. Table C- 2, Table C- 3, and Table C- 4 show several parameters used for calculating PV output for each surface coverage percentage.

Table C- 1. Geographical location of Da Mi and the study reservoirs

Reservoir	Latitude	Longitude
Hoa Binh	20.807169	105.311939
Tri An	11.102473	107.089463
Dau Tieng	11.34276	106.3224053
Đa Mi	11.252405	107.8447843



Address: Eg.Ispra, Italy
Lat/Lon: 20.807169 105.31193

Cursor: 20.823, 105.304
Selected: **20.807, 105.312**
Elevation (m): 118

Use terrain shadows:
☑ Calculated horizon
☐ Upload horizon file
No file chosen

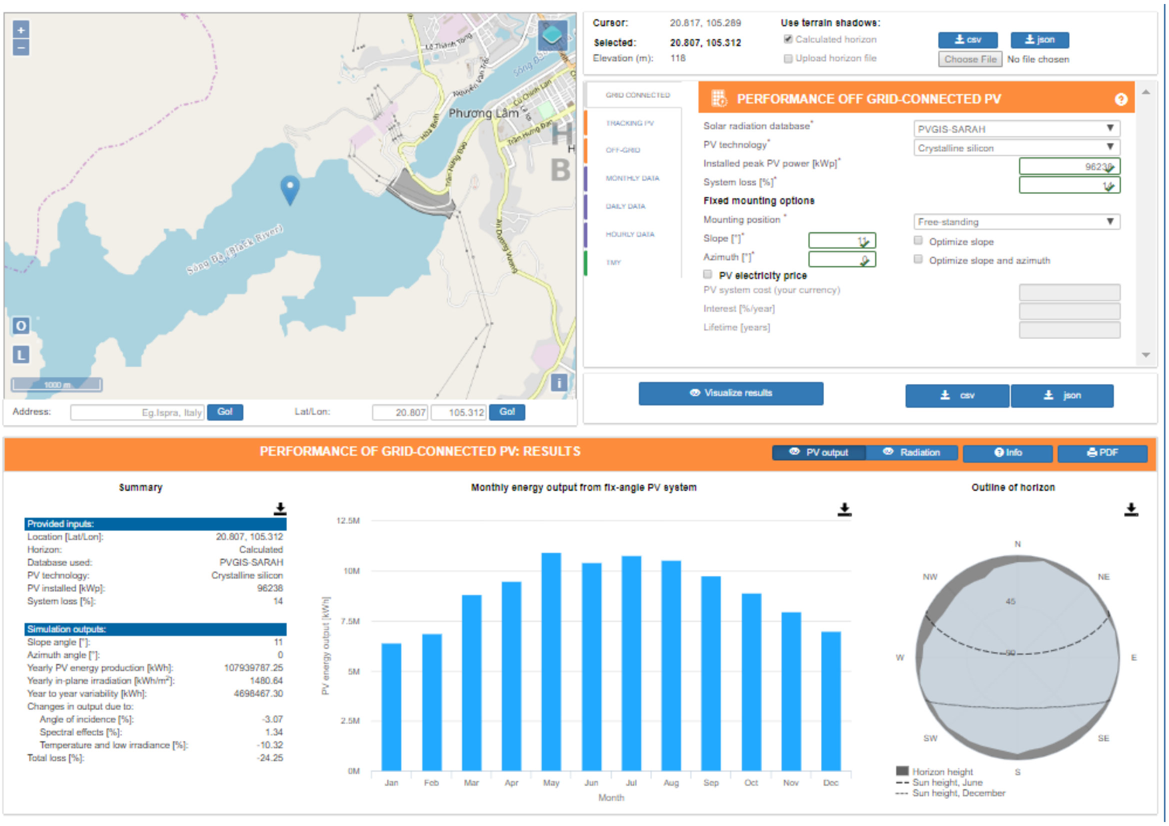
Solar radiation database*: PVGIS-SARAH
PV technology*: Crystalline silicon
Installed peak PV power [kWp]*: 96019
System loss [%]*: 14

Fixed mounting options

Mounting position*: Free-standing
Slope [°]*: 11
☐ Optimize slope
Azimuth [°]*: 0
☐ Optimize slope and azimuth

☐ **PV electricity price**
PV system cost (your currency)
Interest [%/year]
Lifetime [years]

Figure C- 1. Example of PVGIS setting for grid-connected PV as default with PVGIS-SARAH, crystalline silicon PV technology, a specific installed PV peak power, system loss at 14%, free-standing, with panels slope at 11◦, and south-facing or 0◦ azimuth



Cursor: 20.817, 105.289
Selected: 20.807, 105.312
Elevation (m): 118

Use terrain shadows:
☑ Calculated horizon
☐ Upload horizon file

PERFORMANCE OFF GRID-CONNECTED PV

Solar radiation database*: PVGIS-SARAH
PV technology*: Crystalline silicon
Installed peak PV power [kWp]*: 9623
System loss [%]*: 1

Fixed mounting options

Mounting position*: Free-standing
Slope [°]*: 11
Azimuth [°]*: 0
☐ Optimize slope
☐ Optimize slope and azimuth
☐ PV electricity price
PV system cost (your currency)
Interest [%/year]
Lifetime [years]

Address: Eg.Ispra, Italy
Lat/Lon: 20.807 105.312

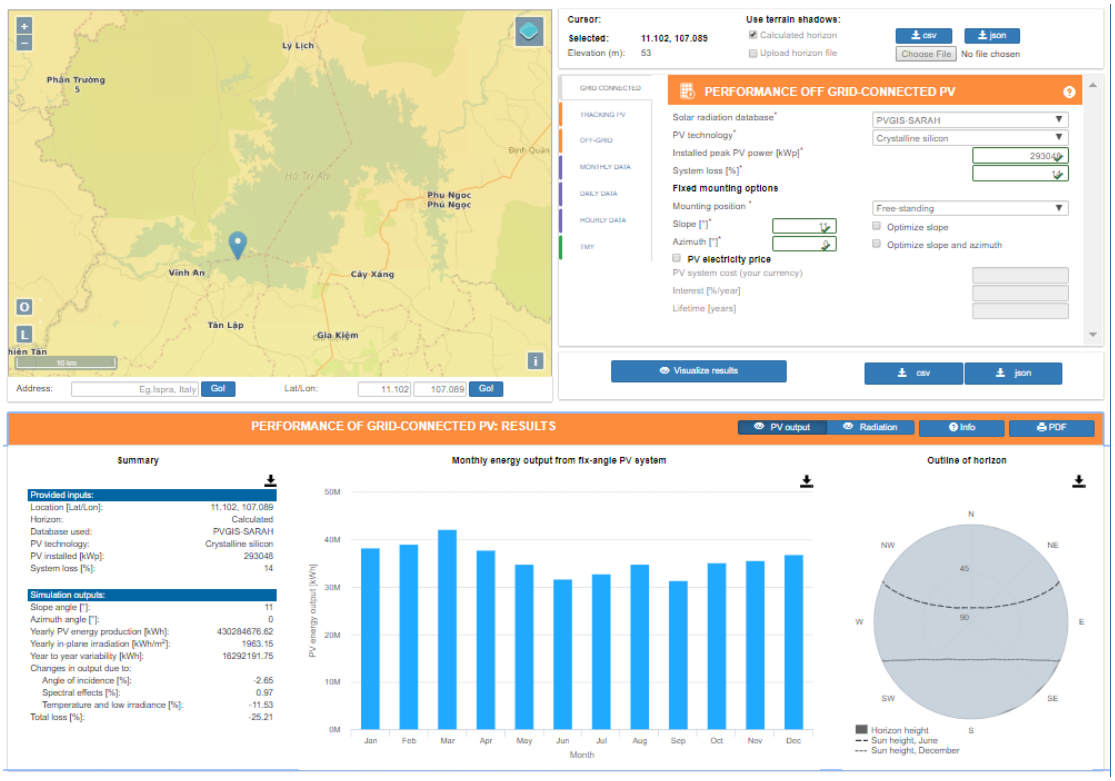
PERFORMANCE OF GRID-CONNECTED PV: RESULTS

