Solar Panel Cleaning Yield Recovery

Soiling Loss, Water-Fed Pole Engineering, and Cleaning ROI for Photovoltaic Systems in Canada

Dave Cook
Binx Professional Cleaning, North Bay, Ontario, Canada
dave@binx.ca

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Abstract

Photovoltaic (PV) system owners and operators lose measurable energy to soiling — the accumulation of dust, pollen, bird debris, road salt, soot, and industrial particulate on module cover glass. Reported annual soiling losses range from under one percent in wet temperate climates with frequent rain reset, to more than ten percent in arid and semi-arid climates where rain does not reliably clean panels. The cleaning decision is not trivial: frequent manual cleaning is expensive and, below a soiling threshold, can be net-negative relative to simply accepting the loss. At the other extreme, letting soil accumulate until a conservative threshold can forfeit a substantial fraction of a system's annual yield.

This working paper presents a reference framework for quantifying PV soiling losses, selecting a cleaning approach, and computing the break-even cleaning interval for residential, commercial, and utility-scale systems. Particular attention is paid to water-fed pole (WFP) cleaning — a technique that delivers deionized pure water through a reach pole with an extended boar's-hair brush, allowing the operator to clean from grade without rooftop access. WFP is both the preferred mechanism for small-to-medium PV arrays on technical grounds (scratch-free, chemical-free, spot-free drying) and on occupational safety grounds (fall exposure is eliminated for arrays reachable with a 20–45 ft pole).

The accompanying repository publishes seven reference datasets (soiling loss rates, deionized water resin capacity, PV geometry to pole-length mapping, Ontario monthly irradiance, cleaning frequency ROI, Canadian municipal tap water TDS profiles, and a regulation crosswalk) and eight language implementations of the cleaning ROI calculator that compute identical results for a canonical test vector. All code is MIT-licensed; all documents and data are CC BY 4.0.

This paper is a reference framework, not professional engineering advice. Decisions about cleaning a specific PV installation should consult the module manufacturer's warranty requirements, the site's fall-protection plan, and a qualified PV operations and maintenance provider.

Contents

I. Soiling physics

Photovoltaic modules convert incident solar irradiance into electrical current. Any material deposited on the module cover glass that intercepts or scatters incoming photons reduces the current that reaches the semiconductor junction, and therefore reduces the instantaneous and time-integrated energy yield of the module. The aggregate of all such material is called *soiling*, and the fractional energy reduction relative to a clean baseline is the *soiling loss*.

The deposition process is driven by atmospheric dust load, wind, local emission sources (vehicles, combustion heating, agriculture, industry), pollen and biogenic particulate, and bird activity. Soil particles that land on a module do not all stay: wind can re-entrain loose particles, and rain can wash away particles that are not yet bound to the glass. The interaction of deposition and removal produces a characteristic soiling ratio curve that rises between rain events and drops after each event.

I.1. Deposition and binding

Freshly deposited dust is weakly bound to the module surface and can be removed by wind or light rain. However, three mechanisms progressively bind particles to the glass, producing soil that resists mechanical removal: (1) dew-cycle wetting and drying, where overnight condensation forms a thin water film that dissolves soluble ions and re-precipitates them as a cementing layer; (2) biogenic activity, where pollen proteins, bird droppings, and tree sap create adhesive films; and (3) electrostatic adhesion between sub-micron particulate and the glass surface, which is difficult to reverse without a solvent.

I.2. Rain reset and the self-cleaning ceiling

Rain is a partial and imperfect cleaner. Light rain (less than approximately 2 mm) is empirically insufficient to reset the soiling ratio and can actually worsen the visual appearance of a module by redistributing dust into streaks. Heavier rain (above approximately 5–10 mm) produces a meaningful reset for loose surface dust but does not remove bound cementing layers. The practical implication is that there is a *self-cleaning ceiling*: the minimum steady-state soiling loss achievable by relying on rain alone, which is a function of climate, local emission sources, and panel tilt.

I.3. Tilt dependence

Steeper panel tilt sheds soil faster. The effect is both gravitational (loose particles roll off) and hydraulic (rain runoff carries particles off a steep surface more effectively than off a shallow one). Empirical studies report soiling loss reductions of approximately 15–30 percent for tilts above 25 degrees relative to tilts near horizontal. Fixed-tilt arrays in Northern Ontario typically use tilts of 30–45 degrees to optimise annual yield for the local latitude, which has the useful side effect of keeping soiling losses comparatively low even without active cleaning.

I.4. Reference soiling curves

The companion dataset *soiling_loss_rates.csv* tabulates transmittance loss as a function of days since cleaning for four climate zones (arid, temperate, humid, cold-snow), five tilt angles (5, 15, 25, 35, 45 degrees), and three soil classes (low, medium, high). The underlying model is an asymptotic approximation:

$$loss(d) = ceiling \cdot [1 - \exp(-k \cdot d / ceiling)]$$

where *k* is the daily deposition rate (percent per day), *d* is days since cleaning or last rain reset, and *ceiling* is the maximum realistic loss before rain or manual cleaning intervenes. Representative values of *k* are given below.

Climate zone	Daily rate k (%/day)	Ceiling (%)	Notes
arid	0.30	12.0	Infrequent rain, significant bound cementing
temperate	0.18	12.0	Periodic rain reset, pollen seasons drive spikes
humid	0.12	12.0	Frequent rain reset, biogenic binding
cold_snow	0.20	12.0	Snow auto-clean, spring road-dust spike

The daily rate is further modulated by a tilt multiplier (ranging from 0.74 at 45° to 1.15 at 5°) and by the soil class multiplier (0.60, 1.00, 1.55 for low, medium, high).

II. Yield loss quantification

Quantifying the energy cost of soiling requires translating a transmittance reduction into a kilowatt-hour loss and then into a dollar loss. The International Electrotechnical Commission standard IEC 61724-1:2021 defines the *soiling ratio* SR as the ratio of the actual measured DC power to the DC power that the same system would produce under the same irradiance and temperature if clean. A soiling ratio of 0.95, for example, indicates a 5 percent loss.

II.1. From transmittance to current

To first order, soiling reduces the short-circuit current I_{SC} of a module in proportion to the transmittance reduction of the cover glass. Because PV modules operate close to their maximum power point, and because I_{SC} scales roughly linearly with irradiance over the operating range, a 1 percent reduction in transmittance produces approximately a 1 percent reduction in instantaneous DC power. Non-uniform soiling complicates this relationship: if one cell in a string is heavily soiled while the rest are clean, string-level current mismatch losses can exceed the simple linear estimate by a factor of two to four.

II.2. From current to energy

Annual energy yield of a PV system is commonly estimated as:

$$E_{ac,annual} = P_{kWp} \cdot GHI_{annual} \cdot 365 \cdot PR$$

where P_{kWp} is the system nameplate capacity in kW DC, GHI_{annual} is the annual-average global horizontal irradiance in kWh/m^2/day at the site, and PR is the performance ratio (typically 0.75–0.85 for well-designed fixed-tilt grid-connected systems, lower for snow-prone or high-shade sites). Soiling enters this expression as a multiplicative factor on PR. The annual soiling loss in kWh is the integral of the instantaneous loss fraction against instantaneous power output, which for a slowly varying soiling ratio is well approximated by the time-average loss fraction multiplied by the clean-system annual yield.

II.3. From kWh to dollars

For residential and commercial PV, the relevant per-kWh value is usually the retail electricity price displaced (net metering or behind-the-meter consumption). For utility-scale PV under a power purchase agreement, the relevant per-kWh value is the PPA price. The Ontario reference price used in the companion calculator is $0.14 CAD/kWh, a mid-band value for residential Time-of-Use and Tiered rates; users can override with their local value.

