The development of floating solar farms on the surface of impounding reservoirs in Hong Kong

Samuel L W Choi[1], Stephen Y S Cheng[1] and Justin Searle[2]
[1] Water Supplies Department, the HKSAR Government, Hong Kong, People's Republic of China
[2] Binnies Hong Kong Limited, Hong Kong, People's Republic of China

ABSTRACT

The initiative to develop Renewable Energy in Hong Kong was first addressed in the 2018 Policy Address and further elaborated in the 'Hong Kong Climate Action Plan 2030+'. In October 2021, the Government of the HKSAR announced the new 'Climate Action Plan 2050' to strive to achieve carbon neutrality by 2050. In response, to promote the development of renewable energy, the Water Supplies Department (WSD) has undertaken studies and three pilot trials of floating photovoltaic (FPV) systems on the surfaces of Hong Kong's reservoirs. With the successful implementation and operation of these pilot systems, the WSD is now embarking on the investigation and design of a large-scale 5-megawatt (MW) capacity floating solar farm (FSF) at Plover Cove Reservoir. Future studies will commence shortly to explore the feasibility of also implementing large-scale FSFs totalling 130 MW on other impounding reservoirs.
The paper discusses some of the design issues and considerations including innovations/technology of FSFs which are specific to Hong Kong. These include the resilience of the FPV system to withstand severe typhoon conditions, environmental and water quality issues, and the proximity of nearby waterworks facilities for utilisation of the generated renewable energy.

KEYWORDS Floating solar farm; photovoltaic; reservoirs; anchoring system; water quality
CONTACT Stephen Y S Cheng searlej@binnies.com
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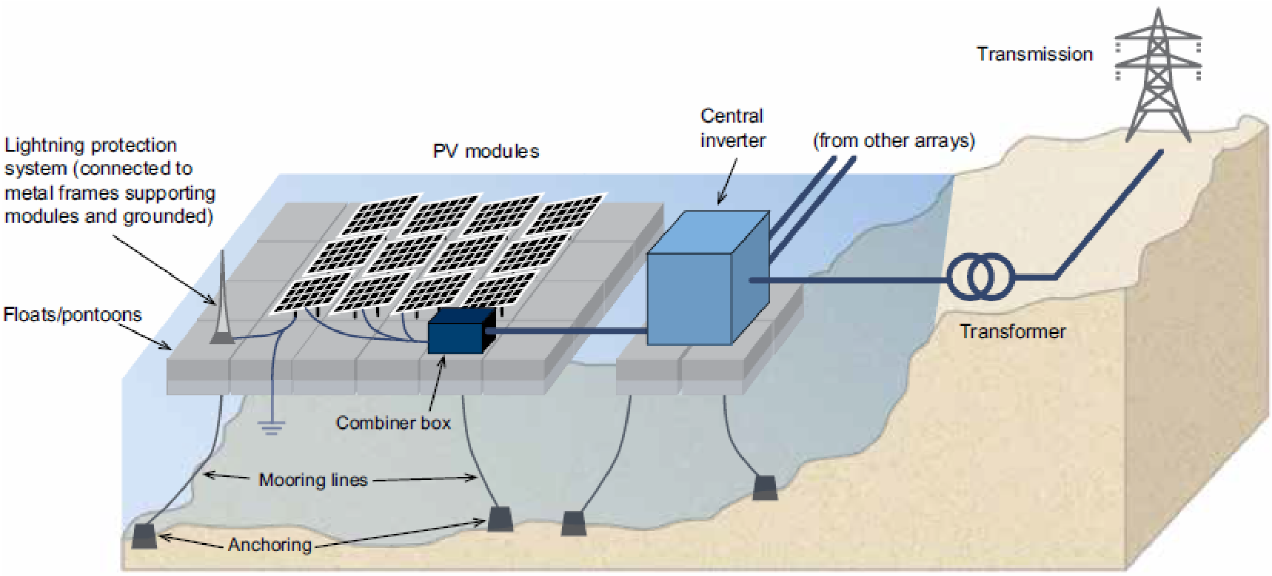
1. Introduction

The siting of solar farms on the surface of water bodies has evolved rapidly in the past 10-15 years, made possible by innovations in photovoltaic (PV) panel technology and the development of floating raft systems to support the PV panels. By the end of 2021, global floating solar capacity had reached an estimated total of more than 1.6 gigawatts (GW) and is projected to reach a capacity of 4.8 GW by 2026 (EQ International, 2022).