Summary

Provided inputs:	
Location [Lat/Lon]:	20.807, 105.312
Horizon:	Calculated
Database used:	PVGIS-SARAH
PV technology:	Crystalline silicon
PV installed [kWp]:	96238
System loss [%]:	14

Simulation outputs:	
Slope angle [°]:	11
Azimuth angle [°]:	0
Yearly PV energy production [kWh]:	107939787.25
Yearly in-plane irradiation [kWh/m^2]:	1480.64
Year to year variability [kWh]:	4698467.30
Changes in output due to:	
Angle of incidence [%]:	-3.07
Spectral effects [%]:	1.34
Temperature and low irradiance [%]:	-10.32
Total loss [%]:	-24.25

Figure C- 2. Hoa Binh reservoir solar output at 1% coverage, showing the reservoir with Open Street map layer. The installed peak power example is 96,239 kWp, the system loss of 14%, free standing mounting position, slope at 11 degree, and azimuth at 0 degree. The output in the summer (May to September) is at average 10 GWh per month and is generally higher than output in the winter, at average 7.5 GWh per month



Cursor:
Selected: 11.102, 107.089
Elevation (m): 53

Use terrain shadows:
☑ Calculated horizon
☐ Upload horizon file

PERFORMANCE OFF GRID-CONNECTED PV

Solar radiation database*: PVGIS-SARAH
PV technology*: Crystalline silicon
Installed peak PV power [kWp]*: 293048
System loss [%]*: 14

Fixed mounting options
Mounting position*: Free-standing
Slope [°]*: 11
Azimuth [°]*: 0
☐ Optimize slope
☐ Optimize slope and azimuth
☐ PV electricity price
PV system cost (your currency)
Interest [%/year]
Lifetime [years]

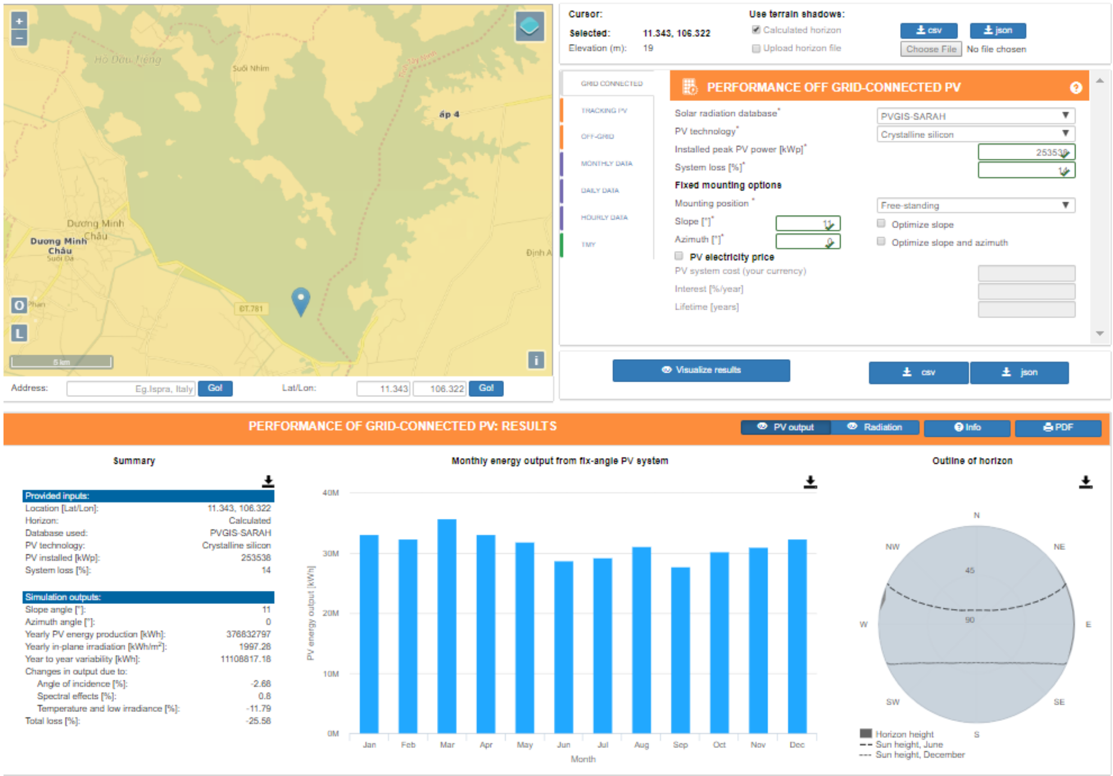
PERFORMANCE OF GRID-CONNECTED PV: RESULTS

Summary

Provided inputs:	
Location [Lat/Lon]:	11.102, 107.089
Horizon:	Calculated
Database used:	PVGIS-SARAH
PV technology:	Crystalline silicon
PV installed [kWp]:	293048
System loss [%]:	14

Simulation outputs:	
Slope angle [°]:	11
Azimuth angle [°]:	0
Yearly PV energy production [kWh]:	430284676.62
Yearly in-plane irradiation [kWh/m²]:	1963.15
Year to year variability [kWh]:	16292191.75
Changes in output due to:	
Angle of incidence [%]:	-2.65
Spectral effects [%]:	0.97
Temperature and low irradiance [%]:	-11.53
Total loss [%]:	-25.21

Figure C- 3. Tri An reservoir solar output at 1% coverage, showing the reservoir with Open Street Map map layer. The installed peak power example is 293,048 kWp, the system loss of 14%, free standing mounting position, slope at 11 degree, and azimuth at 0 degree. The average output in the summer (May to September) is at 28 GWh per month, and is generally lower than output in the winter, at average 37 GWh per month