II.4. Measurement in practice

IEC 61724-1 recommends measuring the soiling ratio directly with a pair of reference cells or short-circuit-current sensors, one cleaned regularly and one left to accumulate. For most small and medium PV installations this instrumentation is impractical, and owners instead infer soiling from the system's own production records using a clean-day baseline regression. The regression approach is noisier than dedicated instrumentation but is sufficient to drive cleaning-interval decisions.

III. Cleaning approach comparison

Five cleaning approaches are in common use for PV arrays. Each has distinct capital and labour costs, panel-safety implications, and scale characteristics.

III.1. Dry brush and air

Soft brushes, microfibre dusters, and compressed-air wands remove loose, dry surface dust without water. Dry methods are fast and low-cost but have two serious drawbacks: they cannot remove any bound soil, and they risk scratching the anti-reflective coating on the module cover glass if grit is dragged across the surface. Most module manufacturers explicitly void warranty for abrasive dry cleaning methods.

III.2. Hose and tap water

A garden hose with tap water is cheap, fast, and effective at removing loose soil. It has one critical drawback: most tap water contains 50–500 ppm of total dissolved solids (TDS), chiefly calcium and magnesium carbonates. When the water evaporates from the module, the dissolved minerals are left behind as a thin scale layer. This *hard-water spotting* reduces transmittance and, over repeated cleanings, accumulates into a permanent haze that can be more damaging than the soil it was meant to remove. Tap water is acceptable only in regions with very low TDS (below approximately 30 ppm) and only if the module is towelled dry before spotting can occur.

III.3. Water-fed pole (WFP) with deionized water

A water-fed pole delivers deionized pure water through a telescoping carbon-fibre or hybrid pole to a soft boar's-hair or synthetic brush head. The operator stands at grade and cleans the panel from below, agitating bound soil with the brush and flushing the surface with deionized water. Because the rinse water contains near-zero dissolved solids, it evaporates without leaving a residue, producing spot-free drying without towelling. The method is scratch-free, chemical-free, warranty-compliant with every major module manufacturer, and crucially eliminates the need for the operator to walk on the roof or array itself. WFP is the subject of Part IV in depth.

III.4. Contact chemistry (soap, acid, solvent)

Some soiling — bird droppings, tree sap, industrial oil residues — resists pure water cleaning. In those cases a dilute, module-compatible cleaning agent may be needed. Cleaning agents must be neutral pH, must be fully rinsed from the surface (residual surfactant attracts new soil), and must not contact module frame seals or junction boxes. Acidic and strongly alkaline cleaners are not compatible with most module coatings and are explicitly prohibited by most warranties.

III.5. Robotic and automated systems

Utility-scale PV plants in dry climates commonly deploy robotic dry-cleaning systems that traverse rows of modules on rails or tracks. These systems have high capital cost and are justified only at scale (typically above 5–10 MWp) and in climates where manual cleaning labour is expensive and soiling losses are high. They are not relevant to the residential, commercial, and sub-megawatt utility-scale systems that are the focus of this paper.

III.6. Comparison matrix

Approach	Scratch risk	Spot-free	Warranty	Fall exposure	Scale fit
Dry brush	high	n/a	often void	on-array	small only
Hose + tap	low	no	conditional	on-array	small
WFP + deionized	near-zero	yes	compliant	at grade	small–medium
Contact chemistry	low	no	restricted	on-array	spot treatment
Robotic systems	low	n/a	site-specific	n/a	utility only

IV. Water-fed pole engineering

Water-fed pole cleaning is a mature technique developed in the late 1990s for commercial window cleaning and adapted in the 2010s for PV module maintenance. The core insight is that pure water — water with substantially all dissolved mineral content removed — dries without leaving residue. When combined with a non-abrasive agitating brush delivered on a reach pole, the operator can clean high surfaces from grade without chemicals, without towelling, and without walking on the surface being cleaned. This section covers the four engineering sub-systems that must be sized correctly for a WFP deployment: water purification, pole geometry, brush selection, and operator technique.

IV.1. Water purification chain

The water purification chain begins at the municipal supply and ends at the brush head. A complete chain for professional PV cleaning includes four stages:

Stage 1 — Sediment prefilter. A 5 or 10 micron spun-polypropylene cartridge removes rust flakes, sand, silt, and other particulate that would otherwise load the downstream resin bed and clog the brush jets. Sediment prefilters are cheap and replaceable; operators typically replace them on a schedule regardless of visible condition.

Stage 2 — Carbon block (optional). A carbon block filter removes chlorine and chloramine, which attack mixed-bed resin and shorten its service life. Carbon is optional in regions with low residual disinfectant but cheap insurance everywhere else.

Stage 3 — Reverse osmosis (optional). In very high TDS regions (above approximately 300 ppm), a reverse osmosis (RO) membrane stage is installed upstream of the deionization cartridge. RO removes 95–99 percent of dissolved solids at a cost of roughly 3–4 litres of reject water per litre of permeate, and dramatically extends the service life of the downstream DI resin. RO is skipped in low-TDS regions where resin alone provides adequate economy.

Stage 4 — Mixed-bed deionization. The final stage is a mixed-bed ion-exchange resin cartridge. Mixed-bed resin combines strong-acid cation resin (which exchanges H^+ for all cations in the water) and strong-base anion resin (which exchanges OH^- for all anions). The hydrogen and hydroxide ions released immediately combine into water, so the output is effectively demineralised. A TDS meter at the cartridge outlet reads below 10 ppm (and often below 1 ppm for fresh resin), comfortably within the ASTM D1193 Type IV reagent water range that defines a spot-free rinse.

IV.2. Resin capacity and cartridge sizing

Mixed-bed resin has a finite exchange capacity measured in kilograins (kgr) of calcium carbonate equivalent. The volume of water that a cartridge can treat to the 10 ppm outlet target is:

$$V_{gal} = (C_{kgr} \cdot 17{,}118) / TDS_{inlet,ppm}$$

where V_{gal} is the usable volume in US gallons, C_{kgr} is the cartridge rated capacity in kilograins, and 17,118 is the conversion constant relating kilograin capacity to gallons at a reference TDS of 1 ppm. The implication is that resin cost per cleaning is roughly proportional to inlet TDS: a 7 litre (5.6 kgr) cartridge will treat about 480 gallons at 200 ppm inlet but more than 1,900 gallons at 50 ppm inlet. Operators in high-TDS regions economise by adding an RO pre-stage, which is usually justified once inlet TDS exceeds 200–250 ppm.

The companion dataset *tds_resin_capacity.csv* tabulates cartridge capacity in US gallons and litres across five common cartridge sizes (1 L handheld, 3 L, 7 L, 14 L, 28 L van-mount tank) and ten inlet TDS values from 20 to 500 ppm. Values in the table are derived directly from the equation above and match within a few percent the published service-life figures in Unger, Tucker, Xero, and Streamline product manuals.

IV.3. Pole reach geometry

The practical range of water-fed poles spans roughly 15–80 feet of working reach. At short lengths (15–25 ft) the pole is stable, light, and usable by a single operator; at medium lengths (25–45 ft) the pole requires more technique but remains single-operator workable; beyond approximately 45 ft the pole becomes heavy, wind-sensitive, and generally requires a second operator or is better replaced by a boom lift. For PV cleaning, the relevant target height is the top edge of the highest module plus approximately 3 ft of working overhead for the brush.

The companion dataset *pv_geometry_reach.csv* maps twelve common PV installation archetypes to minimum and recommended pole lengths. A representative subset is shown below.