The general layout of a floating PV (FPV) system comprises PV arrays mounted on a floating platform. The floating platform is held in place by a mooring and anchoring system. The direct current (DC) electricity generated by PV modules is gathered by combiner boxes and converted to alternating current (AC) by inverters. The inverters may be located onshore, if the distance to the array is short, or otherwise be located on specially designed floats. The AC current is then fed via a transformer to the



Source: Solar Energy Research Institute of Singapore (SERIS) at the National University of Singapore.

Figure 1. Typical arrangement of a floating photovoltaic system.

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local electricity grid, or directly to nearby facilities for consumption. A typical FPV system is illustrated in Figure 1.

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The initiative began with two pilot schemes of 100-kilowatt (kW) capacity each, installed at Plover Cove Reservoir and Shek Pik Reservoir in 2017. A further pilot system of 100 kW capacity was installed at Tai Lam Chung Reservoir in 2022. All three pilot schemes supply renewable energy to nearby WSD facilities, reducing the demand for electricity generated from fossil fuels, thereby saving costs and reducing the carbon footprint of the WSD's operations.

With the successful implementation and operation of these pilot systems, the WSD is now embarking on the investigation and design of a large-scale floating solar farm (FSF) of 5 MW capacity at Plover Cove Reservoir. In addition to supplying power to the WSD's nearby pumping stations, surplus energy will be fed into the grid for consumption by other users. The WSD will also commence future studies shortly to explore the feasibility of also implementing additional large-scale floating solar farms totalling 130 MW at other impounding reservoirs in Hong Kong.

Apart from harvesting renewable energy from the sun, there are additional benefits of installing floating solar systems on the surface of impounding reservoirs. These benefits include reducing water evaporation, suppressing algae growth, saving precious land resources and yielding a higher solar panel power generation efficiency compared to land-based systems due to the cooling effect of the water body. Each of these benefits also translate into further indirect reductions in the carbon footprint.

This paper discusses the design considerations being taken by the WSD in the development of large-scale FPV systems in Hong Kong to address the increasingly urgent need to develop new renewable energy supplies towards the achievement of the Climate Action Plan 2050 goals. Design issues and considerations of FSFs which are specific to Hong Kong are discussed, which include the resilience of the FPV system to withstand severe typhoon conditions, environmental considerations, water quality, and the proximity of nearby waterworks facilities for utilisation of the generated renewable energy.

2. Implementation of pilot floating solar systems

The WSD has installed three small-scale FPV systems of 100 kW each. The first pilot system was constructed at Shek Pik Reservoir and commissioned in February 2017 to supply electricity to the air compressor house of the reservoir. The second pilot system was installed at Plover Cove Reservoir and commissioned in October 2017, also to supply electricity to the air compressor house of the reservoir.

The two pilot systems were subjected to extreme weather conditions with the passage of Typhoon Mangkhut on 16 September 2018, during which the Storm Signal No. 10 was hoisted. A maximum hourly mean windspeed of 139 km/hr with gusts of up to 198 km/hr were recorded at Tai Mei Tuk (Hong Kong Observatory, 2020), close to Plover Cove Reservoir. Following the typhoon, no adverse impacts were observed at the pilot system at Shek Pik Reservoir. However, inspection of the pilot system at Plover Cove Reservoir indicated the failure of some of the polypropylene pins at the connection points of the mooring lines to the floating platforms. In consultation with the contractor and floating platform supplier, the fibreglass and polypropylene connection pins were replaced with stronger stainless steel connection pins throughout the entire pilot system. Subsequent typhoons, though with lower intensity than Mangkhut, have to date passed without incident.