Address: Eg.Ispra, Italy

Lat/Lon: 11.343 106.322

Cursor:

Selected: 11.343, 106.322

Elevation (m): 19

Use terrain shadows:

☑ Calculated horizon

☐ Upload horizon file

PERFORMANCE OFF GRID-CONNECTED PV

Solar radiation database*: PVGIS-SARAH

PV technology*: Crystalline silicon

Installed peak PV power [kWp]*: 253538

System loss [%]*: 14

Fixed mounting options

Mounting position*: Free-standing

Slope [°]*: 11

Azimuth [°]*: 0

☐ Optimize slope

☐ Optimize slope and azimuth

☐ **PV electricity price**

PV system cost (your currency)

Interest [%/year]

Lifetime [years]

PERFORMANCE OF GRID-CONNECTED PV: RESULTS

Summary

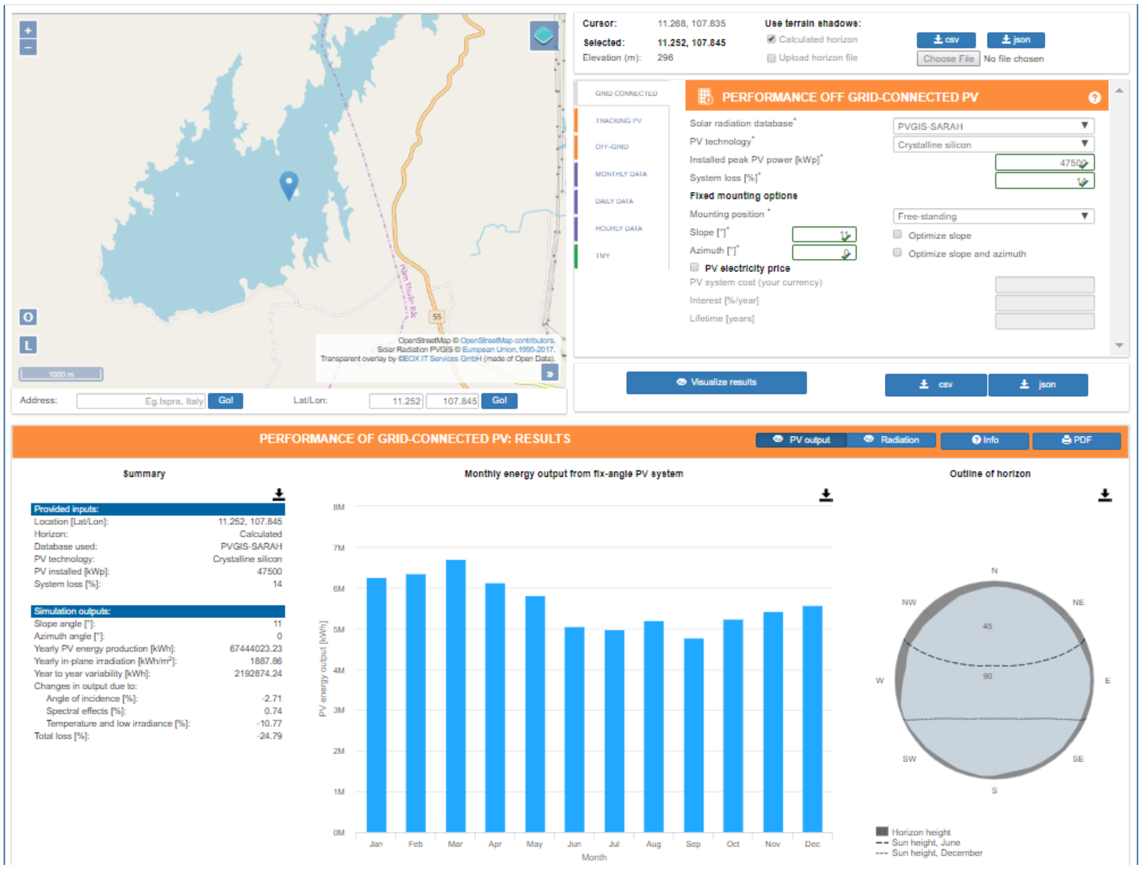
Provided inputs:	
Location [Lat/Lon]:	11.343, 106.322
Horizon:	Calculated
Database used:	PVGIS-SARAH
PV technology:	Crystalline silicon
PV installed [kWp]:	253538
System loss [%]:	14

Simulation outputs:	
Slope angle [°]:	11
Azimuth angle [°]:	0
Yearly PV energy production [kWh]:	376832797
Yearly in-plane irradiation [kWh/m²]:	1997.28
Year to year variability [kWh]:	11108817.18
Changes in output due to:	
Angle of incidence [%]:	-2.68
Spectral effects [%]:	0.8
Temperature and low irradiance [%]:	-11.79
Total loss [%]:	-25.58

Monthly energy output from fix-angle PV system

Outline of horizon

Figure C- 4. Dau Tieng reservoir solar output at 1% reservoir coverage, showing the reservoir with Open Street Map map layer. The installed peak power example is 253,538 kWp, the system loss of 14%, free standing mounting position, slope at 11 degree, and azimuth at 0 degree. The average output in the summer (May to September is 25 GWh, lower than the average output in the winter months, at 32 GWh.



Address: Eg.Ispra, Italy

Lat/Lon: 11.252 107.845

Cursor: 11.268, 107.835

Selected: **11.252, 107.845**

Elevation (m): 296

Use terrain shadows:

☑ Calculated horizon

☐ Upload horizon file

No file chosen

Solar radiation database*: PVGIS-SARAH

PV technology*: Crystalline silicon

Installed peak PV power [kWp]*: 47500

System loss [%]*: 14

Fixed mounting options

Mounting position*: Free-standing

Slope [°]*: 11

Azimuth [°]*: 0

☐ Optimize slope

☐ Optimize slope and azimuth

☐ **PV electricity price**

PV system cost (your currency)

Interest [%/year]

Lifetime [years]

Summary

Provided inputs:	
Location [Lat/Lon]:	11.252, 107.845
Horizon:	Calculated
Database used:	PVGIS-SARAH
PV technology:	Crystalline silicon
PV installed [kWp]:	47500
System loss [%]:	14

Simulation outputs:	
Slope angle [°]:	11
Azimuth angle [°]:	0
Yearly PV energy production [kWh]:	67444023.23
Yearly in-plane irradiation [kWh/m²]:	1887.86
Year to year variability [kWh]:	2192874.24
Changes in output due to:	
Angle of incidence [%]:	-2.71
Spectral effects [%]:	0.74
Temperature and low irradiance [%]:	-10.77
Total loss [%]:	-24.79

Monthly energy output from fix-angle PV system

Outline of horizon

Figure C- 5. Da Mi reservoir solar output with Open Street Map map layer. The installed peak power example is 47,430 kWp, the system loss of 14%, free standing mounting position, slope at 11 degree, and azimuth at 0 degree. The average output in the summer (May to September) is 4.3 GWh, lower than the average output in the winter months, at 6 GWh.

