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Research Article

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Posted Date: November 26th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11864083/v1

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Additional Declarations: The authors declare no competing interests.

Staged Solar Pumping vs Water Trucking to Jebel Jais: A Life-Cycle Sustainability Assessment

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Abstract

Water for the tourism facilities on Jebel Jais, the highest mountain in the United Arab Emirates, is delivered by road tankers that climb about 1,500 m on every trip. This study compares that supply with staged solar pumping: a chain of photovoltaic (PV) pumping stations with break tanks that lifts water from the foot of the mountain to an upper tank at 1,770 m. The pump rating per station was varied from 0.5 to 10 hp, and each layout was sized for the worst month and assessed over 25 years for energy, carbon, cost, structural safety, wildlife water and resilience to road closures. A loaded 22.7 m^3 tanker burns about 54 L of diesel per round trip, or 8.7 kg CO_2e per cubic metre delivered. Staged solar pumping with 5–10 hp stations emits 1.7–1.8 kg CO_2e/m^3 over its life cycle, about 80% less, with a carbon payback of about 5 years; a 1 hp limit would need 132 stations at 40 m^3/day. A 26 km pipeline along the road beats tankers above about 92 m^3/day (67 m^3/day with a carbon price of USD 190/t), and a 12 km direct route above about 39 m^3/day. The GRP tanks pass all structural checks, five troughs supply 0.5 m^3/day to wildlife, and the chain keeps supplying water through the rain and rockfall closures that stop tankers. Staged solar pumping is therefore the low-carbon and more resilient option, and its cost advantage depends on demand and route.

Keywords: solar water pumping; staged pumping; mountain water supply; water trucking; life cycle assessment; levelized cost of water; Jebel Jais

1. Introduction

Supplying water to settlements and facilities high on mountains is costly wherever the source lies far below. Where no pipeline exists, water is usually carried up by road in tankers, a solution that is quick to start but energy-intensive, exposed to fuel prices and dependent on heavy vehicles on steep roads. Studies of mountain supply schemes have instead favoured fixed systems that lift water in stages to intermediate reservoirs and then distribute it by gravity [1]. In urban settings, informal tanker deliveries have been shown to carry the highest energy and carbon intensity of all water sources: in a Beirut

neighbourhood, tanker trucks and bottled water had the highest energy intensity per cubic metre, and informal sources together used 83% of the energy for 23% of the delivered volume [2].

Photovoltaic water pumping is a mature alternative to diesel and grid pumping in remote places. Reviews report that it is economically viable against electricity or diesel, with payback periods of 4–6 years for some systems [3], and that its low operating cost and zero direct emissions make it attractive despite the higher investment [4,5]. Life cycle studies confirm that PV pumping has lower environmental burdens than grid or diesel pumping over a 30-year life [6], and that manufacturing dominates its footprint, about 55% of the total in one Inner Mongolian system [7]. Recent work has extended PV pumping to high heads and high altitudes: a battery-free deep-well system in eastern Türkiye lifted water against 111.7 m with a pump efficiency of 47.9% and a levelized cost of USD 0.112/m^3 [8], and a system in the mountains of Al Baha, Saudi Arabia, met about 98% of the daily demand at a total head of 60 m [9].

For much larger lifts, the head must be split among several stations. Cascade pressurized pump stations in mountain areas are prone to pump-trip transients and need coordinated control [10]. A recent controller for solar-powered pumps in series on hilly terrain kept each station synchronised without communication links, using a reserve tank and level sensing at each station [11]. Experience with solar lift irrigation in Nepal's mid-hills shows that such projects succeed only when feasibility, cost, ownership and operation and maintenance are planned together, and that governance and social dimensions are often neglected [12]. Multi-criteria frameworks for alternative water sources likewise call for economic, environmental and social criteria to be weighed alongside technical feasibility [13]. On the material side, life cycle studies of water tanks [14] and of HDPE and GRP pipes in the UAE [15] show that the production of materials dominates the impacts of the storage and conveyance infrastructure.

Three gaps remain. First, no study has compared, on a common life-cycle basis, the delivery of water by tanker up a high mountain road with a staged solar pumping system serving the same point. Second, the effect of the pump rating per station, which decides how many stations, tanks and arrays are needed, has not been examined; small pumps of about 1 hp are attractive for simplicity and maintenance, but their consequences for the number of stations have not been quantified. Third, the sustainability of such systems has rarely been assessed in all its dimensions, environmental, economic and social, against national targets.

This study addresses these gaps for Jebel Jais in Ras Al Khaimah, the highest mountain in the UAE. Its objectives are to: (i) design staged solar pumping layouts for pump ratings of 0.5–10 hp and demands of 5–250 m^3/day; (ii) model the fuel use and emissions of tanker delivery on the mountain road; (iii) compare the two on energy, life-cycle carbon and levelized cost of water; and (iv) assess the social benefits and the contribution to the Sustainable Development Goals and UAE strategies.

2. Study area

Jebel Jais rises to 1,934 m on the border between Ras Al Khaimah and Oman, in the northern Hajar Mountains [16]. A 36 km road built by the emirate starts in the Wadi Al Beah area at the foot of the range and winds to the upper plateau [17] (Fig. 1). The paved climb is 27.7 km long, gains 1,543 m at an average gradient of 5.6%, and includes 11 hairpin bends, with its top at about 1,827 m [18]. Since the road opened, the upper mountain has become a tourism zone with, from bottom to top, the Bear Grylls Explorers Camp, viewing points, the Jais Viewing Deck Park with the restaurant 1484 by Puro at 1,484 m,

the zipline launch, and Camp 1770, the highest campsite in the UAE [16]. The UAE–Oman border runs a few hundred metres east of these facilities. The emirate received a record 1.35 million overnight visitors in 2025 and targets more than 3.5 million a year by 2030 [19], and a mountain lodge on Jebel Jais was scheduled to open in the last quarter of 2026 [20].