A recent development in the design of FPV mooring systems is the utilisation of elasticated mooring lines. A mooring system which incorporates some degree of elasticity is better able to withstand the high wind and wave forces under storm conditions by allowing flex in the securing loads around the perimeter of each array to reduce stress concentrations and the potential overloading of any one anchor point. Such elasticity in the mooring system may be provided by the adoption of proprietary elastic mooring system components comprising sections of rubber hawser. In view of the damage observed at the mooring connection points of the Plover Cove Reservoir pilot system, such elastic mooring system has been adopted at the third pilot system installed at Tai Lam Chung Reservoir and was commissioned in April 2022. The elasticated mooring system continues to be monitored to assess its performance and to review its cost-effectiveness. As discussed below, this information will help to inform the design of the proposed future large-scale floating solar farms.

Details of the three pilot systems and the cumulative energy outputs to date, are presented in the Appendix.

3. Design considerations for large scale floating solar farms in Hong Kong

3.1. Resilience to withstand typhoon conditions

Typhoons are common in Hong Kong. The frequency and intensity of super-typhoons are expected to increase in the future due to the impacts of climate change. The maximum recorded windspeeds of super-typhoon Mangkhut on 16 September 2018 were recorded at Waglan Island with a maximum 60-minute sustained mean windspeed of 161 km/hr and a maximum 3-second gust speed of 220 km/hr (Hong Kong Observatory, 2020). Such high windspeeds have the potential to cause severe damage to FSFs. This is evidenced by some notable failures of FSFs around the world. For example, Japan's largest FPV plant of 13.7 MW capacity at Yamakura Dam was severely damaged by Typhoon Faxai in September 2019 in which the PV panels became stacked on top of each other leading to short circuiting, excessive heat, and a fire (EnergyFacts.eu, 2021).

Whilst innovations in solar panel technologies are largely in the hands of the research and development departments of specialised manufacturers, a particular area for innovation which is more specific to Hong Kong is the FPV anchoring system which must ensure that the solar arrays are securely held in place under typhoon conditions. To this end, the WSD is conducting a trial use of a flexible anchoring system through the implementation of the 100 kW pilot system at Tai Lam Chung Reservoir.

The current investigation and design for the 5 MW capacity FSF at Plover Cove Reservoir will include wind, wave and hydrodynamic modelling to assess the performance of the anchoring and mooring system under the design typhoon conditions. The distribution of wave characteristics averaged over a period of time will be based on the average 60-minute sustained wind speed. The instantaneous wind load on the floating platform and mooring lines will be based on the maximum 3-second gust speed. The design approach will aim to ensure that the appropriate level of flexibility is achieved to allow sufficient freedom of movement to cater for fluctuating reservoir water levels and distribution of mooring forces, while also providing adequate securing forces to prevent lifting of the floats from the water surface under the effects of the maximum wind gusts.

3.2. Anchoring systems and fixed vs. flexible moorings

FSF platforms must be held in place by mooring lines secured to anchor points either on the bed, or at the banks, of the water body, or a combination of both (as was adopted for the pilot FPV system at Shek Pik Reservoir).

Typical FPV anchoring systems comprise ropes, cables, chains or a combination of these, with connections to the sides of the floating platform fixed to deadweight anchors on the reservoir bed. Although some slack is allowed for some movement of the platform and to accommodate variations in the water depth, such systems nonetheless tend to provide a relatively fixed, inflexible point of connection when tension is taken up. Under cyclical wave loading, sharp snap-loads may be applied to the platform connection points when tension is applied. This arrangement may also lead to concentrated load points at a few connection points.