Table C- 2. Hoa Binh reservoir FPV's output parameters with different water surface coverages

Percentage cover	Project area (km^2)	PV floating structure area(km^2)	PV area (m^2)	Array Peak power (kWp)	Array yearly output (GWh)	Variability (GWh)
1%	0.91	0.56	566,100	96,240	108	4.7
5%	4.56	2.78	2,830,600	481,190	541	23.5
10%	9.11	5.56	5,661,100	962,390	1,080	47.0
15%	13.67	8.34	8,491,700	1,443,580	1,620	70.5

Table C- 3. Tri An reservoir FPV's output parameters with different water surface coverages

Percentage cover	Project area (km^2)	PV floating structure area(km^2)	PV area (m^2)	Array Peak power (kWp)	Array yearly output (GWh)	Variability (GWh)
1%	2.77	1.69	1,723,810	293,050	430	16.3
5%	13.87	8.46	8,619,060	1,465,240	2,150	81.5
10%	27.74	16.92	17,238,110	2,930,480	4,300	162.0
15%	41.61	25.38	25,857,170	4,395,720	6,440	244.0

Table C- 4. Dau Tieng reservoir FPV's output parameters with different water surface coverages

Percentage cover	Project area (km^2)	PV floating structure area(km^2)	PV area (m^2)	Array Peak power (kWp)	Array yearly output (GWh)	Variability (GWh)
1%	2.40	1.46	1,491,400	253,540	376	11.1
5%	12.00	7.32	7,457,010	1,267,690	1,880	55.5
10%	24.00	14.64	14,914,010	2,535,380	3,760	111.1
15%	36.00	21.96	22,371,020	3,803,070	5,640	167.0

APPENDIX D. TECHNICAL ANALYSIS - LAND COVER AND ELECTRICAL SUBSTATIONS

Appendix D shows the land cover and electrical substations near each study reservoir (Figure D- 1, Figure D- 2, and Figure D- 3).