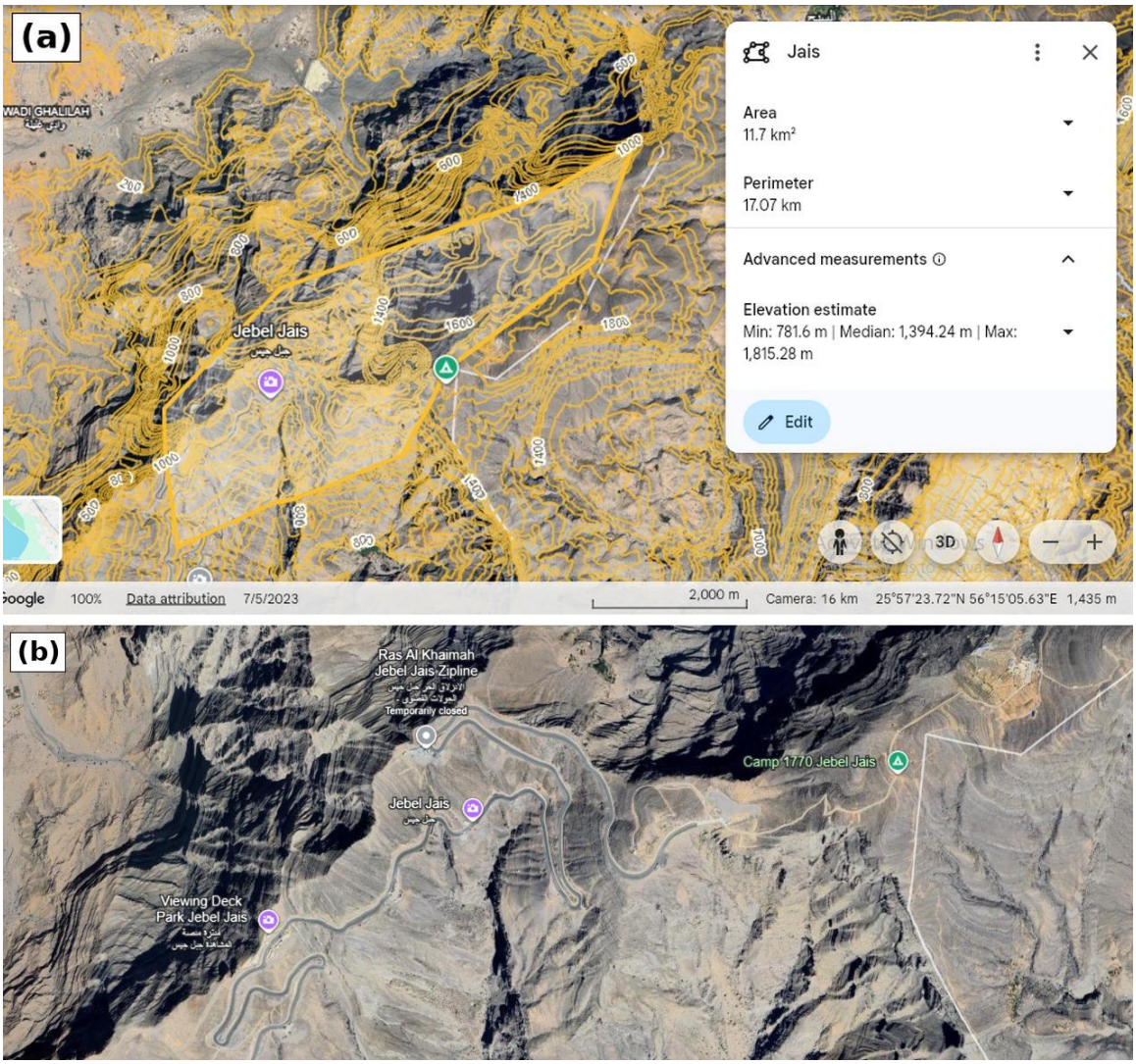


Fig. 1. Study area on Jebel Jais, Ras Al Khaimah: (a) the served area delineated by the authors (11.7 km², perimeter 17.1 km, elevation 782–1,815 m, median 1,394 m) over 40 m elevation contours (scale bar 2,000 m); (b) the mountain road with the zipline, the Jebel Jais viewpoint, the Viewing Deck Park and Camp 1770. Base imagery and contours: Google Earth. Map lines do not necessarily depict accepted national boundaries.

No piped water supply to the upper facilities has been reported. Water tankers on the Jebel Jais road have been documented since the road was built [21], and the facilities rely on stored water that is trucked up. Neither the current tanker trips nor the facility demands are published; the analysis therefore uses transparent assumptions (Table 1) and a wide range of demands (5–250 m³/day).

The upper facilities around the Jebel Jais viewpoint (about 25°56′ N, 56°09′ E) form the core of the served area, which the authors measured on Google Earth as about 1.32 × 2.19 km (2.9 km²) between 1,200 m and 1,636 m (Fig. 2). The whole served area around the summit road and the facilities covers about 11.7 km² (perimeter 17.1 km), with ground elevations of 782–1,815 m (median 1,394 m) (Fig. 1a). These are extents of land served, not built footprints. Spread over them, the base demand of 40 m³/day equals about 34 L/ha/day over the whole area and 140 L/ha/day over the core, or 1.2 and 5 mm of water a year.

