



**OPERATING-MODE OPTIMIZATION OF DRAINAGE PUMPING
STATIONS SUPPLIED BY FLOATING PHOTOVOLTAIC PLANTS:
INTERNATIONAL EXPERIENCE AND PROPOSALS FOR THE REPUBLIC
OF KARAKALPAKSTAN**

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Abstract

Drainage pumping stations in Karakalpakstan consume large amounts of electricity, while the same region receives high solar radiation and collects large volumes of collector-drainage water that can be stored in artificial reservoirs. This paper analyses international experience with floating photovoltaic (FPV) plants, solar-powered pumping and pump scheduling, and derives proposals for Karakalpakstan. The analysis shows that (i) FPV is a mature technology, with plants of 45–150 MW already operating on reservoirs; (ii) a regulating reservoir acts as a hydraulic energy store that can shift pump load to solar hours; (iii) parallel pumps and limits on the number of starts improve both energy use and pump life; and (iv) no published work combines these elements for drainage stations. Six proposals are formulated: station screening, a reference configuration, a solar-following operating rule, saline-water durability requirements, a monitoring programme and a three-phase implementation roadmap. Quantitative targets are expressed as indicators to be verified on site data.

Keywords: drainage pumping station; floating photovoltaics; collector-drainage water; operating mode; self-consumption; Karakalpakstan.

1. Introduction

Irrigated agriculture in the Aral Sea basin depends on drainage: where groundwater cannot leave by gravity, pumping stations lift drainage water into collectors. Energy is the main running cost of such stations, and ageing equipment makes it worse. The Government of Uzbekistan has stated that 235 obsolete pumping stations in Karakalpakstan and the Fergana Valley regions use 1.5–2 times more electricity than they should, and has planned modernisation of 118 of them with EBRD participation [14]. A data analysis of the stations managed by the Karakalpakstan Pumping Stations and Energy Departments also points to the need for better operating modes [15].

The same region offers an unusual resource. The collector-drainage network of the lower Amu Darya was reported to carry up to 2.978 km³ per year, with mineralisation of 3–5 g/l, over about 19,800 km of collectors [16]. Part of this water is already



collected in artificial lakes. A reservoir that receives drainage water is a natural site for a floating PV plant, which needs no land, is cooled by water and reduces evaporation [9–12].

The aim of this paper is to analyse international experience relevant to powering drainage pumping stations with FPV and to formulate proposals for Karakalpakstan. The paper is analytical; the mathematical optimization model on which the proposals rely is outlined in Section 5.3 and will be reported separately.

2. International experience

2.1. Floating photovoltaics at scale

The World Bank estimated a global FPV potential of about 400 GW under conservative assumptions, enough to double the solar capacity installed at the time of the report [1]. Operating plants confirm that the technology has left the pilot stage: Huainan (China) built a 150 MW plant on a lake formed after a coal mine collapsed [2]; Cirata (Indonesia) opened a 145 MW plant in 2023, with a second phase of 500 MW announced [3]; Sirindhorn Dam (Thailand) operates 45 MW in a hydro–floating-solar hybrid [4]. The levelised cost of electricity from FPV is reported to have fallen to 0.05–0.07 USD/kWh [5].

Two cases are especially close to our topic. In Singapore the national water agency PUB contracted a 60 MWp plant on Tengeh Reservoir on a 25-year build-own-operate basis and plans to use its output for water treatment [6]; a water utility thus acts as the anchor consumer of floating PV. In Spain, Redón-Santafé et al. developed polyethylene floating modules that follow the changing water level of an irrigation reservoir; a full-scale plant near Alicante covered 7 % of a 4,700 m² reservoir [7]. A techno-economic study for the 330 ha Aspe irrigation community found that the floating cover would produce more energy than the pumping needed and therefore combined self-consumption with export [8].

2.2. Evaporation and cooling effects

Evaporation suppression depends mainly on the covered fraction of the water surface. Published estimates quote about 31 % reduction at 30 % coverage and about 55 % at 50 % coverage, with higher values for full coverage and much variation between sites [10]. Panel cooling raises energy yield, but reported gains vary widely with climate, structure and water temperature [5, 9]; the model in this study therefore treats the cooling effect as a calibrated coefficient rather than a constant.

2.3. Solar energy for drainage and irrigation pumping



Eshra and Salem studied drainage pump stations on the Algharak drain in Egypt and combined two goals: replacing the fuel used by old drainage pumps with solar power and cutting evaporation from drainage channels; they estimated array area, evaporation loss and CO₂ reduction for two operating scenarios [11]. This is the closest direct precedent, but it is not a floating-reservoir design and it does not optimise the pump schedule.