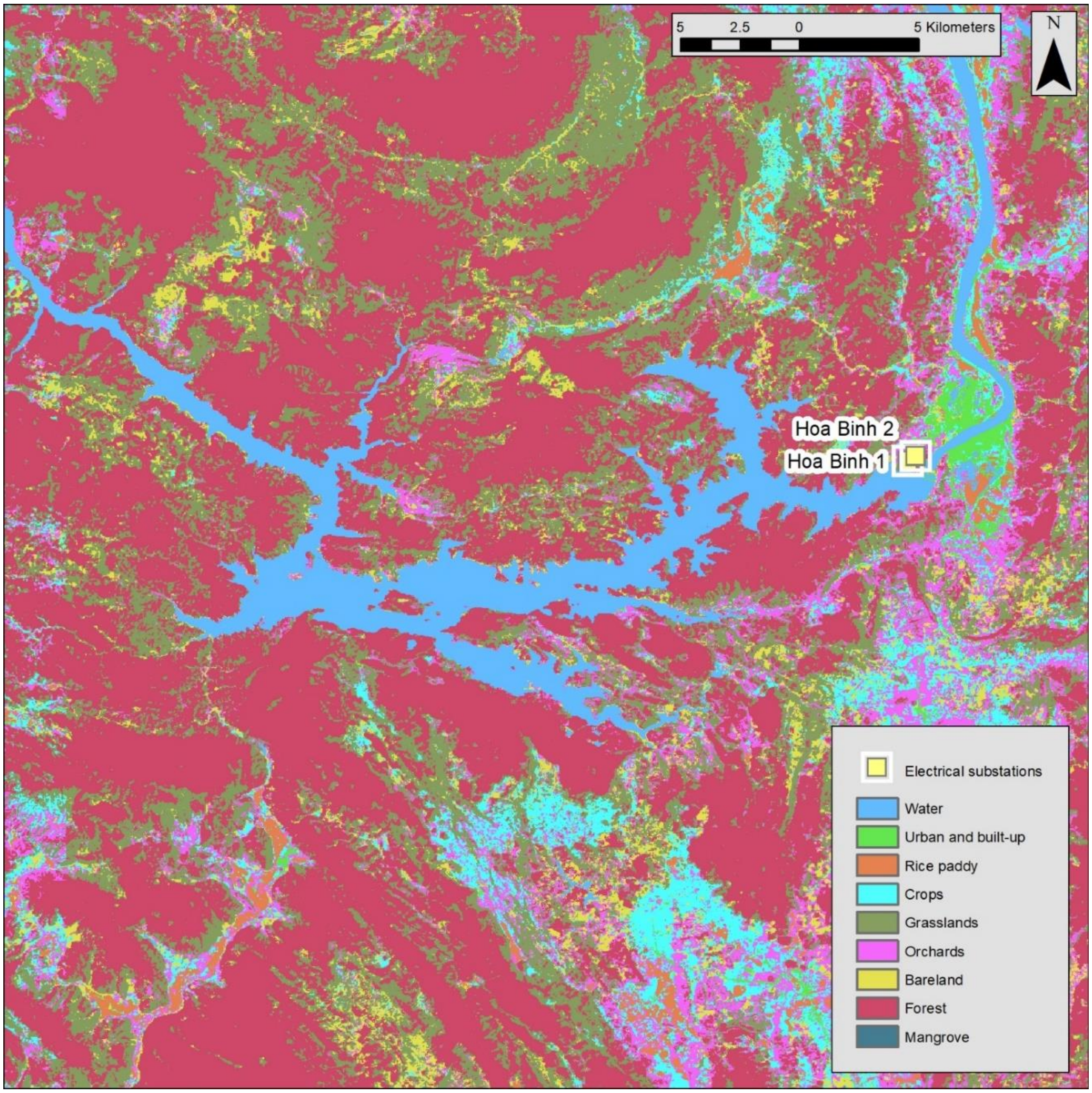


Figure D- 1. Hoa Binh reservoir area's land cover and electrical substations

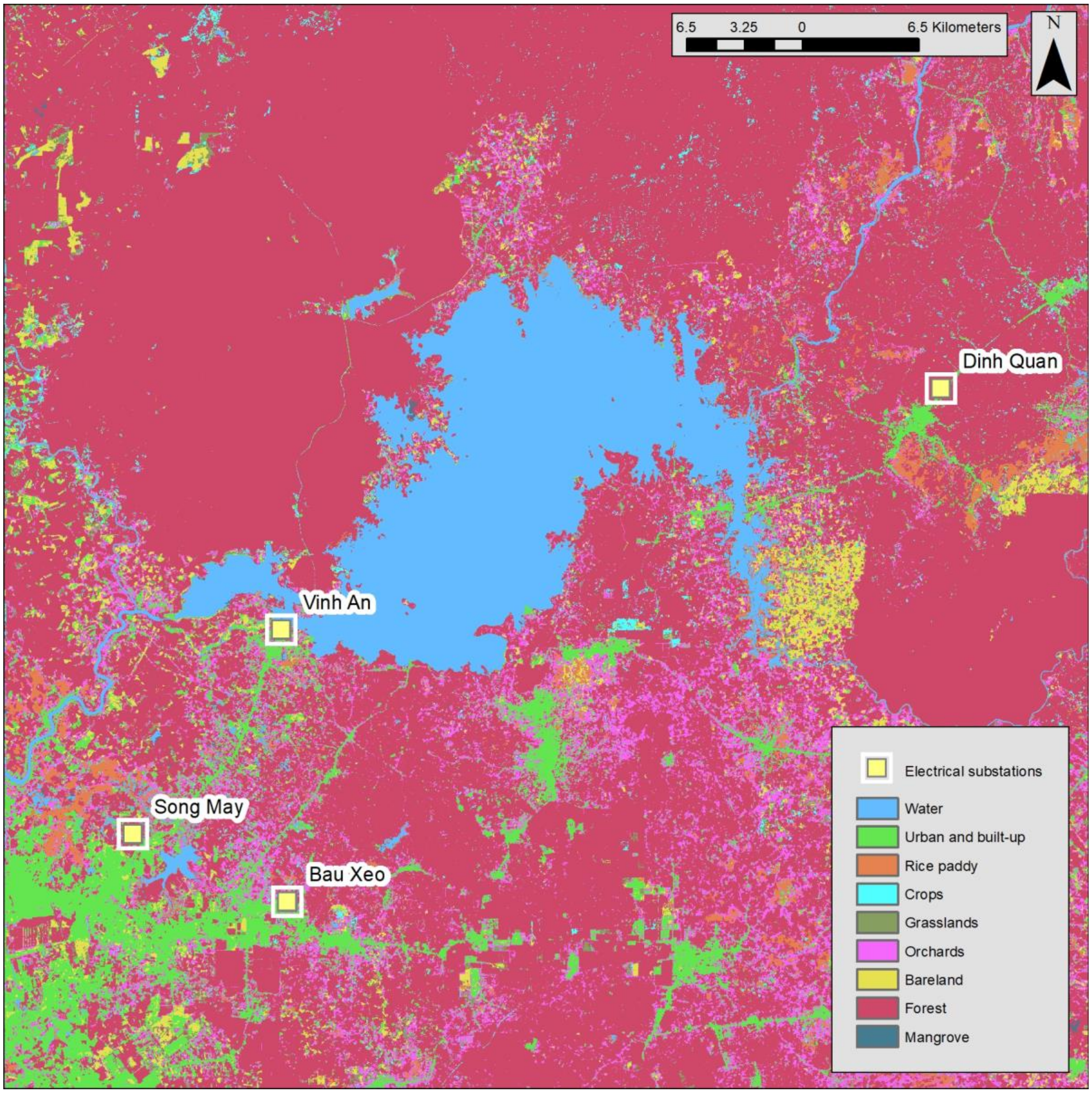


Figure D- 2. Tri An reservoir area's land cover and electrical substations

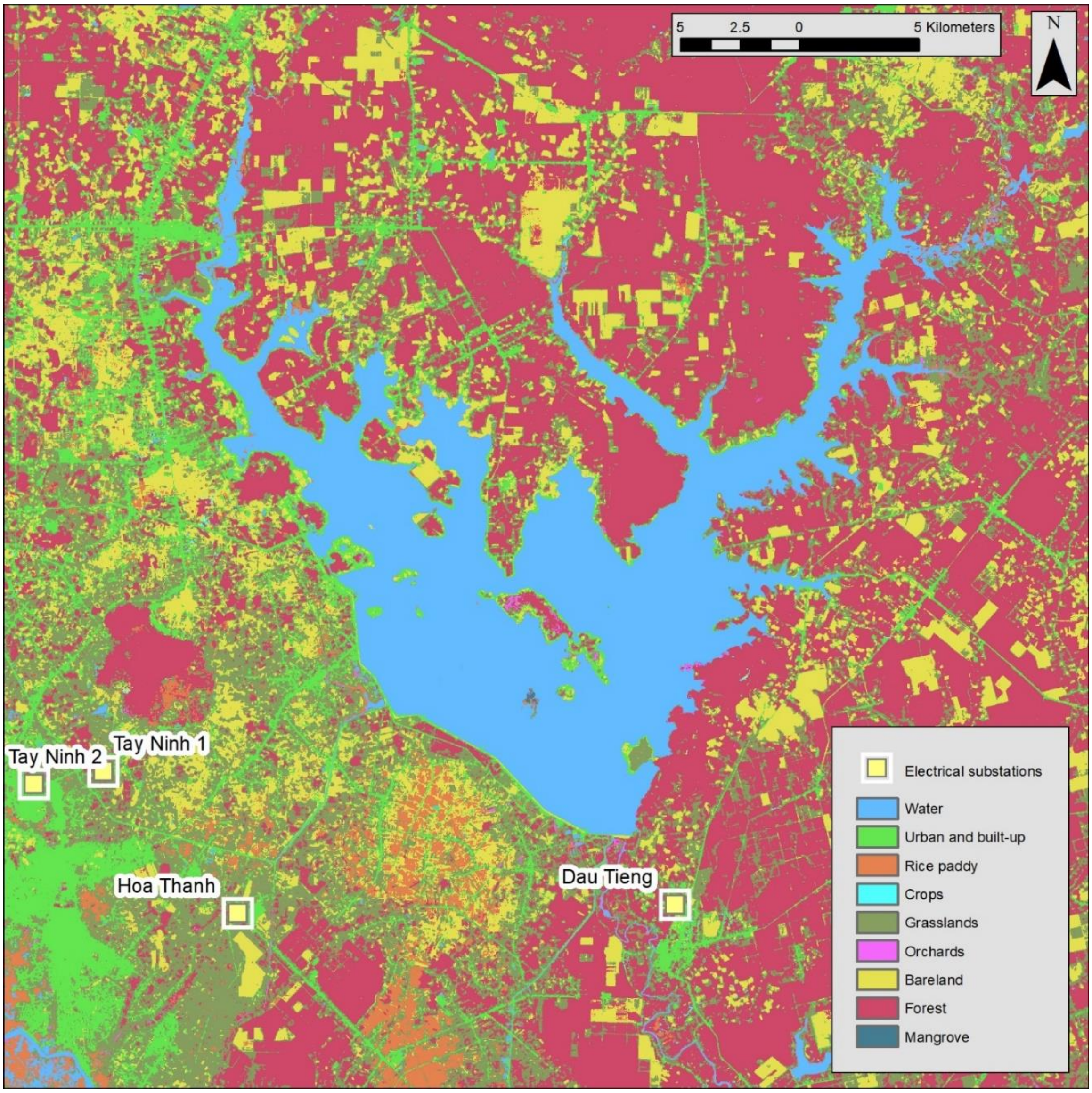
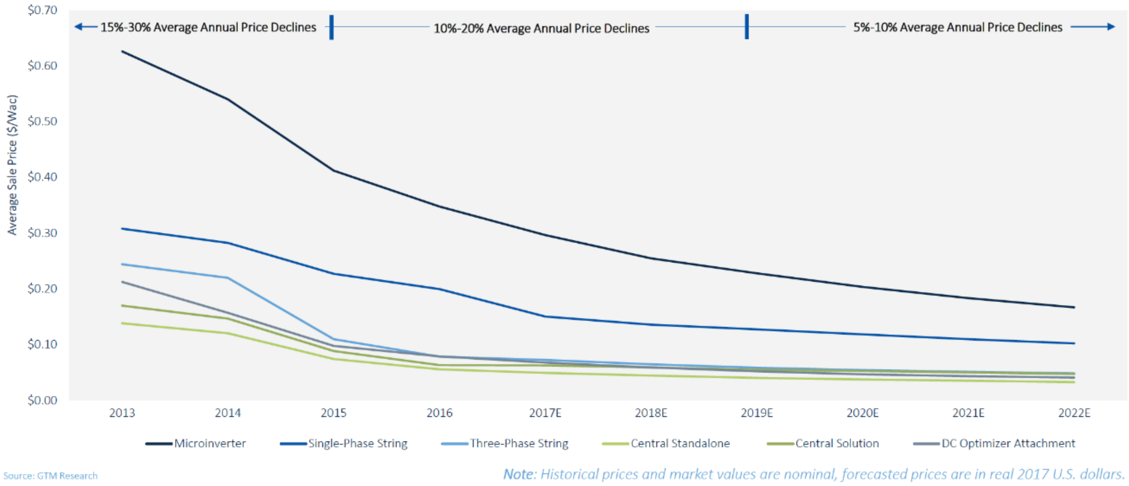