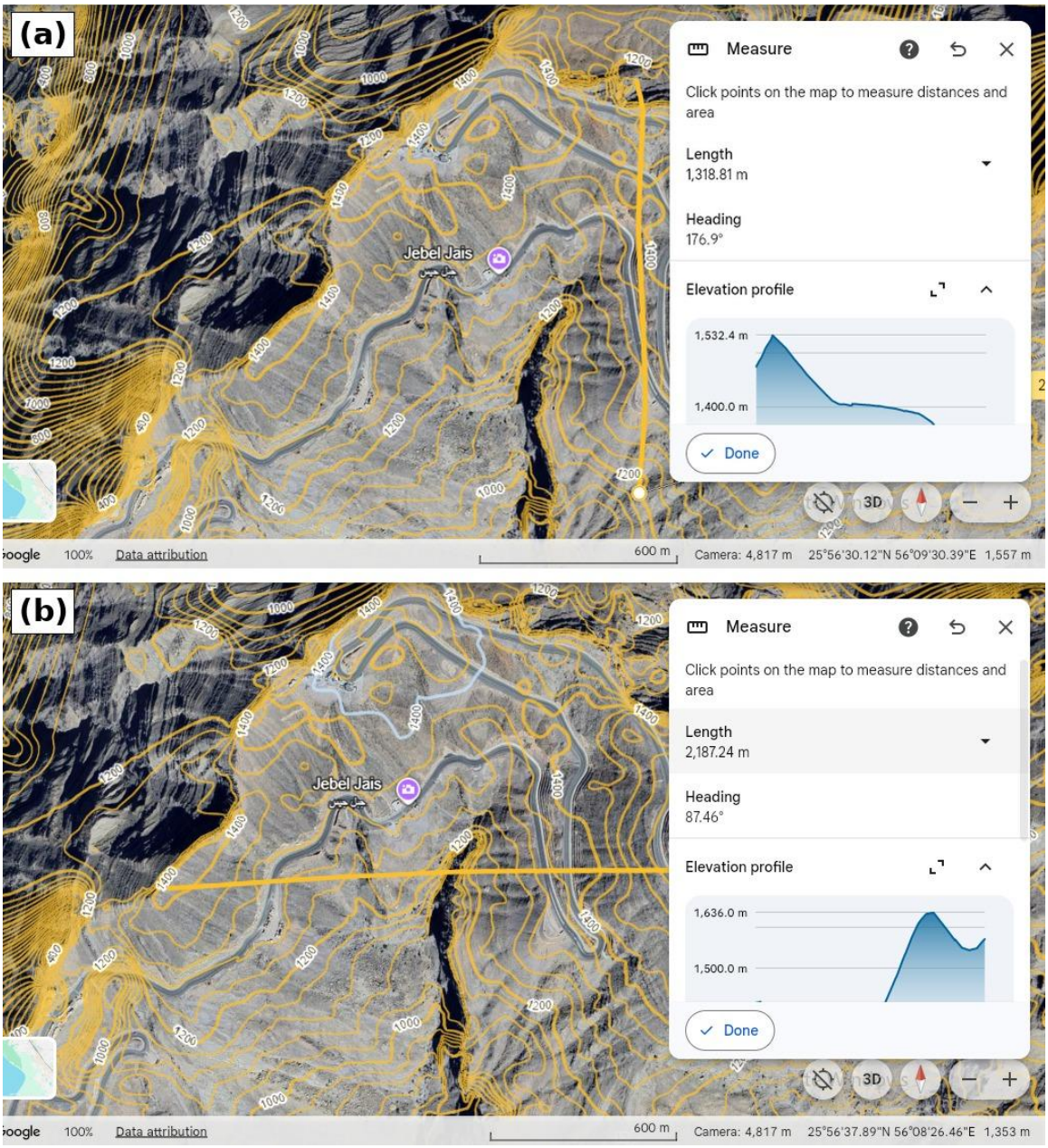


Fig. 2. Extent of the served area around the upper facilities, measured on Google Earth: (a) north–south line, 1,318.8 m; (b) east–west line, 2,187.2 m, each with its elevation profile (scale bar 600 m; 40 m contours). Base imagery: Google Earth. Map lines do not necessarily depict accepted national boundaries.

Table 1. Indicative daily water demand of the upper facilities (base case; assumptions of this study).

Use	Basis	Demand (m³/day)
Restaurants and cafés	300 covers × 25 L	7.5
Camps, cabins and lodge	60 guests × 250 L	15.0
Day visitors (toilets, washing, drinking)	1,500 visitors × 10 L	15.0
Operations, cleaning, landscaping	allowance	2.5
Total (base case)		**40**

For the comparison, the foot of the climb (284 m) is the common starting point: water reaches it by the same means in both options (a short tanker run or a connection to the lowland network), so that leg is excluded. The delivery point is an upper service tank at 1,770 m, from which water would flow by gravity to the facilities below it. The static lift is therefore 1,486 m.

3. Methods

3.1 Staged solar pumping layout

The proposed system has a base tank at 284 m, N identical pumping stations in series along a pipeline, and an upper service tank at 1,770 m. Each station has one PV-direct pump of a given rating, its own PV array (1.25 kWp per kW of pump input, a common oversizing for PV-direct pumps) and a small break tank holding 2 hours of flow, which absorbs differences between neighbouring stations. Because all arrays see the same sky, the stations run together, as in the communication-free series scheme of [11]. The base and upper tanks each hold two days of demand.

The pump rating per station P (0.5, 1, 2, 3, 5, 7.5 and 10 hp; 1 hp = 0.746 kW) is the design variable. The wire-to-water efficiency η rises with size, from 0.38 at 0.5 hp to 0.45 at 1 hp, 0.53 at 5 hp and 0.57 at 10 hp, in line with the 47.9% measured for a high-head PV pump [8]. On the design day the pumps run for an equivalent full-power time t_p, so the flow is given by Eq. (1), where Q_d is the daily demand (m³/day):

$$q = \frac{Q_d}{3600\, t_p} \tag{1}$$

The head one pump can deliver at that flow, and the static rise per station that it allows once pipe friction is included, are:

$$H_{max} = \frac{\eta P}{\rho g q}, \qquad \Delta z = \frac{H_{max}}{1 + J\, L/\Delta Z} \tag{2}$$

where J is the friction gradient (m/m, Hazen–Williams with C = 150, plus 10% for fittings), L the pipeline length and ΔZ = 1,486 m the total static lift. The number of stations is N = [ΔZ/Δz]. The pipe is the smallest HDPE PE100 size that keeps the velocity at or below 1.2 m/s; PN16 is used where 1.3 times the station head is within 160 m and PN25 otherwise. The base case follows the road corridor (L = 26 km); a shorter direct route up the slope (L = 12 km) is tested as a scenario.

3.2 Solar resource and sizing

A daily typical year of plane-of-array irradiation was built with the Haurwitz clear-sky model at 25.9° N on a 25° south-facing plane, scaled to a mean global horizontal irradiation of 5.75 kWh/m²/day, the middle of the 5.5–6.0 kWh/m²/day reported for the mountains of Al Baha [9]. The resulting monthly irradiation ranges from 5.31 kWh/m²/day in December to 6.66 kWh/m²/day in April (2,099 kWh/m²/year on the horizontal). A performance ratio of 0.78 was used, as measured at Al Baha [9]; the cooler air at altitude would improve it slightly, since PV efficiency falls by about 0.48% per °C [22]. The stations were sized by the worst-month method [23,24]: the December day sets t_p = 5.18 h. Every day of the year was then checked; with this sizing, all designs meet the demand on every day of the typical year.

3.3 Tanker delivery model

A 5,000-gallon road tanker (22.7 m³ payload, 12 t tare) is assumed [25]. The fuel for the loaded climb follows from the work against gravity, rolling resistance and air drag:

$$F_{up} = \frac{mg\Delta Z + C_{rr} mg L_r + 1/2 \rho_a C_d A v^2 L_r}{\eta_e \, LHV} \quad (3)$$

with m = 34.7 t, L_r = 26 km, C_{rr} = 0.008, $C_d \cdot A$ = 0.65 × 8.5 m² at 35 km/h, an engine efficiency η_e = 0.33 and LHV = 36 MJ/L. The empty descent uses engine braking at idle fuel (3 L/h for 0.8 h), and 2 L per trip are added for manoeuvring and unloading. Studies of trucks on gradients confirm that the interaction of load and slope dominates fuel use [26]. Diesel emits 2.68 kg CO_2/L at the exhaust; 20% is added for fuel production and 15% for vehicle manufacture and maintenance.

3.4 Life cycle assessment

The functional unit is 1 m³ of water delivered to the 1,770 m tank, over a 25-year life, from the foot of the climb. The solar system includes PV, pumps (replaced every 8 years), pipe, tanks and station works; its operation emits nothing. Emission factors are: PV system 1,450 kg CO_2e/kWp, from 810 kg CO_2e/kWp for glass–backsheet modules made in China [27] divided by the 56% share of modules in PV life-cycle emissions [28]; HDPE pipe 6.7 and GRP tanks 6.9 kg CO_2e/kg, from a UAE life cycle study of the two pipe materials [15]; tanks 70 kg of GRP per m³; pumps 25 kg/kW at 6 kg CO_2e/kg; and 600 kg CO_2e of concrete and steel per station. For reference, grid pumping was evaluated with the UAE grid factor of 0.556 kg CO_2/kWh in 2021 and 0.27 kg CO_2/kWh targeted for 2030 [29].