An alternative approach is to provide a more flexible mooring system in which a portion of each mooring line has some degree of elasticity. This reduces the risk of sharp snap loads under cyclical wave loading and facilitates a more uniform distribution of the securing forces of the mooring line loads applied to the connection points of the floating platform. The elasticity in the mooring lines may be provided by the utilisation of nylon ropes which have a small degree of elasticity, or by proprietary systems which incorporate a section of rubber hawser within the mooring system. These types of systems provide a higher degree of elasticity. A typical arrangement of a flexible anchoring system is shown in Figure 2. The pilot FPV system at Tai Lam Chung Reservoir adopts such a proprietary system and its performance will be monitored through a number of typhoon seasons to assess the cost-benefits of adopting such a system in future large-scale FSFs which are being planned.

Figure 2. typical arrangement of a flexible hawser anchoring system.

The deadweight anchor for FPV systems typically comprises a mass concrete block positioned on the bed of the water body. The required weight of the anchor block is dependent on a number of design considerations, including the wind and wave loads to be resisted, and the number and load capacity of the connection points to the floating platform. The logistics of transportation to site and means of placement of the anchor blocks are also important considerations. Deadweight anchors for FPV systems may typically be in the range of 2-5 tonnes each, subject to these various design considerations. For the three FPV pilot systems installed by the WSD at impounding reservoirs which must remain in service at all times, minimising potential water quality impacts of the construction method is of paramount importance. To avoid the need for any large construction vessels or heavy lifting equipment to place the anchor blocks on the reservoir floor, an innovative design and method of installation were adopted for the three pilot schemes. Instead of a single concrete anchor block, each gravity anchor was formed by placing small concrete blocks packed into a steel cage (Figure 3). The mooring line was then connected to the steel cage, which was weighed down by the concrete blocks. The packing of the cages and placement on the reservoir floor was conducted by divers. This method of construction minimises risks to water quality but tends to be highly labour-intensive. Other innovative approaches will be explored for the construction of the planned large-scale FSF to reduce the time and costs associated with the installation of the larger number of anchor blocks.

Figure 3. Assembly of a gravity anchor at Shek Pik Reservoir comprising a steel cage packed with small concrete blocks.

One such alternative for the construction of the anchor blocks is to use eco-friendly concrete manufactured using locally sourced waste or residual materials from different industries and requires less amounts of energy for production. Compared to traditional concrete, it produces less CO2 and is cheaper. The alternative aggregates would be sourced from inert materials to ensure that there is no adverse impact on water quality.

The utilisation of temporary pontoons with electrically powered motors, which do not have any adverse impact on water quality, will also be examined to develop more efficient construction methods for the fabrication and placement of the gravity anchor blocks.

3.3. Floating platform system

There have been significant innovative developments in recent years for the design of the floating platform system which typically comprise floats made from high-density polyethylene (HDPE) which is designed to protect against UV damage. The connection pins between floats are made from a combination of polypropylene and glass fibre in order to provide sufficient strength whilst remaining lightweight. Manufacturers state that it takes between 15 and 20 years before UV slowly begins to penetrate and damage the floats. A further five to 10 years are required before the floats are actually required to be replaced, giving a total estimated product lifetime of 20 to 30 years.

The metallic fixtures on which the PV modules are mounted are composed of an alloy aluminium 6060. This alloy was originally designed for use in contact with food and is highly corrosion resistant.

With the increasing global application of FPV systems on the surface of reservoirs used to supply raw water for treatment to potable water standards, project proponents are requiring that all components of the FPV system are safe in terms of any potential impacts on water quality. Materials are commonly required to be certified according to the requirements of British Standard BS 6920 for the suitability of non-metallic products for use in contact with water intended for human consumption. The standard includes requirements to ensure no adverse impacts such as odour and flavour, colour and turbidity, and growth of aquatic microorganisms. Compliance with BS 6920 is a requirement for all the FPV systems implemented by the WSD in Hong Kong.

The typical details of a HDPE float system are shown in Figure 4.