In Spain, a mixed-integer nonlinear dispatch model for a pumping station with a grid-connected PV plant and two ponds reached up to 99.41 % self-consumed energy and cut energy cost by 21.56 % [12]. Carricondo-Antón et al. showed that splitting one large pump into several parallel pumps lets the station start at lower irradiance: going from one to five pumps raised annual pumped volume by 27 %, reduced the needed PV power by 44.1 % and the installation cost by 13.3 %, while gains stopped beyond five pumps [13]; the same idea was confirmed for two pumps by Gasque et al. [19]. Barbón et al. showed that the size of an FPV plant relative to a pumped-storage plant decides whether joint operation pays, and that the answer depends on process efficiency [24].

Experience from Pakistan adds a caution: in the lower Indus basin, solar tube wells pumped significantly more groundwater than diesel ones (about 1.6 against 1.3×10^3 mm per year) because energy became cheap [25]. For drainage the concern is reversed, but free energy changes operator behaviour and must be reflected in operating rules.

2.4. Control and operating-mode optimization

Reviews of solar pumping converge on a few points: single-stage converters are cheaper but struggle at low irradiance; scalar V/f control is common in commercial units while vector control is rare because it needs motor parameters; and MPPT, fuzzy and neural methods improve energy capture [26, 17, 18]. Sevilla-Camacho et al. added that pump head variation, not only shading, changes the power the array must deliver, and described it with a third-order head–flow relation [27].

For drainage stations the decisive result is that of Wang et al.: unreasonable start-up depths cause frequent starts and stops that shorten pump life; optimizing start-up depths with SWMM and particle swarm optimization for nine stations in Beijing gave 8–114 starts depending on the storm, and optimizing all stations jointly was better than station by station [28]. They limited each pump to six starts per hour and left the energy supply out of the model.

2.5. What the experience tells us



Lesson	Evidence	Meaning for Karakalpakstan
FPV is bankable at 45–150 MW	Huainan, Cirata, Sirindhorn [2–4]	Technology risk is low; site and water-quality risk remain
A water utility can be the anchor consumer	Tengeh, PUB [6]	The station operator can own or contract the FPV plant
Reservoir level can follow water use	Alicante cover [7, 8]	Floating structures must tolerate level changes in the drainage reservoir
Reservoir volume shifts load to solar hours	Dispatch study [12]	Station can pump more at noon and less at night
Several parallel pumps beat one large pump	Spain, five pumps [13]	Choose 4–6 pumps; check against real inflow
Limit starts per hour	Beijing, six per hour [28]	Include as a hard constraint
Cheap energy may change behaviour	Indus basin [25]	Keep groundwater-level targets in the control rule
Solar for drainage is feasible and saves evaporation	Egypt, Algharak drain [11]	Drainage precedent exists in a similar arid climate

3. Karakalpakstan: conditions and gaps

Water. Collector-drainage flow, salinity and network length are cited above [16]; these are old estimates and need updating. Water of 3–5 g/l is much more corrosive than the fresh water in which most FPV plants float, so structure, anchors and cables need a specific durability review.

Energy. Uzbekistan has about 320 sunny days a year; the average solar level in Karakalpakstan is described as medium, and wind potential is highest in this region [21]. FPV is recognised as an opportunity: the country has 25 reservoirs with 1,500 km² of water surface, 890 km² of it in four hydropower reservoirs [4], and regional ADB work noted that FPV potential in Central Asia remains largely untapped [22].

Pumping. More than 40 % of irrigation supply in three districts of South



Karakalpakstan depended on three large and over 20 floating pumping stations, with a yearly energy bill of about USD 2.4 million [23]. This relates to irrigation rather than drainage, but it shows how large energy costs are in the region.

Gaps. (1) Station-level data on drainage inflow, pump hours and energy per cubic metre are not publicly available. (2) No FPV pilot on a drainage reservoir has been found. (3) Operating rules for drainage stations do not account for solar generation. (4) Cooling and evaporation effects are unknown for local conditions.

4. Analysis: why a drainage station is a good FPV customer

A drainage station differs from a solar irrigation pump in three ways. Its load follows inflow, not crop demand. The pumped water has no storage value downstream, so a larger reservoir level swing is acceptable within safe limits. And the reservoir that supplies the pumps can also host the PV plant. These features make the station a flexible load: pumping can be moved within hours without hurting the service, as long as the groundwater-protection level is kept.