3.5 Life cycle cost

The levelized cost of water (LCOW) is the annualized cost divided by the annual volume:

$$LCOW = \frac{(C_0 + C_{rep})\, CRF + C_{O\&M}}{365\, Q_d}, \qquad CRF = \frac{r(1+r)^n}{(1+r)^n - 1} \quad (4)$$

with r = 6% and n = 25 years. Solar costs (AED): PV 3,000/kWp; pumps 2,500/kW plus 1,500 per unit; tanks 600/m³; 15,000 per station for civil works and controls; pipeline 150/m supplied and laid along the road shoulder in rock (range 100–300/m); O&M 1.5% of capital a year. Tanker costs: diesel at AED 4.75/L (November 2026 [30]; AED 2.67/L in November 2025 [31]), a driver at AED 3,000 a month plus 50% on-costs [32] for three trips a day, a truck at AED 350,000 over 10 years, and AED 0.6/km for maintenance. A carbon-priced comparison adds the social cost of carbon of USD 190/t CO_2 [33] (AED 698/t).

3.6 Social and policy appraisal

The social dimension was assessed by indicators that follow from the model: heavy-vehicle trips and kilometres on the mountain road, exposure to price shocks and supply interruption, and local services enabled. The results were mapped to Sustainable Development Goals 6, 7, 9, 11 and 13 and to the UAE Water Security Strategy 2036 and the UAE Net Zero by 2050 initiative [34,35].

3.7 Structural design of the tanks

Each station has a sectional glass-reinforced plastic (GRP) break tank of 5 × 2 × 2 m (18 m³ at 0.2 m freeboard), and the upper tank is 8 × 5 × 2.2 m (80 m³, two days of demand). Both stand above ground on a 0.25 m reinforced concrete plinth on rock. They were checked for wall pressure, bearing, overturning, sliding and roof uplift under wind with the tank empty, overturning and sliding under earthquake with the tank full, and sloshing, following ASCE/SEI 7-22 [36] in simplified form with the 475-year short-period spectral acceleration of 0.30 g computed for Ras Al Khaimah [37], and ACI 350.3 for sloshing [38]. The equations, inputs and results are given in Supplementary Material S2.

3.8 Water for wildlife

The water chain crosses the habitat of the mountain's wild mammals, among them the Arabian red fox, wildcats and wild goats [16]; the Arabian tahr of the Hajar Mountains is listed as Endangered [39]. Pumping, diversions and fencing can reduce wildlife access to water, and managers of arid ecosystems have long provided artificial water points [40]. The design therefore adds a trough at five break tanks between about 600 m and 1,600 m, fed by a float valve, placed 20–50 m outside the station fence, shaded, shallow, with an escape ramp for small animals, and sized for about 100 L/day. The total of 0.5 m³/day (1.25% of the base demand) is an assumption added to the design flow; as the troughs are fed from intermediate tanks, the extra PV energy and cost are at most 1.25%.

Artificial water has known side effects: pressure on nearby vegetation, altered movements, more predation and disease, and competition among species [40]. Stagnant water is a particular hazard; at least 45 desert bighorn sheep died in 1995 from botulism in water tanks [41]. The troughs are therefore kept flowing and cleaned, can be shut by season, and should be monitored with camera traps [40], at sites agreed with the emirate's environmental authority.

3.9 Resilience to rockfall and road closures

Tanker supply depends on one road. The police closed it during heavy rain in November 2019 [42], January 2020 [43] and December 2022 [44], and once for falling rocks, reopening it after the rocks and debris were cleared [45]. In December 2025 about 127 mm of rain fell in two days and a rockslide was cleared on 19 December [46]; parts of the road and paths were damaged, and the mountain was still closed in January 2026 [47]. Rockfall on mountain roads in western Arabia comes mainly in rainy seasons from steep, jointed cut slopes [48], as on this road. Resilience was measured by the unserved days U of a closure lasting D days, with 2 days of storage autonomy A at the top in both options, and by the storage V_{req} that tankers would need to bridge it:

$$U = \max(0,\, D - A), \qquad V_{req} = Q_d\, D \tag{5}$$

For the solar chain, a road closure does not stop pumping. The storm days themselves cut the solar output, which the same storage covers, and the remaining risk is physical damage to the pipe or a

station by rockfall or flood. This is handled by design: the pipe is buried at least 0.8 m deep, protected by concrete cover below known rockfall cuts and at wadi crossings, and divided by an isolation valve at every station, so that a break empties only one segment; the stations are sited away from the toe of cut slopes and outside wadi channels.

4. Results

4.1 Station layouts and the pump-rating limit

Table 2 gives the staged layouts for the base demand of 40 m³/day, and Fig. 3 shows how the number of stations falls as the pump rating rises. On the December design day the pumps run 5.18 equivalent full-power hours, so each station must pass 2.15 L/s. A DN63 PE100 pipe carries this at 1.03 m/s with a friction gradient of 23.7 m/km, which adds about 620 m of friction head over 26 km to the 1,486 m static lift.

Table 2. Staged solar pumping layouts for 40 m³/day along the 26 km road route.

Pump rating	Stations	Static rise per station (m)	Station head (m)	Pipe class	PV (kWp)	Energy (kWh/m³)	Tank volume (m³)	Capital (AED million)	LCOW (AED/m³)	Life-cycle CO_2e (kg/m³)
0.5 hp	313	5	7	PN16	146	15.1	4,982	12.78	86.8	8.38
1 hp	132	11	16	PN16	123	12.7	2,184	8.00	54.1	4.26
2 hp	62	24	34	PN16	116	11.9	1,103	6.16	41.6	2.67
3 hp	40	37	53	PN16	112	11.5	763	5.58	37.5	2.17
5 hp	23	65	91	PN16	107	10.8	500	5.12	34.4	1.77
7.5 hp	15	99	140	PN25	105	10.4	376	4.90	32.9	1.83
10 hp	11	135	191	PN25	103	10.1	315	4.78	32.0	1.73