3.4. Water quality

3.4.1. Construction phase

During installation of the FSF, it is anticipated that no desilting works will be required. In the event that any minor desilting works at the deadweight anchoring system locations are required, this would be performed by small-scale air-lift suction methods. As no grab dredging would be carried out, and the footprint area of the deadweight system would be small, no significant elevation of

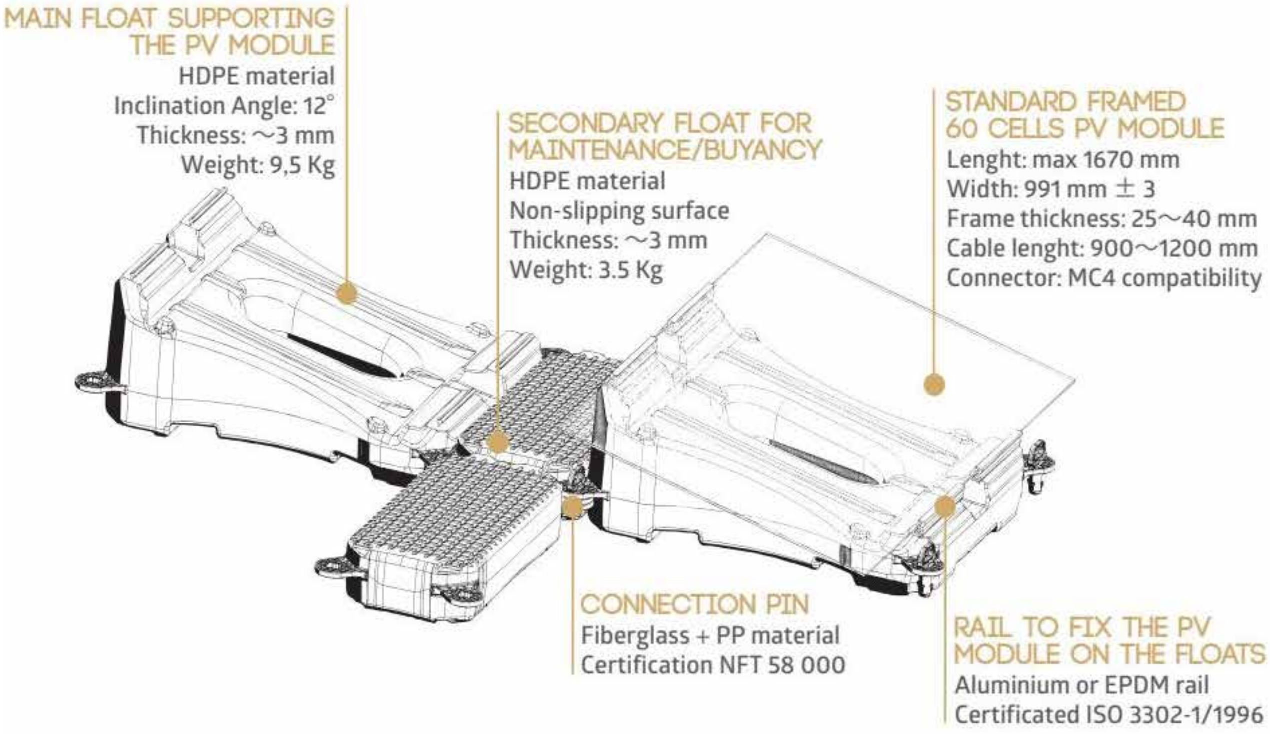

Figure 4. Typical details of floats for floating platform systems (Ciel & Terre, 2021).

suspended solids in the reservoir and release of pollutants into the water column would be expected. The associated potential disturbance of the reservoir floor and elevation of suspended solids would be minor, short-term, and highly localised.

3.4.2. Operation phase

The placement of the FSF on the Plover Cove Reservoir may lead to a change of water temperature, change of dissolved oxygen level, reduction of water evaporation and reduction in algal growth. Water contamination may also arise from the implementation of the FSF in the reservoir due to possible leaching of materials from the FSF as well as cleaning and maintenance of the FSF.