Archetype	Base (ft)	Tilt (deg)	Top (ft)	Pole (ft)	WFP feasible?
Residential 1-storey	10	20	11.9	10	yes
Residential 2-storey	18	25	20.3	20	yes
Residential 2-storey steep	18	35	21.2	20	yes
Commercial flat low	14	5	14.6	15	yes
Commercial flat mid	24	5	24.6	25	yes
Commercial flat high (3-storey)	36	5	36.6	35	marginal
Ground-mount fixed low	2	25	4.7	8	yes
Ground-mount fixed tall	5	35	8.7	8	yes
Carport high	11	10	12.1	10	yes
Agrivoltaic elevated	13	25	15.7	15	yes

Notes on the table: Base is the height of the module mounting point above the operator's standing surface (ground for ground-mount and residential one-storey; roof-edge for commercial). Top is the top edge of the highest module after the tilt rise is added. Pole is the nearest standard commercial pole length that reaches top plus 3 ft of brush overhead, with the operator's eye level taken at 5 ft. Archetypes marked marginal are technically reachable but stretch the upper limit of safe single-operator WFP use and are usually better served by a boom lift.

IV.4. Brush selection and technique

The brush head is the operator's only physical contact with the panel. Three brush types are in common use: natural boar's hair (softest, best for delicate coatings, slowest cleaning), synthetic flagged polyester (medium aggressiveness, most common), and dual-trim hybrid (mixed bristle for combined agitation and rinse). For PV modules the general recommendation is a soft natural or soft synthetic brush; stiffer brushes are appropriate only for very heavily soiled ground-mount arrays where the operator has verified that no grit is being dragged across the surface.

Technique matters. The correct sequence is: (1) flush the panel with pure water to float off loose grit; (2) agitate the wetted surface gently with the brush, working in the long direction of the module; (3) rinse the agitated surface with more pure water and allow it to sheet off; (4) leave the panel to dry without towelling. The water must be pure throughout the rinse phase, not just the initial wetting, otherwise spotting will occur at the trailing edge. Operators should check outlet TDS with a pocket meter every 10–15 gallons of through-flow on high-inlet-TDS days to catch resin exhaustion before it produces visible spotting.

IV.5. Fall protection and the WFP safety argument

The single strongest operational argument for WFP cleaning of PV is that it is performed from grade, eliminating the fall exposure that dominates the occupational risk profile of rooftop PV maintenance. OSHA 29 CFR 1926 Subpart M requires fall protection for any construction-related work above 6 feet in the United States; Ontario Regulation 213/91 Section 26 sets the trigger at 3 metres (approximately 10 feet) for most construction work. For a small or medium PV installation, the full fall-protection compliance stack — anchor point installation, harness, lanyard, rescue plan, trained rescue personnel — often costs more per cleaning visit than the actual labour of cleaning the panels. WFP eliminates the trigger altogether: if the operator remains on the ground, Subpart M does not apply, and the only residual fall exposures are from the pole's own momentum in gusty conditions (which is a workplace safety issue, not a fall-arrest issue).

The feasibility boundary is geometric. Above approximately 45 feet of required reach the pole becomes unwieldy and the economics of a rooftop or boom-lift approach improve. Below that boundary, WFP dominates the alternatives on both safety and cost grounds.

IV.6. Pole material and construction

Three pole material families are commercially available: fibreglass, carbon fibre, and hybrid (carbon fibre in the lower, high-stress sections with fibreglass in the upper, weight-sensitive sections). Fibreglass is the cheapest and most rigid per dollar but is heavy at long reach; a 30 ft all-fibreglass pole weighs approximately 5–6 kg empty, enough to be tiring over a full workday. Carbon fibre is lighter and stiffer per gram but far more expensive: a 30 ft all-carbon pole costs two to four times a comparable fibreglass pole but weighs roughly half as much. The hybrid approach puts carbon in the working upper sections (where weight penalty is greatest due to the lever arm) and fibreglass in the base sections (where stiffness and cost matter more than weight). Most professional operators above 25 ft of working reach select a hybrid pole.

Pole stiffness matters because flexible poles make the brush head difficult to control at reach. A pole that deflects noticeably under its own weight at full extension loses perhaps 2–4 feet of effective working reach, because the operator must shorten the pole to regain control. Nominal rated reach and effective reach are therefore not the same number; operators should confirm effective reach by setting up the pole at full extension with a wet brush (which loads the tip with water weight) before trusting a manufacturer's rated length.

IV.7. Hoses, fittings, and flow control

The water delivery line from the DI cartridge to the brush jets passes through (typically) a reinforced polyurethane hose, a pole-mounted valve or flow controller, and an internal feed tube inside the pole sections to the brush head. Flow rate at the brush head is commonly in the range of 1–3 L/min. Higher flow rates rinse faster but consume more pure water per module; lower flow rates are more economical but slower and risk insufficient sheeting action during the final rinse. A typical 60-cell residential module (approximately 1.7 m^2) takes 20–60 seconds to clean thoroughly and consumes 0.5–1.5 litres of pure water.

A full residential 5 kWp array of sixteen such modules consumes approximately 10–20 litres per visit.

IV.8. Field TDS monitoring

A handheld TDS meter (conductivity-based, auto-temperature-compensated, calibrated against a 342 ppm NaCl solution) is the minimum viable quality control instrument for WFP operation. The operator checks outlet TDS at the start of each job, midway through, and at the end. A reading above 10 ppm at any point indicates resin exhaustion or a leak around the cartridge seal and triggers an immediate stop to prevent spotting. High-end operators install an in-line TDS meter with a dashboard display, which eliminates the manual check but is not essential for small operations. Meter drift is small over months of use, but a quarterly recalibration against a reference solution is good practice.

IV.9. Equipment maintenance

WFP equipment requires modest but consistent maintenance. Prefilters are replaced on a schedule or when the pressure differential across the filter exceeds the manufacturer's recommendation, whichever comes first. Carbon blocks are replaced annually at minimum or more often in high-chloramine supply regions. DI cartridges are replaced when outlet TDS rises above 10 ppm; spent resin should not be landfilled without first being neutralised or returned to the manufacturer for regeneration (most major brands offer a return programme). Brush heads are replaced when bristles become splayed or when fine grit embedded in the boar's hair creates scratch risk — typically every 500–1,000 hours of use for a professional operator. Poles themselves are low-maintenance but should be inspected for delamination at section joints, hairline cracks in the carbon wrap, and wear in the quick-release clamps; a failed clamp at full extension can allow a section to collapse suddenly, which is dangerous to the operator and expensive for the pole.

IV.10. Cold weather considerations

WFP cleaning does not work below freezing. Pure water freezing on a cold PV module can cause thermal shock if the panel is irradiated and warm (spray a cold stream on a 50°C cell and the thermal gradient exceeds typical module tolerance), and freezing inside the pole, hose, or cartridge damages equipment. In Northern Ontario the practical WFP season is mid-April through mid-October. Winter PV cleaning, where it is needed at all (usually only for snow after a storm passes and heavy accumulation remains on shallow-tilt arrays), is better handled by soft-bristle snow rakes or simply by waiting for the post-snow self-clean as snow melts off a north-facing or shallow-tilt surface.

V. Cleaning cost and yield ROI model

The cleaning decision for a given PV installation is a continuous trade-off, not a binary clean-or-don't. For any cleaning interval *T*, the average soiling loss between cleanings is the time-average of the soiling curve over T. The shorter the interval, the lower the average loss but the higher the annual cleaning cost. The optimal interval minimises the sum of the two.

V.1. The loss integral

Given the asymptotic soiling model of Part I, the average loss over a cleaning interval T (in days) is:

$$\langle loss\rangle(T) = ceiling - (ceiling^2 / (k \cdot T)) \cdot [1 - \exp(-k \cdot T / ceiling)]$$

This is the closed-form integral of the asymptotic model divided by T. At very short T it approaches zero (cleaning so often that soil never accumulates). At very long T it approaches *ceiling* (the never-clean baseline). For intermediate T it traces a smooth curve that grows roughly linearly at first and then rolls over toward the ceiling.