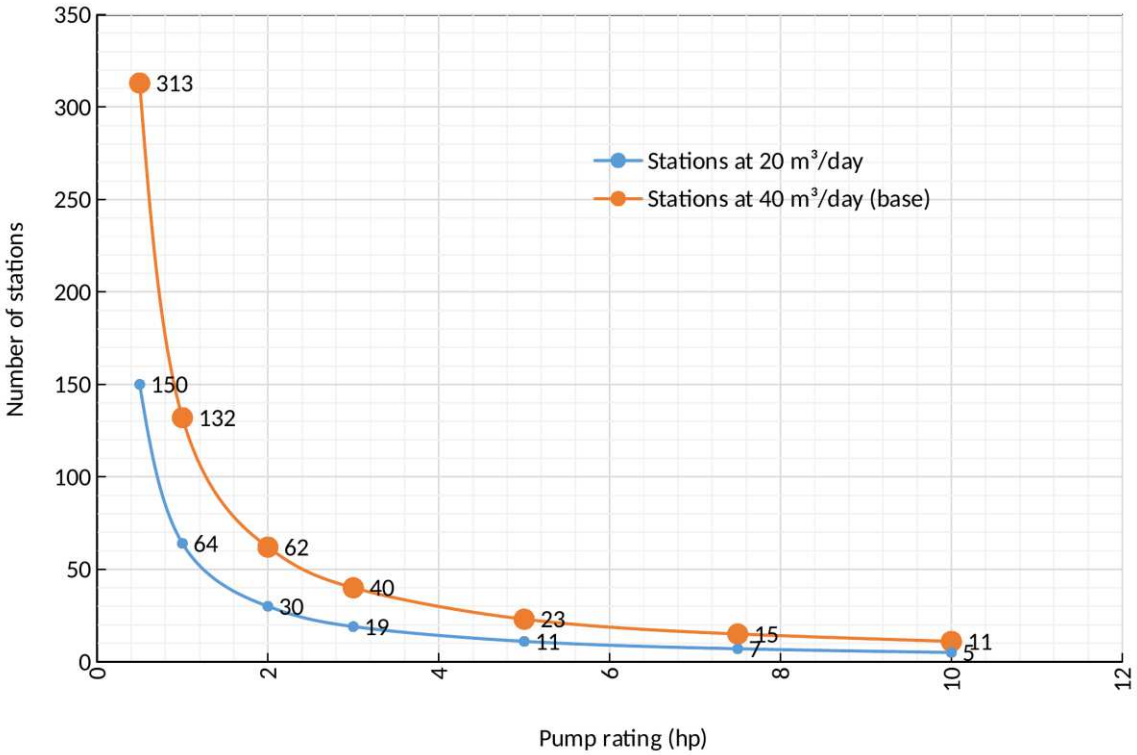


Fig. 3. Number of pumping stations in series from 284 m to 1,770 m versus pump rating per station, for 20 and 40 m³/day (road route, 26 km pipeline).

The total pumping power hardly depends on the rating; the rating decides how that power is divided, and so how many stations, tanks and arrays are built. With a 1 hp limit, each station lifts only 11 m at this flow, and 132 stations would be needed, one about every 200 m of road. Small pumps are also less efficient, so the energy rises from 10.1 kWh/m³ at 10 hp to 12.7 kWh/m³ at 1 hp, and the 2,184 m³ of break tanks become the largest embodied-carbon item. At 5 m³/day, however, 13 stations of 1 hp suffice. For the base demand, 5–10 hp stations give the lowest cost and carbon; 5 hp keeps every station within PN16 pipe, while 7.5–10 hp needs PN25.

4.2 Tanker delivery

The loaded climb of a 34.7 t tanker requires 584 MJ at the wheels, or 49.2 L of diesel; the descent and handling add 4.4 L, giving 53.6 L per round trip, 2.36 L per cubic metre delivered. This equals 23.6 kWh of fuel energy and 8.7 kg CO_2e per cubic metre, including fuel production and the vehicle. At 40 m³/day the mountain road carries 643 tanker climbs a year, 33,400 km of heavy-vehicle travel and 34,500 L of diesel. The delivered cost is AED 17.6/m³, of which fuel is 64%; at the November 2025 diesel price it would be AED 12.7/m³.

4.3 Life-cycle energy and carbon

Table 3 and Fig. 4 compare the options per cubic metre. The tanker uses 2.3 times more energy than the solar pumps, and all of it is fossil fuel. With 10 hp stations the solar system emits 631 t CO_2e over 25 years: the pipe 43%, PV 24%, tanks 24%, pumps 8% and station works 1%. That is 1.73 kg CO_2e/m³, 80% less than the tanker, and the embodied carbon is repaid by avoided diesel in about 5 years. Over the life

of the system about 2,550 t CO_2e are avoided. With 1 hp stations the payback stretches to 12 years and with 0.5 hp to 24 years, because of the large number of tanks. Grid pumping with the same hydraulics would emit 6.0 kg CO_2/m^3 at the 2021 grid factor and 2.9 kg CO_2/m^3 at the 2030 target, both above solar.

Table 3. Energy and life-cycle carbon per cubic metre delivered to 1,770 m (40 m^3/day).

Option	Energy (kWh/m^3)	Energy source	Life-cycle CO_2e (kg/m^3)	Carbon payback (years)
Tanker (22.7 m^3)	23.6	Diesel	8.73	–
Grid pumping, 2021 factor	10.8	Grid	6.0 (operation only)	–
Grid pumping, 2030 factor	10.8	Grid	2.9 (operation only)	–
Solar, 1 hp stations	12.7	PV	4.26	12.2
Solar, 5 hp stations	10.8	PV	1.77	5.1
Solar, 10 hp stations	10.1	PV	1.73	5.0

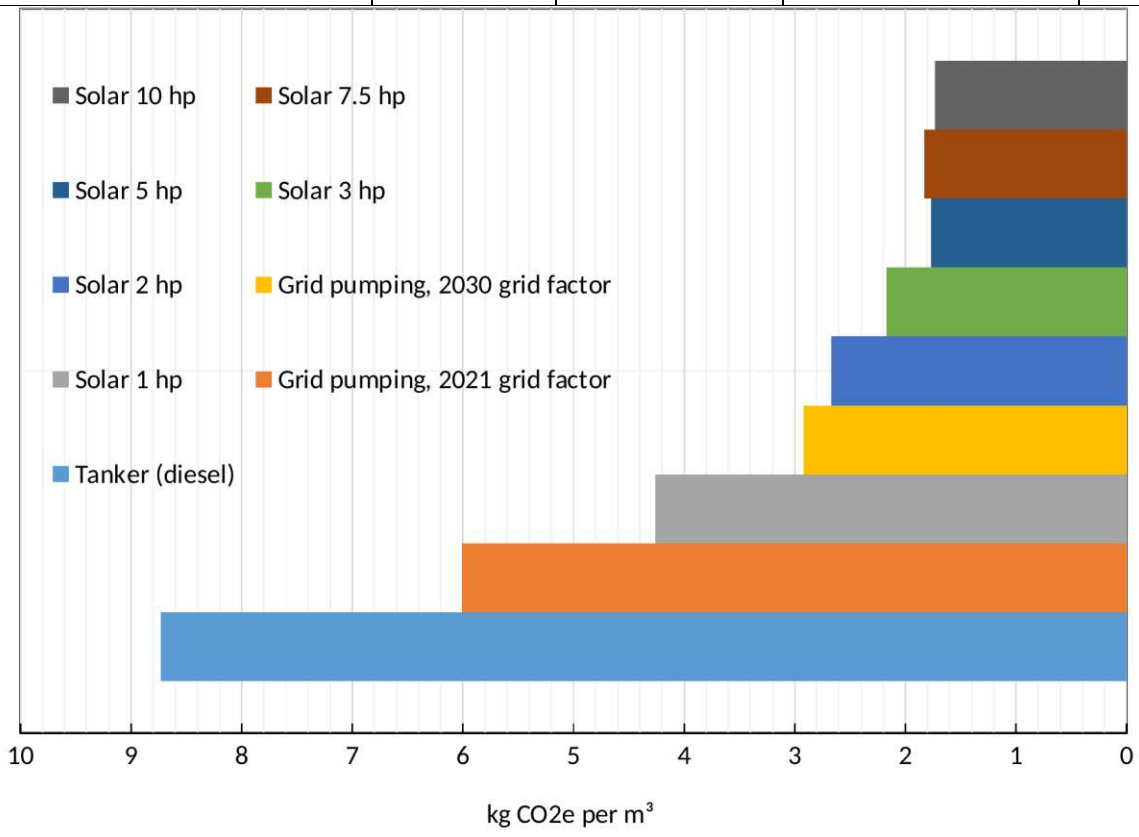


Fig. 4. Life-cycle greenhouse gas emissions per cubic metre delivered to the upper tank at 40 m^3/day: tanker delivery, grid-powered pumping (2021 and 2030 grid factors) and staged solar pumping by pump rating (road route).