The benefit is limited by three factors: the share of the reservoir surface that may be covered; the inflow pattern, which varies strongly between the leaching and the growing seasons; and the grid arrangement, in which surplus solar energy may not be paid for. Self-consumption (SC) and self-sufficiency (SS) are therefore the right first indicators:

$$SC = E_{PV,used} / E_{PV} \quad SS = E_{PV,used} / E_{pumps}$$

Illustration (hypothetical numbers, not field data): a station delivering 0.5 m³/s at 6 m head with a pump efficiency of 0.65 needs about 45 kW; running 3,000 h per year it uses about 136 MWh. With a specific yield of 1,500 kWh/kWp, an FPV plant of about 90 kWp would match this annual energy, but only if pumping coincides with sunshine, which is why reservoir volume and the number of pumps decide SC and SS.

5. Proposals for Karakalpakstan

5.1. Proposal 1: screen the stations

Rank pumping stations by annual energy use, availability of a regulating reservoir with at least 5–10 % of its surface free for FPV, distance to a substation and grid reliability. Select two or three candidates for detailed study. Data needed: hourly or daily pump logs, energy meters, reservoir geometry and the inflow record.

5.2. Proposal 2: a reference configuration

A grid-connected FPV plant on the regulating reservoir, with self-consumption and no export at first; four to six parallel pumps with soft starters and one frequency converter



on the smallest unit; a PV-to-pump power ratio F_p between 1.0 and 1.5 [13, 24]; and water-surface coverage between 20 % and 50 % to balance evaporation savings and operation. Off-grid operation is reserved for stations without reliable supply.

5.3. Proposal 3: a solar-following operating rule

The operator keeps the usual level-based start-up rule but makes it depend on available solar power, so that pumps start earlier when PV output is high. For pump k :

$$h_k^{on}(t) = h_k^0 - \beta_k \cdot P_{PV}(t) / P_{nom}$$

The parameters h^0 and β and the plant size are found by particle swarm optimization over a year-long hourly simulation (water balance, pump hydraulics and PV model), minimising grid energy cost plus a penalty on starts, subject to level limits and at most six starts per hour per pump [28]. A mixed-integer dispatch solution serves as a benchmark [12]. This model is the subject of the author's separate work.

5.4. Proposal 4: durability in saline water

Before procurement, specify corrosion-resistant materials for frames, anchors and connectors, UV-stable HDPE floats, cable glands and connectors rated for continuous immersion, and a cleaning plan for salt and algae. Test one small array on the target water for at least one full year; Spanish experience shows that level-following mooring is essential [7].

5.5. Proposal 5: monitoring and data

Install meters for pump energy, flow and reservoir level, and weather sensors on the reservoir. Record SC, SS, grid energy per cubic metre, starts per hour, water-level violations and evaporation savings. Use the data to calibrate the cooling coefficient and the evaporation reduction before scaling up.

5.6. Proposal 6: implementation roadmap

Phase	Content	Output
1. Study (year 1)	Screening, data collection, model calibration, water-quality and materials review	Ranked station list; calibrated model
2. Pilot (year 2)	One station: FPV plant sized from the model, new operating rule, monitoring	Measured SC, SS, starts, energy per m^3
3. Scale-up (year 3 onward)	Two to three more stations; financing and contracting	Standard design and tender documents



The World Bank and EBRD are already active in the region's water sector [14, 23]; the ADB regional work on FPV offers a further route [22]. A utility-style build-own-operate contract like that of Tengeh [6] could shift investment risk away from the water operator.

6. Risks and limitations

The proposals rest on international evidence and on regional figures that are sometimes old [16]. Specific yield, cooling gain and evaporation reduction are unknown for local conditions. Salinity may shorten equipment life. Grid rules on self-generation and surplus energy were not analysed and must be checked. The groundwater-protection level may restrict how much load can be moved in time. Finally, the figures in this paper are not field data from a Karakalpakstan station.

7. Conclusions

1. FPV is a proven technology on reservoirs; the absence of drainage-station applications in the literature is a research and implementation gap, not a technology gap.
2. A regulating reservoir with FPV above it can shift drainage pumping to solar hours; parallel pumps and a limit of six starts per hour make this feasible without harming pump life.
3. For Karakalpakstan a staged programme is proposed: screening, a pilot with a solar-following operating rule, and scale-up with durability checks in saline water.
4. The first practical step is to collect station-level data to calibrate the model and confirm the indicators SC, SS, grid energy per cubic metre and starts per hour.

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