V.2. The cost curve

Annual cleaning cost is simply the number of visits per year multiplied by the visit cost:

$$C_{annual}(T) = (365 / T) \cdot C_{visit}$$

The per-visit cost depends on system size, access, travel, water quality (which determines resin consumption), and labour rate. Typical Ontario reference values for small and medium PV are $120 per visit for a 5 kWp residential system with ground-accessible or single-storey geometry, $600 per visit for a 50 kWp commercial array with single-storey or ground-mount access, and $8,000 per visit for a 1 MWp utility-scale system cleaned by a crew over one or two days.

V.3. The net recovered function

Define the *avoided loss* at interval T as the dollar value of energy that would have been lost under the never-clean baseline minus the dollar value actually lost at interval T:

$$A(T) = P \cdot [ceiling - \langle loss\rangle(T)] / 100 \cdot E_{clean,annual}$$

where P is the electricity price ($/kWh) and $E_{clean,annual}$ is the annual yield of the same system if always clean. The *net recovered* amount is avoided loss minus annual cleaning cost:

$$N(T) = A(T) - C_{annual}(T)$$

A positive N(T) means the cleaning programme pays for itself relative to never cleaning. A negative N(T) means cleaning at that interval costs more than it saves. The optimal interval T* maximises N(T). For typical Ontario parameters (temperate climate, medium soil class, 20° tilt, $0.14/kWh) T* falls in the 90–180 day range for residential systems and in the 45–90 day range for commercial systems.

V.4. A worked example

Consider a 50 kWp commercial flat-roof array in Ottawa with a temperate-climate soiling profile, an annual-average GHI of 3.79 kWh/m^2/day, a performance ratio of 0.80, an electricity price of $0.14/kWh, and a cleaning visit cost of $600.

Interval (days)	Visits/yr	Avg loss (%)	Avoided loss ($)	Clean cost ($)	Net ($)
30	12.17	2.6	1,930	7,300	-5,370
60	6.08	5.0	1,720	3,650	-1,930
90	4.06	7.0	1,480	2,430	-950
120	3.04	8.6	1,260	1,820	-560
180	2.03	10.6	910	1,220	-310
365	1.00	11.8	180	600	-420

The 50 kWp commercial reference array is cost-negative at every interval in the temperate, low-cost-electricity Ontario regime — which is the central and counter-intuitive finding of this paper: for a substantial fraction of small and medium PV in wet-temperate climates, rain-reset alone dominates any manual cleaning schedule on pure ROI terms. The same model applied to a 50 kWp array in an arid climate (k = 0.30 %/day) and a higher electricity price (say $0.22/kWh) produces a positive net recovered band between 30 and 90 day intervals, and the optimal interval shifts to roughly 60 days.

V.5. When to clean anyway

Several considerations can override the pure ROI calculation:

Warranty and monitoring requirements. Some module manufacturers and some PPA contracts require a documented cleaning schedule to maintain warranty or meet performance guarantees, regardless of whether the cleaning would otherwise be economical.

Non-uniform soiling and hotspot risk. Bird droppings and leaf debris can shade individual cells, causing them to reverse-bias and overheat. Hotspots damage modules even when the average soiling loss is small. A targeted spot clean to remove bird droppings has an ROI that the average-loss model understates by a factor that depends on the probability of a hotspot forming.

Visual and reputational factors. Public-facing solar installations (headquarters buildings, airports, schools) sometimes require a cleaning schedule driven by appearance rather than yield.

Post-event cleaning. Dust storms, wildfire ash, and industrial upset events can deposit enough soil to overwhelm the self-cleaning ceiling for months. A one-off cleaning after a major deposition event is almost always economical even in temperate climates where routine cleaning is not.

VI. Regulatory crosswalk

PV cleaning operations sit at the intersection of several regulatory and standards regimes. This section lists the standards most commonly cited in O&M plans, warranty documentation, and contractor safety documentation, grouped by topic. The companion dataset *regulation_crosswalk.csv* contains the same content in machine-readable form.

VI.1. Fall protection

In the United States, OSHA 29 CFR 1926 Subpart M sets fall protection requirements for construction work (including maintenance contracted to construction firms) at the 6 ft trigger height. In Canada, occupational health and safety is provincial jurisdiction; in Ontario, O. Reg. 213/91 Section 26 sets the trigger at 3 metres for most construction work. Personal fall-arrest equipment in Canada is governed by the CSA Z259 series: Z259.10 for full body harnesses, Z259.11 for energy absorbers, and additional parts for anchors, lanyards, and self-retracting devices. Water-fed pole cleaning from grade does not engage these standards at all and is the preferred risk-control approach where feasible.

VI.2. PV performance monitoring

IEC 61724-1:2021 defines the soiling ratio, performance ratio, and monitoring cadence for PV systems. IEC 61724-2:2016 and 61724-3:2016 cover short-term capacity evaluation and long-term energy evaluation methodologies. These are the reference standards for owners and independent engineers to validate that a claimed soiling loss is real and not an artefact of measurement noise.

VI.3. PV module safety

CSA F382 (adopting IEC 61730) and CSA C22.2 No. 256 define Canadian safety requirements for PV modules. Neither standard addresses cleaning specifically, but module warranties built on these standards commonly restrict approved cleaning methods to non-abrasive, pH-neutral techniques with no pressure-washing, consistent with WFP operation.

VI.4. Water purity

ASTM D1193 defines four grades of reagent water (Types I–IV) for laboratory use. A properly configured WFP cartridge delivering below 10 ppm outlet TDS comfortably meets the Type IV specification (resistivity greater than 0.2 megohm-cm, conductivity below 5 microsiemens/cm), which is the practical threshold for spot-free drying on glass. Health Canada guidelines set an aesthetic TDS objective of 500 mg/L for drinking water, which is also the upper bound beyond which direct-feed deionization becomes economically unattractive without an RO pre-stage.

VI.5. Canadian O&M guidance

The Canadian Renewable Energy Association (CanREA) publishes best-practice guidance on PV operations and maintenance. This guidance is not a binding standard but is commonly referenced in Canadian O&M contracts. Natural Resources Canada (NRCan) publishes the Photovoltaic Potential and Solar Resource Maps of Canada, which provides the canonical irradiance data used in most Canadian yield estimates including those in this paper.

VII. Northern Ontario climate adjustments

Northern Ontario presents a distinctive climate profile for PV cleaning. This section documents the local adjustments relevant to a North Bay, Sudbury, Timmins, or Thunder Bay installation and should be read as a worked application of the general model in Parts I through V.

VII.1. Irradiance profile

Annual-average global horizontal irradiance in Northern Ontario ranges from approximately 3.3 kWh/m^2/day in Timmins to approximately 3.5 kWh/m^2/day in North Bay and Thunder Bay, based on NRCan PV potential data. This is lower than Southern Ontario (Toronto is approximately 3.9 kWh/m^2/day) and much lower than the Canadian prairies. The monthly distribution is heavily winter-weighted toward losses: January irradiance in North Bay is 1.4 kWh/m^2/day, compared to 5.9 in July. Consequently, summer soiling matters far more to annual yield than winter soiling, and optimal cleaning schedules are weighted toward the May–September window.

City	Jan	Apr	Jul	Oct	Annual avg
North Bay	1.4	4.5	5.9	2.4	3.53
Sudbury	1.5	4.6	5.8	2.4	3.54
Timmins	1.3	4.5	5.7	2.2	3.39
Thunder Bay	1.5	4.8	6.0	2.4	3.63
Ottawa	1.8	4.8	5.9	2.6	3.76
Toronto	1.9	4.7	5.8	2.7	3.75

Values in kWh/m^2/day, derived from NRCan PV potential data (see regional_irradiance_ontario.csv).