4.4 Cost of water

The capital cost of the 10 hp layout is AED 4.78 million, of which the 26 km pipeline is 82%. Its LCOW at 40 m³/day is AED 32.0/m³, about 1.8 times the tanker cost; along this route the solar system is the more expensive option at the base demand. Because the pipeline cost is almost fixed while tanker costs grow with every trip, the comparison turns with demand and route length (Fig. 5).

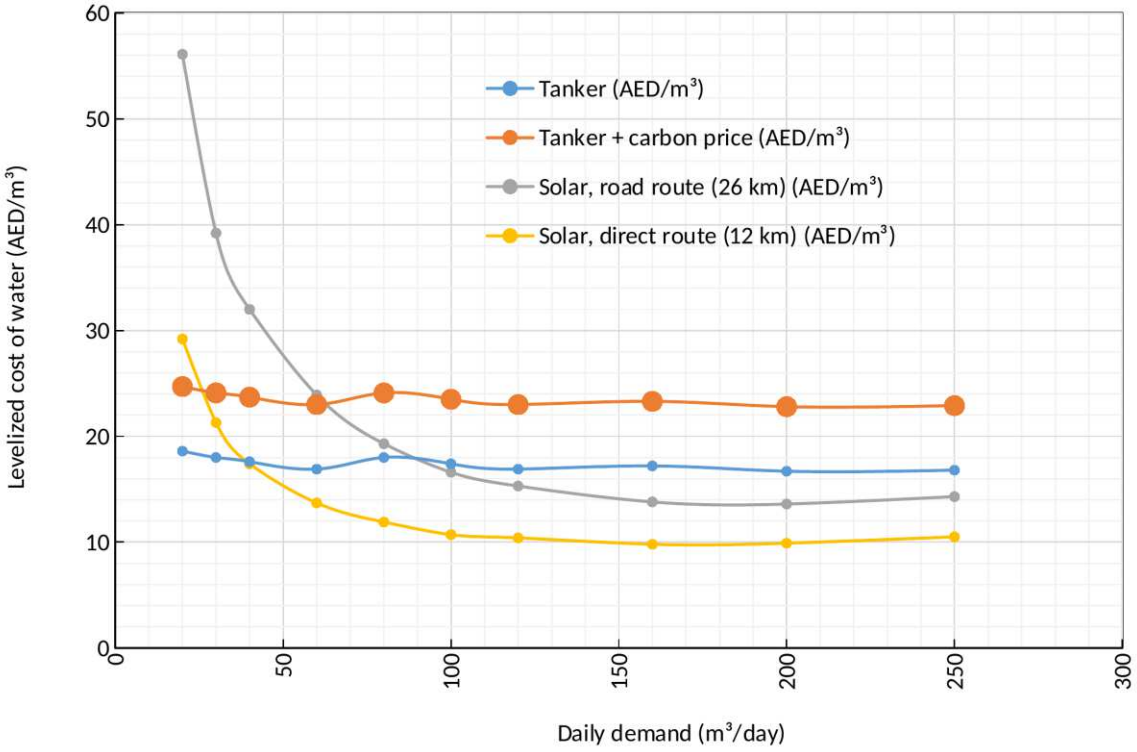


Fig. 5. Levelized cost of water versus daily demand for tanker delivery and for staged solar pumping with 10 hp stations on the road and direct routes (carbon price USD 190/t CO_2).

Table 4. Demand at which staged solar pumping (10 hp stations) becomes cheaper than tankers.

Pipeline route	Without carbon price (m³/day)	With USD 190/t CO_2 (m³/day)
Road corridor, 26 km	92	67
Direct route, 12 km	39	27

4.5 Structural checks of the tanks

All checks pass with factors of safety of 2.4 or more against 1.5 required (Supplementary Table S1). The empty break tank under wind governs; bearing pressures of 20–24 kPa are less than a tenth of the assumed 300 kPa allowable on rock, and sloshing waves of 7–8 cm stay inside the 0.2 m freeboard. A GRP shell cannot resist a falling rock, so exposed sites need to be kept away from cut slopes or protected by an uphill catch fence (Section 3.9).

4.6 Resilience to road closures

Table 5 applies Eq. (5) to the closures on record, and Fig. 6 extends it to any closure length. The short rain closures are covered by 2 days of storage in either option. The December 2025 closure lasted more than two weeks: with tankers, the top would have been without supply for more than 12 days unless storage were raised above 560 m³, seven times the upper tank. The facilities were closed then too, but staff, maintenance crews and the wildlife troughs still need water, and a closure of that length in mid-season would cut the supply to visitors. The solar chain keeps pumping while the pipe and stations are intact, and its storage covers the storm days with low solar output.

Table 5. Road closures on record and their effect on supply to the top (40 m³/day, 2 days of storage at the top).

Event	Reported cause	Closure	Tankers	Staged solar pumping
November 2019 [42]	Heavy rain	Road closed by police; length not reported	Covered if $D \leq 2$ days	Pumping continues
January 2020 [43]	Rain	Road closed by police; length not reported	Covered if $D \leq 2$ days	Pumping continues
December 2022 [44]	Rain, flooded valleys	Road closed by police; length not reported	Covered if $D \leq 2$ days	Pumping continues
Date not reported [45]	Falling rocks and heavy rain	Reopened after rocks and debris were cleared	Covered if $D \leq 2$ days	Continues unless the pipe is hit
December 2025 [46,47]	127 mm in two days, rockslide, road damaged	About 19 December to at least January 2026 (> 14 days)	$U > 12$ days; $V_{req} > 560$ m³	Storm days covered by storage; pumping continues