Figure D- 3. Dau Tieng reservoir area's land cover and electrical substations

APPENDIX E. ECONOMIC ANALYSIS

Appendix E shows the associated figures with economic analysis suchas global average selling price for Chinese Tier 1 crystalline silicon modules (Figure E- 1), global average inverter price (Figure E- 2). Appendix E also includes the economic feasibility results of each reservoir's FPV system, including the payback period (Table E- 1,Table E- 2, and Table E- 3) and the levelized cost of electricity (LCOE) (Table E- 4, Table E- 5, and Table E- 6).

Figure E- 1. Global average selling price for Chinese Tier 1 crystalline sillicon modules. Source: Gtmresearch, 2018.



Source: GTM Research

Note: Historical prices and market values are nominal, forecasted prices are in real 2017 U.S. dollars.

Figure E- 2. Global blended PV inverter average sale prices by product type, 2010-2022 ($/Wac). Source: Gtmresearch, 2018

Table E- 1. Hoa Binh Reservoir FPV economic feasibility

Percentage reservoir cover (%)	kWp	Capital cost ($)	Actual yearly output (kWh)	Yearly revenue ($)	Payback period (years)
1	96,240	67,368,000	108,000,000	10,195,200	9.90
5	481,190	336,833,000	541,000,000	51,070,400	9.87
10	962,390	673,673,000	1,080,000,000	101,952,000	9.90
15	1,443,580	1,010,506,000	1,620,000,000	152,928,000	9.89

Table E- 2. Tri An Reservoir FPV economic feasibility

Percentage reservoir cover (%)	kWp	Capital cost ($)	Actual yearly output (kWh)	Yearly revenue ($)	Payback period (years)
1	293,050	205,135,000	430,000,000	31,304,000	9.78
5	1,465,240	1,025,668,000	2,150,000,000	156,520,000	9.78
10	2,930,480	2,051,336,000	4,300,000,000	313,040,000	9.78
15	4,395,720	3,077,004,000	6,440,000,000	468,832,000	9.81

Table E- 3. Dau Tieng Reservoir FPV economic feasibility

Percentage reservoir cover (%)	kWp	Capital cost ($)	Actual yearly output (kWh)	Yearly revenue ($)	Payback period (years)
1	253,540	178,085,200	376,000,000	27,372,800	9.71
5	1,267,690	887,990,200	1,880,000,000	136,864,000	9.71
10	2,535,380	1,775,373,200	3,760,000,000	273,728,000	9.71
15	3,803,070	2,662,756,200	5,640,000,000	410,592,000	9.71

Table E- 4. LCOE calculation table of Hoa Binh reservoir's FPV system that covers 1% of the reservoir at 6% discount rate. LCOE of the system through 20 years of operation is the quotient of sum of total cost

Year	Capital cost ($)	O&M ($)	Total cost ($)	Electrical production (MWh)
0	67,368,000	2,367,504	63,398,392	108,000
1	0	2,367,504	2,233,494	101,887
2	0	2,367,504	2,107,070	96,120
3	0	2,367,504	1,987,802	90,679
4	0	2,367,504	1,875,285	85,546
5	0	2,367,504	1,769,137	80,704
6	0	2,367,504	1,668,997	76,136
7	0	2,367,504	1,574,525	71,826
8	0	2,367,504	1,485,401	67,761
9	0	2,367,504	1,401,322	63,925
10	0	2,367,504	1,322,002	60,307
11	0	2,367,504	1,247,172	56,893
12	0	2,367,504	1,176,577	53,673
13	0	2,367,504	1,109,978	50,635
14	0	2,367,504	1,047,149	47,769
15	0	2,367,504	987,877	45,065
16	0	2,367,504	931,959	42,514
17	0	2,367,504	879,207	40,107
18	0	2,367,504	829,440	37,837
19	0	2,367,504	782,491	35,695
Sum	67,368,000	47,350,080	96,152,390	1,313,077

Table E- 5. LCOE calculation table of Tri An reservoir's FPV system that covers 1% of the reservoir at 6% discount rate. LCOE of the system through 20 years of operation is the quotient of sum of total cost and sum of electrical production