VII.2. Seasonal soiling drivers

Four Northern Ontario soiling drivers are worth noting:

Road dust after spring sanding. Municipalities across Northern Ontario apply sand and sand-salt mixtures to roads through the winter. When the snow melts in April and early May, a concentrated layer of road dust is released. PV arrays downwind of significant road traffic (highways, residential arterials, rural gravel) often experience a short spike in soiling loss for two to four weeks in May. A single cleaning at the end of this spike typically pays for itself.

Pollen. Spruce, pine, and birch pollen peaks in late May and early June produce a fine yellow layer on horizontal and low-tilt surfaces. Pollen is sticky and does not reliably rain-reset below approximately 8 mm of precipitation. A June cleaning is often justified in pollen-heavy microclimates.

Wood-stove and wildfire smoke. Residential wood heating and episodic wildfire smoke are both significant in Northern Ontario. Wood-stove soot is usually a winter-season issue on arrays near active chimneys; wildfire ash is a summer issue that tracks prevailing wind from active fires. Neither is schedulable in advance, and post-event cleaning is the appropriate response rather than increased routine frequency.

Snow. Snow cover on low-tilt arrays can exceed 95 percent winter yield loss. Snow also auto-cleans the module as it slides off (especially on steep tilts). Mechanical snow removal on residential and small commercial arrays is usually not economical: the weeks of recovered yield rarely repay the visit cost and fall exposure, and waiting for a thaw or wind event is cheaper. This conclusion can flip for large ground-mount and utility-scale arrays where the per-module removal cost amortises across a large production base.

VII.3. Northern Ontario municipal water TDS

Water supplies in Northern Ontario are largely surface-water sourced and have moderate TDS levels. Thunder Bay draws from Loch Lomond and reports mean TDS near 100 ppm. North Bay (Trout Lake) and Sudbury (Wanapitei Lake) are in the 160–180 ppm range. Timmins is similar at approximately 195 ppm. A 7 L mixed-bed cartridge at these TDS levels treats roughly 500–600 US gallons before exhaustion, which is enough for approximately 50–100 residential cleanings depending on panel count and brush discipline.

Operators in Sudbury, North Bay, or Timmins can typically run DI-only without an RO pre-stage and still achieve acceptable resin economy. Operators serving Southern Ontario customers in the Waterloo–Guelph–Kitchener region, where groundwater TDS exceeds 400 ppm, should install an RO pre-stage to keep resin cost per cleaning within economic bounds.

VIII. Case studies

Three illustrative case studies show how the framework in Parts I through VII applies to real Canadian PV installations. All three are composites based on published Canadian residential and commercial PV deployments; they are not identifiable sites.

VIII.1. Case study 1 — 5 kWp residential, Sudbury

A Sudbury homeowner installs a 5 kWp array on a south-facing asphalt-shingle roof, tilt 30 degrees, on a two-storey residential home. Roof edge is at 18 ft; the top of the highest module is approximately 20.3 ft above grade. The owner is asking how often the panels should be cleaned.

Inputs to the model. system_capacity 5.0 kWp; ghi_annual_avg 3.54 kWh/m^2/day; soil_class medium (Sudbury has modest dust load and reliable summer rain); electricity_price 0.135 CAD/kWh (Ontario Tiered residential tier 1); cleaning_visit_cost 140 CAD (two-storey access with travel); tap_water_tds 180 ppm; panel_height 20 ft.

Model output. Clean annual yield approximately 5,170 kWh; never-clean average loss approximately 12 percent; never-clean annual lost value approximately $84. Annual cleaning cost at a 90-day interval is $568; at 180 days it is $284. At every interval the annual cleaning cost exceeds the avoided loss, producing negative net recovered. **The model recommends no routine cleaning.** Rain-reset alone dominates any paid cleaning schedule for this installation.

Caveats the pure ROI model misses. A bird droppings removal visit remains justified whenever visible; a cleaning after a wildfire-smoke event remains justified; the end-of-season pollen clean in early June may be justified subjectively. But a standing monthly or quarterly schedule is not, and the homeowner should decline vendor offers framed as "necessary maintenance."

WFP applicability. With roof edge at 18 ft and highest panel top at 20.3 ft, a 20 ft pole reaches comfortably from grade. Any on-demand cleaning (bird droppings, post-event) can be done from the ground without fall exposure, which makes occasional cleaning cheap and safe relative to roof access.

VIII.2. Case study 2 — 80 kWp commercial flat roof, Ottawa

An Ottawa commercial building owner installs an 80 kWp array on a flat roof with ballasted racking at 5 degree tilt. The building is two storeys, roof edge at 24 ft, panel top at approximately 24.6 ft above grade. The building is bordered by a six-lane arterial road with heavy winter sanding. The owner has an existing facility maintenance contract that already includes quarterly window cleaning with WFP equipment capable of reaching 25 ft.

Inputs to the model. system_capacity 80 kWp; ghi_annual_avg 3.76 kWh/m^2/day (Ottawa); soil_class medium-high (arterial road dust); electricity_price 0.11 CAD/kWh (Ontario commercial rate, post-demand); cleaning_visit_cost 600 CAD (the marginal add-on cost of cleaning the PV array as part of an already-scheduled window cleaning visit rather than a dedicated visit); tap_water_tds 90 ppm (Ottawa River); panel_height 25 ft.

Model output. Clean annual yield approximately 88,000 kWh; under a high soil class assumption the never-clean average loss approaches 15 percent, with an annual lost value of approximately $1,450. A spring (post-road-dust) plus fall cleaning schedule (two visits per year at $600 each marginal cost) avoids approximately $950 of loss, producing a net recovered of roughly –$250 — still slightly negative, but within the noise of the model given the owner's existing window cleaning contract.

The joint-service insight. When the cleaning visit is piggybacked on an existing WFP window cleaning contract, the incremental cost is labour and resin only — no additional truck roll, no additional setup — and the economics shift meaningfully. The case study illustrates a general principle: the ROI of PV cleaning is much stronger when performed by a contractor already on site with compatible equipment (which is exactly the profile of a commercial window cleaning operator equipped with a van-mount WFP system).

VIII.3. Case study 3 — 500 kWp ground-mount, Regina

A Saskatchewan prairie landowner installs a 500 kWp fixed-tilt ground-mount array at latitude 50.5 degrees, tilt 35 degrees, base height 3 ft. The site is in a semi-arid grassland climate with strong summer dust load, very low precipitation between rain events, and heavy pollen in late May. The array feeds into a net-metering arrangement at a retail rate of approximately 0.17 CAD/kWh.

Inputs to the model. system_capacity 500 kWp; ghi_annual_avg 4.4 kWh/m^2/day (Regina, higher than Ontario); soil_class high; climate_zone arid (k = 0.30 %/day); electricity_price 0.17 CAD/kWh; cleaning_visit_cost 3,500 CAD (a two-person crew with a trailer-mounted WFP system for two days); tap_water_tds 480 ppm (Regina draws from Buffalo Pound Lake — high TDS demands an RO pre-stage); panel_height 5 ft (ground-mount, accessible from grade without any pole reach).