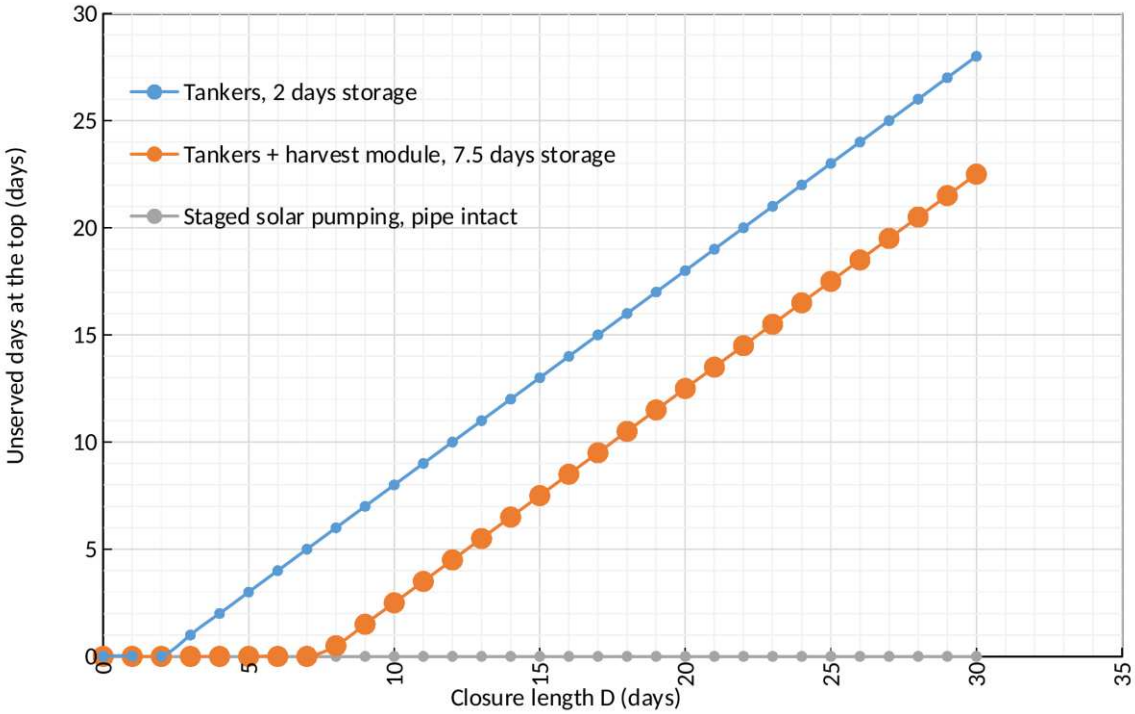


Fig. 6. Unserved days at the upper facilities versus road-closure length at 40 m³/day, for tanker supply with 2 and 7.5 days of storage and for staged solar pumping with an intact pipeline.

Along the road, solar pumping is cheaper than tankers above about 92 m³/day, or 67 m³/day once carbon is priced. On a 12 km direct route the threshold falls to 39 m³/day, close to the base demand, and to 27 m³/day with a carbon price. At 160 m³/day, a plausible demand if visitor numbers grow towards the 2030 target, the solar LCOW is AED 13.8/m³ along the road and AED 9.8/m³ on the direct route, against AED 17.2/m³ by tanker.

5. Sustainability assessment

5.1 Environmental

The environmental case for staged solar pumping is strong at every demand. With 5–10 hp stations, it cuts life-cycle emissions per cubic metre by about 80%, removes all operational fuel use, and repays its embodied carbon in about 5 years of a 25-year life. At the base demand it avoids about 34,500 L of diesel and 100 t CO_2e a year. The pipe is the largest embodied item, so a shorter route lowers both cost and carbon: on the 12 km direct route the footprint falls to about 1.2 kg CO_2e/m³. Fewer, larger stations also disturb fewer sites on a mountain whose high-elevation steppe is already considered vulnerable to habitat loss [16]: 11 sites with 10 hp pumps against 132 with a 1 hp limit.

A fixed supply can also serve wildlife. The five troughs (Section 3.8) provide 0.5 m³/day along the elevation range every day, including hot days, when mountain ungulates drink most [40], and days when the road is closed, for at most 1.25% more PV energy, or about AED 0.4/m³. Tankers could fill troughs only beside the road, and only with extra trips. Managed as in Section 3.8, the troughs make the chain a measure for the Endangered Arabian tahr [39] and the other mammals of the mountain.

5.2 Economic

The economic case depends on scale. At 40 m³/day along the road, tankers remain cheaper (AED 17.6 against 32.0/m³), but the solar system has almost no running cost and no fuel exposure. UAE diesel cost AED 2.67/L in November 2025 and AED 4.75/L in November 2026 [30,31], after a rise of about 80% from February 2026 [49]; the tanker cost moved with it from AED 12.7 to 17.6/m³, while the solar cost is fixed at construction. With demand expected to grow towards the emirate's target of 3.5 million visitors a year by 2030 [19], the system can be built in phases: the pipeline and upper tank first, sized for future flow, then stations and arrays as demand grows.

5.3 Social

The social benefits come mainly from taking heavy vehicles off a steep, winding tourist road. At 40 m³/day the system removes 643 loaded tanker climbs and 33,400 heavy-vehicle kilometres a year, and about 2,570 climbs at 160 m³/day. Each climb is a 35 t vehicle on 11 hairpin bends shared with tourist cars, cyclists and, on race days, the UAE Tour [18], and every descent relies on the brakes of an empty heavy vehicle. Fewer trucks also mean less noise and exhaust at viewpoints and camps, and a supply independent of drivers, road access and fuel prices, which matters on a mountain where all operations were suspended after severe weather in December 2025 [50]. Each station is a small, standard unit that local technicians can maintain, but experience elsewhere shows that ownership, a funded maintenance plan and clear responsibilities decide whether such systems last [12].

The road record (Table 5) shows closures for rain or rockfall in 2019, 2020, 2022 and 2025, one of them longer than two weeks. Pumping removes this single point of failure but moves part of the exposure to the pipe on the same slopes, so burial, concrete cover and isolation valves are part of the social case; a direct route away from the road cuts would avoid most of it.

5.4 Contribution to the SDGs and UAE strategies

Table 6. Contribution of staged solar pumping at Jebel Jais to the Sustainable Development Goals and UAE strategies.

Goal or strategy	Contribution	Indicator from this study
SDG 6 Clean water	Reliable supply to the upper mountain, independent of road access	Demand met on every day of the typical year
SDG 7 Clean energy	Water lifted by on-site solar power instead of diesel	10–12 kWh/m³ of PV electricity; 34,500 L/yr diesel avoided (40 m³/day)
SDG 9 Infrastructure	Modular, staged infrastructure that grows with demand	11–23 standard stations (5–10 hp)
SDG 11 Sustainable communities and tourism	Fewer heavy vehicles on a tourist mountain road	643–2,570 tanker climbs/yr avoided
SDG 13 Climate	Lower life-cycle emissions	−80% CO_2e/m³; about 100 t CO_2e/yr

Goal or strategy	Contribution	Indicator from this study
action		avoided at 40 m^3/day
SDG 15 Life on land	Water for wild mammals along the elevation range; fewer, larger station sites	0.5 m^3/day at 5 wildlife troughs; 11–23 sites (5–10 hp)
UAE Water Security Strategy 2036 [34]	Secure, efficient water supply to remote areas	Storage of 2 days at base and top
UAE Net Zero by 2050 [35]	Removes a diesel-dependent service	Zero operational emissions

6. Sensitivity and discussion

6.1 Sensitivity

Table 7 shows how the base-case results (40 m^3/day, 5 hp stations, road route) respond to the main uncertain inputs. The LCOW is most sensitive to the pipeline cost per metre, the route length and the discount rate, which together decide the annualized cost of the pipe. The solar resource and PV price matter much less, because PV is only 6% of the capital. The life-cycle carbon stays between 1.45 and 2.08 kg CO_2e/m^3 in every case, well below the 8.7 kg CO_2e/m^3 of the tanker, so the environmental conclusion is robust. The tanker cost moves only with the diesel price.