Year	Capital cost ($)	O&M ($)	Total cost ($)	Electrical production (MWh)
0	205,135,000	7,209,030	205,227,542	430,000
1	0	7,209,030	87,304	405,660
2	0	7,209,030	82,362	382,698
3	0	7,209,030	77,700	361,036
4	0	7,209,030	73,302	340,600
5	0	7,209,030	69,153	321,321
6	0	7,209,030	65,239	303,133
7	0	7,209,030	61,546	285,975
8	0	7,209,030	58,062	269,787
9	0	7,209,030	54,776	254,516
10	0	7,209,030	51,675	240,110
11	0	7,209,030	48,750	226,519
12	0	7,209,030	45,991	213,697
13	0	7,209,030	43,387	201,601
14	0	7,209,030	40,931	190,189
15	0	7,209,030	38,615	179,424
16	0	7,209,030	36,429	169,268
17	0	7,209,030	34,367	159,687
18	0	7,209,030	32,422	150,648
19	0	7,209,030	30,586	142,121
Sum	205,135,000	144,180,600	292,783,230	5,227,990

Table E- 6. LCOE calculation table of Dau Tieng reservoir's FPV system that covers 1% of the reservoir at 6% discount rate. LCOE of the system through 20 years of operation is the quotient of sum of total cost and sum of electrical production

Year	Capital cost ($)	O&M ($)	Total cost ($)	Electrical production (MWh)
0	178,085,232	6,237,084	178,165,297	376,000
1	0	6,237,084	75,533	354,717
2	0	6,237,084	71,258	334,639
3	0	6,237,084	67,224	315,697
4	0	6,237,084	63,419	297,827
5	0	6,237,084	59,829	280,969
6	0	6,237,084	56,443	265,065
7	0	6,237,084	53,248	250,061
8	0	6,237,084	50,234	235,907
9	0	6,237,084	47,391	222,554
10	0	6,237,084	44,708	209,956
11	0	6,237,084	42,177	198,072
12	0	6,237,084	39,790	186,860
13	0	6,237,084	37,538	176,283
14	0	6,237,084	35,413	166,305
15	0	6,237,084	33,408	156,892
16	0	6,237,084	31,517	148,011
17	0	6,237,084	29,733	139,633
18	0	6,237,084	28,050	131,729
19	0	6,237,084	26,463	124,273
Sum	178,085,232	124,741,680	254,520,200	4,571,452

APPENDIX F. ENVIRONMENTAL IMPACTS – GHG EMISSION

Appendix F shows the associated tables with GHG emission analysis, including Vietnam power grid's emission factor (Table F- 1) and GHG emission avoided by each reservoir (Table F- 2).

Table F- 1. Emission factor of Vietnam power grid (The Socialist Republic of Vietnam Ministry of Natural Resources and Environment, 2017)

Year	Electricity production (MWh)	Emission (tCO_2e)	Emission factor (tCO_2e/MWh)
2015	96,337,910	76,583,562	0.795
2016	106,762,779	89,958,199	0.843
2017	96,840,719	83,160,505	0.859

Table F- 2. GHG emission avoided by each reservoir coverage

Lake	Percentage cover	GHG emission (thousand tCO2e/MWh)
Hoa Binh	1%	90
Hoa Binh	5%	450
Hoa Binh	10%	900
Hoa Binh	15%	1300
Tri An	1%	400
Tri An	5%	1800
Tri An	10%	3600
Tri An	15%	5300
Dau Tieng	1%	300
Dau Tieng	5%	1600
Dau Tieng	10%	3100
Dau Tieng	15%	4700

APPENDIX G. ENVIRONMENTAL IMPACTS - EVAPORATION SAVINGS

Appendix G shows the associated tables with evaporation savings calculation. Table G- 1 demonstrates the vapor pressure of water at different temperature. Table G- 2 shows wind speed at different heights at each reservoir. Variables such as temperature, realative humidity, sunshine hours, and extraterrestrial radiation used to calculate evaporation savings are shown in Table G- 3, Table G- 5, and Table G- 7. The annual water savings and additional power generation based on reservoirs' coverage percentage are shown in Table G- 4, Table G- 6, and Table G- 8.

Table G- 1. Saturated vapor pressure of water at different temperature (Engineering Toolbox, 2004)

Temperature (°C)	Water saturation pressure (kPa)
0	0.6117
4	0.8136
10	1.2282
14	1.5990
20	2.3393
25	3.1699
30	4.2470
34	5.3251
40	7.3849
44	9.1124
50	12.3520
54	15.0220
60	19.9460

Table G- 2. Wind speed at each reservoir at different heights (DTU Wind Energy & The World Bank Group, n.d)

Reservoirs	Mean wind speed at 50m (m/s)	Mean Wind speed at 2m (m/s)
Hoa Binh	3.25	1.95
Tri An	4.00	2.40
Dau Tieng	4.00	2.40

Table G- 3. Hoa Binh Reservoir’s monthly and evaporation and variables used for calculation

Month	days /week	Tmax (◦C)	Tmin (◦C)	Tmean (◦C)	Saturation vapor pressure (kPa)	Vapor (kPa)	Relative Humidity (%)	N (hours)	Ra (MJ/m^2/day)	sunshine n(hours/day)	Rs (MJ/m^2/day)	Monthly Evaporation (mm/m^2)
1	31	22.5	15.4	19.0	2.2	1.7	78.8	10.7	26.8	1.6	14.4	100.4
2	29	22.2	15.2	18.7	2.2	1.7	80.0	11.2	30.6	2.5	17.0	101.1
3	31	24.4	16.9	20.7	2.4	2.2	88.1	11.9	34.7	1.5	18.4	121.4
4	30	28.1	20.6	24.4	3.1	2.4	78.1	12.7	37.9	2.7	21.0	149.3
5	31	30.9	22.7	26.8	3.6	2.7	74.8	13.2	39.3	4.8	23.2	173.0
6	30	32.7	25.2	29.0	4.0	3.1	78.2	13.5	39.5	4.1	22.8	179.6
7	31	31.2	24.1	27.7	3.7	3.1	83.5	13.3	39.3	3.6	22.3	173.1
8	31	31.7	24.8	28.3	3.9	3.2	82.8	12.8	38.3	3.5	21.8	170.0
9	30	31.7	24.6	28.2	3.8	3.3	84.5	12.0	35.8	3.3	20.3	157.7
10	31	29.3	20.8	25.1	3.2	2.6	81.7	11.3	31.8	3.0	18.0	126.8
11	30	26.0	17.7	21.9	2.6	2.1	78.4	10.7	27.7	2.5	15.5	96.3
12	31	21.9	13.5	17.7	2.0	1.5	73.2	10.5	25.6	2.2	14.1	75.9
Yearly total	NA	NA	NA	NA	NA	NA	NA	143.8	407.3	35.3	228.8	1624.7

Table G- 4. Hoa Binh Reservoir's evaporation reduction and additional power generation based on reservoir coverage percentage

Percentage cover (%)	Project area (km^2)	Project area (m^2)	Evaporation (m^3/year)	Theoretical energy avalailable (GWh/year)
1%	0.91	910,000	1,587,500	0.35
5%	4.56	4,560,000	7,954,700	1.77
10%	9.11	9,110,000	15,891,900	3.54
15%	13.67	13,670,000	23,846,600	5.31