Model output. Clean annual yield approximately 642,000 kWh. Under the arid soiling profile, the never-clean average loss approaches 18 percent, with an annual lost value of roughly $19,600. A 60-day cleaning schedule reduces average loss to approximately 8 percent, avoiding roughly $10,900 of loss per year at an annual cleaning cost of approximately $21,300 — still net-negative. Extending to 120 days raises average loss to approximately 12.5 percent and reduces annual cleaning cost to roughly $10,650, producing a net recovered of approximately +$300. Extending further to 180 days gives a small positive net recovered of approximately +$1,100 at an average loss of roughly 14.5 percent. **The optimal interval is around 180 days** — two cleanings per year, timed to hit the post-pollen window in early June and the late-summer dust peak in late August.

Water infrastructure. At 480 ppm inlet TDS, a 28 L van-mount tank of mixed-bed resin alone would treat only about 800 US gallons before exhaustion — insufficient for the cleaning volume required. The operator installs an RO pre-stage that reduces effective inlet TDS to roughly 15 ppm, extending effective resin capacity by a factor of roughly 25 and keeping consumables cost per cleaning manageable. This illustrates the general rule: RO is economical whenever inlet TDS exceeds 200–250 ppm.

IX. Limitations and caveats

This working paper presents a reference framework, not a site-specific recommendation. Five classes of limitation are worth naming explicitly.

IX.1. The soiling model is an average

The asymptotic soiling model treats deposition as a smooth, continuous process. Real soiling events are punctuated and irregular: a week of nothing followed by a single dust storm that exceeds a month of normal accumulation in one day. For planning purposes the average is a reasonable guide, but the variance is large and a site-specific measurement programme using IEC 61724-1 reference cells is the only rigorous way to characterise a particular installation.

IX.2. Non-uniform soiling is underestimated

The model treats soiling as uniform across the array. In practice, soiling is often non-uniform: the lower edges of modules accumulate more soil than the upper edges because of water runoff patterns during rain; modules near trees or bird perches accumulate biogenic soil disproportionately; and modules adjacent to an exhaust fan or combustion flue can be dramatically worse than the rest of the array. Because of string-level current mismatch, the *worst* module in a string drives the loss for the string. A linear average understates the loss attributable to localised hotspots by a factor that can be two to four.

IX.3. The ROI model ignores risk and warranty

A purely economic ROI calculation ignores the insurance value of maintaining a documented cleaning schedule. Some module warranties and most utility-scale performance guarantees require documented maintenance. A cleaning schedule that is ROI-negative but contractually required is still rational. Similarly, avoiding a cell hotspot that damages a module permanently is worth much more than the modest current savings avoided by the cleaning that would have prevented it.

IX.4. The dataset values are representative, not measured

The companion CSVs contain reference values suitable for planning, not measurements from a specific installation. Municipal TDS values, for example, are typical annual means; actual TDS varies seasonally and by neighbourhood within the same city. Irradiance values are annual averages drawn from NRCan PV potential data; actual irradiance at a specific site depends on horizon shading, ground reflectance, and local weather variability. Users should treat the defaults as starting points and override them with site-specific data when available.

IX.5. This paper is not professional engineering advice

Cleaning a specific PV installation involves module warranty requirements, fall-protection planning, electrical isolation considerations, and sometimes municipal permitting. This paper does not substitute for a qualified PV operations and maintenance provider, a licensed electrician, or a jurisdiction-specific occupational health and safety consultation. Readers should use the framework here as preparation for that conversation, not as a replacement for it.

Acknowledgements, data sources, and references

The author thanks the Binx Professional Cleaning operations team for practical input on water-fed pole technique, resin consumption patterns across Northern Ontario supply regions, and the dual use of WFP systems for window cleaning and PV cleaning work. Irradiance data are drawn from Natural Resources Canada and cross-checked against NASA POWER. Soiling model coefficients are adapted from Kimber et al. (2006), Mejia & Kleissl (2013), Ilse et al. (2019), and Sarver, Al-Qaraghuli & Kazmerski (2013). The performance monitoring methodology follows IEC 61724-1:2021. Water-fed pole and deionization parameters are drawn from published manufacturer documentation (Unger, Tucker, Xero, Streamline) and the Water Quality Association mixed-bed deionization technical information sheet. Canadian fall protection references are OSHA 29 CFR 1926 Subpart M, Ontario O. Reg. 213/91 s. 26, and CSA Z259. Full bibliography is maintained in the repository SOURCES.md file.

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Appendix A. Calculator I/O specification

The companion reference calculator is published as eight language implementations (Python, Rust, Java, Ruby, Elixir, PHP, Go, and a Nostr long-form article bridge) that compute identical results for a canonical test vector. The calculator takes eight inputs and returns five outputs as ranges rather than point estimates.

A.1. Inputs

Input	Type	Units	Range	Default
system_capacity	number	kWp	0.5–5000	5.0
ghi_annual_avg	number	kWh/m2/day	1.0–7.0	3.53 (North Bay)
days_since_cleaning	int	days	0–730	30
soil_class	enum	{low, medium, high}	—	medium
electricity_price	number	CAD/kWh	0.05–0.50	0.14
cleaning_visit_cost	number	CAD	20–50000	120
tap_water_tds	number	ppm	0–1000	160
panel_height	number	ft	3–100	12

A.2. Outputs

Output	Type	Units	Description
current_loss_pct	range	%	Current soiling loss with confidence band
lost_cad_per_day	range	CAD/day	Daily dollar value of soiling loss
optimal_interval_days	range	days	Interval that maximises net recovered
annual_recovered_cad	range	CAD/year	Net recovered at optimal interval
wfp_pole_ft	integer	ft	Recommended pole length
wfp_cartridge	enum	—	Recommended DI cartridge size
water_per_cleaning_l	number	litres	Pure water required per visit

A.3. Canonical test vector

The canonical test vector used to verify cross-language parity is: system_capacity=5.0 kWp, ghi_annual_avg=3.54 kWh/m2/day (Sudbury), days_since_cleaning=30, soil_class=medium, electricity_price=0.14 CAD/kWh, cleaning_visit_cost=120 CAD, tap_water_tds=180 ppm, panel_height=12 ft. All eight engine implementations must produce matching outputs for this vector within floating-point tolerance.

Appendix B. Reproducibility and repository

All datasets, the calculator in eight languages, this working paper, and the generating scripts are published under an open licence. Source code is MIT; documents, datasets, and the dataset card are CC BY 4.0. Regeneration of any dataset in the same Python environment must yield a byte-identical output. Cross-language parity of the calculator is verified against the canonical test vector in Appendix A.3.

B.1. Repository and mirrors

The canonical repository is maintained on GitHub with mirrors on GitLab, Codeberg, SourceHut, and Launchpad. Package registry releases are on PyPI, npm, Crates.io, Maven Central, RubyGems, Hex.pm, Packagist, Docker Hub, and pkg.go.dev. The working paper itself is archived on Zenodo with a permanent DOI, and the dataset is additionally archived on OSF, Dryad, Hugging Face, Kaggle, and the Internet Archive. The full list of live URLs is maintained in the repository README.

Maintainer: Dave Cook, Binx Professional Cleaning, North Bay, Ontario, Canada. Contact: dave@binx.ca. Repository: github.com/DaveCookVectorLabs/solar_panel_yield_2026 (see README for all mirror URLs).

B.2. Citation

Please cite as: Cook, D. (2026). *Solar Panel Cleaning Yield Recovery: Soiling Loss, Water-Fed Pole Engineering, and Cleaning ROI for Photovoltaic Systems in Canada.* Working paper v0.1.0. CC BY 4.0. DOI assigned by Zenodo at publication and recorded in the repository CITATION file.

Appendix C. Selected reference tables

This appendix reproduces selected tables from the companion datasets for convenience. All tables are truncated to a representative subset; the full tables are in the CSV files in the *datasets/* directory of the repository.

C.1. Soiling loss by climate zone and days

Transmittance loss (%) at tilt 15 degrees, medium soil class. Full table in soiling_loss_rates.csv.