Table 7. Sensitivity of the base case (40 m^3/day, 5 hp stations, 26 km road route; base LCOW AED 34.4/m^3 and 1.77 kg CO_2e/m^3; tanker AED 17.6/m^3).

Parameter	Low – high	Solar LCOW (AED/m^3)	Solar CO_2e (kg/m^3)	Tanker cost (AED/m^3)
Pipeline cost (AED/m)	100 – 300	26.1 – 59.3	1.77	17.6
Pipeline length (km)	18 – 30	25.9 – 38.6	1.52 – 1.89	17.6
Discount rate	3% – 9%	27.2 – 42.5	1.77	17.2 – 18.1
Mean GHI (kWh/m^2/day)	5.0 – 6.3	36.5 – 33.1	2.08 – 1.59	17.6
PV cost (AED/kWp)	2,200 – 4,000	33.8 – 35.0	1.77	17.6
Diesel price (AED/L)	2.67 – 6.00	34.4	1.77	12.7 – 20.6
HDPE factor (kg CO_2e/kg)	2.5 – 8.0	34.4	1.45 – 1.86	17.6
PV factor (kg CO_2e/kWp)	800 – 2,000	34.4	1.58 – 1.93	17.6

6.2 Discussion

The results answer the question that motivated this study: can water be lifted to the summit in stages by solar pumps of no more than 1 hp? Physically it can, for any rating. But the number of stations is the hydraulic power divided by the power of one pump, so a 1 hp limit multiplies stations, tanks and sites. It suits flows up to about 5–10 m³/day (13–31 stations) and small branch lifts; for a trunk supply of tens of cubic metres a day, 5–10 hp stations are better on cost, carbon, pump efficiency and number of sites.

Second, the pipeline, not the solar equipment, decides the economics: at 82% of the capital along the road, its route and cost per metre matter more than PV prices or irradiation. The contour map suggests that much of the 1,500 m rise is concentrated in the escarpment below the viewpoints, which a direct pipe could climb in a few kilometres, so surveying such a route is the first feasibility task. The small pipe assumed (DN63 at 1 m/s) adds about 42% friction head; a larger pipe would save pumping energy and PV at the cost of more pipe material, an optimum to be found at design stage.

Third, staged pumping fits the way the mountain is used: the facilities sit at several levels, so break tanks along the route can serve as offtakes. This is the stepped supply recommended for mountain regions [1], with each step running on its own sun.

6.3 Link with flash-flood harvesting

The storms that close the road also bring the most water to the mountain. In a companion study, the authors sized gravity-filled GRP sectional modules (4 × 4 × 2 m) on rock terraces beside small ungauged tributaries in the Hatta catchment [51]; for its 10-year design day (80 mm, CN = 80) a hectare of hillslope yields 346 m³, and seven modules per hectare capture 79% of the long-term runoff [51]. Seven such modules on one hectare of rock catchment near the upper tank would store about 220 m³ after a storm: about 70 days of the non-potable uses and wildlife troughs (3 m³/day), or 5–6 days of the full demand. With the upper tank, the autonomy at the top would reach about 7.5 days, covering most of a closure like that of December 2025, and every cubic metre harvested is one not pumped. The summit rainfall and curve number, which may differ from Hatta, and the treatment needed for drinking use must be settled first; a pilot at the top could test both systems, which share the same modules and plinths.

6.4 Limitations

The study has seven main limitations. (i) Demands, tanker trips and costs are not published, so Table 1 and the cost inputs are assumptions, and the break-even demands should be recalculated with actual records. (ii) The solar year is a scaled clear-sky model; dust, cloud and storms may need extra storage or array capacity. (iii) The tanker model is not calibrated with on-board fuel data. (iv) Transients and control between stations [10,11] were not modelled. (v) Land, permits and landscape value were not costed. (vi) The tank checks use assumed wind, seismic and rock parameters, exclude rockfall impact and must be repeated with site data. (vii) The wildlife allocation is assumed, as the numbers and water needs of the tahr on the mountain are unpublished.

7. Conclusions

This study compared tanker delivery with staged solar pumping for supplying water to the upper facilities of Jebel Jais, 1,486 m above the foot of the climb. The main conclusions are:

1. Tanker delivery uses about 54 L of diesel per 22.7 m^3 round trip, or 2.36 L and 8.7 kg CO_2e per cubic metre.
2. Staged solar pumping with 5–10 hp stations needs 10–12 kWh of PV electricity and emits 1.7–1.8 kg CO_2e per cubic metre over its life cycle, about 80% less, with a carbon payback of about 5 years.
3. The pump rating sets the number of stations, not the total power: a 1 hp limit suits demands up to about 5–10 m^3/day, but 40 m^3/day would need 132 stations against 11–23 at 5–10 hp.
4. The pipeline is 76–82% of the capital cost. Solar pumping becomes cheaper than tankers above about 92 m^3/day along the 26 km road (67 m^3/day with a carbon price of USD 190/t) and above about 39 m^3/day on a 12 km direct route (27 m^3/day).
5. The GRP tanks pass all structural checks with factors of safety of 2.4 or more. Two days of storage at the top cover storm days and short road closures; a closure like that of December 2025 would leave tankers short for more than 12 days, while a protected pipeline keeps supplying water.
6. Five troughs taking 0.5 m^3/day extend the benefit to the Endangered Arabian tahr and other mammals for at most 1.25% more energy and cost, and the system removes hundreds to thousands of heavy-vehicle climbs a year, ends exposure to diesel prices and supports SDGs 6, 7, 9, 11, 13 and 15.

The next steps are to obtain actual tanker records and demands, survey a direct pipeline route with a rockfall hazard rating, investigate the rock at the station sites, agree the trough sites with the emirate's environmental authority, assess the summit catchment for a harvesting module, and build a pilot of two or three 5–10 hp stations.

CRediT authorship contribution statement

R. Y. M. Allam: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review and editing.

Rafik Belarbi: Conceptualization, Supervision, Validation.

Declaration of competing interest

R. Y. M. Allam is employed as a consultant structural engineer by Capital Engineering Consultancy, Dubai. The company did not fund the study and had no role in it. The authors declare no other competing interests.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability

The calculation script and its results file are provided as supplementary material, and Supplementary Material S2 gives the structural checks of the tanks.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the authors used AI tools to search and summarize the literature, write and run the calculation script, and draft and edit the text. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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