Table G- 5. Tri An Reservoir’s monthly and yearly evaporation and variables used for calculation

Month	days /week	Tmax (◦C)	Tmin (◦C)	Tmean (◦C)	Saturation vapor pressure (kPa)	Vapor (kPa)	Relative Humidity (%)	N (hours)	Ra (MJ/m^2/ day)	n(hour s/day)	Rs (MJ/m^2/ day)	Monthly Evaporation (mm/m^2)
1	31	30.8	20.6	25.7	3.3	2.6	78.9	11.3	31.4	5.9	19.8	83.4
2	29	30.2	19.9	25.1	3.2	2.5	78.0	11.6	34.2	7.3	22.5	95.0
3	31	30.9	21.1	26.0	3.4	2.7	78.6	12.0	36.7	9.2	25.4	119.9
4	30	32.3	22.5	27.4	3.7	2.9	77.9	12.4	38	9.6	26.4	124.9
5	31	31.9	23.1	27.5	3.7	3.1	82.9	12.7	37.8	7.7	24.7	119.7
6	30	31.3	23.2	27.3	3.7	3.0	83.0	12.8	37.3	6.7	23.5	110.4
7	31	30.0	22.4	26.2	3.4	2.9	85.2	12.7	37.4	6.0	23.2	111.6
8	31	30.5	22.7	26.6	3.5	3.0	86.0	12.4	37.7	7.5	24.6	116.8
9	30	30.9	23.3	27.1	3.6	3.0	83.4	12.0	37	7.5	24.3	111.3
10	31	30.2	22.5	26.4	3.5	3.0	85.9	11.6	34.8	4.8	21.0	95.9
11	30	30.7	22.8	26.8	3.5	2.9	82.7	11.3	31.1	6.0	19.7	77.3
12	31	29.6	20.6	25.1	3.2	2.5	79.0	11.2	29.5	6.4	19.0	73.7
Yearly total	NA	NA	NA	NA	NA	NA	NA	143.9	422.9	84.7	273.9	1239.8

Table G- 6. Tri An Reservoir's evaporation reduction and additional power generation based on reservoir coverage percentage

Percentage cover (%)	Project area (km^2)	Project area (m^2)	Evaporation (m^3/year)	Additional energy available (GWh/year)
1%	2.77	2,770,000	3,981,373	0.42
5%	13.87	13,870,000	19,935,610	2.12
10%	27.74	27,740,000	39,871,221	4.24
15%	41.61	41,610,000	59,806,831	6.36

Table G- 7. Dau Tieng Reservoir’s monthly and yearly evaporation and variables used for calculation

Month	days /week	Tmax (◦C)	Tmin (◦C)	Tmean (◦C)	Saturation vapor pressure (kPa)	Vapor (kPa)	Relative Humidity (%)	N (hours)	Ra (MJ/m^2/ day)	n(hours/ day)	Rs (MJ/m^2/ day)	Monthly Evaporation (mm/m^2)
1	31	31.7	20.8	26.3	3.4	2.7	79.7	11.3	31.4	5.9	19.8	83.1
2	29	31.3	20.1	25.7	3.2	2.6	80.4	11.6	34.2	7.3	22.5	93.9
3	31	32.1	21.3	26.7	3.5	2.7	77.0	12.0	36.7	9.2	25.4	121.3
4	30	33.5	23.1	28.3	3.9	2.9	75.1	12.4	38	9.6	26.4	127.3
5	31	32.8	23.7	28.3	3.9	3.2	81.5	12.7	37.8	7.7	24.6	120.9
6	30	32.4	24.1	28.3	3.9	3.1	79.9	12.8	37.3	6.7	23.5	112.6
7	31	31.0	23.4	27.2	3.6	3.0	81.9	12.7	37.4	6.0	23.2	113.9
8	31	31.3	23.6	27.5	3.7	3.1	83.4	12.4	37.7	7.5	24.6	118.7
9	30	31.8	24.2	28.0	3.8	3.1	81.1	12.0	37	7.5	24.3	113.1
10	31	31.0	23.2	27.1	3.6	3.0	83.4	11.6	34.8	4.8	21.0	97.4
11	30	31.4	23.2	27.3	3.7	3.0	81.4	11.3	31.1	6.0	19.7	78.1
12	31	30.2	20.9	25.6	3.3	2.6	77.9	11.2	29.5	6.4	19.0	74.3
Yearly total	NA	NA	NA	NA	NA	NA	NA	144	422.9	84.7	273.9	1254.5

Table G- 8. Dau Tieng Reservoir's Evaporation Reduction based on reservoir coverage percentage

Percentage cover (%)	Project area (km^2)	Project area (m^2)	Evaporation (m^3/year)
1%	2.4	2,400,000	3,536,436
5%	12	12,000,000	17,682,181
10%	24	24,000,000	35,364,362
15%	36	36,000,000	53,046,543

APPENDIX H. SENSITIVITY ANALYSIS

Appendix H shows the PV output from some of the sensitivitiy analysis scenarios at all coverage for all reservoirs (Table H- 1, Table H- 2, and Table H- 3).

Table H- 1. Scenarios for PV output (GWh) sensitivity analysis for Hoa Binh Reservoir. Base case is the output from PVGIS5 used in this study. Scenario 1 is the output from adding 30% to the PVGIS 5 output. Scenario 2 is the output from adding PVGIS 5 variability for each reservoir. Scenario 3 is the output from subtracting PVGIS 5 variability. Scenario 6 shows the increase of system loss to 20%. Scenario 7 has the system loss of 8%.

Percentage lake cover (%)	Base case	Scenario 1	Scenario 2	Scenario 3	Scenario 6	Scenario 7
1	108	140	113	103	101	116
5	541	703	565	517	503	579
10	1,080	1,404	1,129	1,031	1,010	1,160
15	1,620	2,106	1,693	1,547	1,510	1,740

Table H- 2. Scenarios for PV output (GWh) sensitivity analysis for Tri An Reservoir.

Percentage lake cover (%)	Base case	Scenario 1	Scenario 2	Scenario 3	Scenario 6	Scenario 7
1	430	559	446	414	400	460
5	2,150	2,795	2,231	2,069	2,000	2,300
10	4,300	5,590	4,462	4,138	4,000	4,600
15	6,440	8,372	6,683	6,197	5,990	6,890

Table H- 3. Scenarios for PV output (GWh) sensitivity analysis for Dau Tieng Reservoir.

Percentage lake cover (%)	Base case	Scenario 1	Scenario 2	Scenario 3	Scenario 6	Scenario 7
1	376	489	387	365	350	402
5	1,880	2,444	1,935	1,825	1,750	2,010
10	3,760	4,888	3,871	3,649	3,500	4,020
15	5,640	7,332	5,806	5,474	5,250	6,040