Days	arid	temperate	humid	cold_snow
7	2.1	1.2	0.8	1.4
14	4.0	2.4	1.6	2.7
30	7.3	4.8	3.2	5.4
60	9.7	7.6	5.6	8.3
90	10.8	9.1	7.2	9.8
120	11.3	10.0	8.3	10.6
180	11.7	10.9	9.7	11.3
365	12.0	11.8	11.3	11.8

C.2. DI resin cartridge capacity (US gallons to 10 ppm outlet)

Rows are inlet TDS (ppm); columns are cartridge size. Full table in tds_resin_capacity.csv.

Inlet TDS (ppm)	1 L	3 L	7 L	14 L	28 L
50	274	822	1,917	3,834	7,668
100	137	411	958	1,917	3,834
160	86	257	599	1,198	2,397
200	68	205	479	958	1,917
300	46	137	320	639	1,278
400	34	103	240	479	958
500	27	82	192	383	767

C.3. Canadian municipal tap water TDS (selected)

Mean tap water TDS (ppm) by city. Full table including low-high band in tap_water_tds_profiles.csv.

City	Province	Mean TDS (ppm)	Source water
Vancouver	BC	35	Capilano/Seymour/Coquitlam
Halifax	NS	45	Pockwock Lake
Ottawa	ON	90	Ottawa River
Thunder Bay	ON	100	Loch Lomond
Montreal	QC	90	St. Lawrence River
Toronto	ON	155	Lake Ontario
North Bay	ON	160	Trout Lake
Sudbury	ON	180	Wanapitei Lake
Timmins	ON	195	Mattagami River / groundwater
Calgary	AB	200	Bow / Elbow Rivers
Winnipeg	MB	250	Shoal Lake
London	ON	310	Lake Huron + groundwater
Saskatoon	SK	330	South Saskatchewan River
Waterloo	ON	420	Waterloo moraine groundwater
Guelph	ON	450	Dolostone aquifer
Regina	SK	480	Buffalo Pound Lake

C.4. PV geometry to pole length (full table)

Archetype	Base (ft)	Tilt	Top (ft)	Min pole	Rec pole	WFP?
Residential 1-storey	10	20	11.9	9.9	10	yes

Archetype	Base (ft)	Tilt	Top (ft)	Min pole	Rec pole	WFP?
Residential 2-storey	18	25	20.3	18.3	20	yes
Residential 2-storey steep	18	35	21.2	19.2	20	yes
Commercial flat low	14	5	14.6	12.6	15	yes
Commercial flat mid	24	5	24.6	22.6	25	yes
Commercial flat high	36	5	36.6	34.6	35	marginal
Ground-mount low	2	25	4.7	8.0	10	yes
Ground-mount mid	3.5	30	6.8	8.0	10	yes
Ground-mount tall	5	35	8.7	8.0	10	yes
Carport low	8	10	9.1	8.0	10	yes
Carport high	11	10	12.1	10.1	15	yes
Agrivoltaic	13	25	15.7	13.7	15	yes

C.5. Cleaning frequency ROI (50 kWp, North Bay)

Net recovered dollars per year for a 50 kWp commercial array in North Bay, temperate soiling profile, medium soil class, 20 degree tilt, $0.14/kWh electricity price, $600 per cleaning visit. Negative values indicate the interval is cost-negative. Full 81-row table in cleaning_frequency_roi.csv.

Interval (days)	Visits/yr	Avg loss (%)	Avoided loss ($)	Cleaning cost ($)	Net ($)
7	52.14	0.6	82	31,285	■31,203
14	26.07	1.2	156	15,643	■15,487
30	12.17	2.6	322	7,301	–6,979
45	8.11	3.9	473	4,867	–4,394
60	6.08	5.0	605	3,650	–3,045
90	4.06	7.0	838	2,433	–1,595
120	3.04	8.6	1,026	1,825	–799
180	2.03	10.6	1,266	1,217	+49
365	1.00	11.8	1,399	600	+799

Notice the sign flip between the 120 and 180 day intervals: for this temperate-climate reference case, the optimal paid-cleaning interval is around 180–365 days, producing a very modest positive net recovered. This is the central counter-intuitive finding of the paper: for much of wet-temperate Ontario, routine paid PV cleaning is not economically justified on pure ROI terms.

C.6. Regulation crosswalk summary

Topic	Authority	Citation
Fall protection (construction, USA)	OSHA	29 CFR 1926 Subpart M
Fall protection (Ontario)	Ontario MOL	O. Reg. 213/91 s. 26
Full body harness	CSA	Z259.10

Topic	Authority	Citation
Energy absorber	CSA	Z259.11
PV monitoring (soiling ratio)	IEC	61724-1:2021
PV capacity evaluation	IEC	61724-2:2016
PV energy evaluation	IEC	61724-3:2016
PV module safety	CSA	F382 (IEC 61730)
Solar photovoltaic modules	CSA	C22.2 No. 256
Reagent water purity	ASTM	D1193
TDS aesthetic objective	Health Canada	GCDWQ — TDS, ≤ 500 mg/L
PV potential / solar resource	NRCan	Photovoltaic Potential Maps
Climate normals (precipitation)	ECCC	Climate Normals 1991–2020
PV O&M guidance	CanREA	Best-practice guidance

Appendix D. Glossary

Technical terms used in this paper, with brief definitions suitable for a reader new to PV operations and water-fed pole cleaning.

Term	Definition
AC	Alternating current. The form of electricity used by the grid.
ADL	Activities of daily living (not relevant to this paper; mentioned only to distinguish this project from its sibling home_care_costs
AR coating	Anti-reflective coating applied to PV module cover glass to increase transmittance. Vulnerable to abrasive cleaning methods
ASTM	American Society for Testing and Materials. Publishes the D1193 reagent water standard.
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers. Not directly cited but publishes indoor-air and bu
Boom lift	A self-propelled elevating work platform used for high-reach access when WFP is infeasible.
CanREA	Canadian Renewable Energy Association, publisher of Canadian PV O&M best-practice guidance.
Carbon block	Activated carbon filter stage used to remove chlorine and chloramine from feed water.
CSA	Canadian Standards Association. Publishes CSA F382, CSA C22.2 No. 256, and the CSA Z259 fall-arrest series.
DC	Direct current. The form of electricity produced natively by PV modules, converted to AC by the inverter.
DI	Deionization / deionized. Water from which substantially all mineral content has been removed by ion-exchange resin.
ECCC	Environment and Climate Change Canada. Source of Canadian climate normals and precipitation data.
Fall arrest	A personal protective system that stops a falling worker after the fall has begun. Triggered in Ontario at 3 m of working heigh
GHI	Global horizontal irradiance. The total solar power per unit area received on a horizontal surface, summed over direct and di
Health Canada	Federal health ministry of Canada. Publishes Guidelines for Canadian Drinking Water Quality.
IEC	International Electrotechnical Commission. Publishes the 61724 PV performance monitoring standard series.
Inverter	Power-electronics device that converts the DC output of PV modules to grid-compatible AC.
Kilograin (kgr)	Unit of ion-exchange capacity. 1 kgr is the capacity to remove one grain of calcium carbonate equivalent hardness per gallo
kWh	Kilowatt-hour. Unit of energy.
kWp	Kilowatt-peak. Unit of PV system capacity, measured under standard test conditions (1000 W/m², 25°C, A
MWp	Megawatt-peak. 1,000 kWp.
NRCan	Natural Resources Canada. Publishes the Photovoltaic Potential and Solar Resource Maps of Canada.
NREL	U.S. National Renewable Energy Laboratory. Publishes extensive soiling and PV performance research.
OSHA	Occupational Safety and Health Administration (United States). Publishes 29 CFR 1926 Subpart M on construction fall prote
Performance ratio (PR)	Ratio of actual AC energy output to theoretical DC energy output under the same irradiance. Captures all losses: temperatur
PPA	Power purchase agreement. Contract under which a utility or retailer purchases the output of a PV installation at a fixed pric
ppm	Parts per million. Used in this paper to express total dissolved solids concentration in water.
PV	Photovoltaic. A solar electricity generation technology that converts sunlight directly to DC electricity.
Reverse osmosis (RO)	A water purification method that forces water through a semi-permeable membrane, removing 95–99% of dissolved solids. U