3.4.2.1. Change of water temperature

Installation of a FSF blocks solar radiation and reduces wind stress at the water surface. The reduction in shortwave radiation by the PV panels can affect both the heat balance and light penetration into the water column and the surface water temperature is expected to decrease. On the other hand, the water surface also can be warmed by thermal radiation (longwave radiation) from the panels and the reduction of evaporative heat flux at the water surface. The net result of these competing mechanisms would be complex and depend on the meteorological conditions as well as the design of the FSF. Both increase and decrease in surface water temperature for locations underneath the solar panel (compared with the reference location outside the solar panel) have been observed in FSFs. The influence of shading on reservoir water temperature is a function of the ratio of the shading area to the water body. As the 5 MW FSF proposed at Plover Cove Reservoir would cover less than 1% of the reservoir surface, the associated effect on temperature change would likely be minimal and localised.

3.4.2.2. Change of dissolved oxygen level

Covering the water surface by the FSF would reduce the active surface for oxygen diffusion into the water body and wind mixing ability. Moreover, covering water bodies could obstruct sunlight from reaching the water column and affect the photosynthesis of phototrophic organisms, and subsequent Dissolved Oxygen (DO) production in the water bodies. The level of DO reduction would depend on the reservoir covered area / total area ratio. As the 5 MW FSF would cover less than 1% of the reservoir surface, the associated effect on DO level reduction would likely be minimal and localised.

3.4.2.3. Reduction of water evaporation

Water evaporation is proportional to the exposed surface area. The installed solar system would partially cover the water surface and reduce the water surface area exposed to air. Thus, the water evaporation rate could be reduced. Implementation of the FSF could thereby reduce the water evaporation and hence help to conserve the precious raw water resource in the reservoir.

3.4.2.4. Potential reduction in algal growth

Shading the reservoirs by PV panels could hinder sunlight penetration. Such less favourable conditions could possibly reduce the risk of algal blooms and result in secondary beneficial effects on water quality. The risk of algal bloom occurrence in other parts of the reservoir outside the FSF site would remain unchanged. The overall effect on algal bloom occurrence in the reservoir due to the FSF implementation will need to be confirmed by comparing historical records with long-term monitoring data to be collected during the FSF operation.

3.4.2.5. Possible leaching of materials from the FSF

There would be a concern of potential risk of water contamination from leaching of pollutants from the materials used for the PV modules and floating structures, mooring systems, and anchoring system.

As the PV modules are placed on the floating structure and not submerged in water, the associated water contamination would not be anticipated during normal operation. However, in the case of damage or delamination, the module components could fall into the reservoir water with the potential for leaching out of certain constituents. For the crystalline silicon PV panels envisaged to be adopted, semiconductor materials (such as silicon) and metals (such as copper, lead, aluminium, etc.) in the panels could potentially be released into the water if the panels are severely damaged. Although the risks of such events are considered to be small, appropriate response procedures will be developed including targeted water quality monitoring at the location of the incident and, if necessary, retrieval of components from the reservoir floor by divers.

Exposed to sunlight, oxidants, physical stress and biofouling, floating structures over time will weather and degrade. This would result in a risk of small particles and chemicals leaching into the water. While the American Water Works Association has approved its use in potable water (American Water Works Association. 2023), HDPE has been identified as a potential source of microplastics release due to the UV degradation and weathering (Kalogerakis et al., 2017). It is however expected that the rate of such release, if any, would be slow and the amount of release at a time would be minimal. Considering that the floating platforms would be monitored and maintained, together with the fact that the reservoir water is regularly replaced by new local yield and Dongjiang water, any possible increase in microplastics concentration in the reservoir water as a result of long-term weathering of HDPE should be negligible. This will be verified by a water quality monitoring programme to be conducted with the implementation of the proposed large-scale FPV systems.

3.5. Utilisation of generated renewable energy

The renewable energy generated by the three FPV pilot systems in Hong Kong is fully utilised by nearby WSD facilities, namely Shek Pik Raw Water Pumping Station, and the air compressor houses of Plover Cove Reservoir and Tai Lam Chung Reservoir. The proposed large-scale FSF at Plover Cove Reservoir will supply RE to the Tai Mei Tuk Raw Water Pumping Station and/or Harbour Island Raw Water Pumping Station. Surplus energy will be fed into the local grid for consumption by other users.