Term	Definition
Self-cleaning ceiling	The minimum steady-state soiling loss a PV array approaches when relying on rain alone without manual cleaning.
Soiling	Accumulation of dust, pollen, bird debris, and other particulate on PV module cover glass, reducing transmittance and theref
Soiling ratio (SR)	Defined in IEC 61724-1:2021. Ratio of actual DC power to the DC power the same system would produce under the same c
TDS	Total dissolved solids. Mineral content of water, commonly measured as parts per million or milligrams per litre. Low TDS is
Transmittance	Fraction of incident light that passes through the PV cover glass to reach the semiconductor junction.
WFP	Water-fed pole. A telescoping cleaning tool that delivers deionized pure water to a soft brush at the end of a reach pole, allo
WQA	Water Quality Association. Trade association publishing technical guidance on water treatment including mixed-bed DI.

Appendix E. Northern Ontario monthly irradiance

This appendix reproduces the full Northern Ontario monthly irradiance table and briefly discusses how to use it in cleaning-schedule planning. The values are annual-average global horizontal irradiance by month, drawn from Natural Resources Canada photovoltaic potential data and cross-checked against NASA POWER. They are applicable to any fixed-tilt PV array at the relevant latitude within approximately 10 percent accuracy, with site-specific deviations driven by local horizon shading, albedo, and microclimate.

The practical implication of the Northern Ontario irradiance distribution is that a calendar-year cleaning schedule is misleading. Roughly 75 percent of annual yield occurs between April and September. Soiling loss in January has only a fraction of the dollar impact of soiling loss in July, even at the same loss percentage, because the underlying production is so much lower in winter. A cleaning programme that weights visits toward the May–September window extracts most of the available benefit; a programme that cleans in equal quarterly intervals wastes effort on the winter half of the year when the production base is small.

A second implication is that snow-cover losses in January and February, while dramatic in percentage terms (often above 90 percent loss on shallow-tilt arrays), represent a small share of annual energy value. A shallow-tilt array that loses most of its January production to snow still loses only approximately 2 percent of its annual production, because January represents approximately 3 percent of the annual irradiance budget in this climate. Mechanical snow removal is therefore rarely justified; the exception is ground-mount utility-scale arrays where even small percentage recoveries amortise across a large production base.

Global horizontal irradiance (kWh/m^2/day) by month for four Northern Ontario cities, from NRCan PV potential data.

Month	North Bay	Sudbury	Timmins	Thunder Bay
Jan	1.4	1.5	1.3	1.5
Feb	2.3	2.4	2.2	2.5
Mar	3.6	3.7	3.6	3.8
Apr	4.5	4.6	4.5	4.8
May	5.4	5.3	5.3	5.5
Jun	5.8	5.7	5.6	5.9
Jul	5.9	5.8	5.7	6.0
Aug	5.0	5.0	4.8	5.1
Sep	3.7	3.7	3.5	3.7
Oct	2.4	2.4	2.2	2.4
Nov	1.3	1.3	1.1	1.3
Dec	1.1	1.1	0.9	1.1
Avg	3.53	3.54	3.39	3.63

Appendix F. Field operations checklist

This checklist summarises the practical steps for a single WFP cleaning visit on a residential or small commercial PV array. It is not a substitute for site-specific safety planning or module-specific warranty guidance.

F.1. Pre-visit preparation

- Confirm weather: no rain forecast during cleaning window, ambient temperature above freezing, wind below manufacturer's pole maximum (typically 25–35 km/h depending on pole length).
- Check feed water TDS at the source with a pocket meter. Values above 200 ppm require an RO pre-stage or more frequent cartridge changes; values below 50 ppm allow bypass of the carbon block stage if resin is fresh.
- Verify resin cartridge outlet reads below 10 ppm before leaving the shop. Replace the cartridge if outlet reads above 8 ppm as a safety margin.
- Inspect the pole: section joints seated, quick-release clamps clean and tight, feed tube free of kinks, brush head bristles soft and splay-free.
- Bring a refractometer or pH pen if cleaning near agricultural runoff or industrial emission sources where feed water quality may vary between the start and end of the job.
- Review the site fall-protection assessment — even though WFP eliminates most fall exposure, any portion of the work above 3 m requires an alternative control (barrier, rescue plan, or substitution).

F.2. On-site setup

- Park the WFP vehicle with the feed hose running the shortest practical route to the work area. Long hose runs reduce pressure at the brush head and slow the job.
- Set up the pole at the ground with the brush head attached but dry. Confirm telescoping action is smooth and that the feed tube is fully connected at every joint.
- Flush the full water chain for 30 seconds with the brush head pointed at a drain or ground. Confirm the outlet TDS meter reads below 10 ppm.
- Photograph the array before cleaning. Capture any pre-existing damage, bird droppings, hotspots, or unusual soiling patterns for the service record.
- Communicate with the building owner or occupant. Ensure no one is beneath the array during cleaning. Water dripping from the lower edge of an elevated array is expected and is not a problem for most surfaces but can be an issue for cars, patio furniture, or pedestrians below.

F.3. Cleaning sequence

- Flush each module with pure water before agitation. The initial flush floats loose grit off the surface so the brush is not dragging abrasive particles across the coating.
- Agitate in the long direction of the module. Short-direction strokes can snag on the lower edge of the frame and jar the brush off the surface.

- Work from the top of the array downward. This prevents redeposition of flushed soil onto already-cleaned modules.
- Rinse each module with pure water after agitation. Allow the rinse water to sheet off without towelling. If the operator sees the water breaking into droplets rather than sheeting, outlet TDS is too high and the cartridge is exhausted.
- Check outlet TDS every ten minutes during the job. A rising trend indicates the cartridge is nearing end of life and the job should be paused to replace the cartridge before spotting begins.

F.4. Post-visit wrap-up

- Photograph the array after cleaning. Before/after photo pairs are the principal service record for customer communication and warranty documentation.
- Record the final outlet TDS reading, the volume of pure water consumed (from the tank level), and any observations about module condition (cracked modules, frame corrosion, bird damage, wildlife nesting).
- Rinse the pole and brush at the shop with fresh water to remove any residual soil before the next job. A soil-loaded brush at the start of the next job is a scratch risk.
- Store the pole horizontally or on a wall-mounted rack. Storing vertically with a wet brush can cause the bristles to set permanently at an angle.
- If the cartridge was exhausted mid-job, label it for return to the resin regeneration programme and replace before the next visit.

F.5. Red flags that should trigger a pause

- Visible hard-water spotting during or after cleaning — indicates cartridge exhaustion; stop immediately.
- Brush grinding or scratching noise when dragged across the module — indicates grit embedded in the brush; rinse brush thoroughly before continuing, and replace if the noise persists.
- Module that is visibly cracked, delaminated, or has visible moisture inside the laminate — electrical hazard; do not clean; flag for owner to contact a qualified PV technician.
- Module that is warm to the touch around a specific cell or area (assess with a non-contact IR thermometer if available) — possible hotspot; clean cautiously and notify owner.
- Pole deflection above manufacturer's specification or noticeable creaking sounds from pole sections — retract to a shorter length or terminate the job.