In the longer term, the development of future large-scale FPV systems in Hong Kong will more predominantly be used to supply renewable energy to the local grid, providing a saving in the amount of power which would otherwise need to be generated from fossil fuels by the local energy supplier.

4. Conclusions

The total water surface area of the 17 impounding reservoirs in Hong Kong is about 23.8 km2. Much of this area is located within Country Parks which are sensitive to visual impacts. Many areas are also quite distant from the existing electricity grid and potential users which hinders the development potential. The WSD will cooperate with other government departments to pilot high-efficiency battery storage technology and consider green hydrogen and other more advanced technologies with a view to overcoming this constraint. Nonetheless, even if only 10% of the available reservoir surface area were to be developed for FPV systems in the long term, this could provide a generating capacity of about 240 MW producing about 288 million kWh annually. This would be sufficient for more than 85,000 households providing a reduction of about 200,000 tonnes of CO2 emissions every year. The WSD's vision is to progressively develop mega FSFs to capitalise reservoirs' water surface area to the maximum extent practicable beyond 240 MW. Combined with the many other carbon reduction initiatives promoted by the Government of the HKSAR, such reduction will significantly help Hong Kong move towards the goal of carbon neutrality by 2050. The WSD aims to be at the forefront of the further innovative applications of PV and FPV systems in Hong Kong towards the achievement of this goal.

Appendix: Details of the WSD's pilot floating photovoltaic (FPV) systems

Figure A1. FPV system at Shek Pik Reservoir.

The first pilot system was successfully installed at Shek Pik Reservoir in February 2017 for supplying electricity to the nearby pumping station of the reservoir. The cumulative output up to November 2022 is as follows:

- Electricity generated 519,000 kWh
- CO_2 reduction 363,000 kg

Figure A2. FPV system at Plover Cove Reservoir.

The second pilot system at Plover Cove Reservoir was successfully installed in October 2017 for supplying electricity to the nearby air compressor house of the reservoir. The cumulative output up to November 2022 is as follows:

- Electricity generated 532,000 kWh
- CO2 reduction 372,000 kg

Figure A3. FPV system at Tai Lam Chung Reservoir.

The third pilot system at Tai Lam Chung Reservoir was successfully installed in April 2022 for supplying electricity to the nearby air compressor house of the reservoir. The cumulative output up to November 2022 is as follows:

- Electricity generated 52,000 kWh
- CO_2 reduction 36,000 kg

Notes on Contributors

Mr Samuel L W Choi is the Chief Electrical & Mechanical Engineer of the Water Supplies Department. He has participated in many waterworks projects including pumping stations, water treatment works, disinfection facilities, floating photovoltaic, renewable energy, etc. for over 30 years and is currently responsible for the administration and control of the planning, design, development, contract engineering, supply and installation of mechanical, electrical and instrumentation plant and equipment for waterworks projects.

Mr Stephen Y S Cheng is the Senior Electrical Engineer of the Water Supplies Department. He has participated in many waterworks projects such as construction of Stage I of Tai Po Water Treatment Works and installation of M&E equipment for Lok On Pai Salt Water Pumping Station. He is currently responsible for renewable energy projects including floating photovoltaic projects at impounding reservoirs.

Mr Justin Searle is a Director of Projects of Binnies Hong Kong Limited. Originally from the UK, Justin has worked in Hong Kong and the Asia region for the past 28 years. He is experienced in a range of water infrastructure projects including water, wastewater, drainage, tunnels, and most recently, floating solar. He is currently Binnies' project manager for the 'Implementation of a Large Scale Floating Solar Farm at Plover Cove Reservoir' for the Water Supplies Department and for the 'Inter Reservoir Transfer Scheme' for the Drainage Services Department of the Government of the HKSAR.

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